Tennessee’s Resiliency and Changing Environmental Conditions

Cooperative Report: Funded by the U.S. Geological Survey and U.S. Fish and Wildlife Service

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Table of Contents

Foreword

Series Overview

The following report is part of a multi-state series synthesizing the potential hazards of changing environmental conditions on southeastern ecoregions and wildlife vulnerabilities. The series was developed through an interagency collaboration among the U.S. Geological Survey (USGS) Southeast Climate Adaptation Science Center (SE CASC), the U.S. Fish and Wildlife Service (USFWS) Southeast Conservation Adaptation Strategy, and partners, with input from the South Central CASC and the Southeastern Association of Fish and Wildlife Agencies' (AFWA) Wildlife Diversity Technical Committee. The effort supports the integration of climate adaptation considerations into 2025 State Wildlife Action Plan (SWAP) revisions, following guidance from the AFWA and USFWS encouragement (AFWA, 2022). To ensure consistency and comparability across states and territories, certain components, such as the Process description, methodological explanations, and summaries of region wide climate trends, are standardized across the series and may appear verbatim from one report to another. Each report then applies this shared framework to the context of an individual state or territory.

How to Use This Report

This report was organized to support Tennessee's SWAP revision team in applying climate adaptation information directly to planning needs. The standardized Series Overview and Process sections provide the foundational framework and methodological approach used throughout the broader series. All subsequent sections present analyses, figures, interpretations, and wildlife impact considerations developed specifically for Tennessee. Readers can use the Tennessee report's tailored results, such as hazard summaries, ecological context, and vulnerability insights, to inform updates to species of greatest conservation need (SGCN) assessments, habitat narratives, monitoring strategies, and adaptation actions within the state's SWAP. Instances where text aligns with other state reports reflect shared series wide methods, while all ecological interpretation and applied management considerations are customized to Tennessee.

Process

To effectively synthesize the potential hazards of changing environmental conditions on ecoregions of the Southeast and vulnerability of their wildlife, the SE CASC developed a process comprised of the following steps: 1) summarize historical means and future projected changes of select environmental risks by ecoregion; 2) summarize available vulnerability assessments and niche models (i.e., species distribution models) for each state's/territory's revised Species of Greatest Conservation Need (SGCN) list; 3) conduct a literature review of impacts from changing environmental conditions to a specific taxon or habitat of each agency's choosing. Ecoregions as characterized by the Environmental Protection Agency (EPA) were chosen to summarize historical means and projections for the continental states of the southeastern U.S., in accordance with how SWAPs are generally organized and to efficiently inform management. We used EPA Level III Ecoregions due to the popularity of use by Southeast state wildlife agencies. Existing data collections of both historical climatology and future projections were used to calculate means for each ecoregion within each state's boundaries and maps of future projections were created using the Fifth National Climate Assessment (NCA5) Interactive Atlas in ArcGIS Pro (Alder, 2024; Pierce et al., 2021; Shanovich et al., 2026; NCA5 Atlas Data). Each state or territory wildlife agency cooperator chose specific Global Warming Levels and projection scenarios for inclusion. Additionally, existing data collations were used to summarize vulnerability assessments and niche models conducted for each state's and territory's SGCN (Armsworth et al., 2025a, 2025b). For each habitat or taxonomic group identified by a state or territory wildlife agency, we reviewed and synthesized available scientific literature. We searched for relevant literature related to these habitats and species that either explicitly mentioned or indirectly discussed impacts of changing environmental conditions.

Executive Summary

Tennessee is experiencing shifts in environmental conditions, many of which are projected to intensify in the coming decades. These changes may have implications for the state's ecosystems, species, and natural resource management. Historical climate analyses and downscaled projections for Tennessee's EPA Level III Ecoregions indicate that the state may face increases in extremely hot days, more intense heatwaves, greater evapotranspiration, and reductions in cold-season extremes.

While Tennessee has warmed less than the national average over the past century, recent years have been among the warmest on record. Projections suggest increases in the number of days with maximum temperatures at or above 95°F across all ecoregions, especially under higher warming scenarios. The number of freezing nights is expected to decline, with statewide decreases depending on the global warming level and timeframe. These patterns could reshape habitat conditions, influence species' thermal stress, and alter ecological processes such as soil moisture retention and stream temperature regimes.

Extreme rainfall events, particularly the most intense 1% of precipitation days, are projected to increase across Tennessee, that in turn could raise risks of flooding, erosion, and altered stream flow. The state's diverse topography means that impacts will vary by ecoregion, with the Appalachian Mountains likely facing increased landslide risks and river valleys experiencing more frequent flooding.

Changing environmental conditions have important consequences for Tennessee's species of greatest conservation need (SGCN). Vulnerability assessments and ecological niche models indicate that many fish, mussel, crayfish, plant, amphibian, bird, and mammal SGCN may face heightened stress due to warming temperatures, shifting hydrology, habitat loss, and increases in extreme events. In particular, freshwater mussels are extremely diverse in the state, critically important for ecosystem health, and have been evaluated as highly vulnerable to climate stressors. Tennessee's rivers, such as the Duck and Clinch, are hotspots for mussel diversity and are the focus of ongoing conservation and monitoring efforts.

Adaptation frameworks such as the Resist-Accept-Direct (RAD) and the Adaptation Workbook can provide actionable options for conservation. Focusing on conservation action within resilient landscapes, areas with diverse microhabitats and strong connectivity, could help sustain biodiversity under future conditions. Tennessee's ongoing and projected environmental changes present both challenges and opportunities for natural resource management. Incorporating adaptation strategies into the State Wildlife Action Plan could assist in sustaining habitats, mitigating risks, and supporting the long-term resilience of Tennessee's wildlife and ecosystems.

