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Feature Article

Stream temperature rise and future stocked-trout management in North Carolina

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ABSTRACT

Objective: Climate warming disproportionately threatens coldwater fishes and presents an immediate challenge for fisheries managers near the southern extent of coldwater sport fish distribution. In North Carolina, some recreational angling opportunities targeting Brook Trout *Salvelinus fontinalis*, Brown Trout *Salmo trutta*, and Rainbow Trout *Oncorhynchus mykiss* are sustained mainly by fall and spring stockings in waters where summer temperatures are marginal for trout. The future of these seasonal fisheries is uncertain, and managers may need to consider management changes to ensure the long-term viability of stocking programs.

Methods: We used a Bayesian hierarchical model to analyze a 33-year stream temperature data set collected at 183 reaches during individual stocking events to characterize warming trends and inform management decisions.

Results: Warming trends varied among stream reaches, with a mean annual warming rate of 0.05°C. We forecasted future thermal exceedance probabilities based on the observed trends; mean July temperatures would more likely (>50% chance) exceed a thermal threshold (21.1°C) and become too warm for trout survival at many reaches by 2050.

Conclusions: Spatially varying warming trends emphasize the importance of reach-specific management to maintain or alter current practices due to warming. Overall, fisheries managers will need such thermal resolution to minimize adverse thermal effects on waters supporting these popular, recreational fisheries.

KEYWORDS: Bayesian statistics, climate change, fisheries management, stream temperature, trout stocking

LAY SUMMARY

Stocked-trout waters are important to numerous North Carolina anglers and communities. We discuss how research can help inform when and where stocked trout are used to maintain and enhance these extremely popular fisheries.

INTRODUCTION

Global scientific societies recognize the current and predicted threats of alterations of climate to the world's aquatic resources (American Fisheries Society et al., 2021). Although impacts are diverse, the timing and intensity of precipitation events and changes in thermal patterns will affect salmonid populations (Kovach et al., 2016; Valentine, Lu, Childress, et al., 2024). Thermal stress is a particular threat to salmonids at their southern range given their limited thermal tolerance (Ficke et al., 2007; Kovach et al., 2016; Mitro et al., 2019). Unfortunately, 2023 was the warmest year in the past 2,000 years and Esper et al. (2024) predicted accelerated warming in future years. Should these thermal trends persist or worsen, trout managers will continue to face new challenges to fisheries under their care.

The North Carolina Wildlife Resources Commission (NCWRC) manages approximately 8,500 km of streams in the westernmost 26 counties of North Carolina in its Public Mountain Trout Waters (PMTW) program, which is formalized

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within NCWRC's Trout Management Plan (NCWRC, 1989, 2013). Most of these streams support and are managed for self-sustaining populations of native Brook Trout *Salvelinus fontinalis* and introduced Brown Trout *Salmo trutta* and Rainbow Trout *Oncorhynchus mykiss*. However, 1,500 km of streams support fisheries dependent upon seasonal stockings of a mix of cultured Brown Trout, Brook Trout, and Rainbow Trout (hereafter, referred to as "stocked trout"). In 2022, over 80% of surveyed PMTW anglers indicated they primarily fished these waters (Jewell et al., 2023). The diversity of coldwater resources in PMTW maintain significant ecological (NCWRC, 2013), recreational (Jewell et al., 2023; Responsive Management, 2015a), and economic (Jewell et al., 2023; Responsive Management, 2015b) values. Approximately 370,000 anglers fished PMTW in 2022 and generated a US$1.38 billion impact on North Carolina's economy (Jewell et al., 2023).

Seasonal stockings by the State of North Carolina have supported trout fishing in North Carolina for over a century (Smith, 1907). Under our current Trout Management Plan (NCWRC, 2013), these trout are stocked into Hatchery Supported Trout Waters (HS) and Delayed Harvest Trout Waters (DH) to provide immediate sportfishing opportunities. Given their elevated size and body condition at time of stocking, lack of growth and reduced feeding (Fischer et al., 2019) are anticipated until periods of legal harvest. Hatchery Supported Trout Waters offer seasonal angling opportunities for stocked trout in the spring and early summer, which are available to harvest following opening day (the first Saturday in April). Delayed Harvest Trout Waters provide catch-and-release fisheries (October through the first Saturday in June) by stocking trout from the fall through early summer and permitting harvest starting the first Saturday in June before water temperatures become too high for trout survival. The majority of HS and DH waters are unable to sustain year-round stockings given thermal limitations, and water temperatures in some western North Carolina streams are more sensitive than others to variation in air temperatures (Valentine, Lu, Dolloff, et al., 2024). Thus, NCWRC fisheries managers consider thermal characteristics of individual waters when developing monthly stocking schedules (e.g., only selected streams have thermal patterns suitable for June or July stockings).

