ASSESSING SUPPLY AND DEMAND FOR TROUT IN NORTH GEORGIA UNDER CURRENT AND PROJECTED THERMAL REGIMES

by

JENNA HAAG

(Under the Direction of Nathan Nibbelink and Cecil Jennings)

ABSTRACT

There is little debate that our climate is warming, and this change may affect the persistence of trout in the cool-water regions of Georgia. This study focused on how warming from May to September could affect both trout-based recreational opportunities and future suitable thermal habitat availability in the state. The potential impact of warming on future habitat availability and recreational opportunities for trout was examined by evaluating thermal habitat under three climate change scenarios. Increases in water temperature were then intersected with angler preference data to determine where habitat and angling opportunity loss would be greatest across northern Georgia. Results revealed a substantial decrease in future suitable thermal habitat and a loss of angling opportunities for anglers during the summer months. Implications include holding fish in hatcheries through the warmest part of the year (June-August) and stocking the majority of fish after summer to increase angler opportunities and avoid increased fish mortality due to high water temperatures during the summer months.

INDEX WORDS: Climate change; Thermal habitat; trout management

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Trout distributions in the Southeastern United States mainly exist within the Appalachian Mountains and the surrounding foothill regions. Trout populations in Georgia are at the southernmost edge of distribution within the Appalachian Mountain range. Northern Georgia has three trout species: rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*), and brook trout *(Salvelinus fontenalis)* (GADNR 2014). Brook trout are native to the state; whereas, brown trout and rainbow trout are introduced species, but are now considered naturalized (Keefer et al. 2000). The salmon family (*Salmonidae)* includes numerous species of trout, and their popularity with the public produces economic value (Marcy et al. 2005; Wenger et al. 2011). Trout fishing activities generate between an estimated $130 million to $172 million in revenue annually in Georgia alone (Keefer et al. 2000; Dorison 2012; GADNR Trout Information Sheet 2014). Due to their popularity, trout species have been stocked outside of their native ranges across the contiguous United States since the late 1800s (Poole 2007; Dunham et al. 2011). The Georgia Department of Natural Resources (GADNR) has stocked rainbow trout and brown trout in North Georgia waters for the better part of 100 years (GADNR 2014). Although stocking of these species has resulted in fish persisting outside of their native ranges (where conditions allow) (Nelson 2006), sometimes they are introduced into areas where conditions do not guarantee long term survival or reproductive success (Marcy et al. 2005; Nelson 2006; Rhode et al. 2009). Currently, brown trout and rainbow trout in Georgia reside in the Tennessee, Coosa, Tallapoosa, Chattahoochee and Savannah river basins (GADNR 2017). Brook trout are restricted to higher elevation streams in the Appalachian Mountains and the surrounding foothills, and are generally found above an impassable barrier (such as waterfalls and dams), which excludes other trout species from the area (Keefer et al. 2000). Brook trout separation from the other two species is due to brown and rainbow trout outcompeting brook trout when sharing the same stream reaches and resources (Meisner 1990; Dallmier 2010).

Though the GADNR stocks over one million trout into over 4,000 miles of streams in northern Georgia, long-term survival of trout is threatened within the state. Trout are a cold-water species and current warming trends could cause their extirpation from many streams where they currently reside (Wenger et al. 2011). While salmonids have diverse life histories and some physiological elasticity to changing environments, thermal maxima are fairly well-established (Eaton and Scheller 1996). Trout populations within Georgia's numerous streams are also threatened by various practices such as channelization of streams, overstory removal, instream gravel mining, stream bank degradation, and poor land-use (Fatora 1976; Trout Unlimited 2006). Thus, identifying potential shifts in thermal habitat could maximize the efficiency of future trout management, including stocking, habitat management, and angler outreach.

Trout management within Georgia is complex and has undergone major changes throughout the last century; however, habitat protection, harvest regulations, and extensive stocking programs remain central tenants of trout management. Trout streams in northern Georgia are generally unproductive and the amount of naturalized trout produced per stream annually is usually low; accordingly, supplemental stocking is essential to deliver quality-fishing opportunities to anglers (Keefer et al. 2000; GADNR 2014). Of the 4,000 miles of trout streams within the state, only about 2,400 miles support naturally reproducing trout populations. The remaining stream reaches are capable of sustaining non-reproducing populations of trout year-round, but supplemental stocking is needed to meet public demands for fishing. Previous studies have shown that proper regulations and stocking can improve fish size and angler usage of a waterway (Fatora 1976; Ott 1985). Personnel from GADNR, (Fisheries Management Section) stock over 1 million catchable (nine-inch) trout in 160 streams within north Georgia (Keefer et al. 2000). The myriad of regulations relating to trout management within Georgia were compiled into a "Trout Management Plan" (TMP) in 2000.

This study projects the distribution of suitable thermal habitat for trout in the future (Chapter 2), along with insight on the spatial pattern of angler preference and satisfaction (demand), given the distribution of GADNR stocking efforts and suitable thermal habitat (supply) (Chapter 3). Moreover, this study explores how the incorporation of angler survey data and Important Satisfaction Analysis (ISA) from a companion study (Yondo 2018) can be used to identify gaps between angler importance and satisfaction ratings for trout fishing attributes, and determine how those differences change across eight county groups in northern Georgia. Findings from this study may aid GADNR officials in the allocation of limited resources to continue to provide a quality trout fishery for anglers in the future.

In Chapters 2 and 3 of this thesis, linear mixed-effect modeling, angler survey data and Importance Satisfaction Analysis (ISA) were combined and used to assess the current and future supply and demand of the trout fishery. Certain regions within the

United States are more susceptible to negative impacts associated with climate change than other regions. Specifically, areas at greater latitudes and altitudes are subject to the most accelerated warming rates on earth (Woodward 2010). The Southeast region of the United States faces a long list of issues associated with climate change, but the negative effects of rapidly changing environments within the Southeast are projected to be the highest in the Appalachian Forest ecoregion (Caldwell 2015). Stream temperature modeling has been completed within the Southeast on multiple occasions (Meisner 1990; Clark et al. 2001; Flebbe 2006; DeWeber and Wagner 2014; Caldwell et al. 2015). Previous modeling attempts have been conducted at relatively coarse scales, generally on a multi-state scale. Meisner (1990) modeled across most of Eastern Canada to Georgia, while Caldwell et al. (2015) focused on the range south of Oklahoma and east to the coast. Other studies (Clark et al. 2001, Flebbe et al. 2006; and DeWeber and Wagner 2014) had a reduced scale and focused on modeling trout habitat in the Appalachian Mountain chain stretching from Virginia to northern Georgia. None of the previously mentioned studies had a specific focus on northern Georgia. Previous modeling attempts within Georgia have not included all areas where trout occur naturally and also artificially by way of stocking Previous studies also use various modeling approaches including linear regression (Flebbe et al. 2006; Caldwell et al. 2015; Segura et al. 2015), logistic regression (Caissie et al. 2001), and quantile regression or stochastic modeling (Clark et al. 2001). Modeling fine-scale effects within this region is difficult because of the rarity of long-term regional temperature data combined with variability in human disturbances and other instabilities. For instance, large rainfall events change stream flow, which can affect stream temperature. Also, interactions among stream temperature and climate are site-specific in this region (Caldwell et al. 2015). Finer-scale models that forecast water temperatures for future suitable thermal habitat availability in regions of management interest (i.e., north Georgia) are needed to assist with trout management planning. In Chapter 2, I model future suitable thermal habitat for 2050 using three climate change scenarios from the International Panel on Climate Change (IPCC) website.

Importance-satisfaction analysis (ISA) is one tool available to fisheries managers that can be used to assess angler satisfaction with recreational fishing attributes. Martilla and James (1977) were the first to employ a precursor to an ISA. They used an Importance-Performance Analysis (IPA) to assess components of a marketing study. The study conducted by Martilla and James (1977) laid the foundation for IPA's continued use within the business sector to pinpoint customers perceived performance of an attribute and their subsequent satisfaction with the performance of the same attribute (Sever 2015). While there has been little use of an ISA by fisheries managers (but see TenHarmsel et al. 2019), an ISA can identify gaps in perceived performance and the importance rankings of fisheries attributes. Importance-satisfaction ratings are then graphed on x and y axes which allows researchers to see a visual display of how each attribute is positioned within the four ISA quadrants such as: Quadrant 1: "Concentrate Here," Quadrant 2: "Keep up Good Work," Quadrant 3: "Low Priority," and Quadrant 4: "Possible Overkill" (Yondo 2018; TenHarmsel et al. 2019). In Chapter 3, I used an ISA to determine which county groups ranked importance of catching wild or stocked trout the highest and on what level each angler group was satisfied with catching trout.

As anglers adjust to shifts in stream temperatures and changing climates, demographic changes and population growth may also affect how a “typical” angler interacts with the fishery resources available to them. As the current TMP approaches 20 years in age, these environmental and demographic changes require the reassessment of angler preferences and satisfaction along with whether current management can continue to provide a quality fishery in a future environment. Survey data collection on angler use, preferences, satisfaction, and attitudes towards fisheries management is not a new method, or unique to Georgia. Numerous studies have used survey data to frame management decisions across the United States (Fisher 2011; Gigliotti and Peyton 2011; Hutt and Bettoli 2011). However, what is missing in the literature is a study that combines data about angler preferences and satisfaction (i.e., demand) with future changes to suitable thermal habitat for trout (i.e., supply) on a finer scale (e.g., north Georgia). Here, I combine surface water temperature modeling with angler preference and satisfaction data gathered from ISA methodology to provide ways GADNR could improve trout management in the future.

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CHAPTER 2

EFFECTS OF CLIMATE CHANGE ON FUTURE SUITABLE THERMAL HABITAT FOR TROUT SPECIES IN GEORGIA[1]

[1] Haag J. M., N. P. Nibbelink, C. A. Jennings, B. J. Irwin, and B. B. Boley. To be submitted to *North American Journal of Fisheries Management.*

Abstract

Meeting expectations of anglers while accounting for environmental changes poses a significant challenge for fisheries managers. Warmer climates and habitat degradation and loss both threaten trout populations nationwide. Warmer water temperatures increase the risk of trout habitat fragmentation and cause local extirpation, while lowering the potential for recolonization. This warming could affect trout-based recreational opportunities and natural communities in the state. I partnered with GA Department of Natural Resources (GADNR) to evaluate how different potential warming scenarios over the next 30 years might affect the future availability of suitable thermal habitat for trout in Georgia. I used stream water temperature data from 156 sites distributed throughout 38 counties in north Georgia to assess the potential availability of suitable thermal habitat for native, naturalized, and stocked trout. I then used linear regression in a model selection framework to predict stream temperatures based on air temperature and watershed geomorphology. Air temperature alone was most often the top model, and I used air temperature estimates based on three warming scenarios to forecast stream temperature throughout the study area through 2050. The three warming scenarios included a conservative version (~1 °C increase in water temperature), an intermediate (~2 °C increase in water temperature), and an extreme version (~2.6 °C increase in water temperature) across north Georgia. All three forecasts showed a reduction of available thermal habitat for trout. Model forecasts predicted a decline in available habitat of 18% to 71% for brook trout and a 7% to 71% for brown trout and rainbow trout. Suitable thermal habitat for all three species will be increasingly restricted to higher elevations

during summer, where refuge from lethal temperatures is forecast to be available. My results can be used by GADNR to inform a revision of their trout management plan, which aims to allocate limited resources to areas where trout are most likely to persist in the future and where anglers will be happiest with resulting trout fishing opportunities.

Introduction

Water temperature is characterized as the rudimentary regulating factor that defines suitable thermal habitat for cold-water salmonid species (Flebbe et al. 2006; Isaak et al. 2012). In the continental United States, average air temperature has risen 0.6 °C since the early 1900s (NAST 2000). Temperature data indicate that water temperature in streams at low elevations throughout North America and Europe has increased at a rate of 0.01 to 0.1°C each year of the last century (Ficklin et al. 2013). Over the course of the next century, air temperatures are predicted to increase as much as another 3-5 °C (NAST 2000). This warming is expected to negatively affect aquatic species such as members of the family Salmonidae, whose distribution is restricted to cooler (< 24 °C) water temperatures.

Though Georgia lies on the southernmost fringe of salmonid (trout) distributions in the United States, trout fishing is still an integral part of fishing activity within the state. The northern portion of the state includes over 4,000 miles of trout streams distributed throughout 38 counties. Georgia is home to brook trout (*Salvelinus fontinalis)*, rainbow trout (*Oncorhynhus mykiss)*, and brown trout (*Salmo trutta)*. Brook trout are the only species native to the state and generally inhabit high elevation headwater streams inaccessible to brown and rainbow trout (Meisner 1990; Keefer et al. 2000; Flebbe et al. 2006; Dallmier 2010). Brook trout are outcompeted by the other two species when sharing the same stream reach and resources (Meisner 1990; Dallmier 2010). Rainbow and brown trout have been stocked in state waters for nearly a century and are now considered naturalized by the Georgia Department of Natural Resources (GADNR) (Keefer et al. 2000; Dallmier 2010).

Of the thousands of miles of designated trout streams in Georgia, few have a naturally reproducing trout population, and supplemental stocking is used to maintain a quality fishery for anglers to enjoy (Keefer et al. 2000; GADNR 2017). The three trout species are stocked through a joint effort by the GADNR and the US Fish and Wildlife Service (USFWS). The GADNR organizes and conducts most of the physical stocking efforts but USFWS National Fish Hatcheries (NFH) play an integral role in the hatching and rearing of juvenile trout. Two NFHs outside of state provide three quarters of the 1.2 million trout eggs raised by the Georgia DNR. The Chattahoochee Forest NFH provides 26% of fingerling size trout and 29% of all catchable size rainbow trout stocked in GA every year. Trout fisheries in Georgia have a large positive effect on the economy. Trout anglers generate between $130-$172 million in revenue annually (Dorison 2012; GADNR Trout Information Sheet 2014). Thus, providing a quality fishery for anglers is mutually beneficial for the anglers in the state and the Georgia economy.

Around the world, areas higher in latitude and altitude are subject to the most accelerated warming rates (Woodward 2010; Caldwell et al. 2015), and certain regions within the United States are more susceptible to negative effects associated with climate change than others. Specifically, the Southeast region of the United States faces a long list of issues associated with climate change, but the negative effects of rapidly changing environments are projected to be the highest in the Appalachian Forest ecoregion

(Caldwell 2015). Trout persistence in the south is threatened by many factors. Land-use decisions (e.g., channel alteration, unregulated construction and timber harvest, and road building) result in trout habitat degradation and population declines (Fatora 1976; Keefer et al. 2000; Cassie et al. 2001; Trout Unlimited 2006; Isaak et al. 2012). Increasing water temperatures coupled with canopy removal and sedimentation are considered the biggest threats to trout perseverance (Keefer et al. 2000; Cassie et al. 2001; Rutherford et al. 2004; Trout Unlimited 2006). The shade provided by riparian vegetation is critical for absorbing short wave solar radiation and regulating stream temperatures (Mullholland et al. 1997; Cassie et al. 2001; Rutherford et al. 2004; Isaak et al. 2012; Studinski et al.2012). Water temperatures are further increased by diversion of stream water, thermal runoff from factories, warm runoff from impervious surfaces (i.e., roads), and water storage within impoundments and lakes (Isaak et al. 2012). As stream temperatures increase, coolwater-dependent fishes are increasingly prone to mortality. All three species in Georgia favor water temperatures in the range of 12-20 °C, but mortality increases as water temperature approaches 23 °C (Cassie et al. 2001; Dorison 2012). Though supplemental stocking has been used to maintain the current trout fishery, the long-term persistence of trout and the fishery they support in Georgia may be threatened by a warming climate.

Forecasting the availability of future suitable thermal habitat is critical for the management of trout in Georgia. Stream temperature forecasting has been done in the Southeastern US on multiple occasions but has generally been done at coarser scales for large multi-state regions (Clark et al. 2001; Flebbe 2006; DeWeber and Wagner 2014; Caldwell et al. 2015). Finer-scale models that forecast surface water temperatures in regions of management interest (i.e., north Georgia) are needed to assist with trout management planning. However, modeling fine-scale effects in this region is difficult for several reasons including: the rarity of long-term regional temperature data, variability in human disturbances and the absence of fine scale modeling efforts in headwater streams in Georgia. North Georgia is at the absolute southern edge of trout distributions within the Southeast. Prior temperature modeling efforts have not included all areas in north Georgia that currently have trout, or where trout are stocked to support a fishery.

