FINAL PROJECT REPORT FOR THE SOUTHEAST CLIMATE ADAPTATION SCIENCE CENTER

1. **ADMINISTRATIVE:**

   Principal Investigator: Dr. Yoichiro Kanno, Associate Professor, Department of Fish, Wildlife, and Conservation Biology, Colorado State University

   Project Title: Modeling brook trout population responses to climate variation in the Southeast USA.

   Agreement Number: G21AC10205-00

   Date of Report: 07/30/2024

   Period of Performance: From 03/19/2021 to 06/30/2024

   Actual Total Cost: $241,737

2. **PUBLIC SUMMARY:** Brook trout is an iconic freshwater fish species that supports recreational fishing and cultural heritage in the Southeast USA. However, human activities, such as habitat degradation and introduction of non-native species, have led to extensive declines of brook trout populations in the region, and climate change is projected to affect this native coldwater species further. Efforts to save this species occur throughout the region, but financial and other resources are limited: conservation practitioners need to understand the status of trout populations in the large landscape and decide where such efforts should occur to maximize our chances of maintaining brook trout populations. In this project, we assembled data sets of trout populations and habitats from Georgia to Maryland and analyzed them using advanced statistical models to provide science to inform conservation. Our unprecedented effort to synthesize big data in a large area led to new discoveries on the brook trout population status and ecology. We found that some watershed characteristics, such as elevation and stream size, harbor more trout in local streams. Trout abundance changed over time to correspond with annual variations in air temperature and precipitation patterns, and this sensitivity to annual weather variation also differed by location and habitat characteristics. Finally, water temperatures in some streams were more stable throughout the year than others due likely to groundwater input. Our findings collectively show that climate change will not affect all streams and trout population equally, supporting the importance of spatial prioritization in conservation efforts. We are working with conservation practitioners and trout managers to use our findings to inform their on-the-ground actions, including habitat restoration, barrier removals, translocations of brook trout, and eradications of non-native trout.

3. **TECHNICAL SUMMARY:** The goals of the original research project were to develop data and statistical model products. We assembled trout population data from 11 organizations (mostly state fisheries agencies) and organized a large, paired air-stream temperature data

set collected by the US Forest Service. Our project has generated 4 peer-reviewed publications and 10 oral and poster conference presentations, which was based on the development of innovative statistical methods and their applications to the brook trout data. The data and model products and links to the peer-reviewed publications have been uploaded to the ScienceBase project page. Overall, this regional-focused SE CASC funding made it possible to synthesize multiple data sets, which had been analyzed only individually, and our synthesis revealed greater degrees of spatial variation in our study area, compared to analyses of data in more geographically limited areas previously.

4. **PURPOSE AND OBJECTIVES:** The original objectives in our Scope of Work were three-fold:

(1) What landscape features affect population responses of brook trout to climate? That is, how does climate interact with local conditions to generate spatial variability in trout population responses?

(2) What is the spatial scale of synchrony in population trends? Are geographically closer sites characterized with more similar temporal population patterns than those farther apart?

(3) Are there “outliers” to the regional population trend (i.e., climate refugia or populations with greater risk), and where are they distributed?

All three objectives were addressed in this project. Details are provided below (6. Project Results).

5. **ORGANIZATION AND APPROACH:** This project was co-led by Dr. Yoichiro Kanno (Colorado State University) and Dr. Mevin Hooten (The University of Texas at Austin). A postdoctoral fellow, Dr. Xinyi Lu, was hired for the analysis to develop statistical methods and apply them to the brook trout data. Our SE CASC project progressed in tandem with a project focused on stream temperature models funded by the US Fish and Wildlife Service, which financially supported one graduate student (George Valentine). In sum, these two funding sources supported different phases of the project to leverage resources.

6. **PROJECT RESULTS:** A summary of our project findings related to each objective (4. Purpose and Objectives) is summarized below based on Valentine et al. (2024a). A summary of each peer-reviewed publication appears in the next section (7. Analysis and Findings).

(1) What landscape features affect population responses of brook trout to climate? That is, how does climate interact with local conditions to generate spatial variability in trout population responses?