In July 1991, hatchery staff began recording details about each stocking event, including the date and time of each stocking and the number and weight of each trout species stocked. Moreover, during each stocking event, hatchery staff recorded a single temperature measurement in the stocking reach. These data were archived into a centralized database in 2001 and have been updated continually. Wheeler et al. (2023) cleaned and reorganized these data to facilitate use and began distributing them along with other agency data sets in an internal R package. The trout stocking events data set currently contains information on 31,426 trout stockings; because our current research is focused on spring–early summer stockings in lotic HS and DH fisheries, 25,704 of these were relevant to this study. Until our current analysis, these temperature data were only used to consider water temperatures encountered at individual stocking events and no attempt had been made to create a model to evaluate temperature trends of individual stream reaches and across the spatial scale of PMTW.

As the NCWRC considers revisions to its current Trout Management Plan, there is a need to inform scheduling decisions regarding future trout stockings. Thus, we sought to analyze these legacy temperature measurements collected over the previous 33 years to understand the monthly thermal suitability of individual stream reaches and predict future thermal trends that may affect stocked-trout management. Specifically, we developed a Bayesian linear mixed-effects model to evaluate the overall and reach-specific trends. Our analysis demonstrated the value that "forgotten" and underappreciated data sets may hold. In our case, these data were collected originally to inform real-time actions, without the intention of long-term interpretation. Despite the opportunistic nature of data collection, the expansive spatial and temporal coverage allowed us to conduct a novel examination of these legacy data and provide interpretation that can guide the PMTW program into the future.

METHODS

Study area

Data utilized in this study were derived from HS and DH fisheries in western North Carolina. Stocking reaches were selected due to available angler access, ability to park hatchery vehicles, access to waters for fish releases, and suitable instream habitat (e.g., diversity of riffles, runs, and pools). Study stream reaches ranged from 272 to 1,111 m in elevation and from 3 to 1,580 km^2 in watershed size. They are most typically characterized as coolwater streams (Beauchene et al., 2014), and common nongame species included Blacknose Dace *Rhinichthys atratulus*, Longnose Dace *Rhinichthys cataractae*, Central Stoneroller *Campostoma anomalum*, and Northern Hog Sucker *Hypentelium nigricans*.

Over 1 million trout are produced annually at NCWRC hatcheries, where mean annual temperatures are approximately 11°C. Stocked trout are allocated to waters at rates of approximately 30 fish/ha (HS) and 60 fish/ha (DH) per month, with targeted species ratios of 20% Brown Trout, 40% Brook Trout, and 40% Rainbow Trout at each stocking. Stockings occur across 8 months (March–November, except September), and 90% of stocking events are in March–July. For each stocking, 96% are of trout that average 267 mm TL and 4% are >356 mm TL. The NCWRC does not stock near self-sustaining Brook Trout populations, utilizes sterile triploid stocked trout, and consults with other management partners to protect sensitive aquatic species, such as eastern hellbender *Cryptobranchus alleganiensis* (NCWRC, 2013). Hatchery fish do not undergo thermal tempering to mitigate difference between hauling and receiving waters due to risks of unintentional transmission of disease or aquatic nuisance species to hatchery equipment. In addition, persistence of stocked trout is low; an estimated 74% of all trout captured in a 1998–1999 HS creel study was harvested (Besler et al., 2005), and large numbers of trout emigrate from DH waters (Flowers et al., 2019).

