MICROHABITAT USE AND MOVEMENT BY

SOUTHERN BROOK TROUT (*SALVELINUS FONTINALIS*)

IN A NORTH CAROLINA STREAM

by

ZACHARY WILLIAM ANGLIN

(Under the Direction of Gary D. Grossman)

ABSTRACT

The southern brook trout is a genetically distinct form of brook trout found in the southern Appalachian Mountains, yet little is known about its ecology. I quantified microhabitat use of southern book trout over six seasonal samples (summer 2010, autumn 2010, spring 2011, summer 2011, autumn 2011, and spring 2012) and movement of southern book trout over three sample seasons (spring 2011, autumn 2011, and spring 2012) in Ball Creek, NC. Trout occupied deeper microhabitats with lower mean velocities and higher amounts of erosional substrata than were randomly available within the site. Upstream and downstream movements were exhibited during all seasons. No individuals exhibited movements greater than 300 meters. My results suggest that most southern brook trout have relatively small home ranges (< 20 m). Limited home ranges suggest that persistent populations require all essential habitat types within a relatively small area and that exchange among populations is likely minimal. Because natural populations of southern brook trout are isolated, microhabitat use and movement information will be useful for management and conservation of this subspecies.

INDEX WORDS: southern brook trout; microhabitat; movement, Appalachia

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ZACHARY WILLIAM ANGLIN

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Major Professor: Gary Grossman

Committee: Robert Bringolf
Nathan Nibbelink

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
The University of Georgia
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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

The natural distribution of brook trout (*Salvelinus fontinalis*) stretches nearly the entire length of the Appalachian Mountains. Although invasive brown (*Salmo trutta*) and rainbow trout (*Oncorhynchus mykiss*) have been widely stocked and are established throughout its native range, the brook trout is the only trout native to the southeastern United States (Behnke 2002). From Maine to Georgia, brook trout survive in small, cool, fast-flowing headwater streams (Cunjak and Power 1986; Johnson and Dropkin 1996) typically above barriers that prevent upstream movement by brown and rainbow trout. There are two genetically distinct forms of brook trout, the northern brook trout, and the southern brook trout, and these forms have fixed genetic differences which demonstrate reproductive isolation (Stoneking et al. 1981; Habera and Moore 2005). These genetic differences likely warrant the reclassification of brook trout into separate subspecies and perhaps even distinct species. Compared to other salmonids, relatively little is known about the southern brook trout's life history and habitat requirements (Grossman et al. 2010) especially microhabitat requirements. For this thesis, microhabitat is defined as the sum of all biotic and abiotic characteristics immediately surrounding an individual. The lack of knowledge about southern brook trout inhibits the implementation of potential conservation regimes to safeguard this species from excessive harvest, invasive species, and habitat degradation. Largely because of the aforementioned activities, the distribution of brook trout has decreased in the past three decades, mostly in the southern portion of its range (Hudy et al. 2008).

In addition to local stressors, large-scale factors such as global climate change may have major impacts on the distribution and abundance of southern brook trout. Although there is controversy regarding the exact effects of global climate change, Flebbe et al. (2006) modeled climate change on trout distribution within the Southern Appalachians and created possible regional distribution maps for trout, including brook trout, in the region. These maps were based on two separate models of predictive climate change; the first of which, the Hadley Centre Global Circulation Model (predicted 2.3°C increase in mean annual temperatures in the Southeast United States by the year 2100), estimated a 53% reduction in brook trout distribution, whereas the second, the Canadian Centre Global Circulation Model (predicted 5.5°C increase in mean annual temperature in the Southeast United States by the year 2100), estimated a more drastic 97% reduction in brook trout distribution within its southern range. Meisner (1990) also predicted reductions in brook trout populations in the southern range of their distribution due to climate change based on the climate warming scenario of the Goddard Institute for Space Studies (predicted 4.5°C increase in mean annual temperature in the Southeast United States by the year 2100). Given that most southern brook trout populations already are isolated above barriers with presumably little exchange among streams, global climate change clearly will result in greater fragmentation by increasing stream temperatures. Some projections suggest that southern brook trout could be driven to extirpation (Flebbe et al. 2006). These factors underpin the necessity for quantification of habitat selection patterns for southern brook trout.

Most of what is known about brook trout biology is based on studies of northern brook trout (Habera and Moore 2005). However, given their genetic uniqueness, it is uncertain if southern brook trout possess the same biological characteristics as their northern counterparts. Here, I review the existing published literature on habitat use by brook trout. Spot-sample electrofishing and snorkeling are the most common methods for determining habitat use by brook trout, with most work being done in warm seasons (Cunjak and Green 1983; Cunjak and Power 1986; Johnson et al. 1992; Lohr and West 1992; Johnson and Dropkin 1996; Sotiropoulos et al. 2006; Johnson 2008). Brook trout microhabitat is generally characterized as slow-flowing waters with large substratum such as cobbles and boulders (Johnson and Dropkin 1996; Sotiropoulos et al. 2006).

Age-related differences in microhabitat use do occur and are characterized by larger brook trout utilizing deeper, slower-flowing microhabitats (pools) with larger substratum and more cover than smaller/young of the year (YOY) brook trout (Cunjak and Power 1986; Johnson et al. 1992; Johnson and Dropkin 1996; Johnson 2008). This generality holds true in invasive populations of brook trout in western streams as well (Griffith 1972). Young of the year (YOY) brook trout are over-represented in shallower, faster flowing waters (riffles) with small substratum materials (sand and gravel) and less cover (Cunjak and Power 1986; Johnson et al. 1992; Johnson and Dropkin 1996; Johnson 2008). It is likely that YOY brook trout are found more frequently in riffle habitats because of frequent antagonistic interactions with larger brook trout (Anglin pers. obs.). Microhabitat quality seems to be related to age, with older fish occupying higher quality microhabitats and younger fish occupying less optimal microhabitats (Hughes 1998; Rosenfeld et al. 2000). However, Lohr and West (1992) did not observe differences in water velocities utilized by YOY and adult brook trout in Palmer Creek, North Carolina, although the origin of this population (i.e., southern, northern, mixed) is unknown. In general, brook trout occupy microhabitats that represent deeper areas (pools) with nearby cover, medium to low water velocities (generally < $0.50 m*s^{-1}$) and a range of substrata (sand to boulder) (Gibson 1978; Cunjak and Green 1983; Cunjak and Power 1986; Johnson et al. 1992; Lohr and West 1992; Johnson and Dropkin 1996; Sotiropoulos et al. 2006; Johnson 2008). However, habitat use by brook trout is strongly dependent on habitat availability as well as brook trout density (Utz and Hartman 2009), and the variability in habitat use by this species (wide range of substratum categories, water velocities) may be attributed to the diversity of available stream habitats found in brook trout streams. With the exception of Lohr & West (1992), our current knowledge of microhabitat characteristics for brook trout is based on fish from northern populations and therefore may not be representative of southern brook trout.

Movement of non-anadromous trout species has been well studied in northern and western states (Bartrand et al. 1994; Downs et al. 2006; James et al. 2007), but as with habitat data there are scant data on movements of southern brook trout. During the majority of the past century, stream-resident fish were considered to be stationary, or non-migratory (Gerking 1959). Challenging this idea, Gowan et al. (1994) presented data from field studies that implied stream-resident salmonids are much more mobile than previously suggested (Fausch and Young 1995; Gowan and Fausch 1996; Young et al. 1997). A combination of factors may influence brook trout movement, including water quality, food availability, reproduction condition, habitat availability, or other essential resources (Riley et al. 1992; Fausch and Young 1995; Logan 2003; Petty et al. 2005; Liller 2006). Roghair (2005) observed central Appalachian brook trout movement and recolonization in a Virginia stream after a natural defaunation event, noting that trout had recolonized the 1.9 kilometer defaunated section, progressing from upstream to downstream, in 2.5 to 3.0 years, which is an average of 0.69 kilometers per year. Movement studies of brook trout have yielded varying results, including examples of both small and large movements within individual populations (Hartman and Logan 2010). Some individuals within populations have been shown to move very little (e.g., <100 m; Adams et al. 2000), while examples of high immigration rates (e.g. >3000m; Gowan et al. 1994; Gowan and Fausch 1996) have also been observed, suggesting that some individuals utilize larger spatial scales than others (Adams et al. 2000).

In summary, relatively little is known about southern brook trout life history and habitat requirements (Grossman et al. 2010). Current knowledge of microhabitat characteristics for brook trout is mainly based on northern populations and therefore may not be representative of southern brook trout. This lack of knowledge inhibits the implementation of potential conservation regimes to safeguard this species from excessive harvest, invasive species, and habitat degradation. These activities have already decreased the natural distribution of southern brook trout, especially in the southern portion of its range (Hudy et al. 2008). In the following chapter, I will describe an observational study I performed to examine the possible non-random use of microhabitats by southern brook trout in a third-order North Carolina headwater stream.

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CHAPTER 2

MICROHABITAT USE BY SOUTHERN BROOK TROUT

(*SALVELINUS FONTINALIS)* IN A

NORTH CAROLINA STREAM [1]

[1] Anglin, Z.W. and G.D. Grossman. To be submitted to Ecology of Freshwater Fish

Abstract

The southern brook trout is a genetically distinct form of brook trout found in the southern Appalachian Mountains, yet little is known about its ecology. I quantified microhabitat use of southern book trout in Ball Creek, NC., a third order stream during six seasonal samples (summer 2010, autumn 2010, spring 2011, summer 2011, autumn 2011, and spring 2012). In summer 2010, young-of-the-year (YOY) southern brook trout utilized microhabitats with greater amounts of sand and bedrock than age 1+ and age 2+ southern brook trout. In autumn 2010, age 1+ southern brook trout occupied deeper areas with more erosional substrata and less silt than YOY and age 2+ southern brook trout. In autumn 2011, YOY southern brook trout utilized deeper areas with greater amounts of small cobble and sand and less debris than age 1+ and age 2+ southern brook trout. In spring 2012, YOY southern brook trout used shallower areas with more silt, lower mean water velocities, and less small cobble and gravel than age 1+ and age 2+ southern brook trout while age 1+ southern brook trout utilized deeper areas with higher mean water velocities, more small cobble and gravel, and less silt than YOY southern brook trout, but shallower areas with less boulder than age 2+ southern brook trout. In general trout preferentially occupied deeper microhabitats with lower mean velocities and higher amounts of erosional substrata than were randomly available within the site. Southern brook trout are found in isolated populations and microhabitat information will be useful for management and conservation of this subspecies.