Tennessee and changing environmental conditions

In the Southeast, changing environmental conditions may have pervasive impacts on natural habitats, ecological processes, and ecosystem services and regional efforts to mitigate or adapt to these impacts could be extremely important (Hoffman et al., 2023). Recent analyses indicate that current trends in the Southeast are likely to continue, such as the rising frequency, strength, and duration of heatwaves, elevated wildfire risk, and ongoing sea-level rise (Hoffman et al., 2023). The most notable projected changes include greater extreme heat, more intense precipitation events, increased drought, rising seas, and tropical cyclones, accompanied by reduced intensity and occurrence of cold-season conditions (Hoffman et al., 2023). Despite the significant threat changing environmental conditions pose to the landscape, understanding the tools and resources available to address changing environmental conditions and develop effective strategies is difficult. As part of the survey administered to SWAP coordinators in 2021, the majority of SEAFWA states/territories reported integrating adaptation as one of the most challenging aspects of the upcoming SWAP revision (SECAS, 2021). Anecdotally, some SWAP coordinators noted that it is difficult to discern what tools are available, decide which tool is the right one to use, and choose the appropriate scale and timeframe when using tools (SECAS, 2021). Like the rest of the Southeast, Tennessee is predicted to experience a number of impacts from changing environmental conditions, though the magnitude of change often varies by ecoregion, scenario, and future timeframe. Generally, these impacts include hotter summers, warmer winters, and more frequent extreme precipitation events (Hoffman et al., 2023).

Hotter summers, warmer winters, and more intense droughts

Generally, the number of extremely hot days (i.e., days with afternoon high temperatures of at least 95°F) in Tennessee are predicted to increase, although there are differences in the degree of how many hotter days are expected across the state (Table 1; Figure 1). Temperatures in Tennessee have risen by 0.5°F since the beginning of the 20th century, which is less than a third of the average warming for the contiguous US (Runkle et al., 2022). However, some recent years have been very warm, including 2012 (2nd warmest), 2016 (3rd warmest), 2017 (5th warmest), and 2019 (7th warmest) on record (Runkle et al., 2022). Annual average temperatures are projected to most likely exceed historical record levels by the middle of this century and could reach unprecedented levels (Runkle et al. 2022).

The number and intensity of heat waves are likely to increase in the future (Runkle and Kunkel et al., 2022). Heatwaves in the U.S. have become hotter, more frequent, larger, and longer lasting in recent decades and are projected to continue, which has implications for drought in the region (Hoffman et al., 2023). The number of extremely hot days (days with maximum temperatures ≥95°F) may increase across Tennessee, with the largest percentage increase occurring in the eastern portion of the state (Table 1). These trends are projected to continue, which has implications for drought in the region (Runkle et al. 2022; Hoffman et al. 2023). Higher temperatures throughout the year in Tennessee may cause more rapid loss of soil moisture during consecutive dry days (i.e., consecutive days without rainfall), increasing the intensity of naturally occurring droughts in the future (Runkle et al. 2022). However, future changes in the annual number of consecutive extreme dry days in Tennessee are not projected to increase substantially (Alder, 2024).

Although hydrological droughts have become less frequent in eastern regions of the country since the 19th century, higher increases in evapotranspiration (the process by which water is transferred to the atmosphere from Earth's surface) have generally made the Southeast more drought-prone than the Northeast (Hoffman et al., 2023). Droughts are a regular occurrence in Tennessee. In about half of the weeks since 2000, at least some portion of the state has been in drought status; in 15% of those weeks at least half of the state experienced some degree of drought conditions (Runke et al., 2022).

Table 1 summarizes historical observed and future projections of extremely hot days (maximum temperatures ≥95°F) under different shared socioeconomic pathways (SSP) scenarios and at global warming level (GWL) 2°C (3.6°F warmer than the 1991-2020 time period) for Tennessee ecoregions. Figure 1 shows the change in the projected number of extremely hot days in Tennessee at GWL of 1.52°C (2.7°F warmer than the 1991-2020 time period) and GWL 2°C (3.6°F warmer than the 1991-2020 time period). Overall, the projections indicate that the number of extremely hot days (maximum temperatures ≥95°F) may increase across Tennessee, with the greatest increase in number occurring in the southwest portion of the state, though the magnitude of change often varies greatly by GWL or SSP scenario and location within the state (Hoffman et al. 2023). Another way to look at future projections is through the lens of GWLs. If the earth surpasses a GWL of 1.5°C (2.7°F) or 2°C (3.6°F) for a sustained period, the number of days where the temperature reaches 95°F or higher may increase across Tennessee, compared to the past 30 years (1991-2020) (Figure 1).