Field data collection

This study utilized temperature data from stocking events that occurred in the spring-to-summer stocking season (March–July) in 1992–2024 at 183 stream reaches, of which 167 are currently managed with stocked trout. Stocking occurred between 0640 and 2110 hours, and the duration of each stocking event averaged 1.1 h. A temperature reading was recorded at each stocking event using thermal expansion thermometers. The thermometers were a mix of Imperial and SI units and observed temperature to the nearest degree Fahrenheit or Celsius. All data were entered initially into a centralized database after each stocking event. An R script standardized the temperature data into Celsius (°C) and interpreted the NCWRC code system (Fish, 1968) used for water bodies and counties into more specific stream-reach location names. Data were then scrutinized for entry errors and added to the NCWRC's R package (Wheeler et al., 2023).

Statistical analyses

Our aim was to characterize thermal trends at the stocking reaches and their spatial variation to inform future stocking decisions. Hatchery staff recorded temperatures at 99.98% of all stocking events; however, our data were characterized with a high frequency of missing data (32%) because some stream reaches entered or exited the PMWT program over the time frame and not all reaches are stocked every month between March to July. Moreover, we needed to account for variable time of the day when stocking events occurred. To address these complexities, we developed a linear mixed-effects model under a Bayesian hierarchical framework (Berliner et al., 1999; Wikle, 2003). The Bayesian approach flexibly accommodates sophisticated model specification and can be readily used for downstream tasks, such as future forecasting with uncertainties (Bal et al., 2014; Santos-Fernandez et al., 2022). In addition, the Bayesian hierarchical framework facilitates parameter estimation by sharing information across space and time, a key property for inferences with missing data.

We denoted $y_{i,t,m}$ the observed stocking temperature at reach i in year t and month m. We characterized temporal dynamics in $y_{i,t,m}$ using a linear combination of fixed and random effects (i.e., mixed-effects or hierarchical model) as follows:

$$y_{i,t,m} \sim \text{Normal}\left(\beta_{0,i} + \beta_{1,i}t + \beta_2 m + \beta_3 x_{i,t,m} + \epsilon_{i,t} + \nu_{i,t,m}, \sigma_y^2\right). \quad (1)$$

The fixed effects (β_2, β_3) accounted for shared thermal characteristics across reaches; that is, stream temperature increases from spring to summer and from morning until midday. To quantify these monthly and hourly rates of temperature increases, we modeled the linear effect of month (β_2) as a numerical variable (i.e., $m=1$ represented March, $m=2$ was April, $m=3$ was May, $m=4$ was June, and $m=5$ was July) and the effect of mean stocking time (β_3; i.e., hour of the day centered at the sample mean of 1209 hours) at reach i in year t and month m, $x_{i,t,m}$. Conditioned on the fixed effects, the random effects accounted for between-reach variation in mean stocking temperatures $(\beta_{0,i})$ and annual trends $(\beta_{1,i})$. We specified these random effects as a linear function of latitude $(\omega_{1,i})$, elevation $(\omega_{2,i})$, and watershed area $(\omega_{3,i})$ because we assumed that the stream reaches differ in mean temperatures and warming rates depending on their landscape attributes as follows:

$$\beta_{0,i} \sim \text{Normal}\left(b_{00} + b_{01}\omega_{1,i} + b_{02}\omega_{2,i} + b_{03}\omega_{3,i}, \sigma_0^2\right), \quad (2)$$

$$\beta_{1,i} \sim \text{Normal}\left(b_{10} + b_{11}\omega_{1,i} + b_{12}\omega_{2,i} + b_{13}\omega_{3,i}, \sigma_1^2\right). \quad (3)$$

Latitude, elevation, and watershed area were not correlated with each other (Pearson's $|r| < 0.20$). We accounted for temporal autocorrelation by specifying first-order autoregressive terms (ρ_ϵ and ρ_ν) for annual random effects, $\epsilon_{i,t}$, and monthly random effects, $\nu_{i,t,m}$, as follows:

$$\epsilon_{i,t} \sim \text{Normal}\left(\rho_\epsilon \epsilon_{i,t-1}, \sigma_\epsilon^2\right),\ \epsilon_{i,1} \sim \text{Normal}\left(0, \sigma_\epsilon^2\right), \quad (4)$$

$$\nu_{i,t,m} \sim \text{Normal}\left(\rho_\nu \nu_{i,t,m-1}, \sigma_\nu^2\right),\ \nu_{i,t,1} \sim \text{Normal}\left(0, \sigma_\nu^2\right). \quad (5)$$

Lastly, we accounted for measurement error in σ_y^2 because each recorded temperature came from a single reading of a portable sensor and was a random sample.