Introduction

Brook trout (*Salvelinus fontinalis*) occur over nearly the entire length of the Appalachian Mountains and are the only char (*Salvelinus sp.*) native to the eastern United States (Behnke 2002). From Maine to Georgia, brook trout inhabit headwater streams with cool, fast-flowing waters (Cunjak and Power 1986; Johnson and Dropkin 1996). Over the past three decades, the natural distribution of brook trout has decreased mostly in the southern portion of its range (Hudy et al. 2008) This decrease is a function of many factors including displacement by stocked, invasive brown (*Salmo trutta*) and rainbow trout (*Oncorhynchus mykiss*) (Habera and Moore 2005). Two distinct forms of brook trout exist; the northern brook trout and the southern brook trout and these forms possess fixed genetic differences and probably warrant at least subspecific status (Stoneking et al. 1981; Habera and Moore 2005). Unlike most other salmonids, relatively little is known about the ecological characteristics and habitat requirements of southern brook trout (Habera and Moore 2005; Grossman et al. 2010) which inhibits scientifically based management for this species.

Large-scale factors such as global climate change may have major impacts on the distribution and abundance of southern brook trout. Although there is controversy regarding the exact effects of global climate change, Flebbe et al. (2006) modeled the effects of climate change on trout distribution within the Southern Appalachians and predicted a 53% and 97% reduction in brook trout distribution respectively, depending on whether the Hadley Centre Global Circulation or the Canadian Centre Global Circulation Model was used. Similar reductions in distribution were obtained by Meisner (1990) using the Goddard Institute for Space Studies model. Because most southern brook trout populations already are physically isolated above barriers with presumably low inter-population exchange among streams, global climate change clearly will result in greater fragmentation and isolation by increasing stream temperatures that may result in localized extirpation of many southern brook trout populations (Flebbe et al. 2006).

Given the paucity of information on southern brook trout and the vulnerability of this species to climate change and invasive species, I quantified microhabitat use of southern brook trout during spring, summer, and autumn in upper Ball Creek, North Carolina. Specifically, I compared microhabitat use by southern brook trout to random microhabitat availability samples to test the hypothesis that microhabitat use did not differ statistically from a random expectation (Skyfield and Grossman 2008). In addition, I tested for significant differences in microhabitat use by YOY, 1+, and 2+ southern brook trout within a season, as well as for seasonal differences within an age class.

Methods and Materials

Study Site

My study site consisted of a 130 meter section of stream located within a third-order stretch of Ball Creek, NC, U.S.A. located on the USDA Forest Service Coweeta Hydrologic Laboratory in Otto, North Carolina (35_11'N; 83_23'W). The study site is bisected by a small natural waterfall and was considered a possible barrier to fish movement. All microhabitat use and microhabitat availability observations were conducted in the two 50 meter sections immediately above and below the stretch of stream containing the possible barrier to fish movement.

The study site consisted of riffle-pool morphology with a mean wetted width of 5.2 meters (± 0.3 meters; 95% C.I.). The surrounding mixed hardwood-conifer forest provided dense canopy cover, shading the stream during the growing season. Riparian vegetation was dominated by rhododendron (*Rhododendron maximum*) which is typical of headwater streams in the southern Appalachian Mountains. The fish assemblage is composed of only three species: southern brook trout (southern strain genetic confirmation by T. King, United States Geological Survey), mottled sculpin (*Cottus bairdi*), and rainbow trout (*Oncorhynchus mykiss*).

Microhabitat Availability Measurements

I quantified microhabitat availability using a stratified sampling design. Sampling dates for both microhabitat availability and southern brook trout microhabitat use were as follows: June 28- July 16, 2010 (SU10); Sept. 12- Sept. 25, 2010 (AU10); April 23- May 10, 2011 (SP11); July 9- July 20, 2011 (SU11); Sept. 24- Oct. 8, 2011 (AU11); April 27- May 5, 2012 (SP12). Cross-stream transects were placed every two meters, yielding a total of 100 transects. I used a random number generator to select a random point on each transect and took the following measurements: water depth (meter stick), mean water column velocity (Marsh-McBirney model 201 velocity meter ± 0.01 m s^{-1}), and substratum composition (visually estimated within a 400 cm^2 quadrant; % bedrock, boulder, large cobble, small cobble, gravel, sand, silt, debris) using the methods of Grossman and Skyfield (2009). Wetted width was measured at 10 m intervals along the stream bank. I collected microhabitat availability data twice (first day of sampling and last day of sampling) during each sampling period resulting in a total of 600 data points (100 points per season per year).

Microhabitat Use Observations

I quantified brook trout microhabitat use with the methods of Grossman and Freeman (1987) and Grossman and Skyfield (2009). This method has been successfully used to quantify microhabitat selection by both salmonid and non-salmonid stream fishes both in North America and Europe (Grossman and de Sostoa 1994; Grossman and Ratajczak 1998). I began observations at the lower end of the site and carefully snorkeled upstream observing undisturbed fish (i.e. those that did not display characteristic disturbance responses, Skyfield & Grossman 2008). As per Skyfield and Grossman (2008), when I encountered an undisturbed brook trout I collected the following measurements: standard length (visual estimate, nearest cm), average water column velocity (Marsh-McBirney model 201 velocity meter ± 0.01 $m\ s^{-1}$, taken at 60% of the water column depth), focal point water velocity (Marsh-McBirney model 201 velocity meter ± 0.01 $m\ s^{-1}$), water column depth (meter stick), depth above substratum (meter stick), distance from shelter (meter stick), shelter type, and substratum composition (visually estimated within a 400 cm^2 quadrant directly below the fish; % bedrock, boulder, large cobble, small cobble, gravel, sand, silt, debris). I defined shelter as any object capable of concealing at least 50% of a fish's body (Skyfield & Grossman 2008). All data were relayed to a recorder stationed downstream. For consistency all observations were made under base flow conditions.

Statistical Analysis

I quantified both seasonal changes in microhabitat availability and non-random microhabitat use in brook trout by using the methods of Grossman and de Sostoa (1994) and Skyfield and Grossman (2008). To test for seasonal and annual differences in microhabitat availability, I ran a principal component analysis (PCA), on all seasonal microhabitat availability data. I only interpreted principal components if they displayed eigenvalues greater than one, were ecologically interpretable and not redundant with components that had greater eignvalues. I then used PCA to compare southern brook trout microhabitat use data with availability data within a season as a test for non-random microhabitat use (Skyfield and Grossman 2008). Finally to test for age-related differences in microhabitat use, I also ran PCA's on microhabitat use data of YOY, 1+, and 2+ southern brook trout (Grossman and Ratajczak 1998) (based on standard length: SU10 & SU10: 4-8 cm young of the year, 10-11cm 1+ year old, and 12-13cm 2+ years old; SP11: 4-8 cm young of the year, 9-11cm 1+ year old, and 12-13cm 2+ years old; SU11: 4-9 cm young of the year, 10-12cm 1+ year old, and 13-15cm 2+ years old; AU11: 4-9 cm young of the year, 10-13cm 1+ year old, and 14-16cm 2+ years old; SP12: 6-12 cm young of the year, 13-14cm 1+ year old, and 16-17cm 2+ years old, Grossman et al. unpublished data). Comparisons of microhabitat use were made among age classes within a season and across seasons (test for seasonal/annual variation) within age classes. Seasonal/annual comparisons were evaluated against seasonal variation in microhabitat availability to discern true seasonal differences from those produced by seasonal/annual changes in microhabitat availability. Means and 95% confidence ellipses were calculated for all comparisons in all sampling seasons and non-overlapping confidence ellipses indicated significance at the 0.05 alpha level or lower (Skyfield and Grossman 2008).

Results

Seasonal and Annual Variation in Microhabitat Availability

The PCA of seasonal microhabitat availability data from 2010-2012 extracted six components with eigenvalues greater than 1.0 and explained 75% of the variance in the microhabitat availability data. Principal components one (PC1) and two (PC2) were ecologically interpretable, non-redundant, and explained 16% and 14% of the variation, respectively (Fig. 2.1). Univariate means for each season are presented in Table 2.1 with variables that loaded significantly on PC1 and 2 in bold. Seasonal comparisons indicated that spring 2011 (SP11) and spring 2012 (SP12) had higher mean water velocities and greater amounts of bedrock than summer and autumn samples; although, both SP11 and SP12 differed from autumn 2010 (AU10) (Fig. 2.1). No other seasons differed significantly on PC1. Results for PC2 demonstrated that SP11 and SP12 tended to have more large cobble than other seasons, although no seasons differed statistically. I observed no significant differences in microhabitat availability between the same season in different years.

Seasonal and Annual Variation in Southern Brook Trout Microhabitat Use

Principal component analyses of seasonal microhabitat availability and southern brook trout microhabitat use data for individual seasons (SU10-SP12) extracted at least two significant components that explained between 69 and 79% of the variance present within the data sets. PC1 always displayed the strongest evidence for non-random microhabitat use and represented a gradient of shallow, high-velocity areas with erosional substrata versus deeper areas with lower water velocities dominated by depositional substrata. Principal component two (PC2) depicted a gradient of high amounts of erosional substratum versus high amounts of depositional substrata. Depth always was negatively correlated with water velocity and positively correlated with increasing depositional substrata. These results indicate that the site contained elements of a riffle-pool continuum.