Our objectives were to identify when and where stream water temperatures pose the greatest limitation to future trout thermal habitat based on three climate warming scenarios. Results may inform trout management through better spatial and temporal targeting of trout stocking and provide information on where stocking efforts may be the most successful in the future.

Study Area

This study was conducted in 38 counties within northern Georgia (Figure 2.1) containing 40,310 km of streams that drain a total area of 46,760 km^2. Our study area consisted of nine USGS 8 digit hydrologic units including the Tennessee (06010202/06010204), Ogeechee (03060201), Oconee (03070101), Ocmulgee (03070103), Savannah (03060103), Flint (03130005), Chattahoochee (03130001/03130002), Upper Tallapoosa (03150108), Coosa (03150150) quarter of Georgia counties. These lotic systems range from first order headwaters in the Appalachian Mountains to eighth order rivers in the surrounding foothills and regions stretching south to include the metro Atlanta area. Because counties do not make great biological boundaries, the nine river basins were included in their entirety even though they exist outside of the selected county boundaries (Figure 2.3).

Methods

Physical variables

I compiled a candidate list of environmental variables (Table 2.1) suspected or known to influence stream temperatures and the presence of trout (Flebbe et al. 2006; Buisson et al. 2007; Isaak et al. 2012; Studinski et al. 2012; Segura et al. 2015). Previous studies have included variables at various large scales, but I aimed to capture the local effects of impervious and forest cover by testing them at a finer scale. I calculated polygon areas based on the position of gauging stations and 1:100,000-scale National Hydrological Dataset version 2 (NHD+) streamlines. I captured the effects of vegetation shading on stream temperature by including an area of 1,000 m upstream of each gauging station along with a buffer of 50 m on each side of the stream line. Changes in shading (40 – 70%) over small streams result in 3 - 4 °C changes in water temperature over 600 - 960 m (Rutherford et al. 2004). So, I chose a conservative value of 1,000 meters upstream from the gauging station because any shading effects from upstream were negated when water flowed from a heavily shaded area towards more open areas. Candidate variables included: watershed area WSA (km^2), difference in elevation from Parameter-elevation Regressions on Independent Slopes Model (PRISIM) raster and digital elevation model (DEM) raster layer (m), Polygon (1,000 m upstream of gauging station and 50-m buffer each side of streamline)‘forest’ cover FP (%), riparian (50-m buffer each side of streamline) ‘forest’ cover FR (%), watershed ‘forest’ cover FW (%), watershed impervious surface cover WI (%), riparian (50-m buffer each side of streamline) impervious surface cover RI (%), and polygon (1,000 m upstream of gauging station and 50-m buffer on each side of streamline) impervious surface cover PI (%) (Table 2.1). I obtained forest and impervious cover variables from the 2011 National Land Cover Dataset (Homer et al. 2015); I included only classes listed as "forest" (Classes: 41-43) and "impervious" (Classes: 21-24) in the analysis. Once I built a candidate list, I evaluated collinearity among variables with a Pearson's correlation and omitted any highly correlated variables at or above |0.7|. I used the four remaining environmental variables for each site. They included: watershed area, difference in elevation between the PRISM and DEM rasters, and impervious surface cover at the polygon scale.

Climate variables

I used surface water temperature data from 78 United States Geological Survey (USGS) temperature gauges and 78 GADNR stream units totaling 158 sites. I omitted four sites from the analysis because they were located on tail water sections of stream immediately downstream of a cold-water release dam. These sites are expected to be less affected by future air temperature increases because of the year-round availability of cool hypolimnetic water. Data from the USGS were from 1999 to 2017; the GADNR data was from 2009 to 2017. Gauging stations were spread fairly evenly throughout the study area encompassing the unique geographic locations (mountains/foothills/urban) (Figure 2.2). I extracted mean daily summer (i.e., May to September) stream temperature maximums from all 158 sites. I chose data from May-September because multiple studies have determined that increasing water temperatures pose the greatest threat to trout persistence in the future (Meisner 1990; Clark et al. 2001; Isaak et al. 2010; Wenger et al. 2011).

May-September is the hottest part of the year in the state and the busiest for trout angling pressure. I omitted from the analysis any months without a minimum of 22 total days of stream temperature data.

I acquired future and past air temperature data from publicly available gridded climate datasets. I obtained historical air temperature data from the PRISM Climate Group (www.prismclimate.org). I downloaded 30-year normal maximum temperature values (1981-2010) for the months of May-September at a resolution of 800 m x 800 m. For future air temperature projections, I downloaded 1x1 km 30 second downscaled and bias-corrected monthly temperatures for 2041 to 2060 from the World Climate Research Program's CMIP5 Climate projections website. I chose the global climate model (GCM) MRI-CGCM3 because of its lack of bias between predicted and observed air temperatures in the Southeastern United States during the time period 1979-2005 for the months of June through September (Yukimoto et al. 2012). I included multiple warming scenarios in the analysis and used these for future projections. I used three of the four Representative Concentration Pathway (RCP) scenarios provided by the World Climate Research Program's CMIP5 climate projections website. They included: RCP 2.6 (conservative warming scenario) which averaged a ~1 °C increase in stream temperature across the study area, RCP 4.5 (intermediate warming scenario) which averaged a ~2 °C increase in stream temperature, and RCP 8.5 (extreme warming scenario) which averaged a ~2.6 °C increase in stream temperature. The ~1 °C, ~2 °C, and ~2.6 °C temperature increases were unique to our study area. Those values were generated by averaging all water temperature increases across our whole study boundary for each warming scenario. RCPs are based on radioactive forcing trajectories and are named for their forcing level at

2100 (Moss et al. 2010; Sun et al. 2015). I omitted RCP 6.0 from the analysis because the atmospheric carbon dioxide (CO_2) concentration by 2050 is similar to that of RCP 4.5.

Model development and analysis

I used a linear mixed effects model with fixed effects to quantify the effects of air temperature and physical variables on water temperatures and with random effects for year and site. I estimated values for the water temperature model with the lme4 package (Bates et al. 2015) in R (RStudio Team, 2017). The model I used to determine the effects of air temperatures along with other physical variables have on water temperatures was as follows: $Y_{ijk} = \beta_0 + \beta_1 T_{ijk} + \beta_2 X_{ijk} + \cdots + \varepsilon_{ijk} + \alpha_k + b_i$ where Y_{ijk} represents water temperature in degrees Celsius for a specific year (*i*), month (*j*), and site (*k*), β_0 is the intercept. T_{ijk} is air temperature for each site, year, and month (β_1 is the fixed effect coefficient for air temperature); and additional continuous covariates (e.g., forest cover, change in elevation, and impervious surface cover) where similarly included as represented by $\beta_2 X_{ijk}$, ε_{ijk} is the random error, α_k is the site random effect term, and b_i represents the year random effect term. Random error was assumed to be normally distributed:$\varepsilon_{ijk} \sim N(0, \sigma_\varepsilon^2)$.

I created a candidate set of nine models where water temperature was the response variable, air temperature was always included as a covariate, and various combinations of environmental variables followed. Once I created a candidate set of models (Table 2.3a, b, c, d, and e), I used a model selection based on AICc values. The use of AICc values to determine the top model in a mixed modeling framework is somewhat controversial (Harrison et al. 2018). To assign an AIC value, the equation counts each random effect variance term as one even though how many “effective” variables are associated with the random effects error is otherwise difficult to determine.

Projecting future thermal habitat

The mixed-effects model chosen used comprehensive time series of observed water and air temperature values for each site to predict changes in future water temperatures across northern Georgia. I used 1981-2010 monthly historical PRISM values and predicted 2041 - 2060 air temperature (°C) projections from the MRI-CGC3 model as input to produce future monthly stream temperatures for each site, month, and RCP scenario. I then used mean max summer temperatures in conjunction with species-specific thermal limits and thermal preferences to map thermally suitable habitat for each species. Temperature of the warmest months is an important factor determining the distribution of cold-water fishes (Rahel and Nibbelink 1999; Isaak et al. 2012; Ficklin 2013). Keefer et al. (2000) determined that stream temperatures at or above 22.2 C° for more than 2 days are lethal to trout within northern Georgia. Eaton and Scheller (1996) found a similar temperature threshold for brook trout and about a 1-degree increase for brown and rainbow trout over the lethal temperature value determined by Keefer et al. (2000). Therefore, the maximum summer temperature cutoff for trout survival was set at 22.2 °C for brook trout and 23.3 °C for brown and rainbow trout. Once I calculated future temperatures, I projected them back out onto the landscape in 200-meter stream segments.

Results

Averaged monthly stream temperature records amounted to 3,377 records. Sumer water temperatures in the study sites varied monthly and ranged from a low of 19 °C during May to a high of 33.7 °C during July. Sites located within the Appalachian Mountains and surrounding foothills tended to be cooler on average throughout the study period when compared to sites at lower elevations. Air temperature was strongly related to water temperature at all sites and was the top model (Table 2.3). The air temperature to water temperature model had an AICc weight of 0.93.

Based on our forecast modeling under the three warming scenarios, there will be declines in trout habitats over the next 30 years. The specific decline of suitable thermal habitat ranged from 7 to 71% for rainbow/brown trout and 18 to 71% for brook trout depending on the month and RCP (+ ~1, 2, 2.6 °C) warming scenario (Table 2.2). Suitable thermal habitat availability for rainbow/brown trout under the conservative RCP 2.6 scenario (+ ~1 °C) ranged from 5,892 kilometers to 37,208 stream kilometers. Under the intermediate RCP 4.5 scenario (+ ~2 °C) stream kilometers ranged from 3,746 km to 32,224 km. Under the extreme RCP 8.5 scenario (+ ~2.6 °C) suitable thermal habitat ranged from 2,918 km to 22,862 km (Figure 2.6). Future thermal habitat projections for brook trout followed the same pattern. Thermal habitat availability for RCP 2.6 (+ ~1 °C) ranged from 30,682 km to 3,636 km. For RCP 4.5 (+ ~2 °C) suitable thermal habitat ranged from 18,870 km to 2,231 km. For the most extreme modeling scenario, RCP 8.5 (+ ~ 2.6 °C), habitat availability ranged from 11,951 km to 1,771 km. The biggest thermal bottleneck for the availability of suitable habitat for both species in every scenario except for RCP 4.5 occurred in August (Figure 2.5, 2.6). The RCP 4.5 climate scenario (+ ~2 °C) had less total stream kilometers (July: 3,747 km (RBT/BNT), 2,231 km (BKT); August: 4,319 km (RBT/BNT), 2,624 km (BKT)) available during July when comparted to August (Table 2.2). The biggest drop in suitable stream kilometers when the base scenario values were compared to the extreme modeling scenario (RCP 8.5) for brook trout (Figure 2.5) occurred in July, when habitat availability ranged from 29 to 56%. Whereas, the biggest decrease in available habitat for the more temperature tolerant rainbow trout and brown trout occurred in June (Table 2.2); available habitat for these two species ranged from 29 to 65% of baseline. Projected stream temperature increases ranged from 0.94 to 2.6 °C across the study area. Even under the most conservative climate change scenario, much of the suitable thermal habitat in Western Georgia is eliminated for rainbow trout and brown trout and almost completely eliminated for brook trout. Western Georgia streams occur at lower average elevations than streams in other groups within the study area, making them more susceptible to negative changes caused by increasing water temperatures. Western Georgia had the largest loss of suitable habitat of any group for both species. Ultimately, as warming increases to 2.6 °C, overlap for remaining suitable thermal habitat becomes more common (Figure 2.4). In such a scenario, all three species will be confined to many of the same stream reaches, which is largely lower order streams and headwaters at higher elevation

Despite the occurrence of a temperature-related bottleneck for habitat availability during the summer months, this phenomenon was not observed for May and September. Water temperatures below the lethal temperature threshold for both species were present in both months. For RCP scenario 8.5 (~ 2.6 °C) during the month of August, stream kilometers below the lethal threshold for brook trout totaled 1,772 and 2,918 kilometers for brown and rainbow trout (Figures 2.6, 2.7). During September, those values increased by 25% for RCP 8.5. The change between habitat availability from August to September is relatively similar through all of the RCP scenarios. May also had large amounts of suitable thermal habitat available. For RCP 8.5, there was 22,862 stream kilometers below the lethal threshold for brown trout and rainbow trout, and 11,951 stream kilometers below 22.2°C for brook trout.

Discussion

I predicted potential thermal habitat for trout in north Georgia and identified when and where temperatures pose the greatest challenge to trout persistence. Although previous studies focused on mapping future thermal habitat in the southeast, they did not capture the potential for suitable stream habitat outside of the Appalachian Mountains in Georgia (Meisner 1990; Clark et al. 2001; Flebbe et al. 2006; Caldwell et al. 2015). Meisner 1990 and Flebbe et al. 2006 concentrated on mapping climate change effects across the entire southeastern United States and found increased rates of warming and higher percentages of habitat loss compared to our state-oriented modeling effort. Our findings suggest an average maximum temperature increase of 2.6 °C and a decrease in suitable thermal habitat of 71% by 2050. Our maximum temperature increases and decline in suitable thermal habitat were in agreement with values reported by Clark et al. 2001. As habitat fragmentation increases within remaining streams, only small headwater regions at higher elevations will provide refuge areas for trout (Flebbe et al. 2006; Isaak et al. 2012). Once sections of streams are isolated (Figure 2.4), the likelihood of trout extirpation within the area increases. The probability of trout existing within those isolated patches is lowered as climate warms. Rising water temperature results in the disappearance of avenues for recolonization and the increase of permanent local extinctions. The effects of climate change are predicted to be more severe in the southern Appalachian Mountains region compared to surrounding areas within the southeast

United States (Flebbe et al. 2006; Caldwell et al. 2015). Loss of trout habitat will result in the decrease of recreational opportunities for anglers and have negative economic consequences in Georgia. Also, as urban populations continue to increase in size impervious surface cover is likely to further increase stream temperatures and accelerate habitat loss.

Though our modeling focused on a finer scale than previous studies, changes in riparian vegetation, macroinvertebrate food sources, trout species distributions, and groundwater inputs are likely to affect warming stream temperatures, but all are nearly impossible to model on a statewide scale. Also, linear mixed effects models are complex and they are often difficult to implement correctly in biological sciences for several reasons. In a linear mixed modeling framework, more assumptions are made about the data than in a typical statistical method like general linear modeling and these assumptions are frequently violated. Understanding the model output properly can be difficult due to the variance components associated with random effects variables. The presence of random effects variables renders the typical model selection techniques difficult to implement because of biases associated with some statistical tests (i.e., Wald tests, Akaike's Information Criterion (AIC) comparisons) (Harrison et al. 2018).

Bias and limitations associated with the data available to us for analysis makes capturing localized effects of previously listed variables difficult. For example, NHD+ streamline locations at the 1:100,000 scale are not accurate in lower order streams (i.e., first and second order). The actual stream can be dozens of meters away from where the NHD+ streamline occurs in the dataset. This disconnect makes capturing the localized effects of riparian vegetation and shading on a meter by meter scale difficult. Warmer water temperatures may also shift spawning patterns and negatively affect fish physiology for all three species (Peer and Miller 2014).

Trout exist near the southernmost fringe of their distribution in Georgia, and most of the streams they inhabit are warmer than their preferred temperature range (12-20 °C) for most of the year (Meisner 1988; Dorison 2012). Prolonged exposure to temperatures above their preferred range can result in an earlier spawning due to a warmer winter, increased metabolism and metabolic costs, and decreased growth rates caused by a lack of adequate food source (Flebbe et. al. 2006; Wilson et al. 2009). Currently, brook trout spawn in the late fall and rainbow trout spawn in the spring. This separation of spawning times is important for brook trout that are generally outcompeted by the other two species. With a warmer climate, brook trout may spawn later in the fall and hatch near the same time rainbow trout, further overlapping the competition among the species for resources in shared areas. Any one, or a combination of these factors, could result in the loss of trout from a particular stream.

Migration upstream towards higher elevations is a possible solution for managing the effects of climate change in certain areas (Isaak et al. 2012). Though, this solution is confounded by the presence of natural and manmade barriers, the absence of consistent water flow throughout the year in headwater streams, or suitable habitats are already occupied by other resident species. Though increasing water temperatures pose a major threat to the persistence of trout in northern Georgia, small pockets of fish may persevere in the future. Local refuges may provide some relief from warmer water and restoration efforts may offset some temperature increases (Isaak et al. 2011; Wenger et al. 2011). These refuge areas could include constant shading, which would negate much of the solar radiation needed to warm stream temperatures, cooler water from groundwater inflows and natural springs, and large sections of streams below cold-water release dams. More research is needed to determine how other effects of climate change could affect tail water habitats where cold-water releases from dams will provide adequate future habitat in some streams. Fisheries managers may find success by implementing management approaches that are adaptable to future changes in landscapes (Battin et al. 2007). For example, splitting stocking efforts to avoid adding fish to streams during the warmest parts of the year may be a solution to low summertime survival. Also, adding more riparian habitat on stream banks to provide shading and refuge from increased water temperatures may be a long-term solution to minimize some of the climate-warming effects.

