Multispecies conservation of freshwater fish assemblages in response to climate change in the southeastern United States

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Abstract

Aim: Streamflow and water temperature are primary variables influencing the distribution of freshwater taxa. Climate-induced changes in these variables are already causing shifts in species distributions, with continued changes projected in the coming decades. The Mobile River Basin (MRB), located in the southeastern United States, contains some of the highest levels of temperate freshwater biodiversity in North America. We integrated species distribution data with contemporary and future streamflow and water temperature data as well as other physical habitat data to characterize occurrence probabilities of fish species in the MRB with the goal of identifying current and future areas of high conservation value.

Location: Mobile River Basin, southeastern United States.

Methods: We used a maximum entropy approach to estimate baseline and future occurrence probability distributions for 88 fish species in the MRB based on model-generated streamflow and water temperature as well as geologic, topographic and land cover data. Areas of conservation prioritization were identified based on regions that contain suitable habitat for high levels of biodiversity according to baseline and future conditions while accounting for uncertainty associated with multiple future climate projections.

Results: On average, flow (28%), water temperature (28%) and geology (30%) contribute evenly to determining suitable habitat for fish species in the MRB. Based on baseline and future species distribution model estimates, high priority streams (best 10%) are largely concentrated in the eastern portion of the MRB, with a majority (51%) located within the Coosa and Tallapoosa River systems.

Main conclusion: We provide a framework that uses relevant hydrologic and environmental data in the context of future climatic uncertainty to estimate areas of freshwater conservation opportunity in the coming decades. While streamflow and water temperature represent important habitat for freshwater fishes in the MRB, distributions are also constrained by other aspects of the physical environment.

KEYWORDS
hydrology, Mobile River Basin, species distribution modelling, SWAT, water temperature, Zonation
Aquatic ecosystems have experienced profound alterations due to anthropogenic activities (Dudgeon et al., 2006), and climate-induced changes to streamflow and water temperature are expected to further accelerate changes to these environments in the coming decades (Knouft & Ficklin, 2017). Climate change has already had observable impacts in various regions due to changes in precipitation patterns and warming temperatures, resulting in altered hydrologic regimes (Jimenez Cisneros et al., 2014). Changes to hydrologic systems are particularly detrimental to species occupying riverine systems, as these taxa are often adapted to natural flow conditions (e.g., Scott & Helfman, 2001; Rahel & Olden, 2008). In addition, freshwater ectotherms rely on their environment for thermal regulation (Brett, 1956; Schmidt-Nielsen, 1997). As a result, riverine species are especially vulnerable to climate-induced changes in streamflow and water temperature (Knouft & Ficklin, 2017).

Characterizing how species have and will continue to respond to climate-induced changes in their environments remains a fundamental goal of conservation biology. Many studies have observed species adaptations to climate change including altered geographic distributions and phenological characteristics (e.g., Beschta et al., 2013; Bormann et al., 2015). Additionally, many studies have employed species distribution models (SDMs) to project future climate-induced changes in suitable habitat for a variety of species (e.g., Buisson, Thuiller, Lek, Lim, & Grenouillet, 2008; Morrongiello et al., 2011). While this approach has been used to model changes in suitable habitat for freshwater taxa, results often lack projections that influence the distributions of freshwater species. Additionally, while studies using projections of future climate may be useful for evaluating potential habitat alterations, variations across global climate models (GCMs) and emissions scenarios can result in high levels of uncertainty for projections of suitable habitat distributions (Beaumont, Hughes, & Pitman, 2008). As a result, developing appropriate regional conservation plans under future conditions remains a challenge for ecosystem managers.