In general, southern brook trout were over-represented in areas with deeper water and higher amounts of depositional substrata. Figure 2.2 displays typical results for individual seasonal analyses, although there was some variation among seasons. This PCA (SP12) extracted six components with eigenvalues greater than 1.0 and explained 77% of the variance in the pooled microhabitat use data. Principal components one and two explained 18% and 14% of the variation, respectively. Principal component one described a microhabitat gradient of high mean water velocities with lower quantities of depositional substrata versus microhabitats with low mean water velocities and greater quantities of depositional substrata (Fig. 2.2). Principal component two portrayed a gradient of deeper areas with greater amounts of boulder and less gravel as opposed to shallower areas with greater amounts gravel and less boulder. Comparing Figures 2.1 and 2.3, it is clear that most seasonal changes in microhabitat use were related to seasonal changes in microhabitat availability (e.g. trout utilized faster water velocities in SP11 than other seasons because microhabitats in SP1l had higher mean water velocities than other seasons). Both autumn and spring samples showed significant shifts in microhabitat use between years, with SP12 exhibiting the largest shift. Book trout in SP12 utilized microhabitats with slower mean water velocities and larger amounts of depositional substrata than brook trout in SP11, even though microhabitat availability for SP11 and SP12 were not significantly different. Brook trout in AU11 utilized microhabitats with higher mean water velocities and less depositional substrata than brook trout in AU10, even though autumn microhabitat availability was not significantly different between years.

Age-related Variation in Southern Brook Trout Microhabitat Use

Age-related differences in microhabitat use varied within seasons, among seasons, and between the same season in different years. Principal component analyses of within-season age-specific microhabitat use (SU10-SP12) extracted at least two significant components that explained between 67 and 80% of the variance in the data sets (Fig. 2.4). Principal component one typically represented a gradient of shallow, high velocity locations with erosional substrata versus deep, low velocity areas and depositional substrata. Principal component two generally depicted a similar gradient with fewer variables.

I observed age related differences in microhabitat use by southern brook trout in multiple years and seasons. Young-of-the-year southern brook trout utilized microhabitats that were significantly different from age 1+ and age 2+ of brook in SU10, AU11, and SP12 (Fig. 2.4). In SU10, YOY occupied microhabitats greater amounts of sand and bedrock than 1+ and 2+ southern brook trout. In AU11, YOY utilized deeper areas with greater amounts of small cobble and sand and less debris than 1+ and 2+

southern brook trout. In SP12, YOY used shallower areas with more silt, lower mean water velocities and less small cobble and gravel than 1+ and 2+ southern brook trout. When YOY occupied microhabitats that differed from older southern brook trout, they generally were found over greater amounts of depositional substrata. Age 1+ southern brook trout utilized microhabitats that were significantly different from YOY and age 2+ southern brook trout in SP12 for two out of six seasons (AU10 and SP12). In AU10, 1+ southern brook trout occupied deeper areas with more erosional substrata and less silt than YOY and 2+ trout. Similarly, in SP12, 1+ southern brook trout utilized deeper areas with higher mean water velocities, more small cobble and gravel, and less silt than YOY southern brook trout (Fig. 2.4). By contrast, in spring 2012, 1+ southern brook trout occupied shallower areas with less boulder than 2+ brook trout (Fig. 2.4). Age 2+ southern brook trout occupied microhabitats that were significantly different from YOY and/or 1+ southern brook trout during SU10, AU10, and SP12. Age 2+ southern brook trout also occupied microhabitats that were significantly different from YOY southern brook trout during SU10, with 2+ fish utilizing deeper, slower microhabitats with more silt and debris and less small cobble than YOY southern brook trout. In AU10, 2+ southern brook trout utilized shallower areas with more silt and less boulder and bedrock than 1+ southern brook trout. Age 2+ microhabitat use for SP12 has been described previously.

Seasonal differences in microhabitat use were observed in YOY, but not in 1+ southern brook trout. Principal component analysis of YOY microhabitat use data extracted five components with eigenvalues greater than 1.0 and explained 69% of the variance in the microhabitat use data. Principal component one and PC2 were ecologically interpretable, non-redundant, and explained 20% and 15% of the variation, respectively (Fig. 2.5). Principal component one described a microhabitat gradient contrasting high mean velocities with high amounts of sand and boulder versus low mean water velocities with greater amounts of silt. PC2 portrayed a gradient of deeper areas with less small erosional substrata versus shallower areas with greater amounts of small erosional substrata. Microhabitat use by YOY in 2010 differed significantly among seasons, although microhabitat availability did not. In SU10, YOY utilized areas with higher average water velocities, less silt and more sand and boulder than YOY in AU10. Microhabitat use in 2011 did not differ among seasons. Over all years, YOY southern brook trout utilized significantly lower mean water velocities and more silt and less sand and boulder in SP12 than in any other season. In AU11 YOY occupied microhabitats with higher mean water velocities and greater amounts of sand and boulder than those used by YOY in AU10. Inter-annual seasonal comparisons did not reveal significant differences in microhabitat use by 1+ southern brook trout attributed to active selection rather than seasonal changes in microhabitat availability (Figs. 2.1 and 2.6)

The principal component analysis of seasonal microhabitat use among years by 2+ southern brook trout for all seasons extracted five components with eigenvalues greater than 1.0 and explained 71% of the variance present in the microhabitat use dataset. Principal component one and PC2 were ecologically interpretable and explained 18% and 16% of the variation, respectively (Fig. 2.7). Microhabitat use by 2+ trout in 2010 was significantly different between seasons, with trout in SU10 occupying deeper microhabitats with lower mean velocities and greater amounts of sand and lower quantities of small cobble and silt than 2+ southern brook trout in AU10. Microhabitat use in 2011 did not differ significantly among seasons. Inter-annual comparisons revealed that in SU11, age 2+ southern brook trout occupied shallower areas with higher mean water velocities and more small cobble and silt and less sand than in SU10 and that these shifts were not associated with shifts in microhabitat availability (Figs. 2.1, 2.2, and 2.7).

Discussion

To my knowledge, this is the first study of southern brook trout microhabitat use. Southern brook trout in upper Ball Creek, N.C., displayed non-random microhabitat use in every season between summer 2010 and spring 2012, although I did not conduct winter sampling. In general, southern brook trout occupied deeper areas with greater quantities of small erosional (i.e. small cobble, gravel) and depositional substratum (i.e. sand, silt, debris) and lower amounts of large erosional substratum (i.e. bedrock, boulder, large cobble). These areas correspond to plunge pools within the stream. There were several clear seasonal/annual changes in microhabitat use and southern book trout in SP12 utilized microhabitats with lower mean velocities and larger quantities of depositional substrata than fish in SP11. In addition, southern brook trout in AU11 utilized microhabitats with higher water velocities and less depositional substrata than specimens in AU10. These shifts may be linked to differences in density (density was much greater in SP12 and AU10 than SP11 and AU11 (pers. obs.)) which is known to affect habitat selection in salmonids (Hill and Grossman 1993).

Age-related seasonal differences in microhabitat use for southern brook trout were more complex. Microhabitat use by age 1+ and 2+ southern brook trout was very similar, with most older trout occupying lower velocity microhabitats with greater quantities of depositional substrata. Autumn 2010 and SP12 were the only seasons where age 1+ and 2+ individuals utilized different microhabitats, with 1+ southern brook trout occupying deeper areas with more erosional substrata and less silt than 2+ southern brook trout in AU10 and shallower microhabitats with less boulder than 2+ southern brook trout in SP12. In SP12, 1+ southern brook trout also utilized deeper areas with higher mean water velocities and more small cobble and gravel and less silt than YOY. In addition, seasonal variation in microhabitat was present in age 2+ trout, which in SU10 occupied deeper areas with lower water velocities and less small cobble and silt and more sand than 2+ trout in SU11. A similar pattern existed for 2+ fish between, SU10 and AU10.

Why do southern brook trout display non-random microhabitat use? Previous studies have shown that individuals that select microhabitats that maximize net energy gain should be favored by natural selection (Hill and Grossman 1993; Grossman et al. 2002). Linking net energy gain to microhabitat use is particularly appropriate for drift feeders like southern brook trout because stream microhabitats differ in their net profitability (Grossman et al. 2002). Southern brook trout must balance the cost of maintaining position against a current versus the increased profitability obtained from occupying faster velocities (Grossman et al. 2002). Thus, velocity is a very important component of microhabitat use for stream water column dwellers, including southern brook trout (Grossman et al. 2002). Hill and Grossman (1993) examined microhabitat use by rainbow trout in the Coweeta Creek drainage as a function of net-energy intake (prey availability and utilization at different water velocities) and found that to maximize energy gain, rainbow trout utilized a mean water velocity of 17.0 ± 3.9 cm/sec (95% C.I.). The mean water velocity observed for southern brook trout in upper Ball Creek fell within the confidence interval of this value (95% C.I. = 17.3 ± 4.3 cm/sec), suggesting that southern brook trout may be selecting microhabitats on the basis of maximizing energy gain. Comparison of age-related mean water velocity use by rainbow trout from Hill and Grossman (1993) and southern brook trout from this study yielded no significant differences for any age class (overlap of 95% C.I.). Utilizing microhabitats that maximize energy gain is not an uncommon strategy in stream salmonids (Hughes and Dill 1990, Hughes et al. 2003). Although I did not sample drift, it seems highly probable that southern brook trout in Ball Creek are utilizing microhabitats that maximize their net-energy intake.