Table 1. *Approximate observed historical and the future projected number of extremely hot days per year (i.e., days with afternoon high temperatures of at least 95°F) by EPA Level III ecoregions within Tennessee. The table summarizes projected future number of days for low, moderate, and high Shared Socioeconomic Pathway (SSP) emission scenarios using CMIP6-LOCA2 threshold and extreme event metric projections (Alder 2024) summarized at the ecoregion level (Shanovich et al. 2026). For each future time period, numbers in parentheses represent the percent change between the models' future projections and the models' historical simulations. Observed historical summaries were generated with data from Pierce et al. (2021).*

Historical & Future Projections: Number of Days with Maximum Temperatures ≥ 95°F			
SSP	Observed Historical: 1950-2014	**2025-2049** projections (percent change from historical simulation)	**2050-2074** projections (percent change from historical simulation)
Blue Ridge Ecoregion			
Low (SSP2-4.5)	0.5 days/year	5 days/year (750%↑)	9 days/year (1566%↑)
Moderate (SSP3-7.0)		5 days/year (646%↑)	11 days/year (1831%↑)
High (SSP5-8.5)		6 days/year (873%↑)	17 days/year (2819%↑)
Central Appalachians Ecoregion			
Low (SSP2-4.5)	0.9 days/year	5 days/year (681%↑)	11 days/year (1485%↑)
Moderate (SSP3-7.0)		5 days/year (574%↑)	13 days/year (1925%↑)
High (SSP5-8.5)		7 days/year (831%↑)	20 days/year (2815%↑)
Southwestern Appalachians Ecoregion			
Low (SSP2-4.5)	1.5 days/year	8 days/year (514%↑)	14 days/year (1008%↑)
Moderate (SSP3-7.0)		7 days/year (437%↑)	16 days/year (1172%↑)
High (SSP5-8.5)		9 days/year (602%↑)	25 days/year (1792%↑)

Ridge and Valley Ecoregion			
Low (SSP2-4.5)	3 days/year	16 days/year (453%↑)	26 days/year (799%↑)
Moderate (SSP3-7.0)		15 days/year (407%↑)	29 days/year (921%↑)
High (SSP5-8.5)		18 days/year (512%↑)	40 days/year (1286%↑)
Interior Plateau Ecoregion			
Low (SSP2-4.5)	7 days/year	26 days/year (283%↑)	38 days/year (455%↑)
Moderate (SSP3-7.0)		24 days/year (251%↑)	42 days/year (507%↑)
High (SSP5-8.5)		29 days/year (313%↑)	54 days/year (678%↑)
Mississippi Alluvial Plain Ecoregion			
Low (SSP2-4.5)	14 days/year	40 days/year (202%↑)	56 days/year (238%↑)
Moderate (SSP3-7.0)		39 days/year (187%↑)	58 days/year (254%↑)
High (SSP5-8.5)		44 days/year (221%↑)	70 days/year (303%↑)
Mississippi Valley Loess Plains Ecoregion			
Low (SSP2-4.5)	13 days/year	40 days/year (231%↑)	55 days/year (350%↑)
Moderate (SSP3-7.0)		38 days/year (212%↑)	58 days/year (378%↑)
High (SSP5-8.5)		43 days/year (251%↑)	70 days/year (471%↑)
Southeastern Plains Ecoregion			
Low (SSP2-4.5)	11 days/year	35 days/year (223%↑)	49 days/year (345%↑)
Moderate (SSP3-7.0)		34 days/year (203%↑)	52 days/year (378%↑)
High (SSP5-8.5)		38 days/year (243%↑)	64 days/year (484%↑)