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Table 2.1 Independent variables included in candidate model sets for the prediction of suitable thermal habitat availability in northern Georgia in 2050. The bold term represents the variable that was used in the final model and statistical analysis.

Variable	Description	Extent	Unit
WSA	Watershed Area	Watershed	km²
AT	**Prism 30-year norm air temperature (1980-2010)**	**Site**	**°C**
E	Difference in elevation between prism raster layer and 30-meter DEM elevation raster layer	Site	m
FP	Polygon 'forest' cover 1000 m upstream of gauging station and 50 m buffer on each side of the streamline, 2011 [sum of deciduous forest, evergreen forest, and mixed forest (classes 41-43)] (Segura et al. 2015)	Polygon	%
FR	Riparian 50 m buffer 'forest' cover, 2011 [sum of deciduous forest, evergreen forest, and mixed forest (classes 41-43), and a buffer of 50 m on each side of the stream line] (Segura et al. 2015)	Riparian	%
FW	Watershed percent 'forest', 2011 [sum of deciduous forest, evergreen forest, and mixed forest (classes 41-43)]	Watershed	%
WI	Watershed impervious surface cover, 2011 [sum of low, medium, and high urban development in the watershed (classes 21-24)]	Watershed	%
RI	Riparian 50 m buffer impervious surface cover, 2011 [sum of low, medium, and high urban development in the watershed (classes 21-24 in a buffer 50 m on each side of the stream line)]	Riparian	%
PI	Polygon impervious surface cover 1000 m upstream of gauging station and 50 m buffer on each side of the streamline, 2011 [sum of low, medium, and high urban development in the watershed (classes 21-24 in a buffer 50 m on each side of the stream line)]	Polygon	%

Table 2.2 Summary of results describing the amount of remaining suitable thermal habitat available for trout in northern Georgia in 2050.

Species	Month	Scenario	Stream km	Total stream length remaining (%)
RBT/BNT	May	Base	40,047	-
RBT/BNT	May	2.6	37,209	93
RBT/BNT	May	4.5	32,224	80
RBT/BNT	May	8.5	22,863	57
RBT/BNT	June	Base	17,465	-
RBT/BNT	June	2.6	11,323	65
RBT/BNT	June	4.5	5,645	32
RBT/BNT	June	8.5	5,064	29
RBT/BNT	July	Base	10,240	-
RBT/BNT	July	2.6	5,892	58
RBT/BNT	July	4.5	3,746	37
RBT/BNT	July	8.5	3,068	30
RBT/BNT	August	Base	9,380	-
RBT/BNT	August	2.6	6,741	72
RBT/BNT	August	4.5	4,319	46
RBT/BNT	August	8.5	2,919	31
RBT/BNT	September	Base	34,857	-
RBT/BNT	September	2.6	28,557	82
RBT/BNT	September	4.5	11,932	34
RBT/BNT	September	8.5	11,332	33
BKT	May	Base	37,270	-
BKT	May	2.6	30,682	82
BKT	May	4.5	18,871	51
BKT	May	8.5	11,952	32
BKT	June	Base	10,781	-
BKT	June	2.6	8,423	78
BKT	June	4.5	3,705	34
BKT	June	8.5	3,273	30
BKT	July	Base	6,445	-
BKT	July	2.6	3,637	56
BKT	July	4.5	2,231	35
BKT	July	8.5	1,853	29
BKT	August	Base	5,136	-
BKT	August	2.6	3,875	75
BKT	August	4.5	2,624	51
BKT	August	8.5	1,772	35
BKT	September	Base	18,272	-
BKT	September	2.6	13,556	74
BKT	September	4.5	7,302	40
BKT	September	8.5	6,921	38

Table 2.3a Lme4 mixed effects output for all candidate model types for predicting suitable thermal habitat availability for trout in northern Georgia for May 2050. For explanations of variables included in each model, consult Table 2.1

Model	Variables Included	K	AICc	Delta_AIC	AICcWt
Model 1	AT	5	1490.09	0.00	0.93
Model 3	AT+PI	6	1495.79	5.70	0.05
Model 2	AT+WSA	6	1498.51	8.43	0.01
Model 4	AT+E	6	1499.99	9.90	0.01
Model 5	AT+WSA+PI	7	1505.52	15.43	0.00
Model 7	AT+PI+E	7	1505.82	15.73	0.00
Model 6	AT+WSA+E	7	1508.38	18.29	0.00
Model 8	AT+WSA+PI+E	8	1515.51	25.42	0.00
Null	--	4	1602.82	112.74	0.00

Table 2.3b Lme4 mixed effects output for all candidate model types for predicting suitable thermal habitat availability in northern Georgia for June 2050. For explanations of variables included in each model, consult Table 2.1

Model	Variables Included	K	AICc	Delta_AIC	AICcWt
Model 1	AT	5	2020.41	0.00	0.87
Model 3	AT+PI	6	2024.41	4.00	0.12
Model 4	AT+E	6	2030.57	10.16	0.01
Model 2	AT+WSA	6	2033.46	13.06	0.00
Model 7	AT+PI+E	7	2034.46	14.06	0.00
Model 5	AT+WSA+PI	7	2038.41	18.00	0.00
Model 6	AT+WSA+E	7	2043.71	23.31	0.00
Model 8	AT+WSA+PI+E	8	2048.58	28.17	0.00
Null	--	4	2243.8	223.39	0.00

Table 2.3c Lme4 mixed effects output for all candidate model types for predicting suitable thermal habitat availability in northern Georgia for July 2050. For explanations of variables included in each model, consult Table 2.1

Model	Variables Included	K	AICc	Delta_AIC	AICcWt
Model 1	AT	5	2047.71	0.00	0.86
Model 3	AT+PI	6	2051.52	3.81	0.13
Model 4	AT+E	6	2058.02	10.31	0.00
Model 2	AT+WSA	6	2061.8	14.09	0.00
Model 7	AT+PI+E	7	2061.82	14.11	0.00
Model 5	AT+WSA+PI	7	2066.5	18.79	0.00
Model 6	AT+WSA+E	7	2072.15	24.44	0.00
Model 8	AT+WSA+PI+E	8	2076.85	29.14	0.00
Null	--	4	2268.88	221.17	0.00

Table 2.3d Lme4 mixed effects output for all candidate model types for predicting suitable thermal habitat availability in northern Georgia for August 2050. For explanations of variables included in each model, consult Table 2.1

Model	Variables Included	K	AICc	Delta_AICc	AICcWt
Model 1	AT	5	1899.01	0.00	0.93
Model 3	AT+PI	6	1904.31	5.30	0.07
Model 4	AT+E	6	1909.38	10.37	0.01
Model 7	AT+PI+E	7	1914.66	15.65	0.00
Model 2	AT+WSA	6	1915.34	16.33	0.00
Model 5	AT+WSA+PI	7	1921.14	22.13	0.00
Model 6	AT+WSA+E	7	1935.72	26.71	0.00
Model 8	AT+WSA+PI+E	8	1931.52	32.51	0.00
Null	--	4	2112.64	213.60	0.00

Table 2.3e Lme4 mixed effects output for all candidate model types for predicting suitable thermal habitat availability in northern Georgia for September 2050. For explanations of variables included in each model, consult Table 2.1

Model	Variables Included	K	AICc	Delta_AIC	AICcWt
Model 1	AT	5	1629.74	0.00	0.95
Model 3	AT+PI	6	1635.79	6.05	0.05
Model 4	AT+E	6	1640.37	10.63	0.00
Model 7	AT+PI+E	7	1646.52	16.76	0.00
Model 2	AT+WSA	6	1648.58	18.84	0.00
Model 5	AT+WSA+PI	7	1654.49	24.74	0.00
Model 6	AT+WSA+E	7	1659.21	29.47	0.00
Model 8	AT+WSA+PI+E	8	1665.21	35.47	0.00
Null	--	4	1851.74	222.00	0.00

Table 2.4 Mixed effects model output for each month (May-Sep.) for the top model (air temperature to water temperature). Values were used to predict suitable thermal habitat availability for trout in 2050 for northern Georgia

Month	β_0	β_1	σ_a^2	σ_b^2	σ_ε^2
May	-18.01 (2.67)	1.47 (0.10)	1.24	0.98	0.58
June	-34.22 (2.34)	1.93 (0.08)	2.17	0.55	0.61
July	-32.10 (2.36)	1.80 (0.07)	2.37	0.82	0.55
August	-30.67 (2.39)	1.79 (0.08)	2.34	1.01	0.42
September	-19.43 (1.71)	1.49 (0.06)	1.45	0.46	0.30

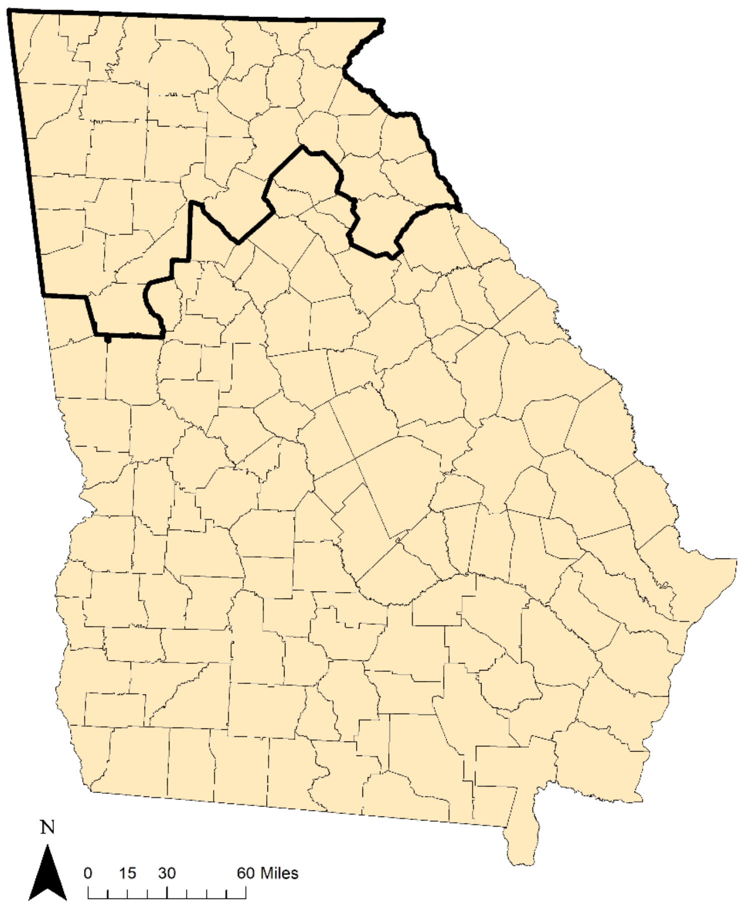

Figure 2.1 Counties outlined in black represent Georgia counties containing trout streams as of 2017.

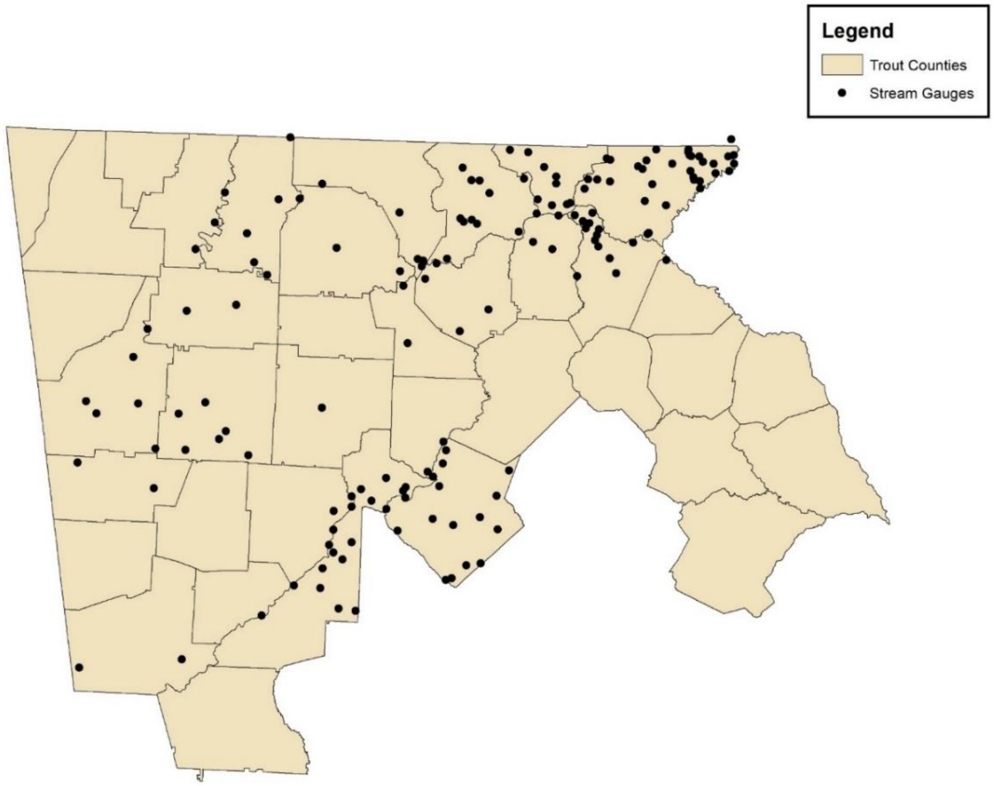

Figure 2.2 Distribution of USGS and DNR water temperature gauging stations from 2017 used for analysis within Georgia counties containing trout fishing opportunities.

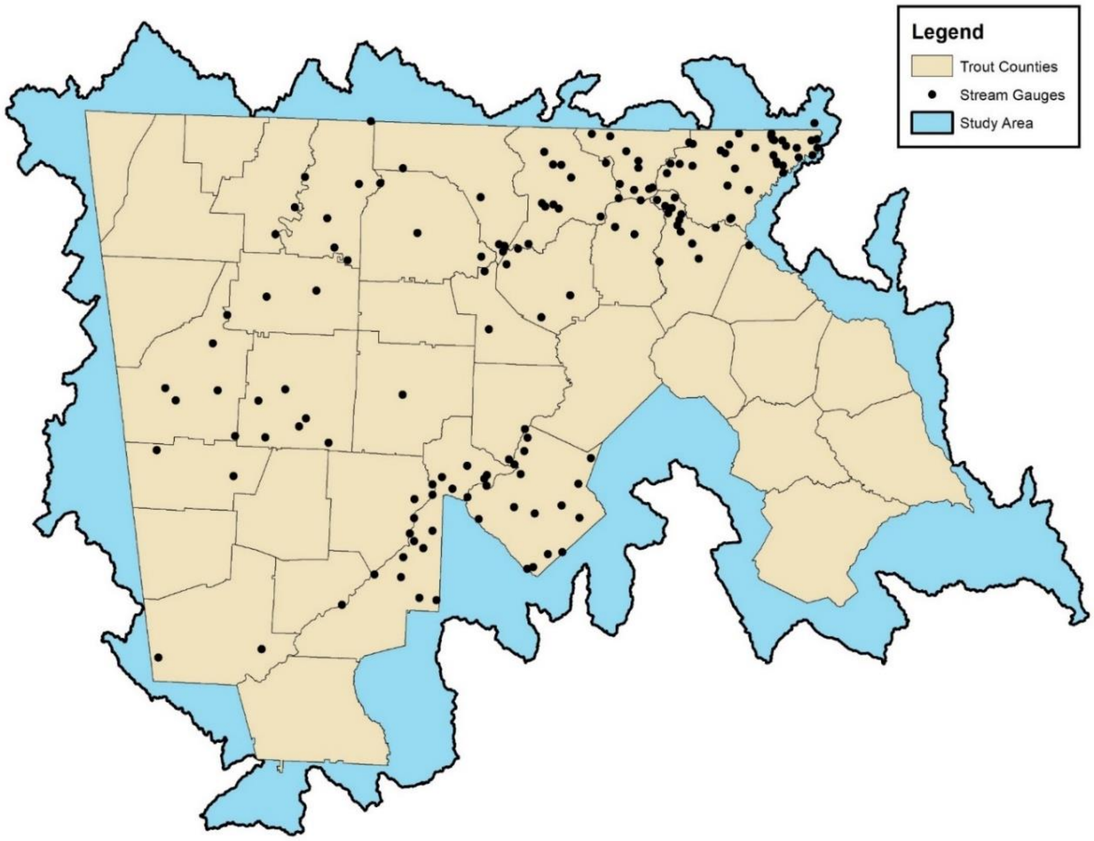

Figure 2.3 Study area outlined in blue containing HUC 8 watersheds in their entirety in northern Georgia.