We implemented our Bayesian hierarchical model using the rjags package (Plummer, 2025) in program R (R Core Team, 2024), which employs an iterative sampling algorithm to maximize the joint posterior distribution (Carlin & Chib, 1995). Diffuse priors were used for all parameters (see online Supplementary Material). We ran the algorithm for three parallel chains, each with 20,000 burn-in iterations (discarded) and then 20,000 iterations thinned at a rate of 1/20. Therefore, posterior inferences were made based on the 3,000 samples for each parameter. All parameters converged, evidenced by Gelman–Rubin $(\hat{R})$ statistics below 1.1 (Gelman & Rubin, 1992). Statistical significance was declared when the 95% credible intervals of a parameter did not cover zero.

We used the Bayesian hierarchical model to forecast river temperatures at each study reach up to 2050 to evaluate their risk of exceeding a thermal threshold of 21.1°C (70°F). Although NCWRC occasionally stocks trout at higher temperatures without observed mortality, this threshold is a general guideline above which trout experience thermal stress and has been used by NCWRC fisheries managers as a rule-of-thumb cutoff to evaluate thermal suitability of stocked reaches. Coldwater streams are broadly defined as those with daily mean water temperature <22°C (Gresswell & Vondracek, 2010). Coolwater streams, where coldwater and warmwater species coexist locally, are characterized with July mean water temperature of 21.0–22.3°C (Beauchene et al., 2014; Lyons et al., 2009; Wehrly et al., 2003). In addition, Eaton et al. (1995) analyzed fish distribution and temperature data to identify the upper thermal threshold (i.e., 95th percentile weekly mean temperature) for Brook Trout (22.3°C), Brown Trout (24.1°C), and Rainbow Trout (24.0°C). Therefore, our thermal threshold of 21.1°C is conservative in defining the availability of coldwater streams for trout stocking in North Carolina.

To forecast mean stocking temperature at reach i in year $t+h$ ($h \geq 1$) and month m, we assumed a centered mean stocking time of zero (i.e., 1209 hours) and obtained the kth ($k = 1, \ldots, 3{,}000$) posterior predictive samples of the temporal random effects as follows:

$$\epsilon_{i,t+h}^{(k)} \sim \text{Normal}\left(\rho_\epsilon^{(k)} \epsilon_{i,t+h-1}^{(k)}, \sigma_\epsilon^{2(k)}\right)$$

$$\nu_{i,t+h,1}^{(k)} \sim \text{Normal}\left(0, \sigma_\nu^{2(k)}\right),$$

Table 1. Marginal posterior distributions of parameters in the linear mixed-effects model. Abbreviations are as follows: CI = credible interval; $\hat{R}$ = Gelman–Rubin statistics to check for convergence.

Parameter	Posterior mean (95% CI)	$\hat{R}$
b_{00} (Overall mean temperature)	4.60 (4.40, 4.80)	1.02
b_{01} (Latitude effect on mean)	−0.13 (−0.30, 0.03)	1.03
b_{02} (Elevation effect on mean)	−0.33 (−0.50, −0.17)	1.01
b_{03} (Watershed area effect on mean)	−0.13 (−0.39, 0.13)	1.01
b_{10} (Overall temperature trend)	0.05 (0.00, 0.09)	1.00
b_{11} (Latitude effect on trend)	−0.01 (−0.06, 0.04)	1.00
b_{12} (Elevation effect on trend)	−0.01 (−0.06, 0.04)	1.00
b_{13} (Watershed area effect on trend)	0.00 (−0.05, 0.05)	1.00
β_2 (Monthly rate of increase in temperature)	2.77 (2.74, 2.79)	1.00
β_3 (Hourly rate of increase in temperature)	0.25 (0.22, 0.28)	1.00
σ_y^2 (Measurement error)	0.90 (0.55, 1.50)	1.00
σ_0^2 (Spatial variation in mean temperature)	0.19 (0.15, 0.25)	1.00
σ_1^2 (Spatial variation in trend)	0.10 (0.08, 0.13)	1.00
ρ_ε (Annual autocorrelation)	0.84 (0.77, 0.88)	1.03
$\sigma_{\hat{a}}^2$ (Annual variation)	0.26 (0.22, 0.31)	1.01
ρ_ν (Monthly autocorrelation)	0.11 (0.08, 0.13)	1.00
σ_ν^2 (Monthly variation)	3.63 (3.04, 4.01)	1.03

$$\nu_{i,t+h,m}^{(k)} \sim \text{Normal}\left(\rho_i^{(k)} \nu_{i,t+h,m-1}^{(k)}, \sigma_\nu^{2(k)}\right), m > 1.$$