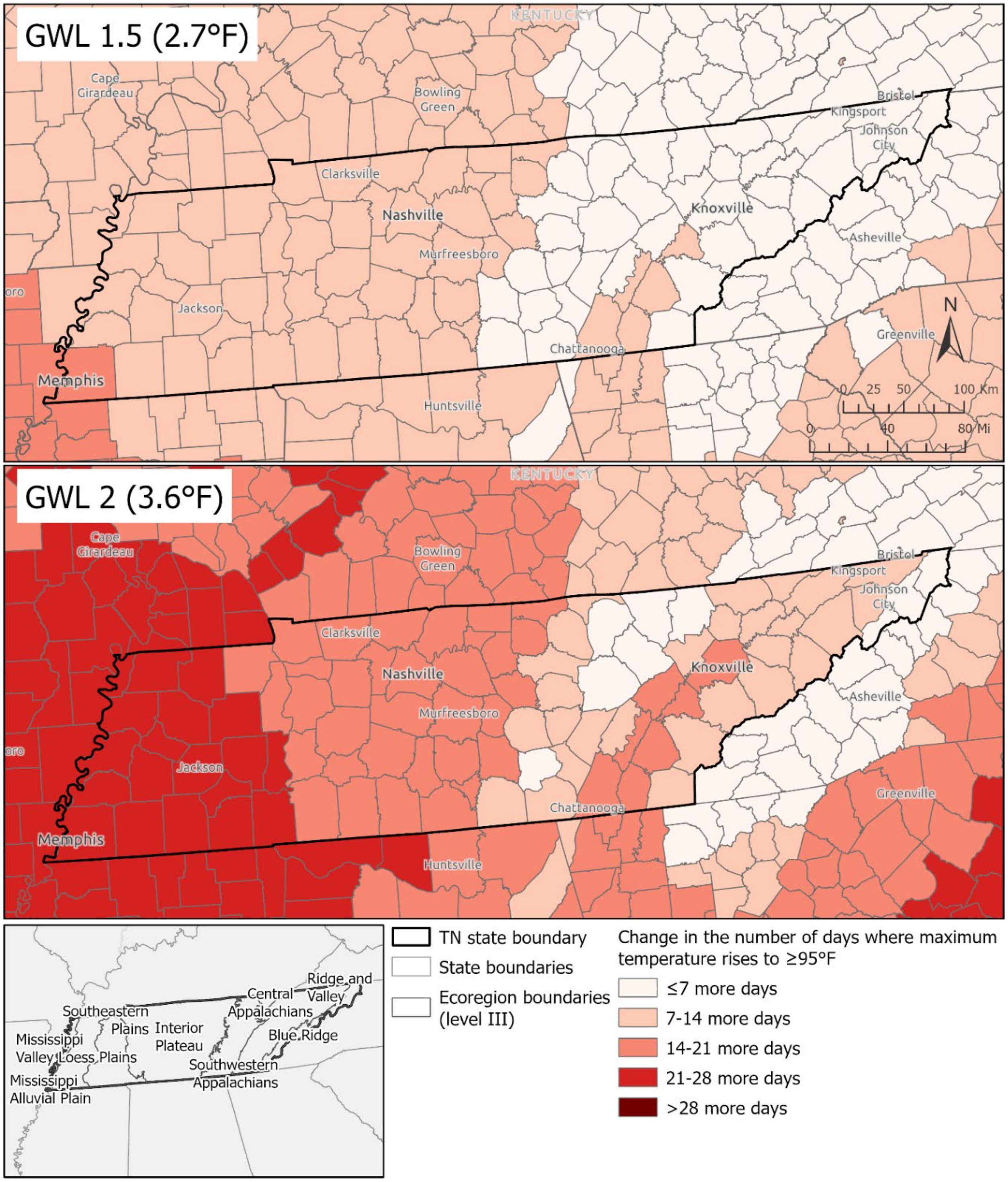

Figure 1. *Projected future changes in the number of days of Extremely Hot Days (i.e., days with maximum temperatures at or above 95°F) compared to preindustrial levels (1851-1900) in Tennessee based on global warming level (GWL) 1.5°C (global temperature increase of 2.7°F) and GWL 2°C (global temperature increase of 3.6°F). Figure created from data in the 'Atlas of the 5th National Climate Assessment" web tool* (National Climate Assessment Interactive Atlas (globalchange.gov).

Additionally, projections indicate that the number of extremely cold days (days with low temperatures of 32°F or below) may decrease across Tennessee, with the most pronounced decreases occurring throughout many northern counties of the state, but the magnitude of change often varies greatly by GWL or SSP scenario and location within the state (Table 2; Figure 2). Any substantial increase in temperature may lead to decreased cold wave intensity (Runkle et al. 2022). If the Earth surpasses a GWL of 1.5°C (2.7°F) or 2°C (3.6°F) for a sustained period, the number of days where the temperature reaches 32°F or lower (freezing temperatures) may decrease across the state, compared to the years between 1991 and 2020 (Table 2).

As low temperatures rise, some species may also be impacted. Warmer nights may have a profound impact on animal and plant health because temperatures are generally lower at night, normally allowing the environment to cool down. Winter months are the fastest warming season in most of the U.S. In general, the number of extremely cold days (i.e., days with low temperatures of at least 32°F or lower) in Tennessee is predicted to decrease in the future (Table 2). Winter conditions are key drivers of individual species performance and community composition in terrestrial habitats because species vary in susceptibility to these winter drivers (Williams et al., 2014). Shorter and warmer winters may cause species range shifts that would allow for warm-adapted species to dominate and shift distributions of cold-adapted species. For example, overwintering bird populations are responding to warming climate (e.g., poleward shifts) by favoring the formation of winter bird communities dominated by warm-adapted species instead of cold-adapted species (Princé and Zuckerberg, 2014; Osland et al., 2021). Additionally, winter conditions (e.g., snowfall, low temperatures) have a major effect on ecological processes such as litter decomposition, mineralization rates, nutrient leaching and gas fluxes in the soil and hydrological processes. Winter soil freezing also affects insect and microbial communities for the subsequent warm season (Campbell et al., 2005).

Table 2. *Approximate observed historical and the future projected number of extremely cold days per year (i.e., days with minimum low temperatures of ≤32°F) by EPA Level III ecoregions within Tennessee. The table summarizes projected future number of days for low, moderate, and high Shared Socioeconomic Pathway (SSP) emission scenarios using CMIP6-LOCA2 threshold and extreme event metric projections (Alder 2024) summarized at the ecoregion level (Shanovich et al. 2026). For each future time period, numbers in parentheses represent the percent change between the models' future projections and the models' historical simulations. Observed historical summaries were generated with data from Pierce et al. (2021).*

Historical & Future Projections: Number of Extremely Cold Days			
SSP	Observed Historical: 1950-2014	**2025-2049** projections (percent change from historical simulation)	**2050-2074** projections (percent change from historical simulation)
Blue Ridge Ecoregion			
Low (SSP2-4.5)	116 days/year	93 days/year (18%↓)	85 days/year (25%↓)
Moderate (SSP3-7.0)		93 days/year (18%↓)	83 days/year (28%↓)
High (SSP5-8.5)		91 days/year (20%↓)	77 days/year (33%↓)
Central Appalachians Ecoregion			
Low (SSP2-4.5)	115 days/year	94 days/year (17%%↓)	87 days/year (23%↓)
Moderate (SSP3-7.0)		94 days/year (16%%↓)	86 days/year (25%↓)
High (SSP5-8.5)		93 days/year (18%%↓)	80 days/year (30%↓)