Projecting potential habitat alterations in response to climate change is especially important for freshwater fish species that are endemic to relatively small geographic ranges. The Mobile River Basin (MRB), located in the southeastern United States, contains some of the highest levels of temperate biodiversity in North America, including many endemic species (Benke & Cushing, 2011). However, the MRB is expected to experience dramatic increases in water temperature and decreases in summer streamflow as a result of ongoing changes in climate (Neupane, Ficklin, Knouft, Ehsani, & Cibin, 2019; van Vliet et al., 2013). Because of the high level of biodiversity and the projected changes to hydrologic and thermal conditions in the region, there is an urgent need to evaluate potential responses of freshwater fish biodiversity to these alterations in environmental conditions and to identify areas that may provide refuge from climate-induced habitat alterations. Here, we used SDMs with an array of environmental data throughout the MRB to characterize occurrence probabilities for 88 fish species for a baseline (1975–1994) and a future (2060–2079) period for 14 GCM projections with a high greenhouse gas emissions scenario [Representative Concentration Pathway (RCP) 8.5]. Occurrence probability distributions were then used to determine areas of high conservation value for baseline conditions, future conditions and transition periods between baseline and future conditions. Areas of high conservation value across all time periods were identified, and the environmental conditions within these areas were evaluated to aid managers in developing conservation plans that are resilient to projected changes in climate.

2 | METHODS

2.1 | Study area

The MRB encompasses an area of over 110,000 km², covering most of Alabama and extending into Georgia, Mississippi and Tennessee (Figure 1; Atkins, 2004). Within the MRB, the major river systems include the Alabama, Black Warrior, Cahaba, Coosa, Tallapoosa and Tombigbee River Basins. While the MRB is the sixth largest basin in area in the United States, it ranks fourth in terms of streamflow, with a mean annual discharge of 1,800 m³/s at the outlet to the Gulf of Mexico (Johnson, Kidd, Journey, Zappia, & Atkins, 2002) and a basin-wide mean annual discharge of 75.2 m³/s and water temperature of 14.2°C for the 1975–1994 time period. Land cover throughout the region is primarily forested (70%), followed by agriculture (26%), and urban areas (3%) (Johnson et al., 2002). Elevation ranges from near...
sea level in the coastal plains to above 900 m in parts of Georgia (Atkins, 2004). Additionally, the basin contains 12 threatened and endangered (TE) and at least 40 endemic fish species (Benke & Cushing, 2011).

2.2 | Data

The Soil and Water Assessment Tool (SWAT) hydrologic model (Arnold et al., 2012) was used to derive streamflow and water temperature estimates across the MRB. Future daily estimates of precipitation and minimum and maximum air temperature were acquired from the Coupled Model Intercomparison Project—Phase 5 (CMIP5) Climate and Hydrology Projections archive (www.gdo-dcp.ucclnl.org; Maurer et al., 2014) for 14 GCMs with the high emissions scenario Representative Concentration Pathway (RCP) 8.5 (Table S1). Precipitation and temperature estimates (1/8 degree resolution) were previously downscaled with the daily bias-corrected and constructed analogues (BCCA) method of Maurer, Hidalgo, Das, Dettinger, and Cayan (2010). These GCM data were input into the calibrated SWAT model to generate streamflow and water temperature projections. See Appendix S1 for full details on the SWAT model, and calibration and validation methods and results.

The previously mentioned SWAT model was used to derive baseline and future monthly estimates of streamflow and water temperatures for a baseline (1975–1994) and future (2060–2079) period. To capture the range of scenarios within RCP 8.5, streamflow and water temperature projections from 14 GCMs models were selected for the species distribution modelling. Monthly averages for the baseline period and for each GCM were used to calculate minimum and maximum annual streamflow (m³/s) and water temperature (°C) and the intra-annual coefficient of variation (CV) of streamflow and water temperature. To determine minimum and maximum values for each reach, the lowest or highest monthly average value, respectively, within each year was used to calculate an average across the 20-year periods. CV values were calculated by dividing the standard deviation of monthly streamflow by the monthly average streamflow for each reach to reflect intra-annual streamflow and water temperature variability.