Seasonal weather patterns affected temporal variation in brook trout abundance differently between the northern sub-region (approximately Virginia, West Virginia, and Maryland) and the southern sub-region (Georgia, Tennessee, South Carolina, and North Carolina). Young-of-year (YOY) abundance was more strongly affected by seasonal weather variations than adult abundance, and YOY abundance was more strongly affected by summer air temperature but less affected by winter and spring flows in the southern sub-region.

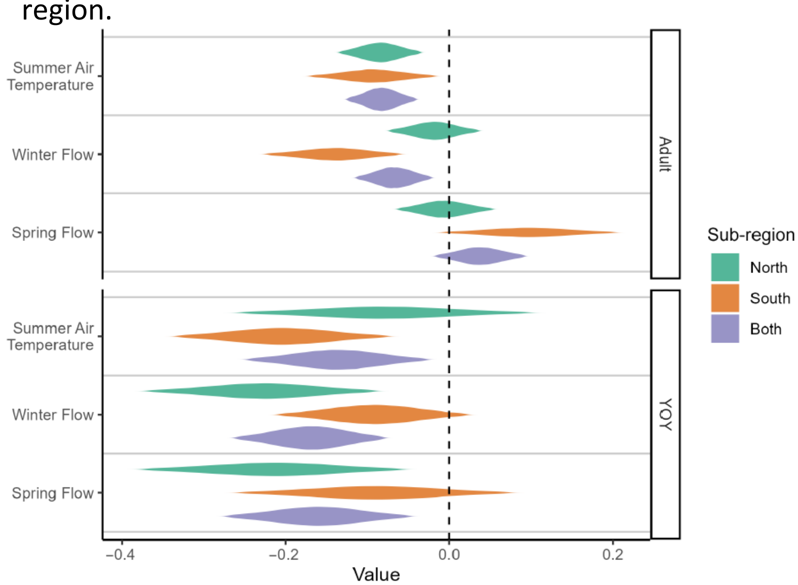

FIGURE 4 Ninety-five percent highest posterior density intervals (HDPIs) for climate effects on brook trout (*Salvelinus fontinalis*) log density by life stage and sub-region. Climate variables: average 0.9Q summer air temperature (year $t-1$), max 0.9Q winter stream flow (year t), max 0.9Q spring stream flow (year t). *Data sources*: US Geological Survey NHDPlus v2.1, National Oceanic and Atmospheric Administration.

(2) What is the spatial scale of synchrony in population trends? Are geographically closer sites characterized with more similar temporal population patterns than those farther apart?

Spatial synchrony of brook trout populations extended to 100-200 km, but it was much weaker and less spatially extensive than seasonal weather variables.

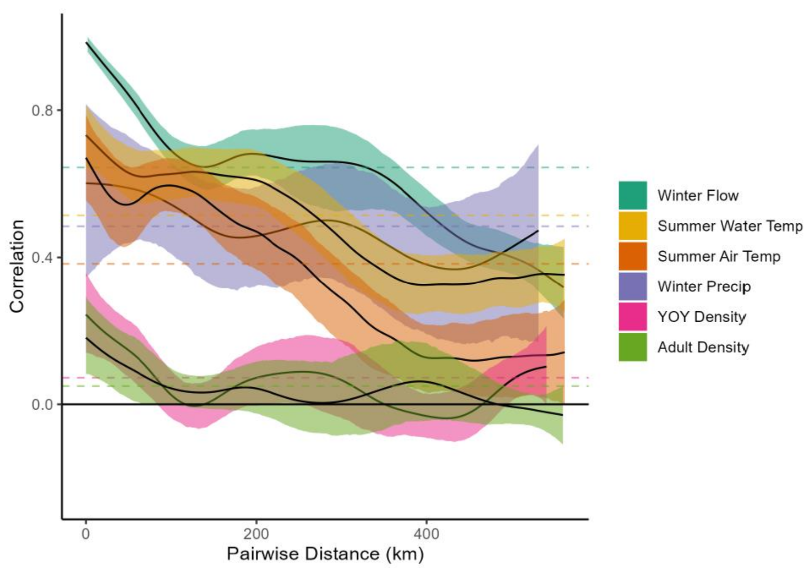

FIGURE 2 Spline correlogram of pairwise correlation in brook trout (*Salvelinus fontinalis*) log density (1995–2015) and selected climate variables for the southeast United States. Climate variables: mean estimated monthly winter (December–February) flow (1980–2015), mean daily observed summer (June–September) air temperature (2010–2015), mean daily observed summer water temperature (2010–2015), and total observed monthly winter precipitation (2008–2013). Shading indicates 95% confidence envelopes. Dashed lines represent average pairwise correlations. *Climate data sources*: US Geological Survey NHDPlus v2.1, US Forest Service, National Oceanic and Atmospheric Administration.