Southwestern Appalachians Ecoregion			
Low (SSP2-4.5)	91 days/year	72 days/year (22%↓)	66 days/year (28%↓)
Moderate (SSP3-7.0)		72 days/year (20%↓)	65 days/year (30%↓)
High (SSP5-8.5)		71 days/year (23%↓)	59 days/year (36%↓)
Ridge and Valley Ecoregion			
Low (SSP2-4.5)	90 days/year	71 days/year (21%↓)	64 days/year (29%↓)
Moderate (SSP3-7.0)		71 days/year (20%↓)	61 days/year (32%↓)
High (SSP5-8.5)		69 days/year (23%↓)	56 days/year (37%↓)
Interior Plateau Ecoregion			
Low (SSP2-4.5)	87 days/year	67 days/year (22%↓)	61 days/year (29%↓)
Moderate (SSP3-7.0)		69 days/year (21%↓)	59 days/year (31%↓)
High (SSP5-8.5)		66 days/year (24%↓)	54 days/year (38%↓)
Mississippi Alluvial Plain Ecoregion			
Low (SSP2-4.5)	65 days/year	48 days/year (29%↓)	41 days/year (39%↓)
Moderate (SSP3-7.0)		48 days/year (27%↓)	38 days/year (42%↓)
High (SSP5-8.5)		46 days/year (32%↓)	35 days/year (48%↓)
Mississippi Valley Loess Plains Ecoregion			
Low (SSP2-4.5)	69 days/year	52 days/year (27%↓)	45 days/year (36%↓)
Moderate (SSP3-7.0)		52 days/year (25%↓)	43 days/year (39%↓)
High (SSP5-8.5)		49 days/year (30%↓)	39 days/year (45%↓)
Southeastern Plains Ecoregion			
Low (SSP2-4.5)	80 days/year	61 days/year (24%↓)	51 days/year (31%↓)
Moderate (SSP3-7.0)		61 days/year (22%↓)	52 days/year (33%↓)
High (SSP5-8.5)		59 days/year (26%↓)	48 days/year (40%↓)

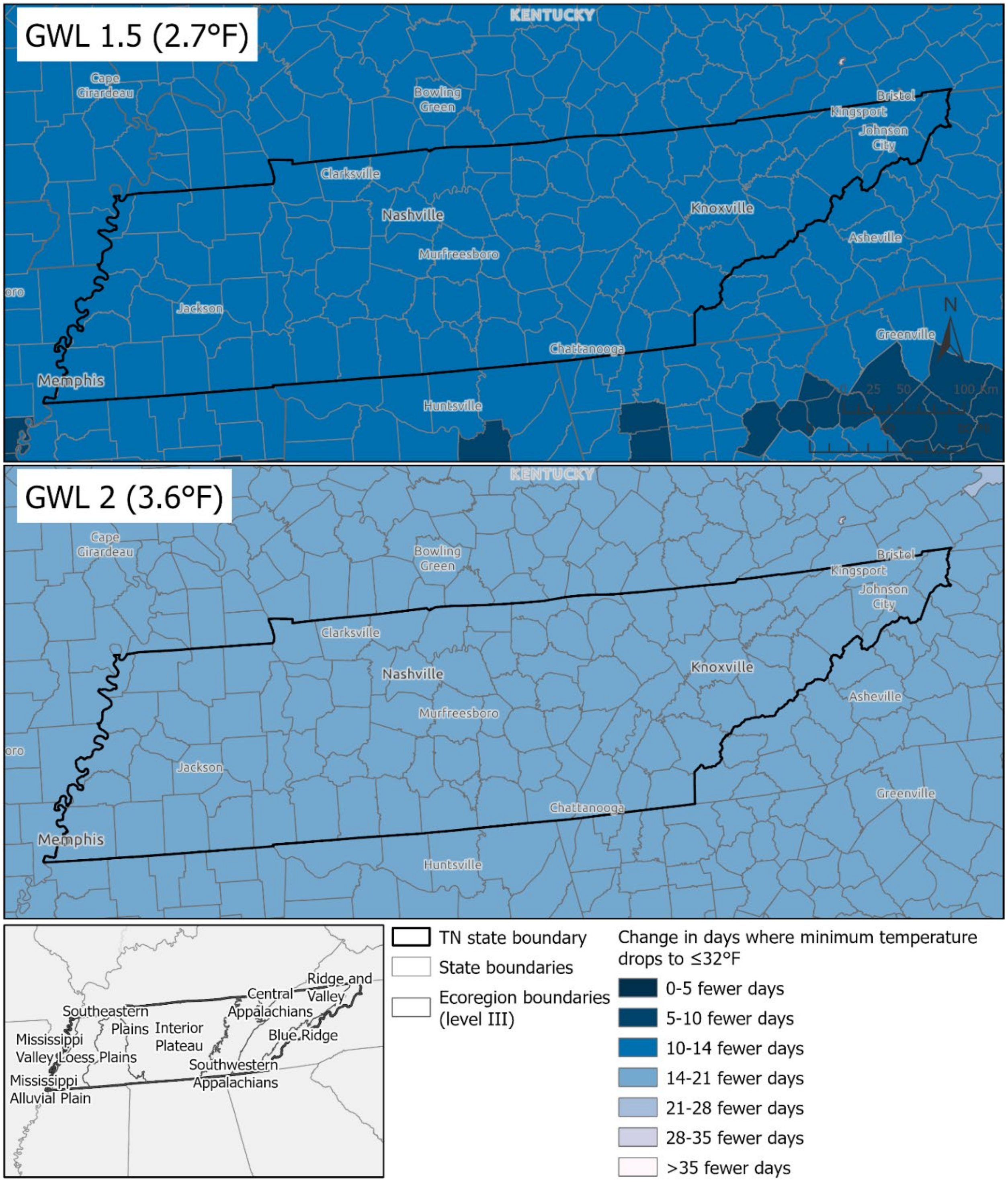

Figure 2. Change in days with minimum temperatures reaching or below freezing (32°F) compared to preindustrial levels (1851-1900) in Tennessee based on global warming level (GWL) 1.5°C (global temperature increase of 2.7°F) and GWL 2°C (global temperature increase of 3.6°F). Figure created from data in the 'Atlas of the 5th National Climate Assessment" web tool (National Climate Assessment Interactive Atlas (globalchange.gov).