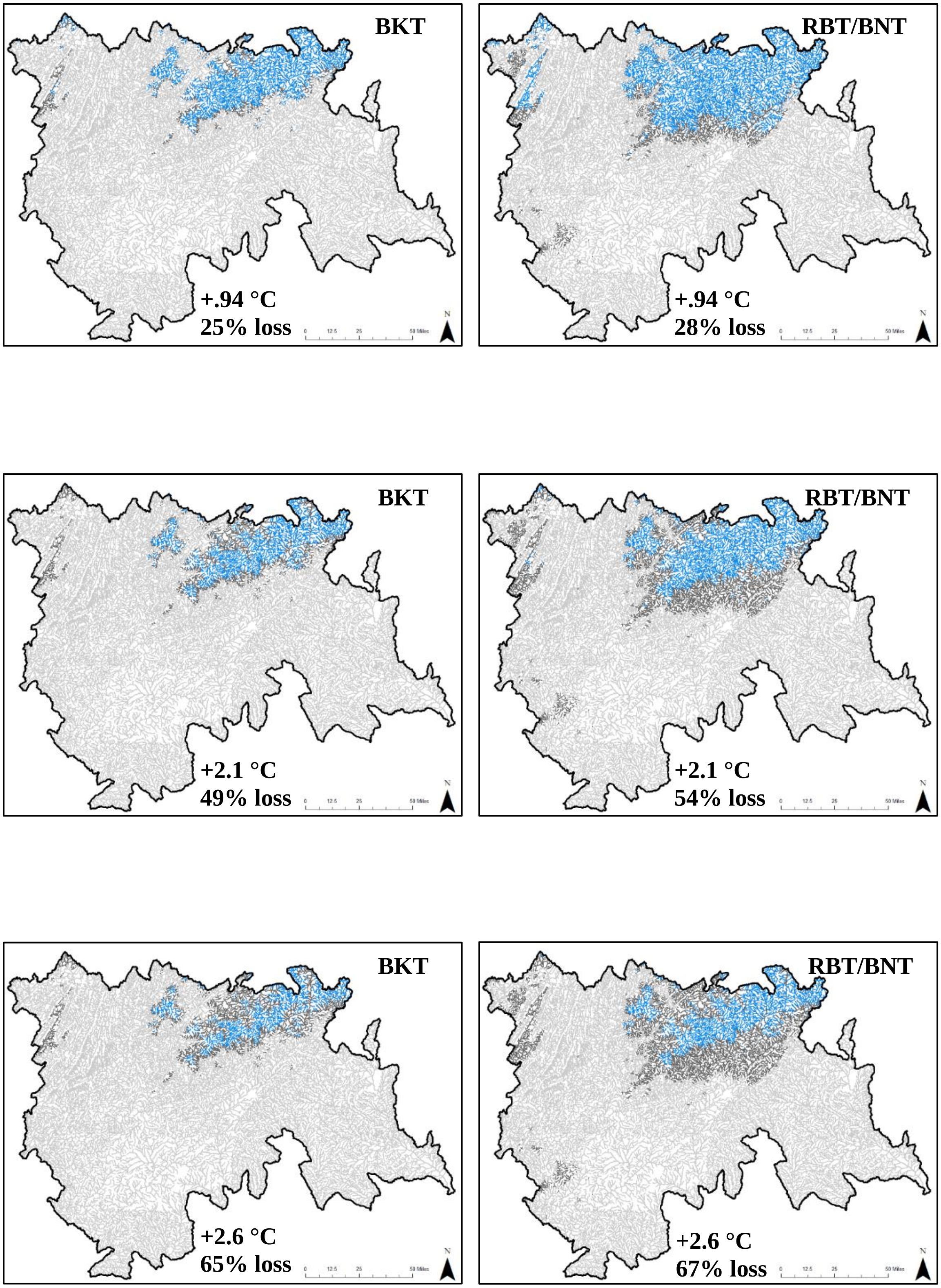

Figure 2.4 Projected availability of suitable thermal habitat for trout in August 2050 in northern Georgia, dark grey lines represent base scenario streams, blue lines represent remaining habitat.

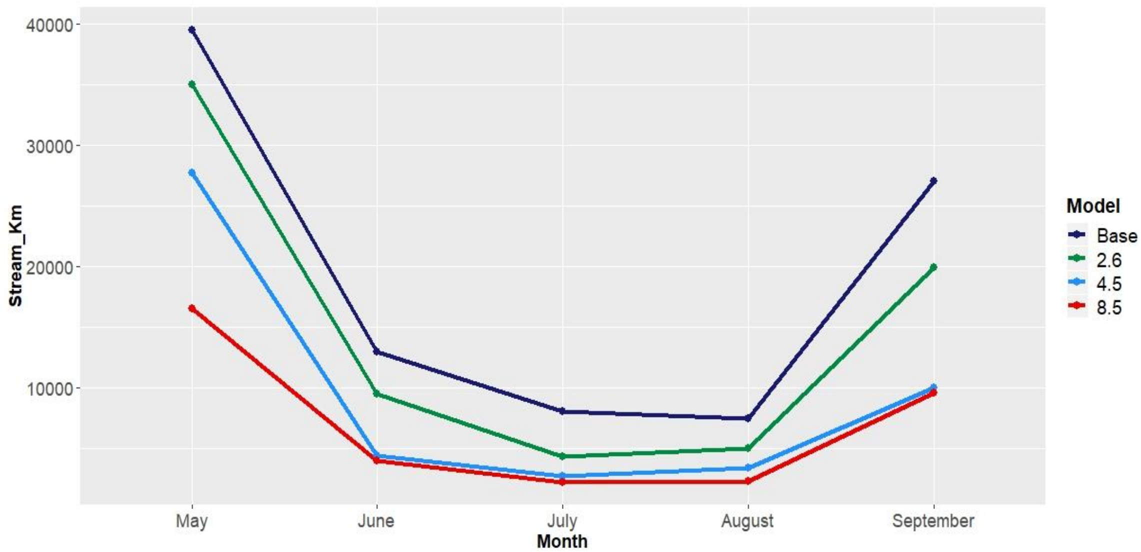

Figure 2.5 Expected suitable thermal habitat availability (km) for May-September 2050 for brook trout in northern Georgia.

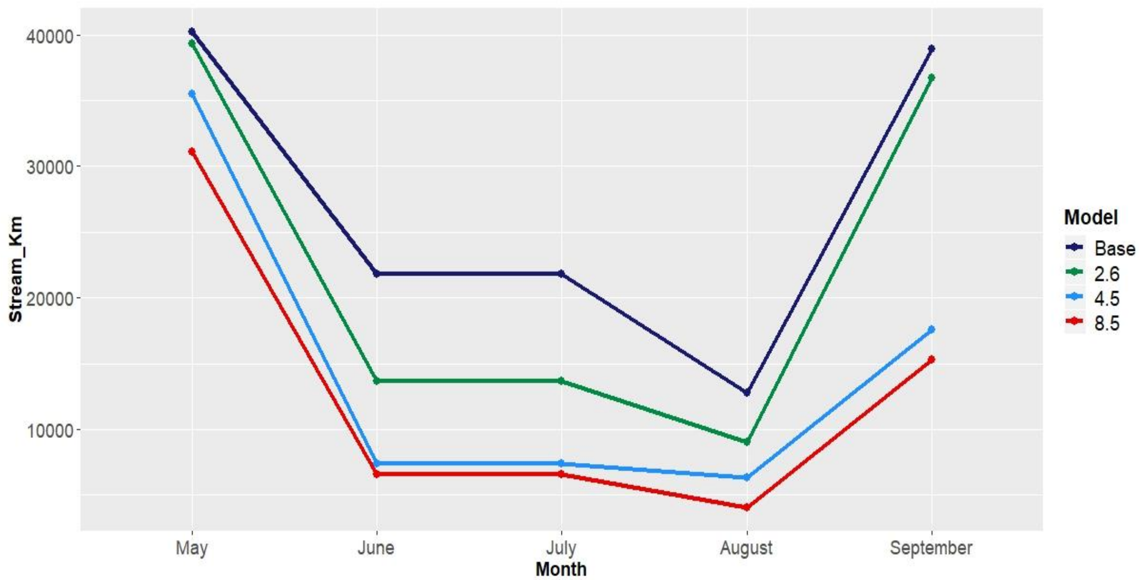

Figure 2.6 Expected suitable thermal habitat availability (km) for May-September 2050 for rainbow and brown trout in northern Georgia.

CHAPTER 3

INTERSECTION OF SUPPLY AND DEMAND UNDER CURRENT AND PROJECTED THERMAL REGIMES[2]

[2] Haag J. M., N. P. Nibbelink, C. A. Jennings, B. J. Irwin, and B. B. Boley. To be submitted to *North American Journal of Fisheries Management.*

Abstract

There is little debate that our climate is warming, and this change may affect the persistence of trout in the cool-water regions of Georgia. This warming could affect trout-based recreational opportunities and natural communities in the state. In Georgia, successful management of the trout fishery requires an understanding of current stocking practices, availability of suitable habitat, along with angler use and preferences. Significant changes in angler demographics (and likely suitable trout habitat) have occurred since the Georgia Department of Natural Resources (GADNR) formalized its last trout management plan in 2000. To provide information for an updated trout management plan, I mapped the current "supply" of trout (sampling and stocking records) and compared those maps to the "demand" for trout. To better plan for both current and future effects of a warming climate to the fishery, I also used spatially-explicit models of surface water temperature to map future habitat suitability for three scenarios (~1°C, ~2°C, ~2.6°C) of increases in future water temperature. I then combined future habitat predictions with survey data collected in 2017 by another graduate student to highlight areas of high angler demand and low trout supply due to loss of future suitable thermal habitat. I was able to compare trout supply provided by stocking efforts, future suitable thermal habitat, and angler demand among eight county groups based on geography and survey response rates. Future projections of suitable thermal habitat for trout along with comparisons of angler demand will help the GADNR to better pinpoint locations where trout are more likely to survive various warming scenarios, and allow the DNR to better allocate their limited stocking resources to locations where trout have the highest chance of survival and where anglers have maximum angling opportunities.

Introduction

Georgia exists at the southernmost edge of native trout distributions within the Appalachian Mountains. North Georgia is home to three trout species: rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*), and brook trout *(Salvelinus fontenalis)* (GADNR 2014). Brook trout are native to the state; whereas, brown trout and rainbow trout are introduced species, but are now considered naturalized. Because of their popularity, and to meet demands by anglers, trout have been introduced outside their native range (Marcy et al. 2005; Nelson 2006; Rohde et al. 2009). Trout management in Georgia has followed the same formula as many other states within the United States. All three trout species (brook, brown, rainbow) were stocked into waters across the continental United States during the late 1800s and early 1900s to provide a recreational fishery, but with little regard as to whether the species are native to the region or not (Poole 2007; Dunham et al. 2011). Early trout management activities within the US were generally not effective because of unfavorable land-use practices (e.g., channel alteration, unregulated construction and timber harvest, and road building) and species exploitation, which resulted in trout habitat degradation and population declines (Fatora 1976; Thorn et al. 1997; Trout Unlimited 2006; Poole 2007). Many factors limit the distribution of all three species within Georgia. For example, seasonably warm temperatures, calcium deficient soils, and various types of impassible barriers negatively affect the fishery. Few natural reproducing trout populations exist within the state's 4,000 miles of trout streams, and the success of the fishery is heavily dependent on stocking. A joint effort between the Department of Natural Resources and the U.S. Fish and Wildlife service leads to stocking of all three species throughout the northern portion of the state to meet anglers' demands.

Trout angling has a large economic impact within the state of Georgia. Recreational trout anglers were estimated to produce 130 million dollars in 2012 and 172 million dollars in revenue in 2014 (Dorison 2012; GADNR Trout Information Sheet 2014). Stocking efforts are focused mostly on public lands, but angler access has become limited in some areas because of urbanization and the conversion of public lands into private property.

Historically, trout management in Georgia focused on the protection and enhancement of proper trout habitat, the management of naturally reproducing trout, and the management of put-and-take fisheries on an *ad hoc* basis. At its core, the Georgia Department of Natural Resources (GADNR) still strives to support the longstanding objective of ensuring the sustainability of trout populations for trout anglers to enjoy (GADNR 2014). To continue to provide great fishing opportunities and meet the needs of over 160,000 trout anglers within the state, the GADNR implemented its first ever coordinated "Trout Management Plan" (TMP) in 2000. Concurrently, the state has experienced rapid demographic changes, growth in human population, and a warming climate. Changing demographics may affect how and when the "typical" trout angler accesses and interacts with the trout fishery. Trout fishing opportunities may also shift with increases in average summer water temperatures, which may lead to extirpation in some areas and changes in fish behavior (Isaak et al. 2010; Wenger 2011; Peer and Miller 2014). Thus, as we approach 20 years since the first TMP, changing human demography, and environmental conditions require a reassessment of angler preferences and whether current management can continue to meet angler expectations in a changing environment. Incorporating survey responses about angler preferences in trout management is not unique to Georgia. Multiple studies have used surveys to collect data about angler use, specialization, preferences, and attitudes towards present fisheries management activities (Fisher 2011; Gigliotti and Peyton 2011; Hutt and Bettoli 2011; TenHarmsel et al. 2019). The effects of climate change on current and future trout persistence has also been studied intensely across the United States, and on a regional scale (Clarke et al. 2001; Flebbe et al. 2006; Wenger et al. 2011; Isaak et al. 2012). Although studies focusing on angler preferences and climate change are numerous, I was unable to find a study that focuses on combining both factors on a finer (i.e., county level) scale in riverine ecosystems. In this study, I combine angler preference data with surface water temperature predictions to inform spatially-explicit trout management planning. I modeled future suitable thermal trout habitats for 2050 and was able to identify areas where trout persistence would be most likely in the future under various warming climate scenarios, potentially informing allocation of GADNR fisheries resources in the future. Specifically, I combined survey data and Importance-Satisfaction Analysis (ISA) methodology from a companion project (Yondo 2018) to identify gaps in angler importance and satisfaction ratings of trout fishing attributes and pinpointed how these differences changed spatially across eight county groups. I then combined the survey data with surface water temperature forecasts of trout thermal habitat (Chapter 1) to 2050 to identify areas where trout persistence would be the most likely in the future.

Study Area

North Georgia is home to over 4,000 miles of designated trout streams spread throughout 38 counties. Our study area consisted of nine USGS 8 digit hydrologic units including the Tennessee (06010202/06010204), Ogeechee (03060201), Oconee (03070101), Ocmulgee (03070103), Savannah (03060103), Flint (03130005), Chattahoochee (03130001/03130002), Upper Tallapoosa (03150108), Coosa (03150150) basins which cover nearly a quarter of the state (Figure 3.1). Stream size ranged from first to fourth order, representing headwaters in the Appalachian Mountains to larger rivers in the surrounding foothills extending south to include the metro Atlanta area.

Methods

Trout Survey Data

A statewide trout angler survey was conducted in 2017 (Yondo 2018). She mailed a questionnaire to 4,000 anglers licensed to fish in the state of Georgia. Questions on the survey generated information about angler's demographics, specializations, preferences for several fishing attributes, the importance of those attributes, along with how satisfied anglers were with the performance and satisfaction of those fishing attributes. Surveys were mailed to potential respondents in January 2017 and data collection concluded in June of 2017. Survey respondents were asked to rate perceived satisfaction and importance of 17 trout fishing attributes using a five-point Likert-type scale. Anglers ranked importance on a scale of 1= "not at all important" to 5= "extremely important" and ranked satisfaction on a scale of 1= "very dissatisfied" to 5= "very satisfied". Of the 17 trout fishing attributes, 10 were related to catching trout (e.g., catching wild or stocked trout, size of trout caught) and the remaining seven were non-catch-related attributes (e.g., campgrounds at access points, access to stocking schedules, the cost of a trout fishing license). Categorical data was also collected by asking anglers questions like "Which species do you prefer to fish for? Choose 1", respondents had the choice of choosing brook, brown or rainbow trout, or no preference. Other preference questions covered the topics of whether anglers preferred to catch, release, or do a combination of both options when they capture fish, whether anglers preferred fishing for stocked or wild trout, or had no preference, and the size of trout anglers preferred to catch. Anglers were instructed to choose only one option when asked about which size and number combination they preferred to capture. They had the choice of one fish measuring 20 inches, two fish measuring 16 inches, four fish measuring 12 inches or eight fish measuring 9 inches. Anglers were also asked to rate the current quality of trout fishing in the state. Respondents rated fishing quality on a 5-point scale with 1= "poor" and 5= "excellent." For more in depth methodology relating to survey collection methods, consult Yondo (2018).