A posterior predictive sample of the forecast was then obtained as follows:

$$\mu_{i,t+h,m}^{(k)} = \beta_{0,i}^{(k)} + \beta_{1,i}^{(k)}(t+h) + \beta_2^{(k)} m + \epsilon_{i,t+h}^{(k)} + \nu_{i,t+h,m}^{(k)}.$$

Using the posterior predictive samples, we identified stream reaches that have >50% and >90% chances of exceeding 21.1°C in June and July by 2050. Assessing the future warming risk probabilistically was an advantage of our Bayesian forecast. Finally, we plotted posterior mean annual warming trend versus mean temperature in July 2024 of all 183 study reaches to identify the most and least thermally suitable reaches for stocking to inform future stocking decisions based on stream reach classification.

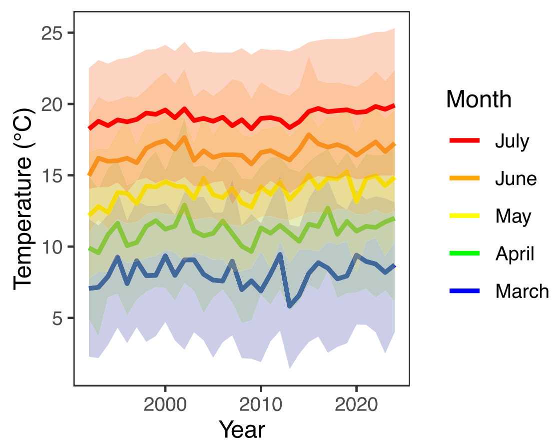

Figure 1. Estimated posterior means of annual stocking temperatures by month with associated 95% credible interval bands.

RESULTS

Our most recent data (year 2024) indicated that the mean temperature during stocking events was 17.29°C in June and 18.97°C in July. The thermal threshold of 21.1°C was exceeded at 9 out of 120 (8%) stocked stream reaches in June 2024 and 6 out of 43 (14%) reaches in July 2024. We found that the study stream reaches warmed, on average, at an annual rate of 0.05°C, and this trend was statistically significant (Table 1). Higher elevation reaches had overall lower mean stream temperatures. Latitude and watershed area had no significant effects on mean temperature, and none of the spatial covariates had significant effects on warming trend. Mean stocking time was significantly related to temperature, where each passing hour of the day was associated with 0.25°C warming. Month was also significantly related to temperature, where stream temperature increased by 2.77°C monthly from March to July (Figure 1). Conditioned on the fixed effects, the monthly random effects demonstrated high variation (3.63) and low autocorrelation (0.11). In comparison, the annual random effects demonstrated lower variation (0.26) and higher autocorrelation (0.84).

Spatial variation was lower than these temporal variations with respect to mean temperatures (0.19) and warming trends (0.10). However, between-reach variation in warming was discernible. Based on our model, some stream reaches were projected to warm faster (e.g., Valley River) than others (e.g., West Fork Pigeon River; Figure 2). By comparing posterior predictive percentiles of our forecasts to the thermal threshold (21.1°C) for all 183 reaches, we inferred that by 2050, one reach (Persimmon Creek, no longer actively stocked) will have 90% or more chance of exceeding the threshold in June and six reaches (Pacolet River, Green River, Little Ivy River, Clear Creek, Beaverdam Creek, Persimmon Creek) will in July. In addition, 19 reaches will have at least 50% chance of exceeding