To my knowledge, this is the first study of microhabitat use in southern brook trout. Even for northern brook trout, underwater observational studies of microhabitat use are not common, nor are similar studies for invasive brook trout populations (Griffith 1972) and it is important to note that northern brook trout are usually found in larger streams than southern strain brook trout. There is evidence suggesting that southern brook trout have been displaced from larger streams by invasive rainbow and brown trout which have pushed southern brook trout into stream reaches that formerly represented the upper end of their distribution in a given stream (Moore et al. 1983). Thus my observations on southern brook trout microhabitat use represent a subset of what would be potentially usable in the absence of rainbow trout, which also occur in Ball Creek.

Microhabitats used by northern brook trout generally consist of deep, slow flowing locations dominated by cobbles and boulders, although some of these studies represent limited seasonal (summer only) or annual time spans (Johnson and Dropkin (1996; Sotiropoulos et al. 2006). My results are similar to these authors with the exception of substratum use. Southern brook trout in Ball Creek generally were found over depositional substrata rather than cobble and boulder. Northern populations also show similar age-linked shifts in microhabitat use to those observed in southern strain fish in Ball Creek. Specifically, older fish utilized deeper, slower flowing microhabitats with larger substrata and greater amounts of cover than YOY (Griffith 1972; Cunjak and Power 1986; Johnson et al. 1992; Johnson and Dropkin 1996; Johnson 2008). However, unlike northern populations, 1+ and 2+ southern brook trout occupied microhabitats with greater amounts of depositional substrata than YOY southern brook trout although this is likely represented a depth response. Comparisons of microhabitat use by southern and northern YOY are not as similar. Southern YOY displayed variable microhabitat use, occupying low to high velocity locations, deep to shallow areas, and a mixture of substrata. This variation may be a result of frequent antagonistic interactions with older brook trout (Anglin pers. obs.) and intraspecific competition has been identified as the dominant process in the regulation of this (Grossman et al. 2010) and other populations (Grossman el al. 2012). Territoriality is present in brook trout with older (larger) fish occupying higher quality microhabitats and younger fish occupying less optimal microhabitats from which young (smaller) fish are displaced (Rosenfeld et al. 2000, Johnson 2008).

Salmonids are one of the most well studied groups of fishes, largely due to their popularity as sportfishes. Generally, salmonid microhabitat use can be characterized as consisting of deeper areas (Johnson and Dropkin 1996) dominated by cobbles, boulders, or gravel, with nearby cover (Johnson and Dropkin 1996; Meyer and Griffith 1997; Grossman and Ratajczak 1998; Huusko et al. 2007). Age related differences in microhabitat selection are common in salmonid species with adults utilizing deeper waters with greater amounts of erosional substrata and substantial cover, whereas YOY salmonids occupying shallower waters with less available cover and greater amounts of depositional substrata(Griffith 1972, Cunjak and Power 1986, Baltz et al. 1991, Johnson et al. 1992). Southern brook trout differ from the general trend in age-related microhabitat use in that older individuals occupy microhabitats with greater amounts of depositional substrata whereas young individuals utilize more erosional substrata. It is important to note that microhabitat use by salmonids frequently varies both seasonally and among systems (Johnson and Dropkin 1996; Gries and Juanes 1998).

My study suffered from several limitations. First, my results are from only one stream. Although unlikely, these results may not be reflective of typical southern brook trout microhabitat use in their southern range. Also, YOY were not present in SP11 and perhaps recruited after sampling occurred. In addition, sample sizes for 2+ fish were low throughout the study (6-15 fish), because most southern brook trout do not live past their third year of life (Grossman et al. 2010). Although not uncommon for microhabitat studies, I did not sample during winter months because fish in this region typically are quiescent during this season (Grossman and Ratajczak 1998). With respect to environmental conditions during my study, regional precipitation was normal for all seasons except for SU 10 (drier than average) and SP11 (wetter than average) (USDA Forest Service Coweeta Hydrologic Laboratory precipitation data; gauge 19). Inter-annual differences in microhabitat use by southern Appalachian stream fishes are not uncommon (Grossman and Ratajczak 1998) nor is this phenomenon uncommon in other regions (Gries and Juanes 1998; Johnson 2008; Johnson and Dropkin 1996). In addition, although my focal-point velocity measurements for southern brook trout were statistically indistinguishable from those of optimal microhabitats for rainbow trout in the same system (Hill and Grossman 1993), it would be beneficial if an energy maximization model were developed specifically for southern brook trout. Such a model might yield insight into why brook trout shifted microhabitat use between spring seasons and autumn seasons of different years while microhabitat availability remained relatively constant for those seasons.

The southern brook trout possesses fixed genetic differences that distinguish it from northern populations (Stoneking et al. 1981, Habera and Moore 2005). Given the declines in this species both throughout its range and especially in the southern Appalachian region, understanding microhabitat use by southern brook trout should aid in management and conservation of remaining populations. It is likely that southern brook trout will continue to face future habitat degradation and fragmentation both via changes in land use (Elser 1968; Chapman and Knudsen 1980) and warming from global climate change (Flebbe et al. 2006). It is my hope that the data thus presented will aid managers in preserving this unique subspecies of trout.

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Table 2.1 Means and (standard deviations) of microhabitat availability, pooled microhabitat use, and age-specific microhabitat use data of southern brook trout in Ball Creek, N.C. for all seasons. Bold means and standard deviations represent significant differences at the 0.05 level using a t-test.

Season	Data Type	n	Ave. Vel. ($m*s^{-1}$)	Depth (cm)	% Bedrock	% Boulder	% Lg. Cob.	% Sm. Cob.	% Gravel	% Sand	% Silt	
Summer	**Available**	100	**0.30 (0.26)**	**14 (10)**	16 (36)	9 (26)	23 (36)	**12 (27)**	**11 (23)**	**11 (25)**	**16 (34)**	**1 (5)**
2010	**Use**	88	**0.19 (0.16)**	**38 (15)**	11 (27)	10 (22)	6 (13)	**7 (17)**	**18 (27)**	**28 (34)**	**11 (27)**	**8 (23)**
	YOY	60	0.21 (0.17)	33 (9)	**13 (28)**	8 (19)	7 (18)	6 (14)	16 (25)	**33 (38)**	10 (25)	7 (21)
	1+	17	0.19 (0.12)	46 (20)	**8 (21)**	22 (30)	8 (17)	5 (8)	12 (18)	**16 (23)**	13 (28)	17 (34)
	2+	11	0.09 (0.05)	51 (17)	**7 (24)**	8 (19)	6 (15)	4 (10)	38 (37)	**19 (27)**	17 (37)	1 (3)
Autumn	**Available**	100	**0.24 (0.26)**	**14 (13)**	11 (31)	18 (32)	19 (30)	**10 (25)**	16 (27)	**3 (11)**	**19 (32)**	4 (12)
2010	**Use**	79	**0.15 (0.42)**	**34 (12)**	10 (22)	13 (28)	9 (21)	**7 (15)**	16 (26)	**20 (29)**	**24 (35)**	3 (14)
	YOY	43	0.10 (0.07)	**30 (11)**	**9 (21)**	**7 (19)**	9 (13)	9 (19)	12 (17)	24 (30)	**27 (35)**	5 (17)
	1+	21	0.11 (0.07)	**42 (13)**	**13 (22)**	**24 (37)**	2 (7)	2 (6)	20 (33)	25 (34)	**14 (31)**	3 (11)
	2+	15	0.35 (0.96)	**34 (11)**	**9 (26)**	**14 (31)**	9 (26)	16 (34)	22 (36)	2 (5)	**29 (41)**	0 (0)
Spring	**Available**	100	**0.46 (0.42)**	**17 (14)**	**17 (35)**	**21 (38)**	**23 (36)**	10 (25)	12 (25)	**3 (12)**	**12 (27)**	2 (11)
2011	**Use**	22	**0.18 (0.25)**	**50 (21)**	**5 (21)**	**4 (11)**	**22 (24)**	26 (29)	20 (21)	**18 (27)**	**3 (8)**	1 (4)
	YOY	-	-	-	-	-	-	-	-	-	-	-
	1+	10	**0.11 (0.10)**	**46 (23)**	10 (32)	**0 (0)**	20 (23)	**34 (34)**	14 (18)	**15 (30)**	**6 (11)**	**0 (1)**
	2+	12	**0.24 (0.31)**	**53 (20)**	0 (0)	**8 (14)**	24 (25)	**20 (22)**	26 (21)	**20 (26)**	**1 (2)**	**2 (5)**

Table 2.1 (continued)