County Grouping

Of the 4,000 surveys mailed to anglers, 624 were completed and returned. For the purposes of this study, I omitted anglers who indicated that they did not fish in Georgia during (2016), resulting in 464 respondents. Our goal was to compare responses on a county by county basis to stocking data from 2017 provided by the GADNR. To accomplish this, each respondent was asked to provide the number of fishing trips each individual took to each county. To minimize counting an angler's response more than once if they indicated fishing in multiple counties, I assigned a "dominant county ID" that represented the county to which each respondent indicated they visited most. Some anglers divided their efforts evenly between two counties, and I made the choice to count their responses once in each of the two counties they indicated. Once each angler had a dominant county assigned, the majority of individual counties had low overall representation. Our solution was to group counties together based on geography until at least 10% of the total sample was represented in each group of counties (Figure 3.2). I chose a 10% threshold because it represented angler participation evenly across all eight county groups. Specifically, all county groups had roughly the same amount of angler responses assigned to them at the 10% threshold. For example, Rabun county was a standalone county with 53 respondents indicating they did most of their fishing in that area; Union and Towns counties were grouped together to reach the 10% threshold, and that group represented 48 respondents. Group 6 (Habersham, Stephens, and Hart) was just below the 10% threshold (9.91%), as no other aggregation scheme resulted in a relatively even distribution of responses. Figure 3.2 visually explains which counties were in each of the eight groups and how many anglers were represented within those groups.

Data Analysis

After anglers were assigned to county groups, survey responses were averaged for each group. One-way analysis of variance (ANOVA) and Bonferroni's Post Hoc Test were used to determine whether within and among group means were statistically different ($\alpha = 0.05$) for interval level data (e.g., Mean satisfaction with overall trout fishing quality in GA). Chi-square was used to test for significant differences ($\alpha = 0.05$) in the percentage of within group responses per category of the categorical data (e.g., for which species do you prefer to fish, brook, brown, rainbow or no preference. Results of statistical testing are given in Appendices A1, A2, and A3.

Importance Satisfaction Analysis (ISA)

A major focus of the trout angling survey conducted in 2017 was identifying anglers perceived performance and satisfaction of certain recreational fishing attributes. To identify gaps between angler's rankings of importance and satisfaction for an attribute, I used the results of a companion analysis (TenHarmsel et al. 2019) to complete our evaluation. I used data and the importance-satisfaction analysis (ISA) methodology from her study to pinpoint the gaps within angler rankings of various catch and non-catch attributes. An ISA is useful when investigating the gaps between a stakeholder's satisfaction with a certain product/service and the level of importance they assign to the same attribute (Sever 2015). Measuring both performance and satisfaction at the same time for each attribute provides the opportunity to visually pinpoint the gaps between how important stakeholders rank an attribute and their level of satisfaction with how the attribute is performing (Yondo 2018). An ISA uses a four-quadrant system to graph the importance-satisfaction ratings. This creates a visual display of how each attribute is positioned within the four ISA quadrants: Quadrant 1: "Concentrate Here" which exhibits high importance and low satisfaction, Quadrant 2: "Keep Up the Good Work" which displays high importance and high satisfaction, Quadrant 3: "Low Priority" which displays low importance and high satisfaction, and Quadrant 4: "Possible Overkill" which exhibits low importance and low satisfaction (Figure 3.8, 3.9).

The ISA uses three different crosshair placements to separate the four quadrants. The first technique is a scale-centered approach. The crosshairs are simply placed in the middle of the five-point Likert scale that was used to measure the importance and satisfaction. This approach is the simplest and most transparent of the three crosshair methods, but it includes some limitations. Most attributes fall into the "Keep up the Good Work' quadrant because survey respondents tend to inflate their importance and satisfaction scores (Boley et al. 2017). Those inflated scores lead to what is referred as "ceiling effects" because researchers generally select attributes for inclusion on the survey that are already “important” on their own as a surrogate to measure importance. To combat “ceiling effects” a data-centered approach was used for cross-hair placement along with the scale-centered method. The data-centered method places the cross-hairs at the mean responses of importance and satisfaction for each attribute. This approach is advantageous because it allows researchers to compare attributes relative to each other, which is vital if management is considering pulling resources from one attribute and allocating them to another (TenHarmsel et al. 2019). The “ceiling effects” problem is solved because the data-centered approach ensures that attributes are positioned within the four quadrant ISA chart according to their relative importance and satisfaction. Although the data-centered method solves the “ceiling effects” issue, it does not solve other limitations, for example how to understand attributes that are positioned near scale thresholds or how to assess attributes that fall within the “Overkill” category. Attributes within the “Overkill” quadrant have performance values that exceed expectation values, which is a positive performance metric due to its strong connection to customer satisfaction. These attributes are problematic because pulling resources from over-performing features could cause a drop in customer satisfaction if those attributes are “basic/threshold attributes” meaning, their presence may not have led directly to the perceived customer satisfaction, but their disappearance may cause increased dissatisfaction (Kano et al. 1984). A third scale-centered method was used in our analysis to decrease the effects of limitations. A 45° iso-priority line was added to the chart to create a threshold where satisfaction exceeds importance, and where satisfaction falls below importance. All points that fall on the iso-priority line have equal satisfaction and importance values. By using an iso-priority line, I was able to use a gap analysis to determine which groups were exceeding attribute expectations and which groups fell below expectations.

Intersecting Supply and Demand with Future Habitat Changes

Once anglers were assigned to groups I was able to compare their responses for certain attributes to 2017 stocking records provided by the GADNR. Anglers were asked to choose if they preferred to fish for rainbow trout, brown trout, brook trout, or no preference and were instructed to choose only one. Those responses were then intersected with the stocking data. Stocking data was split by the same eight county groups used for angler responses. Once data were allocated to the appropriate group, I was able to evaluate proportional stocking effort for each species in each group relative to angler preference for each species. Further, to evaluate supply and demand in the context of current and future climate, expected trout thermal habitat for the present and for 2050 based on surface water temperature predictions (see Chapter 2) were mapped. Conservative (~1 °C), intermediate (~2 °C), and extreme (~2.6 °C) warming scenarios were applied to determine where trout had the greatest chance of persistence and where stocking would be the most effective in the future.

Results

Survey Results

The Georgia Department of Natural Resources stocks nearly one million trout annually across northern Georgia, and anglers report a moderately high degree of satisfaction. Anglers were asked to rate their satisfaction with the current Georgia Department of Natural Resources management of the trout fishery and their satisfaction with the overall fishing experience (Table 3.1) on a scale of very dissatisfied (1) to very satisfied (5). Mean satisfaction scores from all assigned county groups were high (Table 3.1). Anglers in the Fannin county group were the most satisfied (mean = 4.07) with their overall fishing experience and respondents from the Habersham/Stephens/Hart group were the least satisfied on average (mean = 3.71), though according to One-Way ANOVA results, the differences between the two groups were not significant (p =0.329). Satisfaction with GADNR management of the fishery followed the same pattern. Mean satisfaction across all groups was moderate to high. Fannin county group respondents were the most satisfied while anglers from the Western Georgia group were the least satisfied with current management of trout, though according to ANOVA results the differences between these two groups were not significant (p = 0.776). When asked to rate the current quality of fishing (Table 3.1) on a scale of poor (1) to excellent (5), responses indicated a lower trend in satisfaction than the previous responses from satisfaction with overall trout fishing experience and GADNR's management. Anglers from the Fannin group rated fishing quality the highest (mean= 3.27), while people in the Gilmer/Lumpkin/Dawson group rated overall fishing quality the lowest out of all groups (mean= 2.85). According to ANOVA results, the differences in mean scores between Fannin count group and Gilmer/Lumpkin/Dawson group were not significant (p = 0.178). Anglers were asked to rank the importance along with their satisfaction of catching wild and stocked trout (Table 3.3, Table 3.4). Mean scores indicated that catching wild trout was more important to anglers in every assigned county group than catching stocked trout. Anglers in the Western Georgia group had the highest score (mean= 3.55) while the White County group had the lowest score of 3.25. Though overall importance scores for catching stocked trout were lower than values for catching wild trout, a significant difference at the 0.05 level was detected between Fannin and Western Georgia groups (sig: .025). Fannin group had the lowest importance score of 2.81 while Western Georgia had the highest score of 3.40 (Table 3.3). Survey respondents were also more satisfied with catching wild trout versus catching stocked trout. Anglers in Union/Towns (p = 0.035) and White ($p = 0.022$) groups had the highest satisfaction for catching wild trout and were significantly different than respondents from Western Georgia (Table 3.4). Respondents from Western Georgia had the lowest satisfaction of all groups.

Importance Satisfaction Analysis (ISA)

Our ISA figures showed that anglers in almost every group ranked catching wild trout/ stocked trout fairly high and were mostly satisfied (Figure 3.8, Figure 3.9). When asked about catching stocked trout, every county group fell into either Quadrat 1 "Keep up the Good Work" where both importance and satisfaction rank high, Quadrat 3 "Low Priority" where satisfaction ranks high but importance scores are low, or Quadrant 4 "Possible Overkill" where both satisfaction and importance are low (Figure 3.9). All county groups fell below the 45° iso-priority line, which indicates angler satisfaction scores were higher than their importance ranking in each group.

ISA rankings for catching wild trout were more mixed than results from angler responses regarding stocked trout (Figure 3.8). None of the county groups fell into the "Low Priority" or "Possible Overkill" quadrants. Most fell into Quadrant 2 "Keep up the Good Work", but Rabun (A), Union/Towns (B), and Metro Atlanta (G) groups all fell above the iso-priority line.

Responses from anglers in Western Georgia (H) to multiple questions about catching wild trout were significantly different from those in Fannin (C), Habersham/Stephens/Hart (F), and White (E) county groups. Responses from anglers in Western Georgia were often the highest or the lowest when ranking importance and satisfaction for multiple survey questions and often at odds with responses from Fannin county. Anglers from the Western GA group were the most likely to value adding fishing waters compared Fannin County respondents who ranked new fishable waters as their lowest priority (Table 3.3). Once again, Western Georgia ranked the highest and Fannin county ranked near the bottom in importance number of trout anglers saw. In general, anglers from Western Georgia were less satisfied with the trout fishery than anglers from Northeastern county groups (i.e., Rabun, Union/Towns, Fannin). Western Georgia ranked second to last in satisfaction of overall experience and satisfaction with GADNR management, while Fannin ranked first in both categories (Table 3.1).

Species Preferences

Survey respondents were asked to choose which species they preferred to fish for, their options included: brook trout, brown trout, rainbow trout, and no preference (Table 3.2). Anglers were asked to choose only one of the options. Responses indicated that the "no preference" option was the top choice in every county group. The "no preference" choice accounted for over half of all responses in every county group. If anglers did indicate a species preference, rainbow trout was the top choice in each group. Western Georgia had the highest percentage of anglers favoring rainbow trout. To highlight differences in the proportion of fish stocked and the proportion of species preference in each group I removed all no-preference data and proceeded to calculate species preference in proportion to the new total (i.e., for brook, brown, or rainbow; Figure 3.6, Figure 3.7). The proportion of fish stocked in each county group was calculated by adding up the total number of all individual fish from each trout species and then dividing by the total of all trout species stocked. Each county group exhibited differences in the proportion of each species stocked and which species were preferred by anglers. Metro Atlanta had the greatest difference between fish stocked and preference for rainbow trout (Figure 3.7). Out of the anglers that had a preference, 49% of them preferred rainbow trout and 35% preferred brown trout (Table 3.2). Of all trout stocked in the Metro Atlanta area, 90% are rainbow trout. Anglers were also asked to indicate whether they preferred to fish for stocked or wild trout (Table 3.5). The “no preference” option was once again the top choice by a large majority. After “no preference,” wild trout was preferred in every group except Rabun county, 20.4% of respondents preferred to fish for stocked trout instead of wild trout.

When survey responses were intersected with stocking data, the results indicated that angler’s species preferences coincided with the species that are stocked in most areas (Figure 3.6, Figure 3.7). Discrepancies were noted between angler preferences and species stocked in the Metro Atlanta area and Fannin county areas. For both of these groups, responses show that a somewhat higher percentage of rainbow trout are stocked than what anglers indicated they preferred. Most stocking that occurs in these two county groups focuses heavily on rainbow trout with and minimal amounts of brown trout stocking. Both group’s preference for brown trout was above the proportion of brown trout stocked by the DNR. Habersham/Stephens/Hart and Western Georgia groups followed this same trend, but the differences between the proportion of brown and rainbow trout stocked and the proportion of people that indicated they would prefer to fish for either species were not as large when compared to Metro Atlanta and Fannin groups.

Intersecting Supply and Demand

I had the unique opportunity to couple species preference data with possible future thermal habitat losses caused by a warming climate across northern Georgia. I used conservative (~ 1 °C), intermediate (~ 2 °C increase), and extreme (~ 2.6 °C) warming scenarios for the month of August in 2050 to determine which county groups would be affected the most by loss of suitable thermal habitat. I chose to compare future habitat losses to angler preferences for rainbow trout because they are the most common choice when anglers indicated a species preference. All of our modeling scenarios for August 2050 determined that Metro Atlanta streams, excluding tailwater habitats, would lose 100% of suitable thermal habitat in August (Figure 3.3, 3.4, 3.5). Though the 100% loss of habitat in Metro Atlanta is not all that alarming because, excluding tailwater habitats, Metro Atlanta has little to no present habitat suitable for trout.

Discussion

I intersected ISA results with stocking records and forecasting preferences with potential future loss of trout habitat on a county group scale. I identified angler use and satisfaction trends based on geography that will be integral in future decisions regarding the success of trout fisheries within the state. Coupling survey data with future habitat monitoring can provide managers with finer scale information to aid in the direction of limited resources.

Importance-Satisfaction Analysis (ISA) figures were used to better illustrate the differences in importance and satisfaction among eight county groups and to indicate where the GADNR could allocate their stocking and management efforts. The ISA for catching wild trout indicated that most groups fell right above the iso-priority line, which indicates their importance was slightly above their satisfaction (Figure 3.8). Western Georgia was the only group to fall into the “Concentrate Here” section and was statistically different (ANOVA results in Appendices A4 and A5) from Fannin, White, and Habersham/Stephen/Hart groups. Important-satisfaction analysis for catching stocked trout showed that Rabun, Metro Atlanta, and Western Georgia groups fell into the “Keep up Good Work” quadrant and their satisfaction exceeded their importance (Figure 3.9). Anglers in Habersham/Stephens/Hart, Gilmer/Lumpkin/Dawson, and White county groups were less satisfied with catching stocked trout than other groups but ranked low in importance. Fannin county ranked highest in satisfaction but lowest in importance and fell firmly within “Possible Overkill.” The most important take home message from the ISA figures is that Western Georgia (H) fell firmly into the “Concentrate Here” quadrant and the Gilmer/Lumpkin/Dawson (D) group is in danger of shifting into the “Concentrate Here” quadrant (Figure 3.8). Western Georgia anglers ranked importance of catching wild and stocked trout the highest of all eight county groups. Western Georgia anglers were also the least satisfied with catching wild trout, and rank near the middle in satisfaction for catching stocked trout. Western Georgia’s consistently opposite ranking from northeastern county groups could be attributed to its geography. Outside of the foothills region of the Appalachians, anglers have less trout fishing opportunities and depend more on stocked fish along with put-and-take fisheries. Counties within the Western Georgia group are generally lower in elevation and have fewer trout streams than other sections of the state. Some of the dissatisfaction in Western Georgia may be mitigated through careful allocation of resources from groups where angler's satisfaction far outranks their importance.