(3) Are there "outliers" to the regional population trend (i.e., climate refugia or populations with greater risk), and where are they distributed?

We located "outlier" sites, defined as those sites containing brook trout populations with asynchronous temporal population dynamics relative to the overall regional mean dynamics. For example, we identified five asynchronous sites (those with lower values of intraclass correlation coefficient) with three located at the southern end of the study region and two at the northern end.

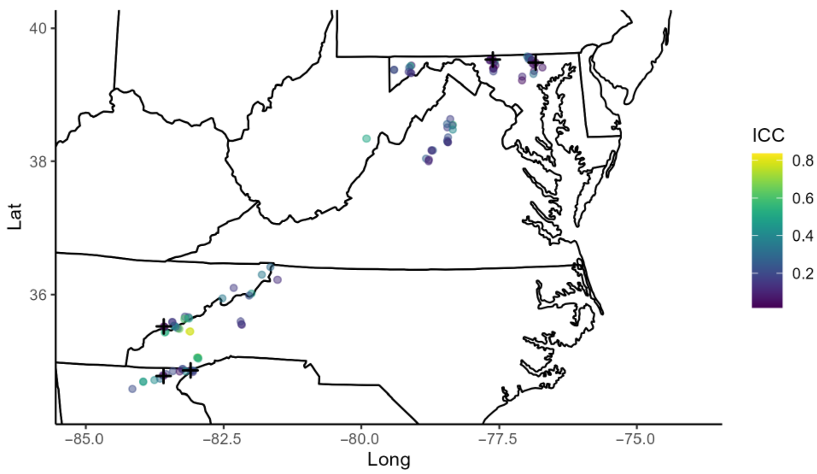

FIGURE 6 Intraclass correlation coefficient (ICC) values for young-of-the-year brook trout (*Salvelinus fontinalis*) abundance in the southeastern United States. High ICC values indicate synchrony relative to the temporal variation averaged across segments, while low ICC values indicate asynchrony. The five stream segments with lowest ICC (least synchronous) are indicated by "+".

7. ANALYSIS AND FINDINGS: Key findings are summarized below for each peer-reviewed publication (see 10. Outreach and Communications):

Lu et al. (2024a): Using multi-scale spatial models of dendritic ecosystems to infer abundance of a stream salmonid. [Journal of Applied Ecology] – We developed a statistical model to account for the spatially nested stream habitat structure (i.e., stream segments nested within networks, then within watersheds) to predict brook trout abundance while accounting for spatial dependency in North Carolina's trout count data. Trout abundance and its temporal trend were different between the eastern and western side of the Appalachian Continental Divide, providing a basis for setting different management expectations by region.

Lu et al. (2024a): Regularized latent trajectory models for space-time population dynamics. [Journal of Agricultural, Biological, and Environmental Statistics] – We developed an innovative Bayesian hierarchical framework to infer how climate sensitivity of brook trout populations shifts over space and time in the Great Smoky Mountains National Park. The climate sensitivity was dynamic and complicated, with a notable pattern that more rain in summer alleviated negative effects of high summer air temperatures.

Valentine et al. (2024a): Spatial asynchrony and cross-scale climate interactions in populations of a coldwater stream fish. [Global Change Biology] – We showed that climate effects on brook trout abundance differs by watershed and site in the southeastern USA, resulting in heterogeneous responses to climate change and thus highlighting the importance of spatial prioritization for brook trout management at the regional scale. This study also showed the value of combining multiple data sets at a broad spatial scale for gaining novel ecological insights.

Valentine et al. (2024b): Landscape influences on thermal sensitivity and predicted spatial variability among brook trout streams in the southeastern USA. [River Research and Applications] – We used paired stream-air temperatures to quantify spatial variation in water temperature warming rates and predicted where thermal refugia might occur in the southeast. We found that thermal refugia were spatially clustered with more frequent occurrences at the southern end of the study area (North Carolina and Tennessee) due to higher elevations and groundwater input.