Season	Data Type		Ave. Vel. (m*s^{-1})	Depth (cm)	% Bedrock	% Boulder	% Lg. Cob.	% Sm. Cob.	% Gravel	% Sand	% Silt	% Debris
Summer	**Available**	100	**0.22 (0.28)**	13 (13)	13 (34)	16 (35)	21 (31)	**7 (22)**	**19 (31)**	5 (21)	16 (33)	**1 (10)**
2011	**Use**	64	**0.20 (0.11)**	39 (11)	14 (27)	16 (25)	14 (16)	**7 (14)**	**11 (17)**	18 (24)	16 (27)	**4 (12)**
	YOY	20	**0.19 (0.08)**	37 (12)	**6 (17)**	18 (25)	14 (18)	9 (14)	**8 (12)**	**29 (29)**	**14 (21)**	**3 (11)**
	1+	35	**0.21 (0.11)**	40 (12)	**22 (32)**	15 (24)	14 (14)	5 (13)	**14 (21)**	**12 (19)**	**16 (29)**	**2 (8)**
	2+	9	**0.16 (0.14)**	39 (11)	**2 (7)**	14	15 (18)	7 (13)	**6 (6)**	**15 (22)**	**26 (33)**	**14 (22)**
Autumn	**Available**	100	**0.28 (0.29)**	**12 (10)**	**15 (34)**	13 (31)	23 (34)	11 (27)	**16 (27)**	**10 (25)**	7 (21)	5 (19)
2011	**Use**	39	**0.17 (0.06)**	**38 (12)**	**6 (19)**	17 (29)	15 (22)	6 (16)	**24 (29)**	**20 (25)**	7 (20)	4 (13)
	YOY	14	0.19 (0.06)	**35 (11)**	7 (15)	7 (7)	25 (24)	**3 (7)**	26 (29)	**31 (24)**	1 (3)	**2 (5)**
	1+	19	0.16 (0.07)	**37 (13)**	5 (23)	28 (39)	12 (21)	**9 (21)**	19 (27)	**9 (21)**	9 (24)	**7 (17)**
	2+	6	0.14 (0.05)	**51 (5)**	7 (10)	7 (11)	3 (6)	**6 (7)**	35 (33)	**31 (27)**	12 (28)	**1 (2)**
Spring	**Available**	100	**0.36 (0.30)**	**15 (11)**	11 (31)	**21 (39)**	19 (30)	**11 (26)**	**19 (31)**	**6 (15)**	**11 (27)**	2 (10)
2012	**Use**	76	**0.15 (0.10)**	**28 (13)**	4 (17)	**8 (25)**	11 (21)	**3 (11)**	**24 (35)**	**11 (22)**	**29 (41)**	10 (27)
	YOY	49	**0.12 (0.06)**	**23 (11)**	0 (0)	**0 (0)**	8 (18)	**0 (0)**	**22 (33)**	12 (25)	**44 (45)**	15 (33)
	1+	14	**0.20 (0.13)**	**35 (12)**	3 (13)	**4 (13)**	29 (32)	**10 (20)**	**34 (38)**	15 (16)	**4 (7)**	1 (2)
	2+	13	**0.23 (0.10)**	**41 (12)**	17 (37)	**43 (44)**	5 (9)	**6 (16)**	**22 (37)**	3 (6)	**2 (5)**	2 (3)

Figure Legends

Figure 2.1 Inter-seasonal differences in microhabitat availability in Ball Creek, N.C. Centroids represent sample means and ellipses are 95% confidence intervals. Only loadings ≥ 0.40 are presented. SU10, summer 2010; AU10, autumn 2010; SP11, spring 2011; SU11, summer 2011; AU11, autumn 2011; SP12, spring 2012. Ellipses that do not overlap represent samples that are significantly different at the 0.05 level (or lower) using a t-test.

Figure 2.2 Test for nonrandom microhabitat use by southern brook trout (SF) during spring 2012 in Ball Creek, N.C. Centroids represent sample means 95% confidence intervals. Only loadings ≥ 0.40 are presented and HAB represents microhabitat availability, (n = sample size). Non-overlapping ellipses demonstrate significance at the 0.05 level (or lower) using a t-test.

Figure 2.3 Inter-seasonal differences in southern brook trout microhabitat use in Ball Creek, N.C. Centroids represent sample means and 95% confidence intervals. Only loadings ≥ 0.40 are presented. SU10, summer 2010; AU10, autumn 2010; SP11, spring 2011; SU11, summer 2011; AU11, autumn 2011; SP12, spring 2012. Non-overlapping ellipses demonstrate significance at the 0.05 level (or lower) using a t-test.

Figure 2.4 Test for age-related differences in microhabitat use by southern brook trout during spring 2012. YOY represents young of the year brook trout; 1+ represents age 1+ brook trout; 2+ represents age 2+ brook trout, (n = sample size). Non-overlapping ellipses demonstrate significance at the 0.05 level (or lower) using a t-test.

Figure 2.5 Inter-seasonal differences in YOY southern brook trout microhabitat use in Ball Creek, N.C. Centroids represent sample means and ellipses are 95% confidence intervals. Only loadings ≥ 0.40 are presented. SU10, summer 2010; AU10, autumn 2010; SP11, spring 2011; SU11, summer 2011; AU11, autumn 2011; SP12, spring 2012. Non-overlapping ellipses demonstrate significance at the 0.05 level (or lower) using a t-test.

Figure 2.6 Inter-seasonal differences in age 1+ southern brook trout microhabitat use in Ball Creek, N.C. Centroids represent sample means and ellipses are 95% confidence intervals. Only loadings ≥ 0.40 are presented. SU10, summer 2010; AU10, autumn 2010; SP11, spring 2011; SU11, summer 2011; AU11, autumn 2011; SP12, spring 2012. Non-overlapping ellipses demonstrate significance at the 0.05 level (or lower) using a t-test.

Figure 2.7 Inter-seasonal differences in age 2+ southern brook trout microhabitat use in Ball Creek, N.C. Centroids represent sample means and ellipses are 95% confidence intervals. Only loadings ≥ 0.40 are presented. SU10, summer 2010; AU10, autumn 2010; SP11, spring 2011; SU11, summer 2011; AU11, autumn 2011; SP12, spring 2012. Non-overlapping ellipses demonstrate significance at the 0.05 level (or lower) using a t-test.

Figure 2.1

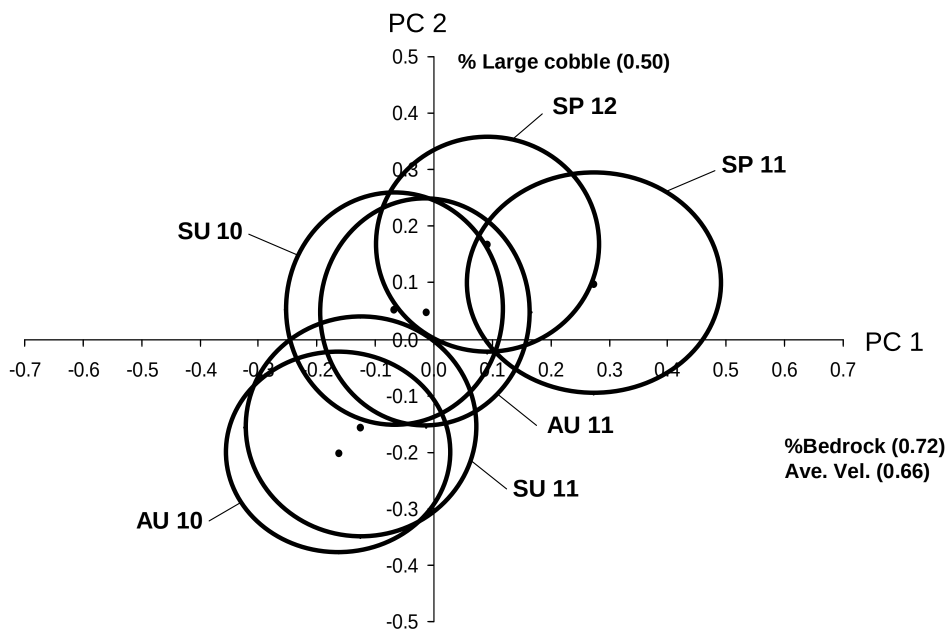
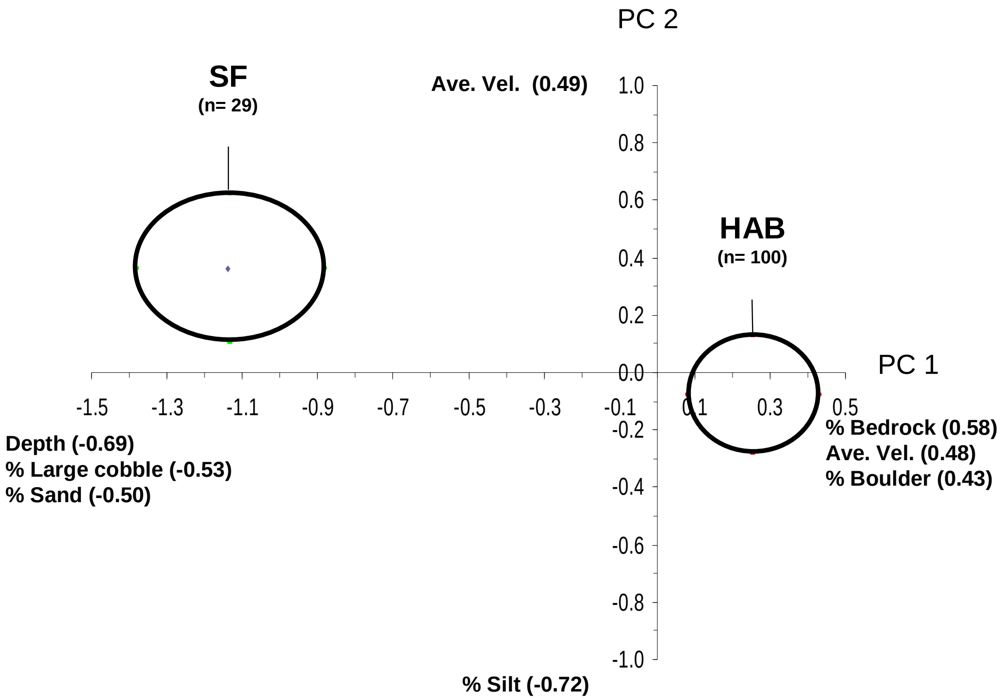

PC 2
% Large cobble (0.50)
SP 12
SP 11
SU 10
PC 1
AU 11
SU 11
AU 10
%Bedrock (0.72)
Ave. Vel. (0.66)
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

Figure 2.2



PC 2
SF
(n= 29)
Ave. Vel. (0.49)
1.0
0.8
0.6
HAB
(n= 100)
0.4
0.2
0.0
PC 1
-1.5
-1.3
-1.1
-0.9
-0.7
-0.5
-0.3
-0.1
0.1
0.3
0.5
-0.2
% Bedrock (0.58)
Ave. Vel. (0.48)
% Boulder (0.43)
Depth (-0.69)
% Large cobble (-0.53)
% Sand (-0.50)
-0.4
-0.6
-0.8
-1.0
% Silt (-0.72)

