Global climate change and fragmentation of native brook trout distribution in the southern Appalachian Mountains

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Abstract — Current distributions of native brook trout (*Salvelinus fontinalis*) in the southern Appalachians are restricted to upper elevations by multiple factors, including habitat requirements, introduced rainbow (*Oncorhynchus mykiss*) and brown (*Salmo trutta*) trout, and other human activities. Present-day distribution of brook trout habitat is already fragmented. Increased temperatures predicted by various global warming models are likely to further limit suitable brook trout habitat. Predicted changes in hydrologic cycles may exacerbate temperature effects, and hydrologic effects on trout may differ across the region. Models of present-day trout guild distribution were used in a Geographic Information System (GIS) to examine the changes in trout distribution that might occur with temperature increase. Both suitable area and stream length for trout decrease as suitable habitat is increasingly restricted to mountaintops. Furthermore, the remaining trout habitat is likely to be even more fragmented than at present. If trout habitat becomes more fragmented under warming trends, common local extinctions may become irreversible as avenues for recolonization are eliminated.

CURRENT TROUT DISTRIBUTION

The southern Appalachians represent the southern margin of trout in eastern North America. For this discussion, the southern Appalachians consists of the mountain areas of Georgia, South Carolina, North Carolina, Tennessee, and Virginia. Originally, only native brook trout (*Salvelinus fontinalis*) were found in this area. During the late 19th and early 20th centuries, rainbow (*Oncorhynchus mykiss*) and brown (*Salmo trutta*) trout were introduced into the region. The guild of these three species now occupies streams in about 40,700 km^2 of these states (Fig. 1).

Current distribution of native brook trout in the southern Appalachians is restricted to upper elevations by multiple factors, including habitat requirements, introduced rainbow and brown trout, and other human activities. Stream temperature is a basic limiting factor that defines suitable habitat for all salmonids, which require relatively low temperatures. Brook trout are found at slightly lower temperatures in field settings than are rainbow and brown trout (Eaton et al. 1995), and stream temperature generally increases with decreasing elevation in mountains. Other habitat conditions no doubt contribute to the current distribution patterns. In the early years of the 20th century, logging and conversion to homesteads, fires, overfishing, and stocking all contributed to loss of brook trout habitat as European settlement moved upward.

Historically, introduction of rainbow and brown trout certainly restricted the distribution of brook trout; many streams that now have introduced trout are known to have had brook trout at one time. But, the extent to which this replacement process continues today is unknown and some think that relative distributions of the three species have

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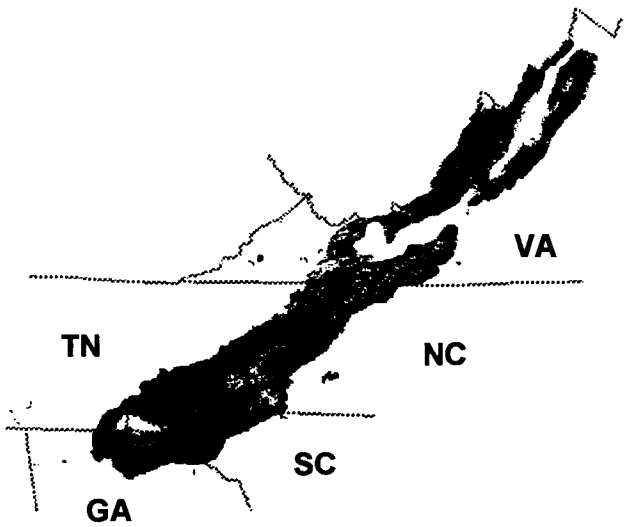

Figure 1.–Present-day suitable trout habitat in the southern Appalachians

largely stabilized in the last few decades. In general, the introduced trouts have been more successful at lower elevations and latitudes, and brook trout tend to occupy higher elevations and latitudes (Larson and Moore 1985, Flebbe 1994). But brook trout remain most common and abundant in North Carolina and Virginia (Flebbe 1994). Sympatry is common, and within the region, these distribution patterns vary (Flebbe 1994).

Present-day distribution of brook trout habitat is already fragmented. Some fragmentation is due to geomorphology, drainage patterns, and the fact that brook trout are at higher elevations in the southern Appalachian Mountains. Brook trout in the southern Appalachians are in major drainages of the Potomac (Shenandoah), Rappahannock, James, Roanoke, Yadkin, Catawba, Savannah, Alabama, Tennessee, and Ohio rivers. Even within these major drainages, brook trout are often restricted to headwater watersheds. Presence of unsuitable land uses also fragments brook trout distribution within watersheds. With few exceptions, developed land surrounding a stream makes that stream habitat unsuitable. Most agricultural land use also renders stream habitat unsuitable. Conversion of forest land to developed or agricultural land has tended to proceed from lower elevations to higher ones.

If this is the present-day situation for brook trout in the southern Appalachians, what do predictions of global climate change hold for brook trout here?