8. **CONCLUSIONS AND RECOMMENDATIONS:** Our synthesis of existing trout and habitat data in a large region indicated that brook trout population responses to climate change differ spatially, with some streams more likely to serve as climate refugia than others. Communicating this information with conservation practitioners and fisheries managers is important to advance landscape-scale conservation of brook trout in the Southeast USA. Our logical next step is to expand the analysis to the entire eastern range of brook trout through Maine from Georgia, using an array of statistical models developed in the Southeast project. In fact, we received funding from the US Fish and Wildlife Service's Multi-State Conservation Program in 2024 to implement the range-wide analysis. This new effort will continue through 2026. The current SE CASC funding was instrumental in realizing the ongoing range-wide analysis, which now involves trout managers in 16 states.

9. **MANAGEMENT APPLICATIONS AND PRODCUTS:** We worked with trout managers in the southeast to develop our regional brook trout population data set and discuss management applications of our project deliverables. In particular, we worked most closely with Jake Rash, Coldwater Research Coordinator for the North Carolina Wildlife Resources Commission. He has also served as Chair of the Eastern Brook Trout Joint Venture's Steering Committee since 2023 and played a key role in funding acquisitions, conception, manager engagement, and management applications. Here is his quote: "This project was an ambitious effort to inform Brook Trout conservation across multiple scales by working with fisheries managers from Georgia to Maryland. As such, this novel research has provided insight into spatial and temporal patterns of Brook Trout populations that will help guide on-the-ground action."

   To develop our regional brook trout population data set, we obtained survey data from the following contacts:

   - Georgia Department of Natural Resources (Sarah Baker)
   - South Carolina Department of Natural Resources (Dan Rankin)

- North Carolina Wildlife Resources Commission (Jake Rash)
- Tennessee Wildlife Resources Agency (Jim Habera, Will Collier)
- Virginia Department of Wildlife Resources (Stephen Reeser, Brad Fink)
- West Virginia Department of Natural Resources (David Thorne)
- Maryland Department of Natural Resources (Michael Kashiwagi)
- Great Smoky Mountains National Park (Matt Kulp)
- Shenandoah National Park (Evan Childress)
- US Fish and Wildlife Service (John Sweka)
- Clemson University (Todd Petty)

A key event for trout manager engagement happened during the annual meeting of the Eastern Brook Trout Joint Venture in November 2023 held at the National Conservation Training Center, West Virginia. PI Kanno presented a summary of our southeastern analysis of trout population and temperature data to trout managers in the entire eastern native range of brook trout (from Georgia to Maine). PI Kanno's attendance in this annual meeting was financially supported by the additional SE CASC funding approved in June 2023 ($18,284). From this event and throughout the project period, we gained the following key insights regarding how trout managers would use our project deliverables:

(1) The Eastern Brook Trout Joint Venture currently updates their range-wide brook trout population status assessment based on presence/absence data and professional judgment by state fisheries biologists. We discussed incorporating trout abundance data and temperature data (i.e., locations of thermal refugia) in their range-wide population status assessment, and this discussion is on-going.

(2) Much interest was expressed in developing a data visualization tool (e.g., interactive website page) to present our data and statistical models visually. This is a logical next step of this project, and such a visualization tool would be particularly useful once our analysis has expanded to the entire eastern native range. PI Kanno is currently testing this idea with a single data set from the Great Smoky Mountains National Park to develop a prototype of this tool.

Finally, many trout managers listened to the webinar by PI Kanno's SE CASC seminar in November 2023, which helped information dissemination. We thank SE CASC for setting up this webinar.

10. OUTREACH AND COMMUNICATIONS:

Peer-reviewed Publications:

Lu, X., Kanno, Y., Valentine, G.P., Rash, J.M., Hooten, M.B. (2024a). Using multi-scale spatial models of dendritic ecosystems to infer abundance of a stream salmonid. *Journal of Applied Ecology*, *61(7),* 1703-1715. DOI: 10.1111/1365-2664.14665

Lu, X., Kanno, Y., Valentine, G.P., Kulp, M.A., Hooten, M.B. (2024b). Regularized latent trajectory models for space-time population dynamics. *Journal of Agricultural, Biological, and Environmental Statistics, Early View*. DOI: 10.1007/s13253-024-00616-y