Figure 2.3

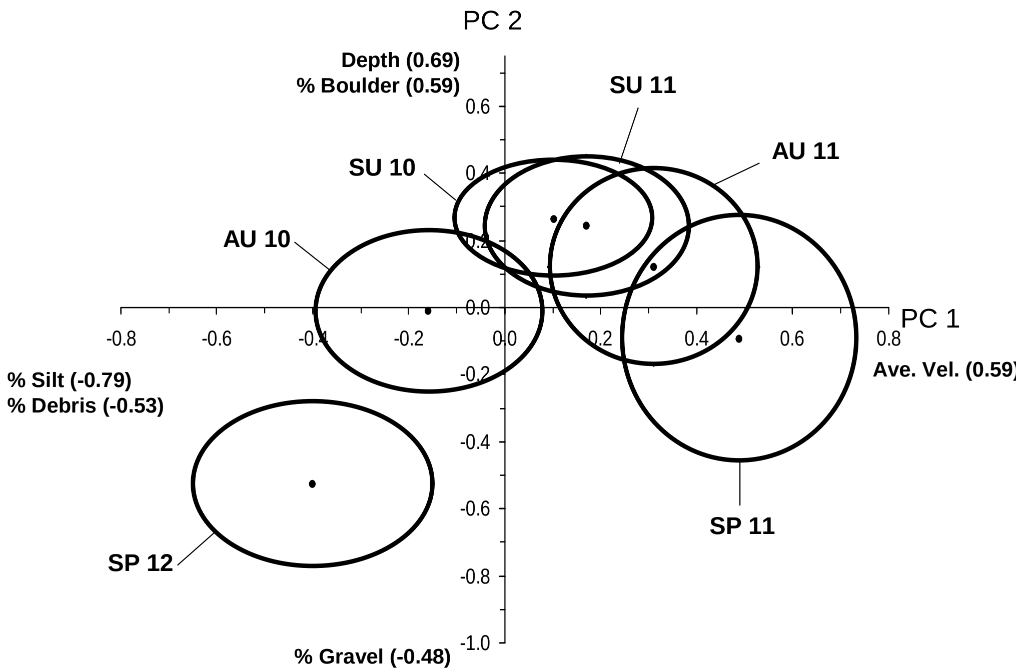

PC 2
Depth (0.69)
% Boulder (0.59)
SU 11
AU 11
SU 10
AU 10
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
PC 1
Ave. Vel. (0.59)
% Silt (-0.79)
% Debris (-0.53)
SP 11
SP 12
% Gravel (-0.48)

Figure 2.4

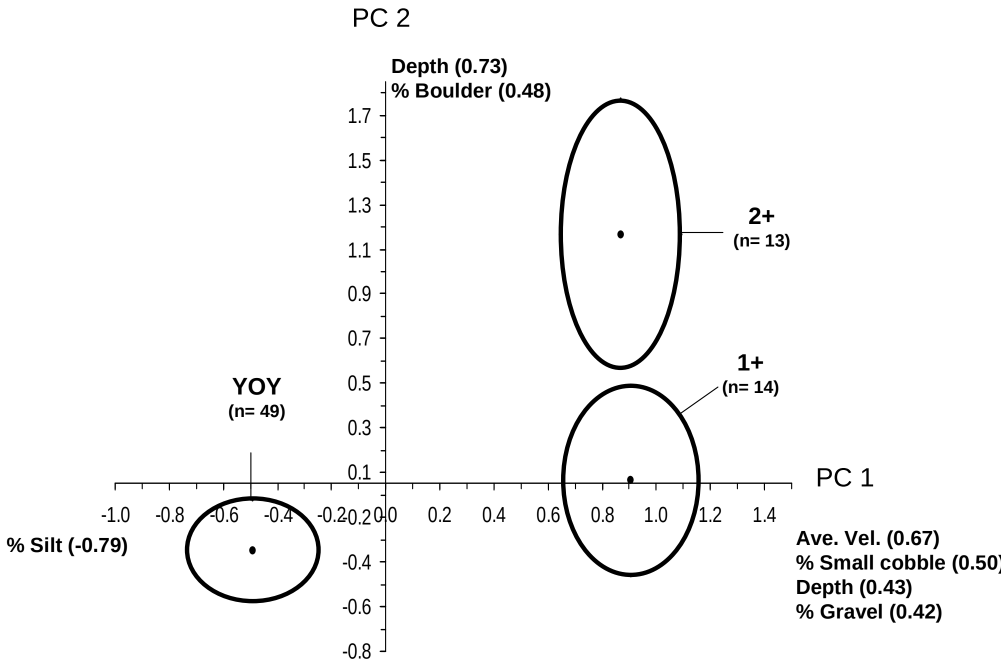

PC 2
Depth (0.73)
% Boulder (0.48)
1.7
1.5
1.3
1.1
0.9
0.7
0.5
0.3
0.1
-0.2
-0.4
-0.6
-0.8
2+
(n= 13)
1+
(n= 14)
YOY
(n= 49)
PC 1
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
% Silt (-0.79)
Ave. Vel. (0.67)
% Small cobble (0.50)
Depth (0.43)
% Gravel (0.42)

Figure 2.5

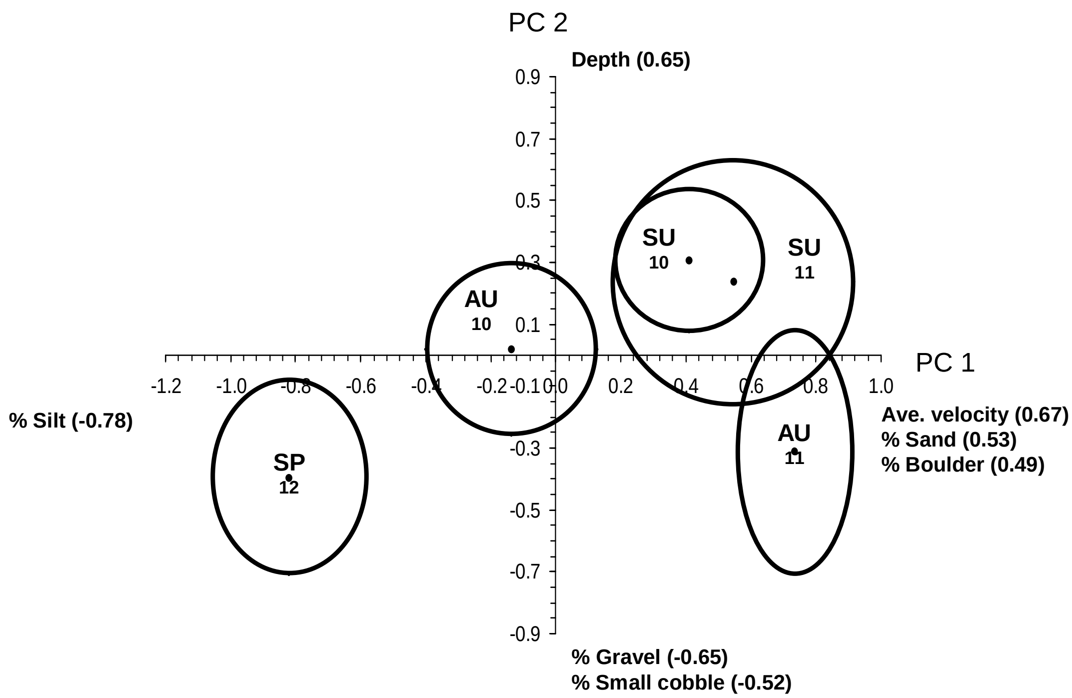

PC 2
Depth (0.65)
0.9
0.7
0.5
0.3
0.1
-0.3
-0.5
-0.7
-0.9
PC 1
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
-0.1
0.0
0.2
0.4
0.6
0.8
1.0
SU
10
SU
11
AU
10
AU
11
SP
12
% Silt (-0.78)
Ave. velocity (0.67)
% Sand (0.53)
% Boulder (0.49)
% Gravel (-0.65)
% Small cobble (-0.52)