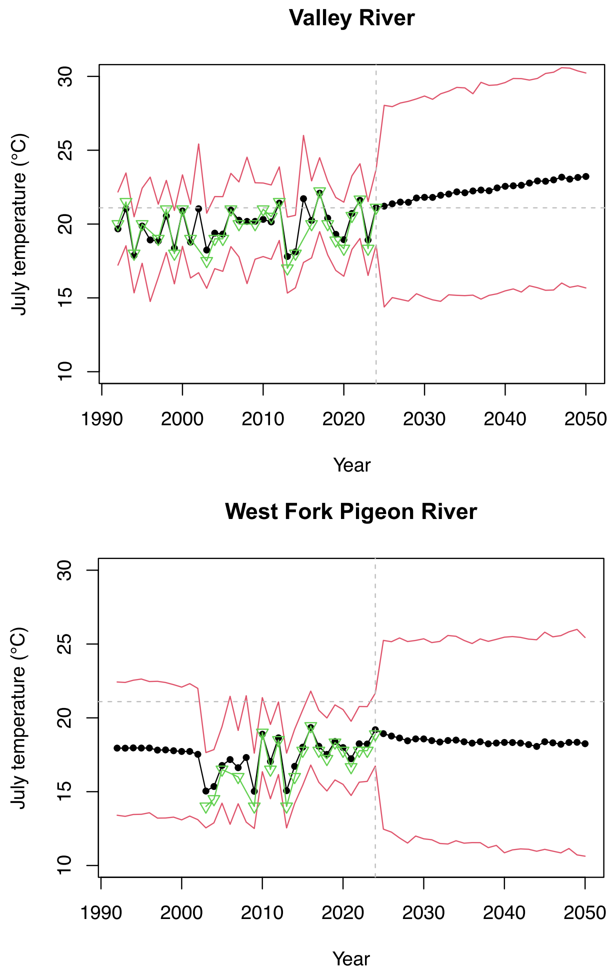

Figure 2. Observed, estimated, and predicted temperatures in July at two example reaches with contrasting warming trends; warming is faster in Valley River compared with West Fork Pigeon River, where stream temperatures have been stable. Green points represent observations. Black points represent estimated and predicted posterior means, with associated 95% credible intervals in red lines. The vertical dashed line represents the most recent year with data (2024). The horizontal dashed line represents the thermal threshold at 21.1°C (70°F).

the threshold in June and 88 reaches in July. There are 50 of the 167 reaches stocked currently that have significant warming rates (95% credible intervals not covering zero) and a mean warming rate of 0.08°C (Figure 3). The 50 reaches with significant warming trends were split equally into "Low" and "High" rates of warming ($N=25$ each), and the two groups were located throughout the study area (Figure 3).

Despite missing data (32%), our estimations adhered to the observed temperatures during stocking with a root mean square error of 1.40°C. Based on a plot of posterior mean annual warming trend versus mean temperature in July 2024, we classified 104 stream reaches as the most thermally suitable for stocking (annual warming rate <0.05°C [mean rate across the 183 reaches with active and inactive stocking programs] and mean temperature in July 2024 <21.1°C) and 39 reaches as the least thermally suitable (exceeding these thresholds) (Figure 4).

DISCUSSION

Our analysis of long-term stream temperature data showed an overall annual warming rate of 0.05°C across all streams, which is similar to other lotic habitats (Kaushal et al., 2010 ; van Vilet et al., 2011), and spatial heterogeneity in warming rates commonly found in previous studies (Johnson et al., 2020; Valentine, Lu, Dolloff, et al., 2024). Using linear extrapolation, our model assumed that future warming rates are comparable to recent warming rates, which may lead to conservative projection of future warming for our study streams, if the nonlinear temperature increase predicted by others proves true (Esper et al., 2024). Despite this assumption, forecasting helped characterize and visualize spatially heterogeneous warming patterns, which emphasizes the importance of stream-specific management approaches. Although stream warming poses a challenge to coldwater managers at the southern range, we discuss below implications of our analysis in adaptive stocking decisions in North Carolina's PMTW.