Valentine, G.P., Lu, X., Childress, E.S., Dolloff, C.A., Hitt, N.P., Kulp, M.A., Letcher, B.H., Pregler, K.C., Rash, J.M., Hooten, M.B., Kanno, Y. (2024a). Spatial asynchrony and cross-scale climate interactions in populations of a coldwater stream fish. *Global Change Biology, 30(1),* e17029. DOI: 10.1111/gcb.17029

Valentine, G.P., Lu, X., Dolloff, C.A., Roghair, C.N., Rash, J.M., Hooten, M.B., Kanno, Y. (2024b). Landscape influences on thermal sensitivity and predicated spatial variability among brook trout streams in the southeastern USA. *River Research and Applications, Early View.* DOI: 10.1002/rra.4305

Webinar:

Kanno, Y. 2023. Climate change impacts on brook trout populations in the southeastern USA. Webinar hosted by US Geological Survey Southeast Climate Adaptation and Science Center. Online. November 29, 2023.

SE CASC Science Blog:

Brook trout populations are different in neighboring streams due to climate impacts. April 23, 2024. https://secasc.ncsu.edu/2024/04/23/brook-trout-populations-statistical-method/

Conference Presentations (Oral):

Lu, X., Kanno, Y., Valentine, G.P., Kulp, M.A., Hooten, M.B. 2023. Regularized latent trajectory models for space-time population dynamics. Spatial Statistics 2023: Climate and the Environment. Boulder, CO. July 21, 2023.

Lu, X., Kanno, Y., Valentine, G.P., Kulp, M.A., Hooten, M.B. 2023. Regularized latent trajectory models for space-time population dynamics. Annual Meeting of the Western North American Region of the International Biometrics Society. Anchorage, AK. June 21, 2023.

Lu, X., Kanno, Y., Hooten, M.B., G.P. Valentine, Kulp, M.A. 2023. Spatio-temporal models identify climate change refugia using trout population surveys. Annual Meeting of the Colorado/Wyoming Chapter of the American Fisheries Society. Fort Collins, CO. March 1, 2023.

Valentine, G.P., Lu, X., Rash, J.M., Kulp, M.A., Childress, E., Hitt, N.P., Hooten, M.B., Dolloff, C.A., Letcher, B.H., Kanno, Y. 2023. Spatial asynchrony and cross-scale climate interactions in populations of coldwater stream fish. Annual Meeting of the Colorado/Wyoming Chapter of the American Fisheries Society. Fort Collins, CO. March 1, 2023.

Valentine, G.P., Lu, X., Rash, J.M., Kulp, M.A., Childress, E., Hitt, N.P., Hooten, M.B., Dolloff, C.A., Letcher, B.H., Kanno, Y. Structure and scale of spatial synchrony in southeastern US brook trout populations. Annual Meeting of Southern Division American Fisheries Society, Norfolk, VA. February 4, 2023.

Valentine, G.P., Hooten, M.B., Rash, J.M., Hitt, N.P., Letcher, B.H., Childress, E., Kanno, Y. 2021. Structure and scale in spatially synchronous southeastern US trout populations. Annual Meeting of the American Fisheries Society. Baltimore, MD. November 7, 2021.

Conference Presentations (Poster):

Valentine, G.P., Lu, X., Hooten, M.B., Rash, J.M., Hitt, N.P., Letcher, B.H., Childress, E., Dolloff, C.A., Kanno, Y. 2022. Landscape variables characterize thermal stability in Southeastern US brook trout streams. Wild Trout Symposium XIII, West Yellowstone, MT. September 28, 2022.

Valentine, G.P., Lu, X., Rash, J.M., Kulp, M.A., Hitt, N.P., Hooten, M.B., Kanno, Y. 2022. Structure and scale in spatially synchronous southeastern US brook trout populations. Joint Aquatic Sciences Meeting, Grand Rapids, MI. May 16, 2022.

Valentine, G.P., Hooten, M.B., Rash, J.M., Hitt, N.P., Letcher, B.H., Childress, E., Dolloff, C.A., Kanno, Y. 2021. Landscape variables characterize thermal stability in southeastern US brook trout streams. Annual Meeting of the American Fisheries Society, Baltimore, MD. November 7, 2021.