Figure 2.6

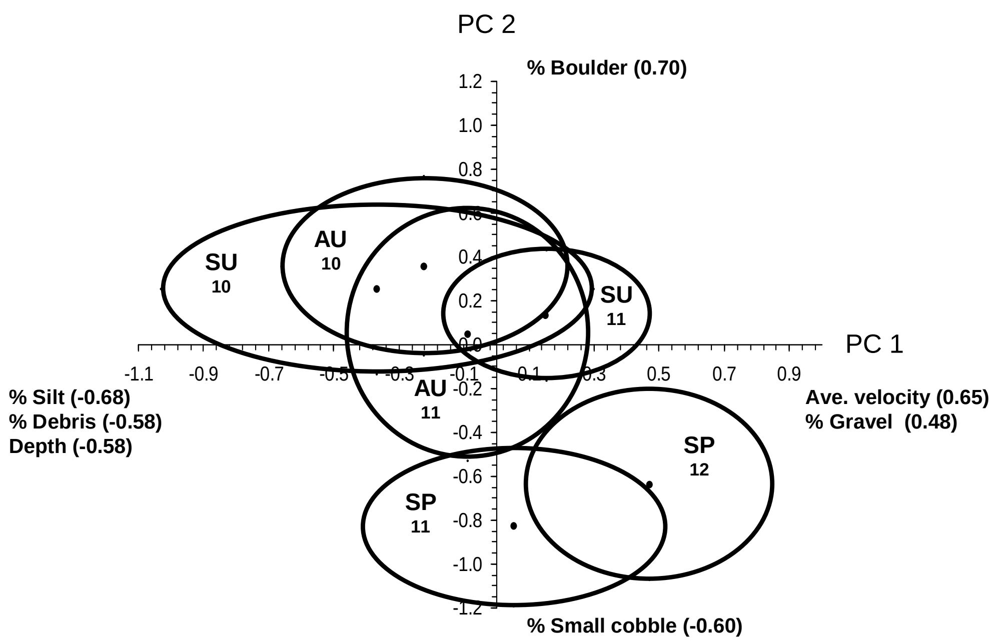
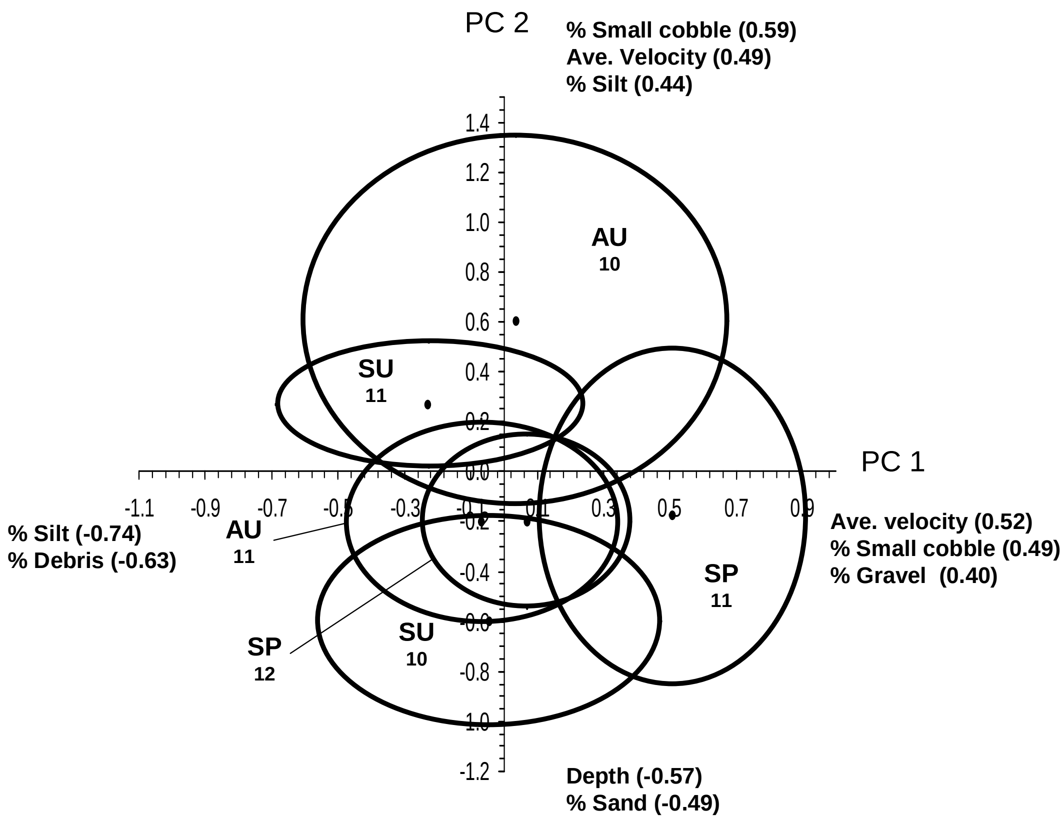

PC 2
% Boulder (0.70)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
PC 1
-1.1
-0.9
-0.7
-0.5
-0.3
-0.1
0.1
0.3
0.5
0.7
0.9
SU 10
AU 10
SU 11
AU 11
SP 12
SP 11
% Silt (-0.68)
% Debris (-0.58)
Depth (-0.58)
Ave. velocity (0.65)
% Gravel (0.48)
% Small cobble (-0.60)

Figure 2.7


PC 2
% Small cobble (0.59)
Ave. Velocity (0.49)
% Silt (0.44)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
PC 1
-1.1
-0.9
-0.7
-0.5
-0.3
-0.1
0.1
0.3
0.5
0.7
0.9
AU
10
SU
11
% Silt (-0.74)
% Debris (-0.63)
AU
11
Ave. velocity (0.52)
% Small cobble (0.49)
% Gravel (0.40)
SP
11
SU
10
SP
12
Depth (-0.57)
% Sand (-0.49)

CHAPTER 3

MOVEMENT OF SOUTHERN BROOK TROUT (*SALVELINUS FONTINALIS*) IN A NORTH CAROLINA STREAM [1]

[1] Anglin, Z.W. and G.D. Grossman. To be submitted to Southeastern Naturalist

Abstract

Little is known about the life history and ecology of the genetically distinct southern brook trout (*Salvelinus fontinalis*); therefore I quantified seasonal movements of southern brook trout in Ball Creek, N.C. over 14 months. Initial tagging occurred in March 2011. In May 2011 recaptured individuals had an average standard length of 13.2 cm and moved an average of nine meters downstream over a period of 55 days. In October 2011 recaptured individuals had an average standard length of 15.1 cm and moved an average of 7 meters upstream over a period of 159 days. In May 2012 recaptured individuals had an average standard length of 16.2 cm and moved an average of six meters over nearly a seven month period. Southern brook trout displayed both upstream and downstream movement for all seasons. There was no relationship between fish length and distance or direction moved. No individuals exhibited movements greater than 300 meters. My results suggest that most southern brook trout have relatively small home ranges (< 20 m). Limited home ranges suggest that persistent populations require all essential habitat types within a relatively small area and that exchange among populations is likely minimal.

Introduction

The natural distribution of brook trout (*Salvelinus fontinalis*) encompasses nearly the entire length of the Appalachian Mountain system. Within their natural distribution, brook trout populations typically occur above barriers to fish movement in headwater streams (Galbreath et al. 2001). These barriers prevent displacement of brook trout by invasive brown (*Salmo trutta*) and rainbow (*Oncorhynchus mykiss*) trout, which were both introduced in the late 19th century (Behnke 2002). Previous research has identified two genetically distinct forms of brook trout: i.e. northern and southern forms (Stoneking et al. 1981; Habera and Moore 2005). These differences likely warrant the reclassification of brook trout into separate subspecies and perhaps even distinct species and highlight the need for information on the little known southern form (Stoneking el al. 1981; Habera and Moore 2005).

Our knowledge of brook trout biology primarily is based on studies of northern populations or those of unknown origin (Habera and Moore 2005). However, because of their genetic and habitat-related differences, it is unclear whether southern brook trout display the same biological characteristics as their northern counterparts. Specifically little is known about the ecology, life history, and habitat requirements of this subspecies, although Grossman et al. 2010 identified strong density-dependence in both individual and population growth for southern brook trout. Nonetheless, the lack of knowledge of habitat requirements and movements inhibits development of management and conservation plans that would protect southern brook trout from ongoing habitat degradation, excessive harvest, and further invasions by potential competitors (Anglin and Grossman 2012). The need for ecological information is particularly salient because abundance and distribution of brook trout, especially southern brook trout, have decreased in the past three decades primarily due to anthropogenic causes (Hudy et al. 2008).

In addition to localized impacts such as habitat degradation, large-scale factors such as global climate change may affect the distribution and abundance of southern brook trout. Although the precise effects of global climate change on the southeastern United States are uncertain, two studies using three different climate models both predicted substantial declines in the distribution of brook trout in the southeast due to increasing stream temperatures (Meisner 1990; Flebbe et al. 2006). Given that most populations of southern brook trout already are isolated with presumably little exchange, increased stream temperatures likely will result in greater fragmentation with many populations projected to go extinct (Flebbe et al. 2006). Consequently, an understanding of the movement patterns of southern brook trout may be essential for future conservation of the species.

My goal was to qualify movement of southern brook trout in a North Carolina headwater stream via mark-recapture sampling and Passive Integrated Transponder (PIT) tagging over a period of 14 months. I hypothesized that movements of southern brook trout would be affected by season, and that older (larger) fish would move greater distances than younger (smaller) fish.

Methods and Materials

Study Site

The study site consisted of a 330 meter section of stream located within a third-order stretch of Ball Creek, NC, U.S.A. located on the USDA Forest Service Coweeta Hydrologic Laboratory (35_11'N; 83_23'W) in Otto, North Carolina. The study site was bisected a small natural waterfall that was considered a possible barrier to fish movement. I used this natural separation to split the site into upper and lower segments, each measuring roughly 150 meters in length. The upper and lower sections were further sub-divided and marked off at ten meter increments. The entire 330m site will be called the main site.

The main site is composed of riffle-pool stream morphology with a mean wetted width of 5.2 meters (± 0.3 meters; 95% C.I.). The surrounding mixed hardwood-conifer forest provides dense canopy cover, shading the stream during the growing season. Riparian vegetation is dominated by rhododendron (*Rhododendron maximum*) typical of headwater streams in the Blue Ridge Province of the southern Appalachian Mountains. The fish assemblage within the site is composed of only three species: pure southern brook trout (T. King, United States Geological Survey), mottled sculpin (*Cottus bairdi*), and rainbow trout (*Oncorhynchus mykiss*).

Movement

I quantified movement patterns of southern brook trout using mark-recapture techniques with electrofishing as a sampling technique. Passive integrated transponder tags were used in this study because they have minimal affect on tagged specimens

(Ombridane et al. 1998; Acolas et al. 2007). On March 25th, 2011, I made a preliminary one-pass electrofishing sweep, starting 50 meters above the downstream border of the main site and ending 50 meters below the upstream border of the main site (the middle 230 meters). All captured southern brook trout longer than 7.0 cm (standard length, SL) were injected with a PIT tag (Biomark, 11.5 mm). Southern brook trout smaller than 7.0 cm SL were not tagged for fear of internal injuries that would induce abnormal movement behavior, and were returned to their point of capture. I injected the PIT tags into the body cavity using a syringe tipped with a 12-gauge hypodermic needle. Each tag had a unique code that allowed me to identify individual fish. I weighed (digital scale, ± 0.01 g), and measured (standard length, straight edge, ± 1.0 mm), each tagged fish and held them for a 30 minute recovery period prior to release at the site of capture. All fish capture locations were recorded to the nearest meter using maps of the main site. Movements were calculated as the linear distance between recaptures. The first and last 50 meters of the site were used as control sites (no fish were PIT tagged in these areas).