Contemporary geology, topography and land cover data were also included in our species distribution models. Primary surface rock type data were obtained from the USGS Mineral Resources Database (Hardeman, Miller, & Swingle, 1966; Lawton et al., 1976; Moore, 1969; Szabo, Osborne, Copeland, & Neathery, 1988) and represented geology at 400-m resolution. Slope, representing topography, was calculated from a digital elevation model (30-m resolution; Gesch et al., 2002) and converted to 400-m resolution to match the minimum pixel size of available geology data. Land cover data were acquired from the National Land Cover Database (NLCD) at 30-m resolution (Fry et al., 2011). The dominant land cover type within 2,000 m of each pixel in the stream channel was determined at 400-m resolution. Fish locality data for native species (non-native species were not included in analyses) were obtained from the FishNet 2 Portal from surveys conducted by a variety of institutions (Table S2; www.fishnet2.com; 12 February 2017) for 1975–1994 to coincide with the baseline streamflow and water temperature data. The final native species data set consisted of 15,337 individual observations including 119 species, each represented by at least 20 unique localities within the MRB.

2.3 | Species distribution modelling

Probability of occurrence distributions throughout the MRB were generated for each species with Maxent, an SDM requiring species presence-only data integrated with environmental variables to project species occurrence probability (i.e., suitable habitat) across a defined region (Phillips, Anderson, & Schapire, 2006). Maxent has been widely used for modelling species distributions (Elith et al., 2011) and has produced models with relatively high predictive accuracy (e.g., Moreno, Zamora, Molina, Vasquez, & Herrera, 2011; Yang, Kushwaha, Saran, Xu, & Roy, 2013). Distributions are generated by extracting a sample of background locations with unknown presence information and comparing the associated environmental data with those at locations where a species is known to occur (Merow, Smith, & Silander, 2013).

Environmental data input into Maxent included geology, topography, slope, maximum and minimum annual baseline streamflow and water temperature, and average annual CV of baseline streamflow and water temperature data. Geology and land cover data were input as categorical data and all other variables as continuous data. Half of each species’ occurrence data were randomly used as training data and the other half to test the model. We set the maximum number of iterations to 100,000 and retained all other parameters at their default settings. Maxent used the model parameters estimated from baseline hydrologic and thermal conditions to generate distributions for each species under future projected streamflow and water temperature conditions. To generate future estimates of suitable habitat for each species, the Maxent model was run 14 times representing each of the GCM projections, with training and testing species data and contemporary geology, topography and slope data remaining consistent for all models.

The area under the receiving operator curve (AUC) was used to determine accuracy of the Maxent models, with a value of 0.5 representing a random model and a value of 1.0 representing the best possible AUC value for the validation data (Phillips & Dudík, 2008). Any species with a test data AUC value <0.70 was excluded from further analysis (Hijmans, 2012; Hosmer & Lemeshow, 1989). Probability of occurrence distributions were generated using Maxent for the baseline conditions and for each of the 14 future scenarios for every species, where each cell is assigned an occurrence probability value ranging from 0 to 1, with 1 indicating the highest probability of occurrence. The 14 future distributions were consolidated into one raster for each species by subtracting the standard deviation of occurrence probabilities from the mean occurrence probability at a 400-m resolution. With this method, cells with a high level of variability across scenarios are given lower
priority in further analyses (Moilanen, Wintle, Elith, & Burgman, 2006). Finally, measures of permutation importance were calculated with Maxent, which indicate the relative contribution of each variable to determining areas of suitable habitat for a given species. This value is calculated by taking each variable, altering the value at training localities and measuring the resulting drop in AUC, which is then normalized to produce a percentage (Phillips et al., 2006). While collinearity among variables in SDMs can cause models to overlook important variables that are highly correlated with others, the use of permutation importance (as opposed to “percent contribution”) reduces this problem. Unlike “percent contribution” which depends on the particular path used by Maxent to determine a species distribution, permutation importance is dependent on the final model produced by Maxent (Phillips, 2017).