Stocking will remain an important part of trout management in the future. Our future suitable habitat predictions indicated that all county groups will lose suitable thermal habitat in the future. Groups at higher elevations (i.e., Rabun, Fannin, Union/Towns) will be less affected by temperature increases than groups lower in elevation and farther west in the state (i.e., Western Georgia, Metro Atlanta) (Figure 3.3, 3.4, 3.5). Our future habitat predictions coincided with other studies that focused on trout habitat loss in the Southeast (Clark et al. 2001; Flebbe 2006; DeWeber and Wagner 2014; Caldwell et al. 2015). I chose to model future thermal habitat for rainbow trout because when anglers indicated a species preference, rainbow trout was the most common response. I also chose to use predictions from August because those temperatures caused the greatest potential bottleneck in thermal habitat for the year (See Chapter 2). Our results showed that Western Georgia and Metro Atlanta will lose the largest percentage of suitable thermal habitat out of the eight county groups (Figure 3.3, 3.4, 3.5). Future habitat losses in Metro Atlanta may not be as problematic because the group had low numbers of people who prefer to fish for rainbow trout over other species. Those counties include large sections of river that are below cold-water release dams which provide suitable thermal habitat year-round. The tailwater fisheries in Metro Atlanta currently experience heavy use by trout anglers. Western Georgia had the highest percentage of anglers preferring to fish for rainbow trout out of all eight county groups (Table 3.2). Our intermediate climate model predicts an 89% loss of suitable thermal habitat for rainbow trout during August for Western Georgia (Figure 3.3). This creates an interesting challenge for managers because the Western Georgia region is heavily dependent on stocking. Current management focuses on stocking from March until August and one possible solution may be to shift or split stocking efforts to avoid adding fish to streams during the warmest part of the year. As spring temperatures rise, stream temperatures may be within the appropriate range to stock a small percentage of trout earlier in April - May to provide fishing opportunities up to the hottest parts of the summer. Then, when stream temperatures are below a lethal threshold after the month of August, the GADNR could stock the bulk of their fish into streams and have them available for angler enjoyment until the following summer. While winter is not a popular fishing period for anglers, theoretically as the climate warms prime fishing seasons will most likely shift from the summer months to spring.

Our study accomplished the goals we set but some limitations were noted. Finer scale stream lines on a 1:25,000 scale would be a vast improvement over the 1:100,000 scale NHD+ stream lines currently available for public use. Improvements in stream line scale could lead to more accurate data on riparian shading on a 30 by 30-meter basis. Model predictions could be improved with finer scale data for diurnal temperature cycles, groundwater inflows and which stream tracts anglers are fishing on. Combining angler use data on a stream by stream basis with pinpointed stocking data coupled with future habitat predictions could uncover small stream sections where suitable thermal habitat does exist that had been previously labeled as unsuitable. I also struggled with a lack of data for many counties included in our sample. Nearly half of our study area (i.e., Western Georgia) had to be lumped together to reach an appropriate amount of angler representation comparable to the other county groups. In the future, this issue could be mitigated through asking questions based on specific spatial locations (i.e., streams) or asking questions about singular counties.

Ultimately, spatially explicit data on stocking, thermal habitat data from this study and angler use, preference, and satisfaction data from the companion study conducted by Yondo (2018) will be used to create a decision support tool for the GADNR to use to guide and improve the management of the trout fishery. The decision support tool created from these two studies will be unique because most current support tools are only based on biology and are missing a human dimensions component. I was able to successfully intersect both aspects in this study, which will hopefully enable GADNR to devise adaptive and effective management of the state's cool-water trout fisheries faced with the threat of a potentially warming climate over the next 50 years.

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Table 3.1 Mean satisfaction scores of overall trout fishing experience, satisfaction w/ GADNR management of trout, and rating of current fishing quality ranked on a scale of 1 to 5 for Georgia anglers in 2017. Full Chi-Squared results can be found in Appendix A3.

Group	Overall Satisfaction (F: 1.153, *p* = 0.329)	Satisfaction w/ GADNR Management of trout (F: .575, *p* = .776)	Rating of Current Fishing Quality (F: 1.463, *p* = 0.178)
Rabun	3.94	3.78	3.07
Union/Towns	3.96	3.73	3.00
Fannin	4.07	3.85	3.27
Gilmer/Lumpkin/Dawson	3.84	3.83	2.89
White	3.90	3.69	3.13
Habersham/Stephens/Hart	3.71	3.60	2.85
Metro Atlanta	3.88	3.83	3.08
Western Georgia	3.73	3.63	2.91

Table 3.2 Species preferences broken down by species category in percentages for Georgia anglers in 2017 (Pearson's Chi-Squared Value = 32.756, p =.049, Full statistics in Appendix A1).

Group	BKT (%)	BNT (%)	RBT (%)	No Preference (%)
Rabun	1.9	11.5	17.3	69.2
Union/Towns	2.3	2.3	34.9	60.5
Fannin	5.0	13.3	31.7	50.0
Gilmer/Lumpkin/Dawson	0.0	8.5	35.6	55.9
White	0.0	15.7	31.4	52.9
Habersham/Stephens	0.0	17.4	34.8	47.8
Metro Atlanta	5.7	11.4	15.7	67.1
Western Georgia	1.7	10.2	42.4	45.8

Table 3.3 Mean importance rankings of various attributes of the trout angling experience for Georgia trout anglers in 2017. Anglers ranked importance based on a 5-point scale with 1 being low and 5 being high. Bold values represent statistically significant values at the α=0.05 level and small letters represent which groups the significant values differ from. Full ANOVA results are found in Appendix A4.

Survey Question (Importance)	Rabun[A] n=53	UT[B] n=48	Fannin[C] n=61	GLD[D] n=62	White[E] n=54	HSH[F] n=46	Metro Atlanta[G] n=74	Western Georgia[H] n=66
The number of trout you catch	3.50	3.29	3.27	3.26	3.17	3.27	3.09	3.45
The size of the trout you catch	3.35	3.39	3.40	3.51	3.33	3.27	3.39	3.51
Catching wild trout	3.35	3.35	3.33	3.31	3.25	3.13	3.33	3.55
Catching stocked trout	3.32	2.91	**2.81[H]**	2.84	2.84	2.94	3.29	**3.40[C]**
Adding new fishable waters	4.19	3.96	4.00	3.90	4.09	**3.73[H]**	3.91	**4.32[F]**
Bathroom availability at access	3.26	3.26	3.24	3.11	3.13	2.88	3.57	3.56
Clear signage of regulations	4.15	3.83	4.12	3.90	4.09	3.98	4.08	4.15
Campgrounds at access points	3.15	2.87	2.90	3.31	3.30	3.10	3.04	3.48
Access stocking schedules	3.47	3.54	3.30	3.41	3.30	3.58	3.36	3.91
Access reports on fishing conditions	3.49	3.57	3.50	3.48	3.55	3.31	3.71	3.69
The number of trout you see	3.52	3.85	3.34	**3.33[H]**	3.70	3.65	3.75	**4.05[D]**
The number of trophy managed trout streams	3.09	3.02	2.90	2.98	3.08	3.02	3.13	3.26
The cost of a trout fishing license	2.91	2.62	3.02	2.89	2.92	3.31	2.93	3.25
The distance to the trout stream from your residence	3.69	3.11	3.45	3.47	3.40	3.63	3.51	3.55
Youth education programs on trout fishing	3.43	3.85	3.75	3.60	3.69	3.75	3.69	3.72
The recruitment of new trout anglers	3.26	3.31	3.23	3.14	3.45	3.24	3.20	3.57
Habitat improvement initiatives	4.07	4.09	4.13	3.84	4.25	3.94	4.17	4.35

Table 3.4 Mean satisfaction rankings of various attributes of the trout angling experience for Georgia trout anglers in 2017. Anglers ranked importance based on a 5-point scale with 1 being low and 5 being high. Bold values represent statistically significant values at the α=0.05 level and small letters represent which groups the significant values differ from. Full ANOVA results are found in Appendix A5.

Survey Question (Satisfaction)	Rabun[A] n=53	UT[B] n=48	Fannin[C] n=61	GLD[D] n=62	White[E] n=54	HSH[F] n=46	Metro Atlanta[G] n=74	Western Georgia[H] n=66
The number of trout you catch	3.37	3.53	3.35	3.21	3.40	3.31	3.31	3.46
The size of the trout you catch	3.19	3.36	3.23	3.07	3.37	3.06	3.26	3.44
Catching wild trout	3.19	**3.31[EH]**	3.32	3.00	**3.31[BH]**	3.21	3.11	**2.79[BE]**
Catching stocked trout	3.50	3.44	3.58	3.34	3.38	3.33	3.51	3.45
Adding new fishable waters	3.19	2.84	3.12	2.93	3.15	3.17	3.15	3.11
Bathroom availability at access	3.24	3.40	3.34	3.25	3.40	3.29	3.48	3.52
Clear signage of regulations	3.17	3.44	3.40	2.90	3.08	3.29	3.35	3.15
Campgrounds at access points	3.48	3.39	3.23	3.18	3.17	3.19	3.20	3.27
Access stocking schedules	3.08	3.14	3.05	2.83	3.14	3.19	3.15	3.06
Access reports on fishing conditions	3.22	3.02	3.27	3.05	3.17	3.17	3.38	3.20
The number of trout you see	3.17	3.20	3.19	2.97	3.35	3.33	3.24	3.23
The number of trophy managed trout streams	3.09	3.07	3.20	2.85	3.02	3.06	3.06	2.87
The cost of a trout fishing license	4.02	3.67	4.02	3.70	3.96	3.77	3.75	4.18
The distance to the trout stream from your residence	3.00	3.29	3.43	3.22	3.29	3.21	3.44	3.31
Youth education programs on trout fishing	3.00	3.06	3.18	3.11	3.25	3.02	3.18	3.21
The recruitment of new trout anglers	3.24	3.00	3.18	3.07	3.21	3.43	3.06	3.11
Habitat improvement initiatives	3.07	2.96	3.38	3.08	3.15	3.29	3.21	3.34

Table 3.5 Mean responses for catching wild vs stocked trout for Georgia trout anglers in 2017 in percentages (Pearson's Chi-Squared value = 13.224, $p = 0.509$, Full results can be found in Appendix A2).

Group	Stocked (%)	Wild (%)	No Preference (%)
Rabun	20.4	16.7	63.0
Union/Towns	13.3	15.6	71.1
Fannin	11.9	23.7	64.4
Gilmer/Lumpkin/Dawson	4.8	25.8	69.4
White	13.2	24.5	62.3
Habersham/Stephens/Hart	14.6	16.7	68.8
Metro Atlanta	12.0	21.3	66.7
Western Georgia	19.7	27.3	53.0

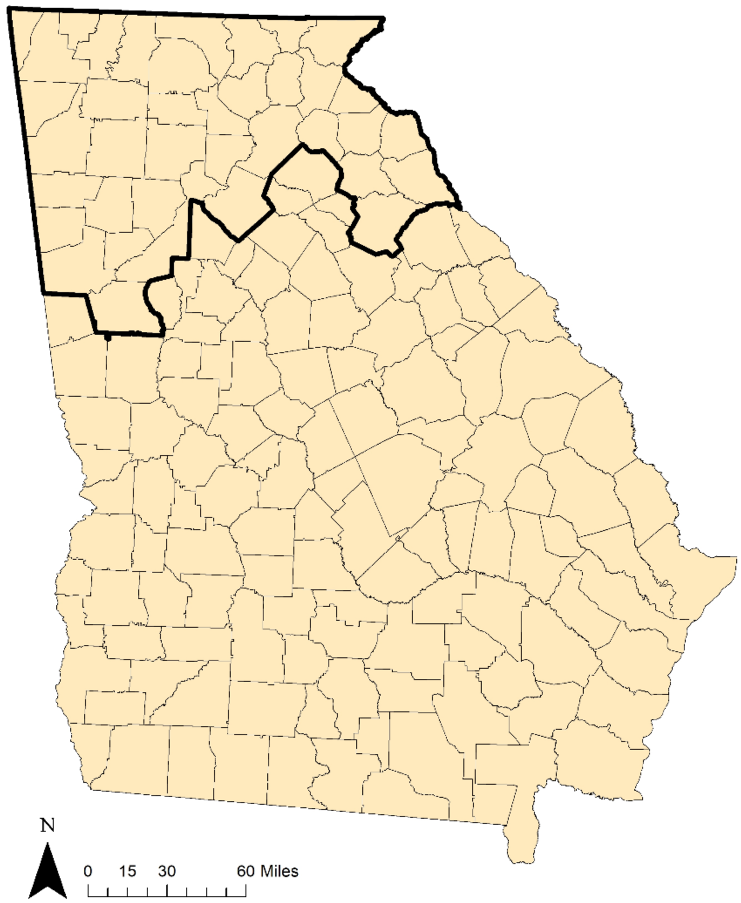

Figure 3.1 Counties outlined in black represent Georgia counties containing trout streams as of 2017.

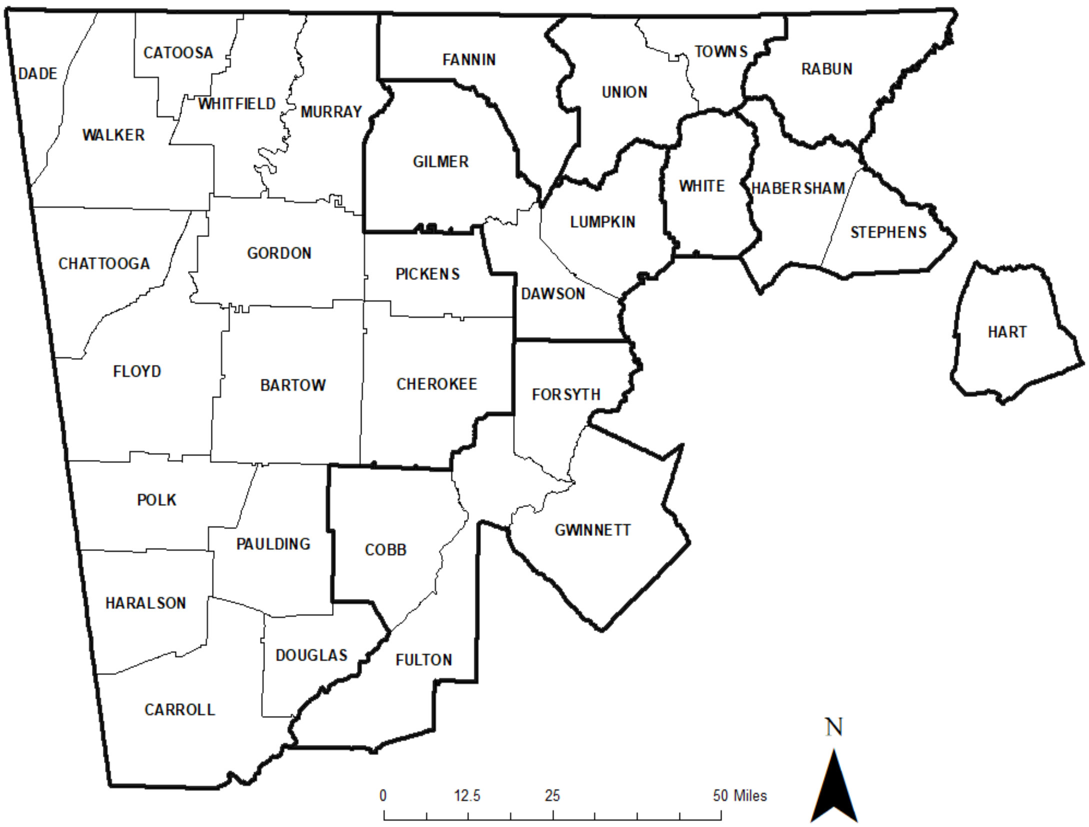

Figure 3.2 Visual representation of Georgia county groups: **Group A (Rabun):** Rabun county (n=53), **Group B (Union/Towns):** Union, Towns counties (n=48), **Group C (Fannin):** Fannin county (n=61), **Group D (Gilmer/Lumpkin/Dawson):** Gilmer, Lumpkin, Dawson counties (n=62), **Group E (White):** White county (n=54), **Group F (Habersham/Stephens/Hart):** Habersham, Stephens, Hart counties (n=46), **Group G (Metro Atlanta):** Forsyth, Gwinnett, Cobb, Fulton counties (n=74), **Group H (Western Georgia):** Dade, Walker, Catoosa, Whitfield, Murray, Chattooga, Gordon, Floyd, Bartow, Pickens, Cherokee, Polk, Paulding, Haralson, Carroll, Douglas counties (n=66). The number of anglers assigned to each county group are provided in parentheses