GLOBAL CLIMATE CHANGE THREATS

Global average air temperature has probably increased about 0.5°C over the last century and, due to increasing levels of greenhouse gases, primarily carbon dioxide, may further increase by 1.0 to 3.5 °C during the next 100 years or so (Karl et al. 1997). The amount of temperature increase is not uniform over the planet and various models predict different magnitude of temperature increase. In the Southeast, models project increases of about 3 to 4 °C (or more) with a doubling of atmospheric CO_2 (Mulholland et al. 1997). Effects of increased air temperature on water temperature will vary from site to site, depending on such factors as degree of groundwater influence, amount of shading by watershed and riparian vegetation, watershed aspect, etc.

Possible changes to the hydrologic cycle are even more complex and uncertain than temperature change. Along with increased air and stream temperature, precipitation in the Southeast is also expected to increase, especially in the summer (Mulholland et al. 1997). Models indicate that summer convection storms will become more intense and frequent, with longer dry periods between them -- a clustering effect (Mulholland et al. 1997). As a result, some small mountain streams may be more likely to dry out between storms and more intense storms may cause flash flooding and damage to streams. Evapotranspiration may or may not increase with increased carbon dioxide and warming, adding to the difficulty of predicting hydrologic changes. Experts do not agree on effects of climate change on hurricanes because processes are complex (Karl et al. 1997). Furthermore, effects of concomitant increased demand for water by humans add another source of uncertainty to predictions for hydrologic changes.

CONSEQUENCES FOR TROUT IN THE SOUTHERN APPALACHIANS

Increased temperatures and hydrologic changes predicted by various global warming models are likely to further limit suitable brook trout habitat. Many other, indirect effects of climate change on the stream environment of trout are possible, but will not be considered in this paper. For example, riparian zone vegetation may change, which in turn can alter inputs of allochthonous material and large woody debris. Changes in macroinvertebrate community structure and metabolism in response to all these changes represent changes in trout food availability.

To date, consequences of hydrologic changes have not been proposed for trout in the southern Appalachians,

largely because both the sign and magnitude of hydrologic changes is uncertain, and also because we know less about how hydrologic changes are likely to affect trout. Predicted changes in hydrologic cycles may exacerbate temperature effects and may do so differently across the region. For example, many streams in Virginia are already susceptible to drying out during the summer, and trout there are forced into small, isolated refuges in deeper pools. Prolonged concentration of trout in these refuges could lead to increased mortality. These streams already experience flashy flows during summer storms, at times scouring out the stream. To the south, however, summer flows are more reliable.

Two different kinds of consequences of temperature increases for trout have been proposed in the literature: changes in trout physiology and changes in the distribution of trout.

Physiological Responses

Increased temperatures generally increase metabolism in fish, and growth rate of fish may either increase or decrease with warming, depending on whether stream temperatures are below or above the optimum temperature, respectively. Whether food is limiting also affects the extent to which growth can increase when below-optimum temperatures increase. In a model based on streams in northern West Virginia, brook trout growth increased with modest temperature increases of 2°C, but food could became limiting if temperature increased more (Ries and Perry 1995). In the southern Appalachians, however, brook trout may already be food-limited in summer (Ensign et al. 1990), and in many streams, temperature may already be above the optimum for growth for much of the year.

Trout Distribution Changes

Greater attention has been paid to possible changes in trout distribution with a warmer climate, particularly in areas like the southern Appalachians where trout are near the southern margin of their distribution in North America. At the margin, trout are probably at or near their temperature limits, and further increases in temperature can critically increase metabolic costs or exceed thermal limits, resulting in loss of the species from a stream site.

Meisner (1990) found that minimum elevation for brook trout in the southern Appalachians now rises from about sea level near 39°N to about 640 m at about 34°40'N (the southern margin). Furthermore, using a model, he predicted that the 3.8°C increase in temperature predicted for mid-21st century by the Goddard Institute for Space Studies model would increase minimum elevation for brook trout by up to 714 m, leading to a reduction of area suitable to brook trout. Using his model and trout inventory sample data for North Carolina and Virginia, Flebbe (1993) estimated that 89% of brook trout streams in the sample would be lost. Losses would be greater in Virginia than North Carolina because Virginia has fewer high elevation refuges. Increased fragmentation of brook trout habitat is likely (Meisner 1990, Flebbe 1993).

Predictions from a GIS Model

A more detailed analysis of changes to the distribution of trout in the southern Appalachians has been produced from a model constructed in a geographic information system (GIS). The trout guild, consisting of all three trout species, was modeled because the distributions overlap and a regional distribution of individual trout species is particularly difficult to obtain (Flebbe et al. 1996).

A preliminary version of present-day potential trout habitat (Flebbe et al. 1996) was further refined by consulting coldwater fisheries experts in the region. Areas with unsuitable developed and agricultural land uses were also eliminated. An empirical model, which relates elevation to latitude at the boundary, was fitted to the boundary of current trout habitat (Fig. 1).

An empirical relation equating 189 m of elevation change to 1°C change in air temperature, based on temperature data from the southern Appalachians (Meisner 1990), was applied to the trout boundary model to estimate trout habitat area for a range of temperature increases. Rather than linking effects on trout to projections of any particular global change model, effects of 1-5°C increases on suitable trout habitat were assessed. Projected trout habitat areas were used to select blue-line streams (Flebbe et al. 1996, Hermann 1996) in the GIS and predict corresponding stream lengths for the range of temperature increases.