2.4 | Zonation algorithm

Using projected occurrence probability distributions, Zonation determines areas of high conservation priority by identifying regions that are vital for retaining habitat quality and connectivity (Moilanen et al., 2005). The Zonation algorithm identifies these areas through hierarchical prioritization which ranks cells based on projected occurrence levels of weighted biodiversity. Zonation then iteratively removes the least valuable cells one by one, resulting in the retention of increasingly important biodiversity features. Because the landscape undergoes this hierarchical prioritization, the most valuable 5% of the study area must fall within the most valuable 10%, which must fall within the most valuable 15%, etc. (Moilanen et al., 2005). Biodiversity features included stream fish species with suitable SDM results (AUC > 0.70), with TE and/or endemic species having a weight of 5.0 and all remaining species having a weight of 1.0 (Lehtomäki, Moilanen, Toivonen, & Leathwick, 2016). Species were considered endemic if their entire known range fell within the MRB and TE if they had a near threatened, vulnerable, endangered or critically endangered status (IUCN, 2001).

The core-area Zonation (CAZ) cell removal method was employed due to its ability to minimize loss of conservation value by removing cells with the smallest occurrence probabilities for the highest weighted biodiversity features. The CAZ method attempts to retain core areas for all species by increasing the proportion of each remaining cell once a cell is removed that represented part of a given species’ distribution (Moilanen et al., 2005). Groups of cells within a stream segment were aggregated into planning units (PLUs) rather than using individual cells for the removal process (Moilanen, Leathwick, & Elith, 2008). The CAZ removal rule operates as previously stated, but instead of removing a single stream cell, an entire PLU is simultaneously removed. For use in the MRB, PLUs were represented by hydrologically linked catchment areas, resulting in 1,228 individual PLUs. Outputs from Zonation include a ranked conservation priority map for the study area indicating the relative importance of each PLU for conservation purposes.

2.5 | Conservation planning

To determine regions of the MRB with high conservation value under climate change scenarios, Zonation analyses were conducted for baseline conditions, future conditions and two transition scenarios (dispersal sources and stepping stones). The Maxent-generated baseline occurrence probability output was used for each species for the baseline scenario and the future occurrence probabilities after uncertainty analyses for each species for the future scenario. The interaction connectivity feature in Zonation was employed for dispersal sources and stepping stones analyses. With this tool, connectivity between two distributions is calculated given dispersal rates for each species (Moilanen et al., 2014). In the case of non-migratory stream fish, dispersal capabilities are typically quite low. As a result, a conservative dispersal rate of 0.1 km/year was selected. Dispersal sources represent areas of high conservation value that will facilitate connectivity from baseline to future distributions by identifying regions with high value during baseline conditions and moving towards future distributions (at a rate of 0.1 km/year). These areas are considered streams from which species will be expected to disperse given future climate projections. Conversely, stepping stones represent areas of high conservation value that will facilitate connectivity from baseline to future conditions by identifying regions with high conservation value during future conditions and moving back towards baseline conditions (Moilanen et al., 2014).

Ranked conservation priority maps were used to identify high priority conservation streams (best 10% of the MRB) for each scenario (baseline, future, dispersal sources and stepping stones) and were overlaid to extract stream segments that contain the high priority streams across all scenarios. The remaining high priority stream segments were joined with the environmental data input from Maxent to determine conditions in the high priority areas, with streamflow and stream temperature calculated for both baseline and future periods and geology, land cover, and slope for the baseline period. Because 14 GCMs contributed to the future conditions, scenario, maximum, minimum and CV of monthly streamflow and water temperature were averaged across all 14 GCMs. Environmental conditions for all stream segments within the MRB that did not fall within the high priority streams (low priority streams) were determined for comparison. Additionally, individual river systems within the MRB were evaluated to assess which areas contained large amounts of high priority streams.