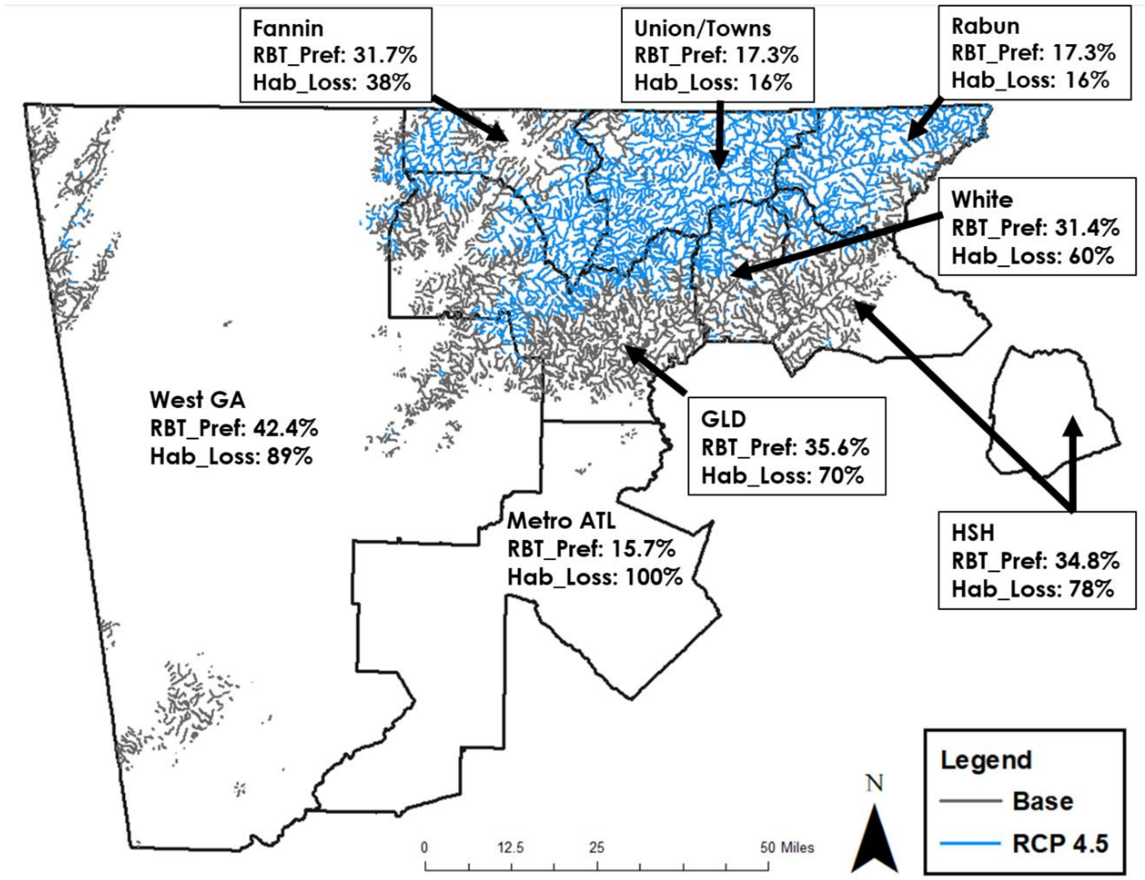

Figure 3.3: County groups featuring proportion of Georgia trout anglers that preferred rainbow trout when "no preference" values were removed along with the percent habitat loss predicted by the intermediate (RCP 4.5, ~2 °C) climate change scenario.

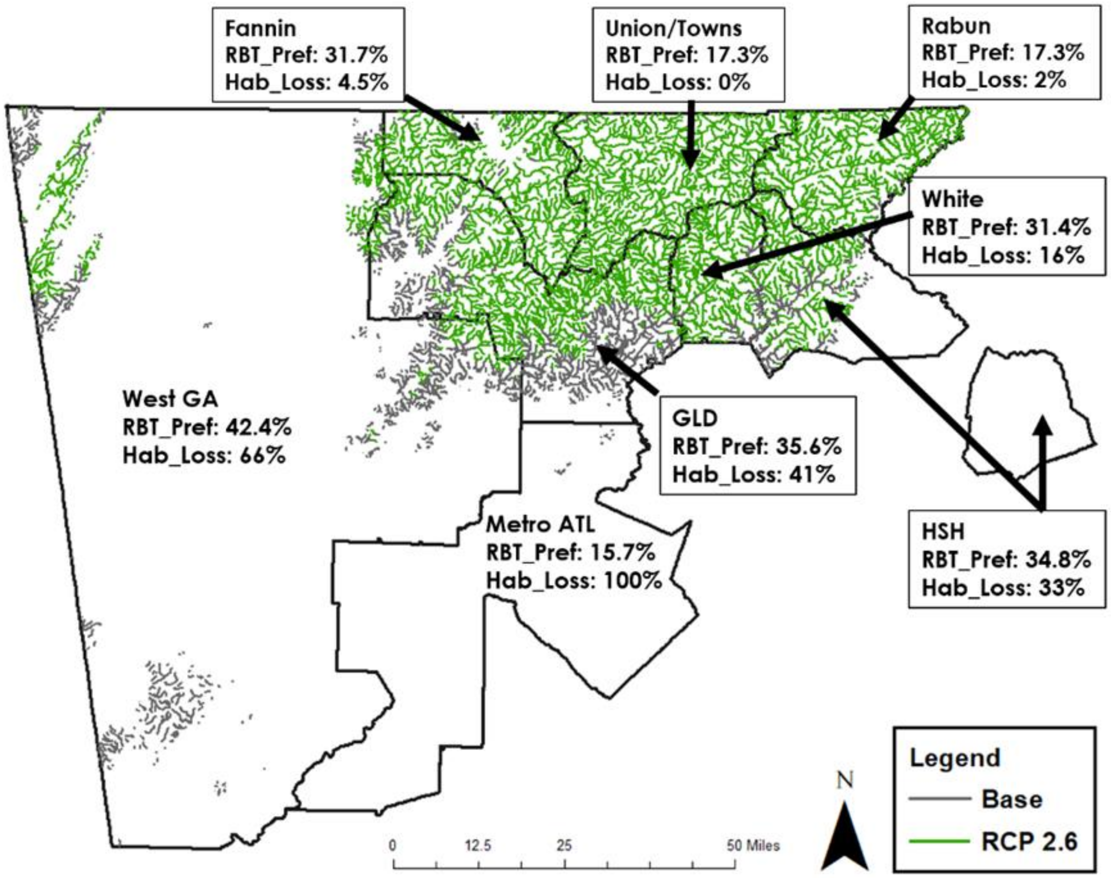

Figure 3.4 County groups featuring proportion of Georgia trout anglers that preferred rainbow trout when “no preference” values were removed along with the percent habitat loss predicted by the conservative (RCP 2.6, ~1°C) climate change scenario.

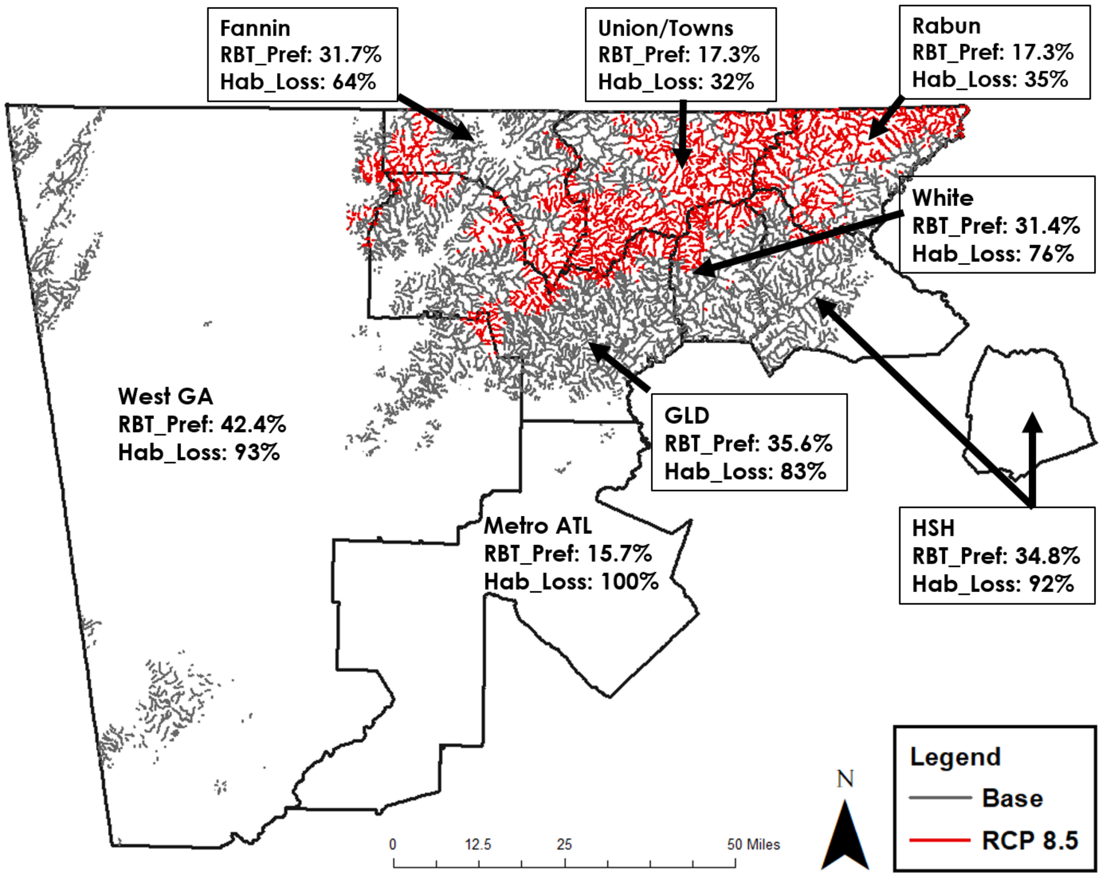

Figure 3.5 County groups featuring proportion of Georgia trout anglers that preferred rainbow trout when "no preference" values were removed along with the percentage of habitat loss predicted by the extreme (RCP 8.5, ~2.6°C) climate change scenario.

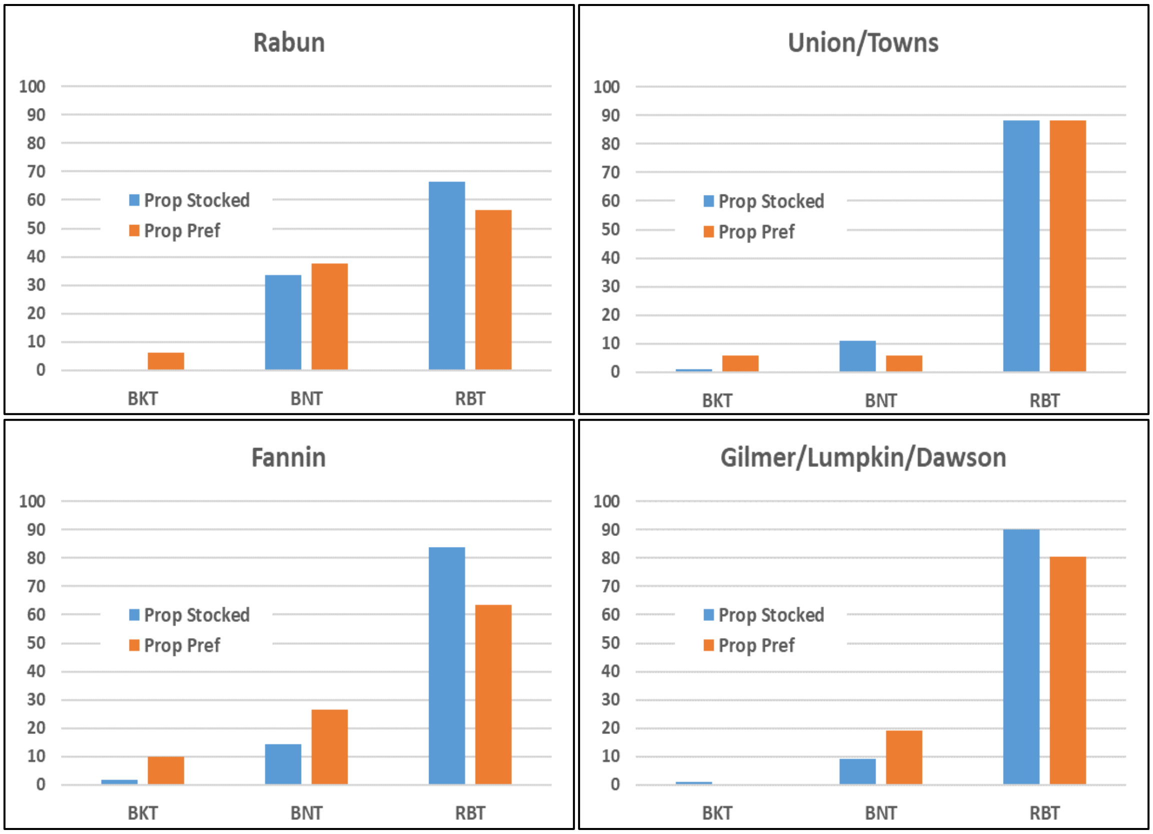

Figure 3.6 Proportion of brook, brown, and rainbow trout stocked by GADNR in 2017 compared to the proportion of Georgia anglers that preferred each species in Groups A-D.

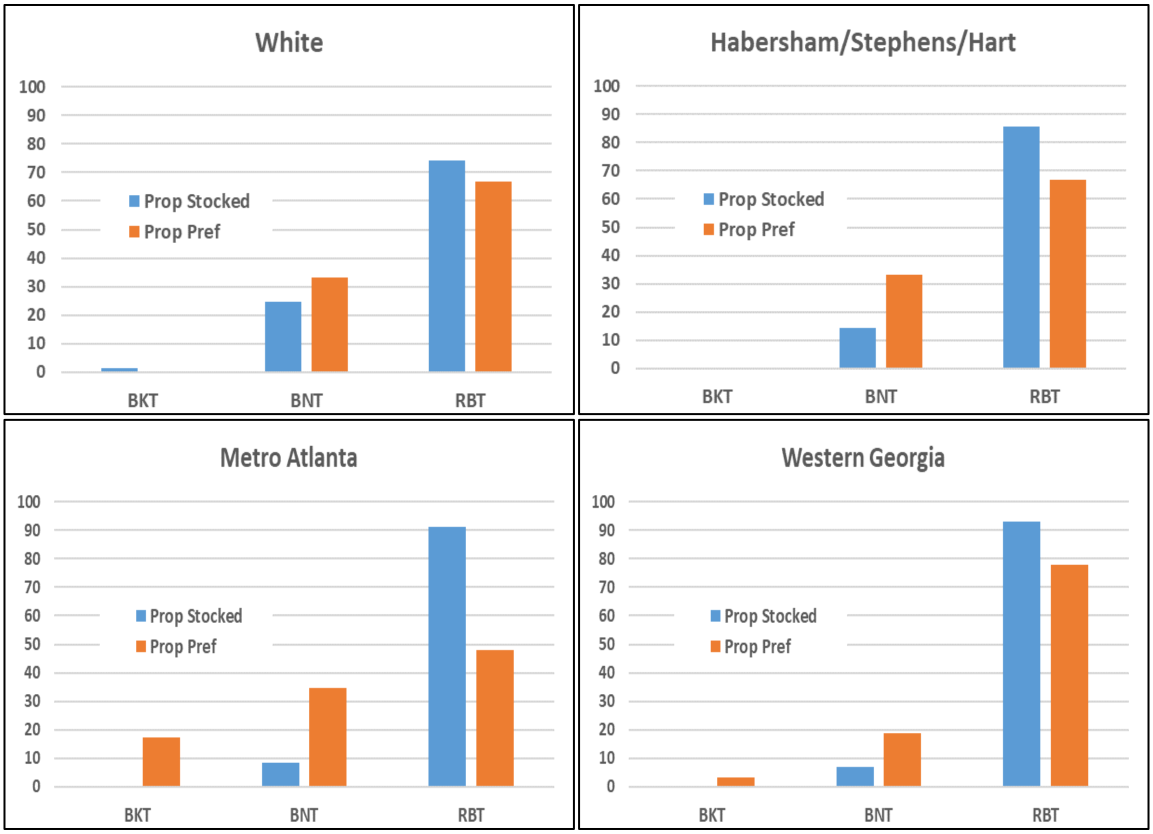

Figure 3.7 Proportion of brook, brown, and rainbow trout stocked by GADNR in 2017 compared to the proportion of Georgia anglers that preferred each species in Groups E-H.