More extreme precipitation events

Other potential climate hazards may impact the state, such as extreme precipitation events, which are expected to increase in the future and often manifest as extreme weather and increased flooding (Wong et al., 2014). Future projections suggest that the Southeast region is projected to get slightly wetter overall, with increases of some seasonal averages and the annual average. Also, extreme precipitation amounts may increase across the region, driven mainly by more extreme events (e.g., precipitation of 3 or more inches in 24 hours) at higher levels of global warming (Hoffman et al., 2023). In other words, although little change in total annual precipitation is projected over this century, the timing and intensity of precipitation events may change (Hoffman et al., 2023).

Annual precipitation is projected to increase in Tennessee, as the state is part of a large area across the northern and central US that shows projected increases in precipitation by midcentury (Runkle and Kunkel et al., 2022; Figure 3). Additionally, the number and intensity of extreme precipitation events are also projected to increase, continuing recent trends. The wettest consecutive 5-year interval for Tennessee was 2016–2020, with the wettest year on record being 2018 (statewide total of 67 inches) (Runkle and Kunkel et al., 2022). Extreme precipitation events that frequently occur in Tennessee include severe thunderstorms, winter storms, and flooding. Since 2000, the state has received 33 major disaster declarations involving severe storms and flooding; one example being the extreme rainfall and flooding event that occurred in August 2021, when 20.73 inches of rain fell in less than 23 hours in the McEwen area of middle Tennessee, breaking the state record by far (Runkle et al., 2022).

Table 3 summarizes approximate values for historical observed and future projections of extreme rainfall under different SSP scenarios for Tennessee ecoregions; while Figure 3 shows the projected future percent change in the number of days per year with extreme precipitation (e.g., days with the top 1% of rainfall) in Tennessee at GWL 1.5°C (2.7°F warming) and GWL 2°C (3.6°F warming) compared to the last 30 years. Estimates of when these GWL might be reached depend on the emission scenario. While all ecoregions within Tennessee may experience changes in days with extreme precipitation, the eastern to middle part of the state, in the Central Appalachians, Mississippi Alluvial and Valley Loess Plains Ecoregions, is projected to experience the greatest percent change by GWL 2°C (Figure 3).

Table 3. *Approximate observed historical number of days with extreme rainfall per year (i.e., days with the top 1% of rainfall) and future projected increases by EPA Level III ecoregions within Tennessee. The table summarizes projected future number of days for low, moderate, and high Shared Socioeconomic Pathway (SSP) emission scenarios using CMIP6-LOCA2 threshold and extreme event metric projections (Alder 2024) summarized at the ecoregion level (Shanovich et al. 2026). Observed historical summaries were generated with data from Pierce et al. (2021).*

Historical & Future Projections: Number of Days with Extreme Precipitation			
SSP	Observed Historical: 1950-2014	**2025-2049** projections (percent change from historical simulation)	**2050-2074** projections (percent change from historical simulation)
Blue Ridge Ecoregion			
Low (SSP2-4.5)	0.5 days/year	29% increase	34% increase
Moderate (SSP3-7.0)		29% increase	36% increase
High (SSP5-8.5)		30% increase	45% increase

Central Appalachians Ecoregion			
Low (SSP2-4.5)	0.9 days/year	36% increase	45% increase
Moderate (SSP3-7.0)		32% increase	51% increase
High (SSP5-8.5)		39% increase	50% increase
Southwestern Appalachians Ecoregion			
Low (SSP2-4.5)	1.5 days/year	32% increase	39% increase
Moderate (SSP3-7.0)		33% increase	43% increase
High (SSP5-8.5)		36% increase	48% increase
Ridge and Valley Ecoregion			
Low (SSP2-4.5)	3 days/year	32% increase	37% increase
Moderate (SSP3-7.0)		32% increase	40% increase
High (SSP5-8.5)		31% increase	46% increase
Interior Plateau Ecoregion			
Low (SSP2-4.5)	7 days/year	30% increase	37% increase
Moderate (SSP3-7.0)		29% increase	46% increase
High (SSP5-8.5)		32% increase	43% increase
Mississippi Alluvial Plain Ecoregion			
Low (SSP2-4.5)	14 days/year	28% increase	38% increase
Moderate (SSP3-7.0)		27% increase	48% increase
High (SSP5-8.5)		37% increase	56% increase
Mississippi Valley Loess Plains Ecoregion			
Low (SSP2-4.5)	13 days/year	28% increase	37% increase
Moderate (SSP3-7.0)		26% increase	50% increase
High (SSP5-8.5)		35% increase	51% increase
Southeastern Plains Ecoregion			
Low (SSP2-4.5)	11 days/year	30% increase	39% increase
Moderate (SSP3-7.0)		27% increase	50% increase
High (SSP5-8.5)		35% increase	47% increase