3 | RESULTS

3.1 | Influence of environmental variables

Maxent modelling resulted in 88 of the 119 species with a test data AUC > 0.70 (Table S3), 28 of which were considered as endemic and/or TE. Permutation importance for these species indicated that, on average, flow variables (28.0%), water temperature variables (28.1%) and geology (29.6%) contributed evenly to determining areas of suitable habitat, while land cover (9.9%) and slope (4.5%)
played more limited roles. Of the 88 species, water temperature was the most important variable for determining suitable habitat for 32 species, geology for 29 species, flow for 24 species, slope for two species and land cover for one species. Minimum and maximum flow (12.5% and 11.3%, respectively) tended to contribute more to model predictions than CV of flow (4.1%). Maximum water temperature (13.6%) tended to be more important than minimum water temperature (7.9%) and CV of water temperature (6.5%). Changes in climate, streamflow and water temperature conditions between baseline and future periods are summarized in Tables S4 and S5.

3.2 Variation across Zonation scenarios and sub-basins

Based on identification of high priority streams (best 10% of the MRB) from all four Zonation scenarios (baseline, future, dispersal sources and stepping stones), 3.3% of total streams by length (nearly 500 km) were retained, indicating that approximately one-third of the high priority streams were shared among the four scenarios (Figure 2). The Coosa River Basin (Figure 3c) is the second largest sub-basin in the MRB (23.9%...
in terms of stream length) and contained the largest proportion of the high priority streams for all four Zonation scenarios (Table 1). The Tombigbee River Basin (Figure 3a), the largest sub-basin in the MRB (30.1%), contained the second largest proportion of high priority streams for the transition scenarios and the third highest for baseline and future conditions. After the spatial overlay, the Coosa and Tombigbee watersheds contained the second and third largest proportion of high priority streams (23.2% and 17.4%, respectively). The Tallapoosa River Basin (Figure 3f) is the second smallest sub-basin (10.6%), but contained the second largest proportion of the high priority streams for baseline and future conditions, the third largest for transition periods and the largest amount of high priority streams (32.3%) after the spatial overlay (Table 1). The Alabama (Figure 3d), Black Warrior (Figure 3b) and Cahaba (Figure 3e) River Basins contained relatively lower proportions of high priority streams for each of the four scenarios, as well as after the spatial overlay (Table 1).

### 3.3 Characterizing high priority streams

Evaluation of baseline and future hydrologic conditions in the high priority stream sections indicated that these conditions differ from those of low priority streams. Baseline average maximum and minimum annual and CV of streamflow conditions are considerably lower for high priority streams (−7.3%, −47.7% and −58.4%, respectively) compared to low priority streams (Table 2). Future average maximum and minimum annual streamflows are considerably lower (−52.3% and −59.6%, respectively) in high priority streams (Table 2). Unlike baseline conditions, future average CV of streamflow is slightly higher for high priority streams (+3.0%). Additionally, high priority streams tended to experience smaller changes in streamflow conditions from baseline to future time periods than those of low priority streams.

There was less variation in average water temperature conditions between high and low priority streams. For the baseline period, average maximum annual and CV of water temperature are only slightly lower in the high priority streams (−0.05°C and −0.01°C,
respectively), while average minimum annual water temperatures are slightly increased in high priority streams (+0.16°C; Table 2). However, for the future period, average maximum and minimum annual and CV of water temperatures are slightly higher for high priority streams (+0.71°C, +0.18°C and +0.01°C, respectively). Despite similarity between the high and low priority streams for the means of these water temperature variables, the range for each variable is considerably lower for high priority streams for both baseline and future conditions (Figure 4).

Of the 45 primary surface rock types found within the MRB, 17 were present within the high priority streams. Beach sand is the dominant primary surface rock type (geology) for the MRB, representing almost a third of low priority streams, but only 10.2% of high priority streams. Shale was the second most common in low priority streams (13.0%) and most common in high priority streams (23.3%). Sand is the third most common geology type in low priority streams (9.1%) and second most common in high priority streams (16.9%). Dolostone and mica schist represent relatively small portions of low priority streams (3.4% and 2.4%, respectively), but make up relatively large portions of high priority streams (16.3% and 14.8%, respectively). The majority of land cover surrounding low priority streams consists of forests (39.3%), wetlands (33.9%), crops (14.1%) and water (8.7%), with the remainder being barren, developed, herbaceous or shrubland. For high priority streams, forests make up 57.3% of land cover, while crops and wetlands also make up relatively high portions (17.8 and 17.7%, respectively).