Projected trout habitat areas for 2°C and 4°C temperature increases are shown in figures 2 and 3, respectively, and projected changes in area and stream length are shown in table 1. Both the area and stream length suitable for trout decline with increasing temperature (Table 1). At each sequential 1 °C increase in temperature, a larger proportion of the remaining area and stream length is lost. Stream length declines slightly faster than does area. In the southern Appalachians, stream density is high, and in our GIS layer, density doesn't vary greatly with elevation.

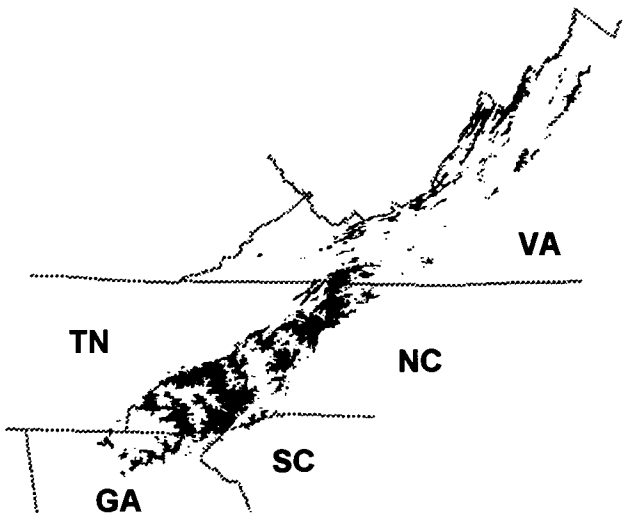

Figure 2.--Suitable trout habitat projected for a 2°C increase in air temperature.

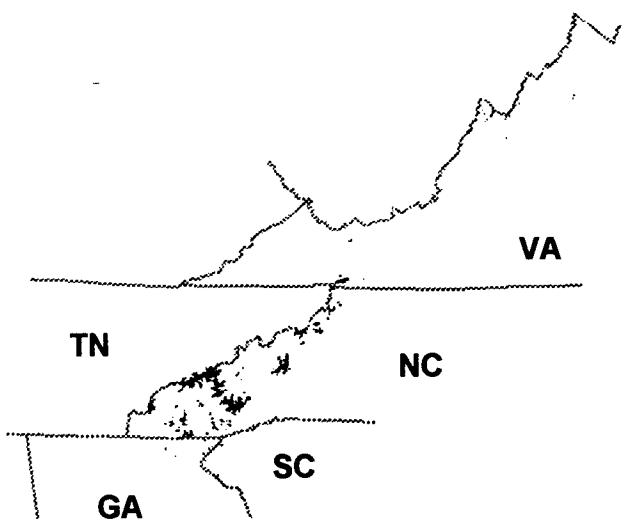

Figure 3.--Suitable trout habitat projected for a 4°C increase in air temperature.

Suitable habitat is eliminated almost completely from Virginia at +4°C (Fig. 3). At +5°C, the largest remaining refuge is in the peaks of the Great Smoky Mountains and the Blue Ridge Mountains of North Carolina. Virtually no stream habitat remains in these high mountain enclaves.

Furthermore, the remaining trout habitat becomes even more fragmented than at present. With increasing temperature, the size of the largest trout habitat patch declines (Table 2). Presently, there are several large areas of habitat >1000 km^2. At increased temperatures, these large patches break up and eventually disappear. If trout habitat becomes more fragmented under warming trends, common local extinctions may become irreversible as avenues for recolonization are eliminated.

Table 1.--Projected trout habitat area and stream length, expressed as a percentage of current area and stream length, corresponding to possible changes in air temperature for the southern Appalachians.

Temperature change (°C)	Area (%)	Stream length (%)
+1	65.4	54.9
+2	31.7	22.1
+3	12.6	7.5
+4	4.2	2.1
+5	1.3	0.5

Table 2.--Projected maximum trout habitat patch size and number of patches >1000 square km.

Temperature change (°C)	Area of largest patch (square km)	Number of patches >1000 square km
Baseline	27,562	4
+1	7,129	4
+2	3,469	2
+3	1,026	1
+4	572	0
+5	164	0

CONCLUSION

Effects of global climate change could be significant, both for brook trout and the trout guild in the southern Applachians, where present-day distributions are already fragmented and restricted to higher elevations. Whether rainbow and brown trout might retreat to higher elevations, displacing brook trout as air and stream temperatures increase, or would be lost from the region before brook trout cannot be determined. Certainly, multiple factors interact to determine the final outcome. Temperature changes, if they happen, will be accompanied by hydrologic changes, riparian vegetation changes, continuing stream sedimentation and acidification, and changes in land use patterns.

ACKNOWLEDGMENTS

I thank Jennifer Bush for her hard work on all aspects of the GIS model; Randolph Wynne for his assistance with the GIS; and the 30-odd coldwater fisheries experts in the southern Appalachians who helped find the present-day boundary for the GIS model.

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