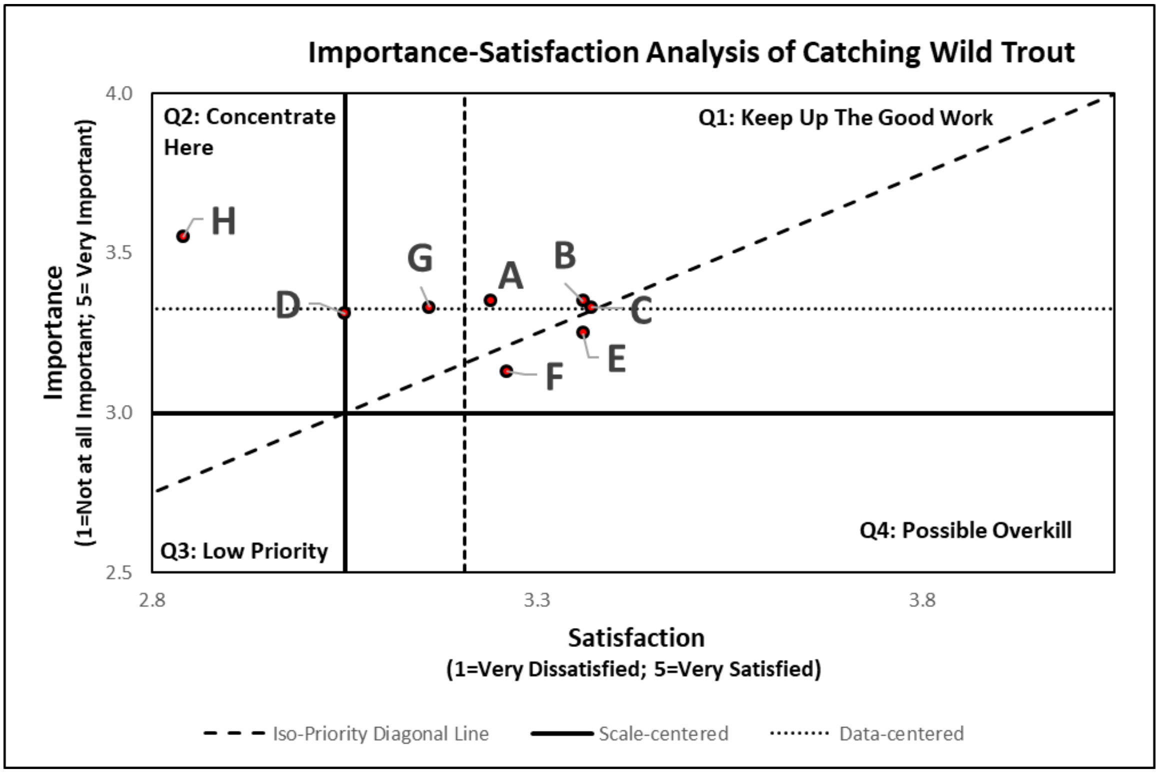

Figure 3.8 Importance-satisfaction analysis (Yondo 2018) of catching wild trout for Georgia anglers in 2017. Rabun (A), Union/Towns (B), Fannin (C), Gilmer/Lumpkin/Dawson (D), White (E), Habersham/Stephens/Hart (F), Metro Atlanta (G), Western Georgia (H).

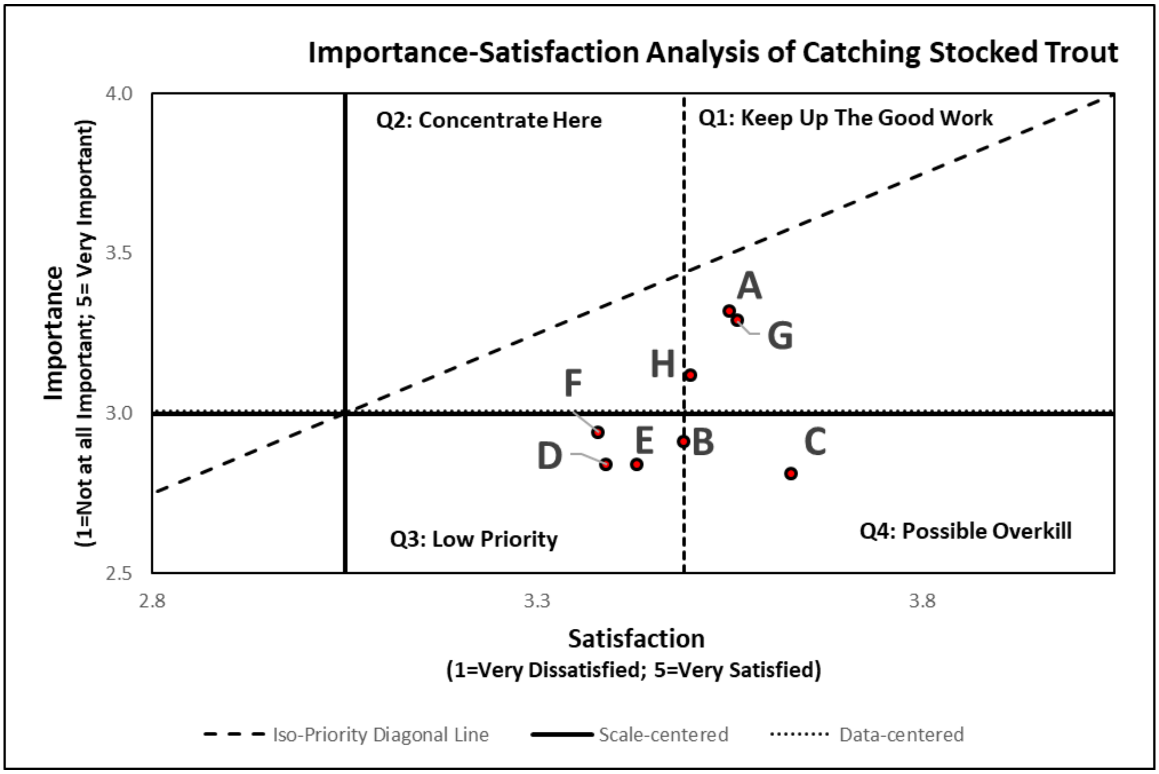

Figure 3.9 Importance-satisfaction analysis (Yondo 2018) of catching stocked trout for Georgia anglers in 2017. Rabun (A), Union/Towns (B), Fannin (C), Gilmer/Lumpkin/Dawson (D), White (E), Habersham/Stephens/Hart (F), Metro Atlanta (G), Western Georgia (H).

CHAPTER 4

CONCLUSIONS

Directly modeling air temperature to water temperature in a mixed modeling framework was an acceptable way to create more spatially explicit maps of future suitable thermal habitat for trout in northern Georgia. Summer air temperatures are expected to pose the greatest challenge to trout persistence in the future, with August providing the least amount of thermally suitable habitat for all three species. The decline of future suitable habitat and the possibility of increased overlap among all three species are problematic because, presently, brook trout are largely separated from the other two species. As suitable habitat decreases, the likelihood of stream fragmentation increases, and as water temperatures rise, fish will have to travel upstream or seek out local temperature refuge areas. Upstream travel will be difficult because of both natural and manmade barriers (i.e., dams and low flows during certain parts of the year).

Effects of climate change on the southern Appalachian populations of trout could be substantial. Trout already exist in a highly fragmented ecosystem and in many streams that are above their preferred temperature threshold for most of the year. If the forecasted climate increases come to pass, the persistence of wild trout populations in the future will be difficult. Barriers to migration upstream are numerous but local refuge may be possible. Additional research on how groundwater inflows, diurnal temperature cycles, and shading of stream habitats will be affected by climate change may provide a better understanding of the possible fate of trout in Georgia, as these pieces have the potential to provide refuge from warmer stream temperatures. In the future, the success of the trout fishery will likely rely heavily on stocking and consist of fishing mainly small fragmented populations of trout, tail waters, and put-and-take fisheries.

We uncovered angler use and satisfaction trends centered on geography that could be informative for future trout management decisions. Coupling survey data and Importance Satisfaction Analysis (ISA) methodology with future suitable thermal habitat projections for trout was an adequate way to intersect supply with angler demand. This information can provide managers with finer scale information to aid in the redirection of limited resources to areas where anglers will be the most satisfied and where long-term success is more probable.

All county groups are expected to experience a loss of suitable habitat in the future (excluding Rabun county in the conservative scenario for rainbow/brown trout). Areas contained within the Appalachian Mountains and surrounding foothills (i.e., Rabun, Union/Towns, and Fannin) will have little to moderate amounts of future habitat loss. Western Georgia and Metro Atlanta will lose the greatest percentage of trout habitat for all species, with anglers from the Western Georgia group indicating the highest preference for rainbow trout of any of the eight groups. Stocking will remain an integral part of successful trout management in the future. As the climate shifts, a possible solution for managers is to avoid stocking during the warmest parts of the year by splitting their stocking schedule. Managers may have more success when stocking a small amount of their total fish during the spring, so anglers have recreational opportunities and holding the rest of the biota through the warmest parts of the summer. Once water temperatures are appropriate, fish may be stocked into various streams and available for a longer time compared to if they were stocked during the warmest part of the year and die. Most decision support tools for fisheries management are based only on biology and must speculate about angler preferences. Our thermal habitat data along with the human dimensions data from a companion study provide both pieces for a successful decision support tool for trout managers to utilize.

Appendix A1. Chi-Squared test results for differences in angler preference for catching different trout species between county groups. Significant test indicates differences exist in angler preference between groups

Chi-Squared Test Output

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	32.756	21	0.049
Likelihood Ratio	37.006	21	0.017
Linear-by-Linear Association	1.511	1	0.219
N of Valid Cases	440		

Appendix A2. Chi-Squared test results for differences in angler preference for stocked vs. wild trout among county groups. Insignificant test indicates no differences exist in angler preference between groups

Chi-Squared Test Output

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	13.224	14	0.509
Likelihood Ratio	14.131	14	0.44
Linear-by-Linear Association	0.665	1	0.415
N of Valid Cases	462		

Appendix A3. One-Way ANOVA results for differences between county groups in overall angling satisfaction, satisfaction with GADNR management, and rating of fishing quality. No significant differences exist between groups.

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Satisfied w/ overall experience	Between Groups	5.64	7.00	0.80	1.15	0.33
	Within Groups	318.33	455.00	0.70		
	Total	323.98	462.00			
Satisfaction with GADNR management	Between Groups	3.53	7.00	0.50	0.57	0.78
	Within Groups	397.28	453.00	0.87		
	Total	400.81	460.00			
Fishing Quality Rating	Between Groups	7.94	7.00	1.13	1.46	0.18
	Within Groups	354.68	457.00	0.77		
	Total	362.63	464.00			

Appendix A4. One-way ANOVA test results for differences between county groups in angler importance rankings for trout fishery characteristics. Significant differences in importance exist between groups for importance of catching stocked trout, adding new fishable waters, bathroom availability at accesses, access to stocking schedules, number of trout seen, and habitat
improvement initiatives

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Import Number	Between Groups	7.66	7.00	1.10	0.83	0.56
	Within Groups	597.68	453.00	1.32		
	Total	605.34	460.00			
Import Size	Between Groups	2.71	7.00	0.39	0.36	0.93
	Within Groups	494.37	455.00	1.09		
	Total	497.08	462.00			
Import Wild Trout	Between Groups	5.73	7.00	0.82	0.68	0.69
	Within Groups	545.05	455.00	1.20		
	Total	550.78	462.00			
Import Stocked Trout	Between Groups	22.07	7.00	3.15	3.32	0.00
	Within Groups	430.80	453.00	0.95		
	Total	452.87	460.00			
Import New Fishable Water	Between Groups	13.80	7.00	1.97	2.15	0.04
	Within Groups	418.06	455.00	0.92		
	Total	431.86	462.00			
Import Bathroom at Access	Between Groups	22.19	7.00	3.17	1.81	0.08
	Within Groups	793.37	453.00	1.75		
	Total	815.56	460.00			
Import Reg Signs	Between Groups	5.53	7.00	0.79	0.80	0.59
	Within Groups	450.52	456.00	0.99		
	Total	456.05	463.00			
Import Camp at Access	Between Groups	18.04	7.00	2.58	1.63	0.13
	Within Groups	717.35	454.00	1.58		
	Total	735.39	461.00			
Import Stocking Schedule	Between Groups	17.58	7.00	2.51	1.86	0.07
	Within Groups	614.05	455.00	1.35		
	Total	631.63	462.00			
Import Condition Reports	Between Groups	6.45	7.00	0.92	0.81	0.58
	Within Groups	514.01	454.00	1.13		
	Total	520.45	461.00			

Import Num Trout Seen	Between Groups	25.78	7.00	3.68	3.71	0.00
	Within Groups	451.83	455.00	0.99		
	Total	477.62	462.00			
Import Num Trophy Managed Streams	Between Groups	5.13	7.00	0.73	0.56	0.79
	Within Groups	597.80	456.00	1.31		
	Total	602.93	463.00			
Import License Cost	Between Groups	16.89	7.00	2.41	1.53	0.16
	Within Groups	711.04	451.00	1.58		
	Total	727.92	458.00			
Import Distance From House	Between Groups	10.40	7.00	1.49	1.19	0.31
	Within Groups	566.93	454.00	1.25		
	Total	577.33	461.00			
Import Youth Ed	Between Groups	5.82	7.00	0.83	0.68	0.69
	Within Groups	560.51	455.00	1.23		
	Total	566.33	462.00			
Import New Angler Recruit	Between Groups	8.79	7.00	1.26	1.11	0.36
	Within Groups	513.90	453.00	1.13		
	Total	522.69	460.00			
Import Habitat Improvement	Between Groups	11.24	7.00	1.61	1.92	0.06
	Within Groups	380.93	456.00	0.84		
	Total	392.17	463.00			

Appendix A5. One-way ANOVA test results for differences between county groups in angler satisfaction rankings for trout fishery characteristics. Significant differences in satisfaction exist between groups for catching wild trout, clear signage of regulations, and cost of a trout fishing license.

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Satisf Number	Between Groups	3.66	7.00	0.52	0.61	0.75
	Within Groups	382.83	444.00	0.86		
	Total	386.50	451.00			
Satisf Size	Between Groups	7.40	7.00	1.06	1.20	0.30
	Within Groups	390.28	443.00	0.88		
	Total	397.68	450.00			
Satisf Wild Trout	Between Groups	13.93	7.00	1.99	2.97	0.01
	Within Groups	294.93	440.00	0.67		
	Total	308.86	447.00			
Satisf Stocked Trout	Between Groups	2.86	7.00	0.41	0.60	0.76
	Within Groups	300.36	442.00	0.68		
	Total	303.22	449.00			
Satisf New Fishable Water	Between Groups	5.59	7.00	0.80	0.99	0.44
	Within Groups	356.86	443.00	0.81		
	Total	362.45	450.00			
Satisf Bathroom at Access	Between Groups	4.43	7.00	0.63	0.92	0.49
	Within Groups	304.34	442.00	0.69		
	Total	308.76	449.00			
Satisf Reg Signs	Between Groups	13.44	7.00	1.92	2.32	0.03
	Within Groups	367.92	445.00	0.83		
	Total	381.36	452.00			
Satisf Camp at Access	Between Groups	4.69	7.00	0.67	0.97	0.45
	Within Groups	305.96	443.00	0.69		
	Total	310.65	450.00			
Satisf Stocking Sched	Between Groups	4.99	7.00	0.71	0.89	0.52
	Within Groups	352.43	439.00	0.80		
	Total	357.41	446.00			

Satisf Condition Reports	Between Groups	5.49	7.00	0.78	1.14	0.34
	Within Groups	305.38	444.00	0.69		
	Total	310.87	451.00			
Satisf Num Trout Seen	Between Groups	5.55	7.00	0.79	1.03	0.41
	Within Groups	337.51	439.00	0.77		
	Total	343.07	446.00			
Satisf Num Trophy Managed	Between Groups	5.62	7.00	0.80	1.38	0.21
	Within Groups	257.12	442.00	0.58		
	Total	262.73	449.00			
Satisf License Cost	Between Groups	13.52	7.00	1.93	2.25	0.03
	Within Groups	378.91	441.00	0.86		
	Total	392.43	448.00			
Satisf Dist From House	Between Groups	7.94	7.00	1.13	1.01	0.43
	Within Groups	499.30	443.00	1.13		
	Total	507.24	450.00			
Satisf Youth Ed	Between Groups	3.11	7.00	0.45	0.66	0.71
	Within Groups	298.38	444.00	0.67		
	Total	301.50	451.00			
Satisf New Angler Recruit	Between Groups	6.56	7.00	0.94	1.61	0.13
	Within Groups	256.55	442.00	0.58		
	Total	263.11	449.00			
Satisf Habitat Improvement	Between Groups	8.11	7.00	1.16	1.49	0.17
	Within Groups	346.79	445.00	0.78		
	Total	354.91	452.00			