Fisheries managers are well versed at handling complicated interactions among fish, aquatic habitats, and humans. Often, managers are required to react to emerging challenges to ensure

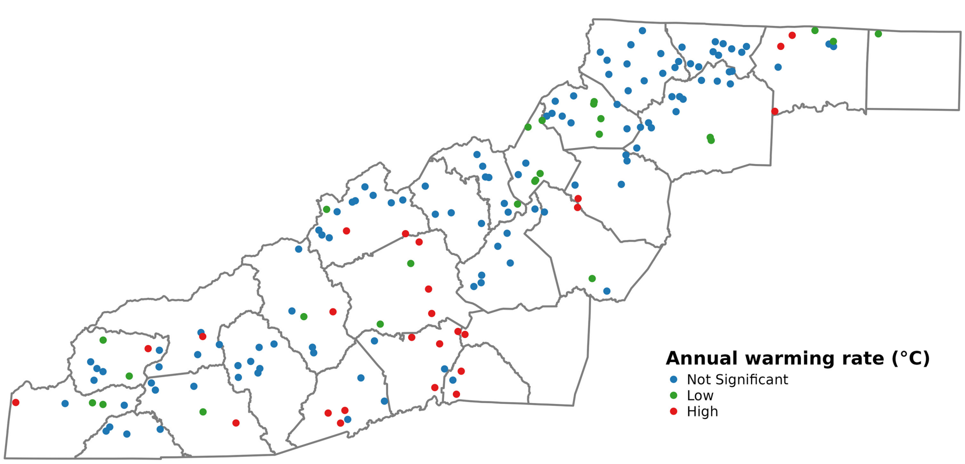

Figure 3. Spatial patterns of annual warming rates at 167 study reaches with active stocking programs. Reaches with significant warming trends (i.e., 95% credible intervals not covering zero) are split equally into "Low" and "High" rates of warming ($N=117$ reaches for "Not Significant," 25 for "Low," and 25 for "High"). The mean warming rate among significantly warming reaches was 0.08°C annually.

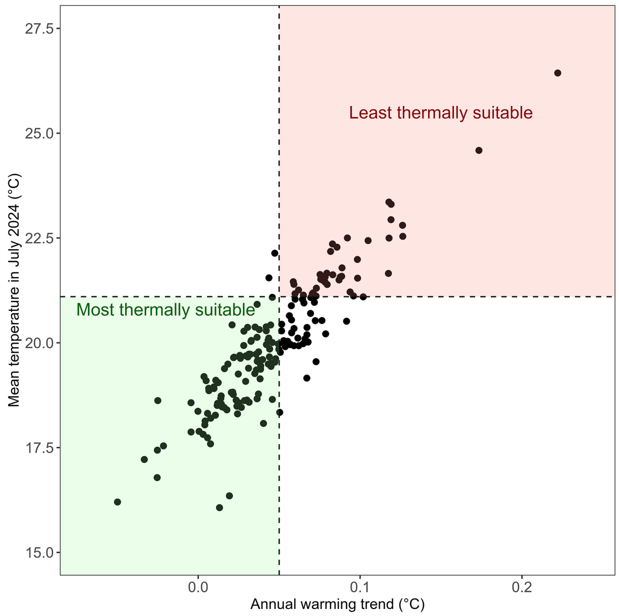

Figure 4. Posterior mean annual warming trend versus mean temperature in July 2024 (°C) of 183 study reaches, shown in black circles. The most thermally suitable reaches ($N = 104$) are characterized by an annual warming trend <0.05°C (the mean warming rate across the 183 stream reaches) and mean temperature in July 2024 < 21.1°C, and the least thermally suitable reaches ($N = 39$) exceed these thresholds.

the sustainability of fisheries, but our analysis provides a proactive framework that may help mitigate the identified threat of warming waters. By understanding the differences among thermal regimes, managers can schedule trout stocking events to avoid problems with elevated water temperatures, such as physiological stress (Coutant, 1977; Raleigh et al., 1984; Xu et al., 2010), low catch rates (Meyer et al., 2023), and unmet expectations of anglers. In addition, such refined planning can assist hatchery personnel by reducing handling and hauling stress, preventing time-consuming tempering events that disrupt intricate stocking schedules, and avoiding unfortunate scenarios such as a hatchery vehicle arriving at a stream too warm for stocking with trout that are too stressed to return to the hatchery. Fortunately, our modeling approach provides a framework for managers to anticipate these potential thermal challenges before they become immediate threats. Such an assessment tool can help develop and maintain an efficient range of stocking programs. For example, Hessenauer and Wehrly (2022) evaluated put-grow-and-take fisheries in Michigan, and PMTW utilizes trout stocked at a target size and condition to provide put-and-take fisheries in North Carolina.