All subsequent samples (May 19th, 2011, October 25th, 2011, and May 25th, 2012) utilized the previously described sampling methodology although the entire 330 meter site was sampled. I did not sample during summer because the combination of high water temperatures and tagging may have overly stressed fish. I examined all captured southern brook trout PIT tags with a hand-held PIT tag reader to identify recaptured fish and tagged all fish larger than 7.0 cm SL. After the October 25th, 2011 sample, I also sampled two 50 meter sites both 300 m below and above the borders of the main to check for tagged individuals that had moved longer distances. I used Analysis of Variance

(ANOVA) to test for differences in movement based on southern brook trout age (SL), mass, and season. Significance was assigned based on an alpha value of 0.05.

Results

Over three seasons, I tagged a total of 35 southern brook trout and recaptured 13 fish (Fig. 3.1). Recaptures included 10 single recaptures, one double recapture and one triple recapture. Recaptured fish ranged in size from 12 to 17 cm SL. Southern brook trout exhibited both upstream and downstream movement for all seasons. One of the double recaptures exhibited both upstream (7 meters) and downstream (8 meters) movement, whereas the remaining double recapture moved downstream twice (7 m and 2 m). Of the 10 southern brook trout recaptured once 1) one remained at the initial position of capture, 2) six moved an average of 18.2 (SD = 11.6) meters upstream, 3) two moved an average of 6.5 (SD = 2.1) meters downstream, and 4) one individual moved 49 meters downstream. The six individuals recaptured on May 19th, 2011 moved an average of nine (SD = 20.3) meters downstream and grew an average of 25 (SD = 5.0) mm SL over a 55 day period. The five individuals recaptured on October 25th, 2011, moved an average of 11.4 (SD = 13.2) meters upstream and grew an average of 13 (SD = 14.7) mm SL over a 159 day period. The three individuals recaptured on May 25th, 2012 grew an average of 10 (SD = 15.0) mm SL and moved an average of six (SD = 22.8) meters upstream from their locations on October 25th 2011, nearly a seven month period. There were no upstream or downstream movements over the waterfall. Movement data suggest that home ranges of most southern brook trout in upper Ball Creek are likely less than 20 meters. Brook trout length did not significantly affect patterns of upstream or downstream movement ($F_{1, 11}$ = 0.46, P = 0.51), nor was there a relationship between growth rate and distance moved ($F_{1, 11}$ = 0.21, P = 0.66). No tagged individuals were recaptured in the sites 300 meters below or above the main site.

Discussion

My results lend support to the contention of Gerking (1959) that many stream fishes display relatively restricted movements. In general, southern brook trout in Ball Creek exhibited fairly limited movement between seasons. Because most populations of southern brook trout are confined to headwater streams above barriers, it is fortuitous that southern brook trout appear to possess small home ranges. In Ball Creek, the habitats necessary for population maintenance of southern brook trout are present even above barriers to fish movement (Grossman et al. 2010). Nonetheless, these populations are still isolated and subject to genetic drift and inbreeding because of the almost certainly limited genetic exchange among populations.

All but two recaptured southern brook trout were at least two years old. This may be an artifact of electrofishing (i.e. older/larger individuals are easier to capture with electrofishing (Hense et al. 2010)). Consequently, my movement data may only be valid for older southern brook trout, although in previous studies older fish have been shown to be the most mobile segment of the population (Petty et al. 2005). Although most southern brook trout display some movement in all seasons, total distances moved were small (generally less than 20 meters). Nonetheless my data are from a single year, without summer sampling, and should be used with caution in years with differing environmental conditions (e.g. low flows). My results also were affected by the low numbers of southern brook trout present in the main site when compared to previous years (Grossman et al. 2010). Recapture success (mean recapture rate = 31%) was similar compared to other trout tagging studies (Creswell 1981; Dieterman and Hoxmeier 2009; Turek et al 2010) however I cannot account for southern brook trout that were not recaptured. Some of these fish likely shed tags and others may have died. Nonetheless, long-term tagging mortality in my study due to PIT-tagging was likely low (Dieterman and Hoxmeier 2009).

Movements of non-anadromous trout species have been well studied in western and northern states (Bartrand et al. 1994; Downs et al. 2006; James et al. 2007). Previous studies of brook trout movement have shown that multiple factors affect movement, including water quality, reproduction, and resource competition, (Riley et al. 1992; Fausch and Young 1995; Logan 2003; Petty et al. 2005; Liller 2006). Roghair and Dolloff (2005) observed movement and recolonization of brook trout in a Virginia stream after a natural defaunation event, noting that brook trout recolonized the 1.9 kilometer defaunated section, progressing from upstream to downstream, in 2.5 to 3.0 years (average 0.69 $km^{-1}year^{-1}$). Salmonid movement studies have yielded varying results with examples of both small and large-scale movements (Hartman and Logan 2010). Individuals in some populations display very small movements (e.g., <100 m; Adams et al. 2000), whereas others show large-scale movements (e.g. >3000m; Gowan and Fausch 1996; Gowan et al. 1994), although the latter are from populations of invasive trout. It is likely that there is substantial variability in movement in some populations, with individuals typically classified as movers or stayers (Adams et al. 2000; Petty and

Grossman 2004), and movement may be affected by sampling technique such as electrofishing versus hand capture.

Degradation of trout habitat leading to decreased trout abundance has become a broad problem for fisheries managers in North America (Elwood and Waters 1969; Mortensen 1977; Gosset et al. 2006). My movement data for southern brook trout should assist fisheries managers in developing management plans that ensure access to all essential habitat types. For example, spawning areas must be sufficiently close to foraging and shelter habitat so that a roughly 50 meter section of stream contains all of these habitat types. These management strategies may aid in the preservation of this unique subspecies.

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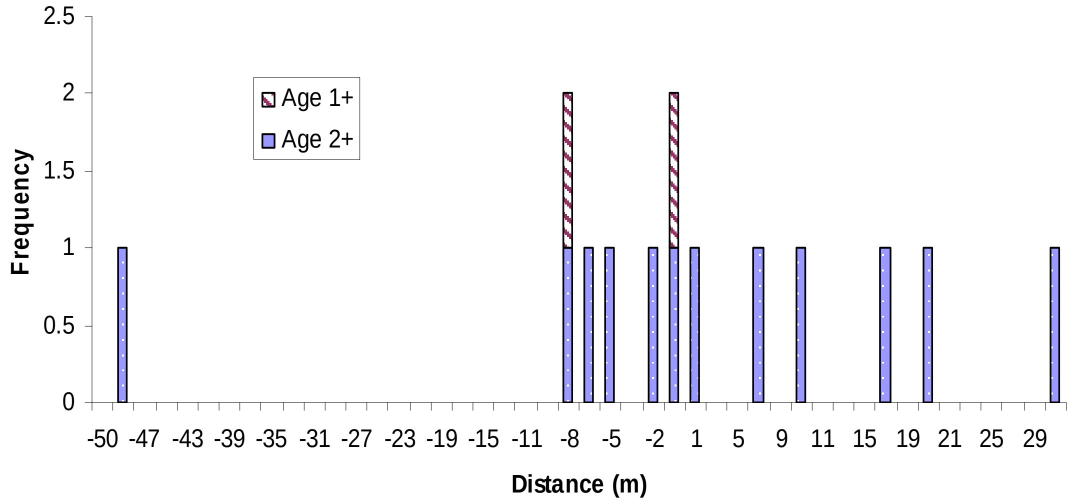
Figure Legends

Figure 3.1 Total movement data for age 1+ (9 -12 cm) and age 2+ (>12 cm) southern brook trout in Ball Creek for all sampling seasons. Negative x-values indicate downstream movement whereas positive x-values indicate upstream movement.

Figure 3.1



2.5
2
1.5
1
0.5
0
Frequency
Age 1+
Age 2+
-50 -47 -43 -39 -35 -31 -27 -23 -19 -15 -11 -8 -5 -2 1 5 9 11 15 19 21 25 29
Distance (m)

CHAPTER FOUR

CONCLUSION

Although many studies have investigated microhabitat use and movement of brook trout (Cunjak and Green 1983; Cunjak and Power 1986; Johnson et al. 1992; Lohr and West 1992; Johnson and Dropkin 1996; Roghair and Dolloff 2005; Sotiropoulos et al. 2006; Johnson 2008), most of these studies were performed on northern populations. Genetic testing has confirmed fixed differences between southern brook trout and northern populations of brook trout. This thesis helps fill a gap in the knowledge of southern brook trout ecology.

I have successfully demonstrated that southern brook trout in Ball Creek exhibit non-random microhabitat use during the spring, summer, and autumn seasons. Southern brook trout exhibited this non-random microhabitat use over a span of three years. I have documented that microhabitats utilized by southern brook trout are comprised of deeper areas with lower mean water velocities and greater amounts of depositional substrata. Age-related differences in microhabitat are present in this population with older (age 1+, age 2+) brook trout generally inhabiting deeper areas with lower mean water velocities and greater amounts of depositional substrata than YOY individuals. Annual and seasonal movements of southern brook trout appear to be limited (< 100 m). Very few fish moved distances greater than 20 meters between seasons/years. This small scale movement suggests that the home range of southern brook trout is relatively small, although it is important to remember that movement sample sizes were low.

The threat of climate change poses a danger to this population. If Flebbe et al. (2006) are correct in their predictions, the future existence of southern brook is unsure, especially for populations at the southern end of their range. Invasive species such as rainbow and brown trout continue to exclude southern brook trout from downstream reaches, forcing the existence of southern brook trout into headwater streams above barriers (Galbreath et al. 2001). The results of habitat fragmentation, from either thermal (i.e. climate change) or biological (i.e. invasive species) threats will result in the same outcome: decreased abundance of the southern brook trout (Hudy et al. 2008). By qualifying southern brook trout microhabitat use and movement, I have provided information that will enable the development of management plans to ensure the future existence of this species.

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