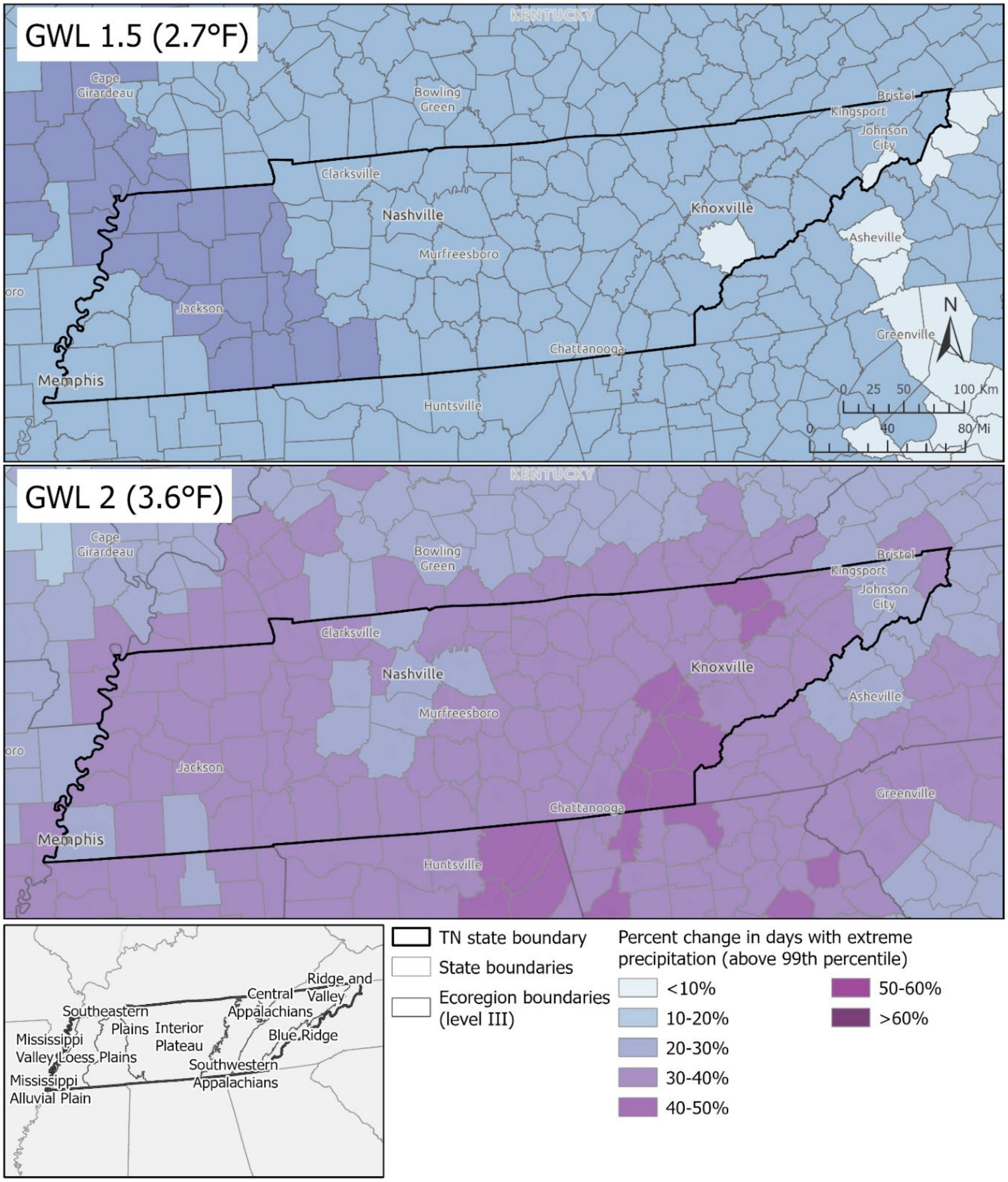

Figure 3. Change in days with extreme rainfall events compared to preindustrial levels (1851-1900) in Tennessee based on global warming level (GWL) 1.5°C (global temperature increase of 2.7°F) and GWL 2°C (global temperature increase of 3.6°F). Figure created from data in the 'Atlas of the 5th National Climate Assessment" web tool ([National Climate Assessment Interactive Atlas (globalchange.gov).](National Climate Assessment Interactive Atlas (globalchange.gov)))

The remnants of hurricanes also occasionally track across the state which contribute to increases in river and stream flooding across the landscape, which have different effects in different ecoregions and topographies. For example, in the Appalachian Mountains where the susceptibility to landslides is already high, increases in extreme rainfall may lead to increases in landslides (Mirus et al., 2020). Hurricanes can produce widespread and damaging landslides in the mountains, like the recent Hurricane Helene that dumped heavy rain across eastern Tennessee (Martinez et al., 2024). For example, Cove Mountain, TN, received almost nine inches of rain over four days, which is the highest all-time rank for that weather station, and had the highest wind report in the area for the event of 62 mph on 28 September 2024 (https://www.weather.gov/mrx/Hurricane_Helene).

Landslides, flooding and large amounts of surface water runoff from extreme precipitation events and hurricanes have many negative impacts on wildlife including increased sediment and contaminated floodwater draining into waterways, flooding of animal nests, and erosion and more (Mirus et al., 2020). There is high spatial overlap between landslide susceptibility and biodiversity in the Appalachians which provides an opportunity to achieve co-benefits in both species' conservation and development if these vulnerable sites are protected and restored (Li et al., 2022).