### TABLE 2  Summary of hydrologic and thermal conditions within high (top 10%) and low (bottom 90%) priority streams for baseline (1975–1994) and future (2060–2079) periods

|          | High priority streams | Low priority streams |
|----------|-----------------------|----------------------|
| Baseline |                       |                      |
| Coefficient of variation of streamflow | 0.83 | 0.90 |
| Maximum streamflow (m³/s) | 97.8 | 186.8 |
| Minimum streamflow (m³/s) | 7.2 | 17.3 |
| Coefficient of variation of water temperature | 0.37 | 0.37 |
| Maximum water temperature (°C) | 21.96 | 22.01 |
| Minimum water temperature (°C) | 6.85 | 6.69 |
| Future |                       |                      |
| Coefficient of variation of streamflow | 0.73 | 0.71 |
| Maximum streamflow (m³/s) | 108.1 | 226.5 |
| Minimum streamflow (m³/s) | 12.7 | 31.3 |
| Coefficient of variation of water temperature | 0.29 | 0.29 |
| Maximum water temperature (°C) | 22.11 | 21.40 |
| Minimum water temperature (°C) | 8.60 | 8.42 |

*Values averaged across 14 global climate models.

### DISCUSSION

Freshwater species in flowing systems are especially vulnerable to climate-induced changes in hydrologic and thermal conditions. Given the range of projected changes in climate, streamflows and water temperatures, developing appropriate conservation plans that will be resilient to climate change remains a challenge for aquatic managers. Through the use of species distribution modelling with a GCM ensemble, we were able to assess a more complete range of projected changes to streamflow and water temperature in the MRB and, as a result, a more complete view of projected changes in suitable habitat for freshwater fishes in a biologically diverse watershed. Furthermore, while SDMs are useful for predicting shifts in suitable habitat distributions for individual species, intensive output processing is necessary to evaluate these results for multispecies conservation planning. With the implementation of Zonation, regions with high levels of suitable habitat for many species were identified with these SDM results.

By selecting high priority streams for baseline, future and transition periods, we retained 3.3% of the entire study basin. While this is a relatively small portion of the MRB, it contains nearly 500 km of streams spanning four states. Additionally, by only considering streams which are identified as high priority for all scenarios, long-term conservation plans can be developed that will be resilient to climate change. For example, if only evaluating baseline conditions, considerable management effort would be needed in the Alabama
River Basin. However, the southern portion of the MRB, including the Alabama River Basin and southern half of the Tombigbee River Basin, does not include any overlapping high priority streams across all four scenarios, suggesting long-term management efforts would be better suited for more northern streams. These findings are somewhat intuitive, as priority areas shift northward with warming temperatures and increasing streamflow occurring closer to the outlet at the Gulf of Mexico.

Through our analysis of environmental conditions in high and low priority streams, we found that, in general, these groupings of streams exhibited considerable differences in environmental conditions. On average, high priority streams tended to have lower streamflow discharge with smaller projected changes between baseline and future periods than those of low priority streams. Differences in average water temperature variables were not as pronounced as those of streamflow variables between high and low priority areas. However, differences in the range of water temperature variables indicate that fish tend to prefer streams with less thermal variability.