Understanding the warming trend of different stream reaches allows managers to develop resource-specific strategies to maximize the fishery potential of individual reaches (Figure 4). In addition to avoidance of warming waters, managers may wish to focus limited production capacity on more resilient reaches to maximize the sportfishing potential of each stocked trout and to help offset the loss of trout angling opportunities as other reaches become too warm. For example, the diverging trends of West Fork Pigeon (DH) and Valley (HS) rivers (Figure 2) demonstrate the long-term, thermal suitability of these stream reaches and highlight the dynamic and heterogeneous nature of PMTW (Figures 3, 4). Predicted thermal trends for West Fork Pigeon River suggest its current DH management strategy is likely to remain appropriate well into the future, and given its suitability, any alterations to this fishery (e.g., stocking events, increased angler access, or development of parking areas) can be considered with the expectation of enhancing a long-term trout fishery. However, the predicted warming of Valley River may cause managers to reconsider its prolonged management and associated stocking events. Now that our model has provided managers with this information, the NCWRC can monitor this resource closely to guide future stockings while considering if an alternative management regime (e.g., DH) would be more appropriate. In addition, anglers may shift their behavior and expectations based on available spatial information on angling (Mee et al., 2016). Sharing information on stream warming and justification for management decisions could garner more public support as managers adapt to a changing climate (Venturelli et al., 2017).

Our model found a significant overall warming rate across HS and DH waters, which is a larger programmatic challenge. Potential pathways to address this programwide issue will be explored during revision of the NCWRC's Trout Management Plan (NCWRC, 2013). For example, traditional HS stocking events occur in spring and early summer, but going forward, stockings may need to focus on cooler months for warmer waters. Where appropriate, this alteration would provide additional angling opportunities that are supported by trout anglers (Jewell et al., 2023) while mitigating the potential loss of traditional stocking events due to stream warming. These adjustments can ensure that a finite supply of hatchery-reared trout is used efficiently and effectively on a stream-by-stream basis, which contributes to positive angling experiences and economic impact locally and throughout programs like PMTW. Without this understanding, managers would have to continue to react to changing conditions in lieu of planning actively for them.

Our model was sophisticated in decomposing and delineating temporal variation and autocorrelation, while accounting for spatially varying mean and warming trends. The emphasis on the temporal dimension reflected our study aim to characterize warming trends and use them for forecasting, and this approach was further justified by lack of strong spatial clustering in temporal trends (Figure 3). In cases when spatial autocorrelation is evident, such as intensive sampling of river networks with hydrological connectivity among sites, extensions of our model could use Markov random fields such as conditional autoregressive models or simultaneous autoregressive models (Lu et al., 2024; Ver Hoef et al., 2018) on the random intercepts and trends to address spatial correlation. Fitting more complex models may require more spatial and temporal replicates with a smaller frequency of missing data, and this requires care especially when analyzing opportunistically collected historical data such as ours.

In conclusion, alterations to climate threaten traditional coldwater fisheries at their southern range and fisheries managers need to adapt to stream warming to sustain fisheries in their jurisdictional waters. This study also demonstrated a case study in which an analysis of a historical data set recently organized and stored in the NCWRC R package (Wheeler et al., 2023) proved informative to fisheries management decisions. We think that stream temperature data at the time of stocking are routinely collected by other fisheries agencies, and single-point river temperature data are used to infer trends in other studies (Childress et al., 2024). These data can be harnessed to understand warming trends at a broad spatial scale. In fact, our Bayesian hierarchical framework is suitable for a simultaneous analysis of hierarchical data from multiple data sources (Valentine, Lu, Childress, et al., 2024). Additional data curation and model development are warranted to monitor the thermal riverscapes of coldwater habitats to inform stocking and other management decisions at the southern range.

SUPPLEMENTARY MATERIAL

Supplementary material is available at *North American Journal of Fisheries Management* online.

DATA AVAILABILITY

At the time of publication, data were not publicly available. All data inquires can be directed to J. M. Rash (jacob.rash@ncwildlife.org).

ETHICS STATEMENT

There were no ethical guidelines applicable to this study.

FUNDING

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CONFLICTS OF INTEREST

None declared.

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