Pronounced differences in the geology between high and low priority streams indicate that, in general, the type of primary surface rock influences suitable habitat distributions for stream fishes. These findings are consistent with many studies which have found...
the fish assemblage compositions to be heavily influenced by substrate type (e.g., Smith & Kraft, 2005; Pease, González-Díaz, Rodil-Hernández, & Winemiller, 2012), in addition to a study of crayfishes in the MRB (Krause et al., 2019). However, the mechanism influencing preferences in geology is unclear for stream fishes in the MRB, with dominant surface rock types in high priority streams ranging in grain size. The finding that the high priority streams contain considerably smaller proportions of beach sand despite being nearly a third of low priority streams is likely due to beach sand being primarily located in southern portions of the MRB, which have higher water temperatures and streamflow.

Results for land cover indicate that high priority streams are surrounded by higher proportions of forests than low priority streams, which is likely a result of higher water quality and lower stream temperatures in forested regions (Beschta, Bilby, Brown, Holtby, & Hofstra, 1987). The finding that high priority streams contain higher proportions of cultivated and developed land cover and smaller proportions of wetlands is less intuitive. However, because our species locality dataset only includes occurrence data (as opposed to presence/absence data), these findings could be a result of uneven sampling practices across land cover types.

For our Maxent models, we assumed geology, land cover and slope will remain static over the next half-century. While this will likely be true for geology and slope, we recognize that land cover will likely undergo changes. However, future estimates of these data are not available at the resolution necessary for the MRB. Regardless, the finding that one-third of fish species in this study are primarily influenced by geology, land cover and/or slope demonstrates the importance of estimating individual species’ responses to the physical environment (and maintaining these habitats in the future) when generating SDMs and considering conservation actions. Without the inclusion of “non-climate” variables, SDMs risk overestimating the influence of climate-related changes in streamflow and water temperature (Krause et al., 2019).

While this study considers dispersal limitations of stream fish with a conservative dispersal rate (0.1 km/year), we acknowledge that stream fishes face unique dispersal barriers, such as dams or reservoirs, which were not accounted for in this study. As such, areas considered to be suitable habitat for species may not be accessible without additional management practices (i.e., species translocations, developing or improving fish ladders, dam removal). Additionally, our modelling approaches did not include an analysis of additional aquatic species such as freshwater mussels and crayfish, or methods for determining and incorporating inter- or intraspecific biotic interactions. Because of the uncertainty in species interactions and actual dispersal capabilities, areas designated as high priority are intended to guide managers in identifying streams with suitable abiotic environmental conditions over the next half-century.

A small proportion (<5%) of baseline high priority streams is located in federally managed areas, primarily in the central part of the MRB in the Talladega National Forest. However, this area is not identified as high priority under future climate scenarios. A similarly small proportion (<5%) of future high priority streams is located in the northeastern part of the MRB in the Chattahoochee National Forest, which could provide a source of managed suitable habitat in the future. Nevertheless, the vast amount of baseline and future high priority streams are located outside of conservation areas, thus suggesting the need for focused management actions based on local socio-ecological systems. Considering the importance of flow and water temperature in predicting suitable habitat among species, actions that preserve natural flow and water temperature regimes should be a priority for managers.

Our results indicate that more northern streams in the MRB will be more consistently suitable for stream fishes throughout the next half-century, especially within the Coosa and Tallapoosa watersheds. Additionally, by evaluating baseline and future environmental conditions within high priority streams, we attempted to better understand the abiotic characteristics that constitute suitable habitat for a wide range of temperate stream fishes. These conditions include relatively lower streamflow and water temperature conditions, streams with shale, sand or dolostone primary surface rock types, and forest-dominated land cover types. While further work should include additional considerations (e.g., biotic interactions, dispersal barriers, cost analysis), we recommend that aquatic managers consider these methods when developing conservation plans for stream ecosystems that will be resilient to potential changes in climate.

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DATA ACCESSIBILITY

Data used for this study are available through Dryad (https://doi.org/10.5061/dryad.83dt5sq).

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**Author contributions:** M.V., J.K. and D.F. conceived the study and assembled the data; M.V. analysed the data; and M.V., J.K. and D.F. contributed to the writing of the manuscript.

**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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