The Southeast has the highest aquatic diversity of any temperate system; however, the ecological relationships and life histories of many of the endemic species are not yet well understood within the constraints of changing conditions (Ingram et al., 2013). Freshwater ecosystems (e.g., streams, rivers, lakes, and wetlands) of the Southeast are highly vulnerable to warming. Impacts on rare species of fish and mussels are of particular concern in a changing climate. The combined effects of warming and changes in precipitation likely may alter overall hydrology including increased evapotranspiration and reduced stream base flow. Currently, many species declines are associated with widespread alteration of flow regimes and are expected to be exacerbated by changing environmental conditions. Impacts of changing conditions on riverine and wetland ecosystems are predicted to also include increased water temperatures, which dictate many species ranges and exacerbate low dissolved oxygen conditions (Ingram et al., 2013). In general, temperature regimes of freshwater ecosystems are projected to increase in parallel with shifts in air temperatures, which in turn may alter plant and animal communities including migratory birds (Princé and Zuckerberg, 2015).

Species' Responses to Changing Environmental Conditions

As the regional landscape and weather patterns change, there is value in identifying regional strategies and conservation actions to support the species of greatest conservation need (SGCN) and regional SGCN that are most vulnerable to the impacts. A species is considered vulnerable to changing conditions if it is both sensitive and exposed to potential impacts (Williams et al., 2008). For example, a species may be exposed to changing environmental conditions because it experiences an impact like warmer stream temperatures, but if it is resilient to that change or able to disperse into new habitats, it may ultimately have low vulnerability. Conversely, a species that would be sensitive to changing environmental conditions but is unlikely to experience any impacts and is therefore not exposed, may also not be vulnerable. Understanding if a species is sensitive and exposed to changing environmental conditions may help managers develop strategies to support the species most likely to be impacted.

The NatureServe Climate Change Vulnerability Index (CCVI) is a worksheet-based tool where users apply readily available information about a species' natural history, distribution, landscape circumstances, and expert opinions to predict whether it may likely suffer a range contraction and/or population reduction due to changing environmental conditions, which is then summarized in the form of a vulnerability score. By design, this score is distinct from NatureServe's global and national conservation status ranking system which considers other threats. A species could score as not particularly vulnerable in terms of its Global or State rank (G or S-rank), which is based on other factors, but could still be rated as vulnerable to changing environmental conditions.

CCVI is based on an evaluation of the species' direct and indirect exposure to changing environmental conditions and its sensitivity to changing environmental conditions. To date, several SEAFWA states (West Virginia, Byers & Norris 2011; Tennessee, Glick et al. 2015; Florida, DuBois et al. 2011; and Louisiana) have used the CCVI tool to conduct assessments of their SGCN to inform previous SWAPs, management priorities, and research and conservation planning. Their previous CCVI assessments can be accessed from their 2015 SWAPs or from an archived online integrated dataset collated by the Armsworth lab at the University of Tennessee - Knoxville (Armsworth et al. 2025a) and could serve as references for what has been done before and to shape future planning and conservation efforts.

Ecological niche models (also called species distribution models) are a common approach for evaluating a species' vulnerability to changing environmental conditions by the academic research community. These models start by identifying shared climate conditions at sites where a species is known to have occurred and then predict where similar climate conditions may be found on the landscape in the future. Some models also consider the ability of a species to disperse to new areas that may become suitable. The models' predictions allow researchers to create spatially explicit estimates of whether suitable climate conditions for a species are likely to remain stable, become more widespread in the landscape (i.e. increase), or become more geographically rare in the future (i.e. decrease). For example, if suitable climate conditions for a species were projected to decrease greatly in an area in the future, then the species would be considered more vulnerable to changing environmental conditions than a species for which such conditions were predicted to remain stable. It is important to note that raw data from niche models (e.g., spatial raster data) are not usually readily available to the public due to the large size of the files but instead are available in summary form in the research literature (i.e., academic journal articles). Therefore, more translational effort is needed with niche model results as the form of the data might not be readily interpretable by users.

Niche model results may be used in tandem with CCVI estimates to enhance the understanding of a given species' vulnerability, because CCVIs and niche models have complementary strengths that could help managers make informed conservation decisions. Niche models offer more refined and spatially explicit predictions (i.e., changes in suitable habitat) about the direct exposure of a species to changing environmental conditions but are only available for a limited set of species, in part because the models require extensive data on a species before they can be applied. CCVI estimates use an expert judgment-based approach that allows integration of different types of species information including characteristics might make them vulnerable to changing environmental conditions (e.g., their natural history). It is important to compare CCVI estimates with available ecological niche model predictions (when available) for SGCN to fully understand a given species' vulnerability to changing environmental conditions while keeping in mind the geographic (e.g., region or habitat evaluated) and biological contexts (e.g., estimated dispersal distance) of these assessments.

Summary of available vulnerability indices

For Tennessee, 211 SGCN have been scored via CCVI estimates by Southeast states to date or by other regional institutions; most of which to date have focused on birds (Armsworth et al., 2025a & 2025b). Many of these CCVI assessments indicate that while some bird species may be vulnerable, a larger proportion may remain stable or increase in their suitable habitat under changing conditions (Figure 4). Though more assessments are needed for other taxa, especially those that are not as well studied (e.g., invertebrates), these current CCVI estimates show that assessed fish, mussels and plant SGCN have the largest proportion vulnerable to changing environmental conditions; and reptiles have the least. For example, all assessed mussel SGCN in Tennessee are vulnerable to changing environmental conditions (Figure 4).

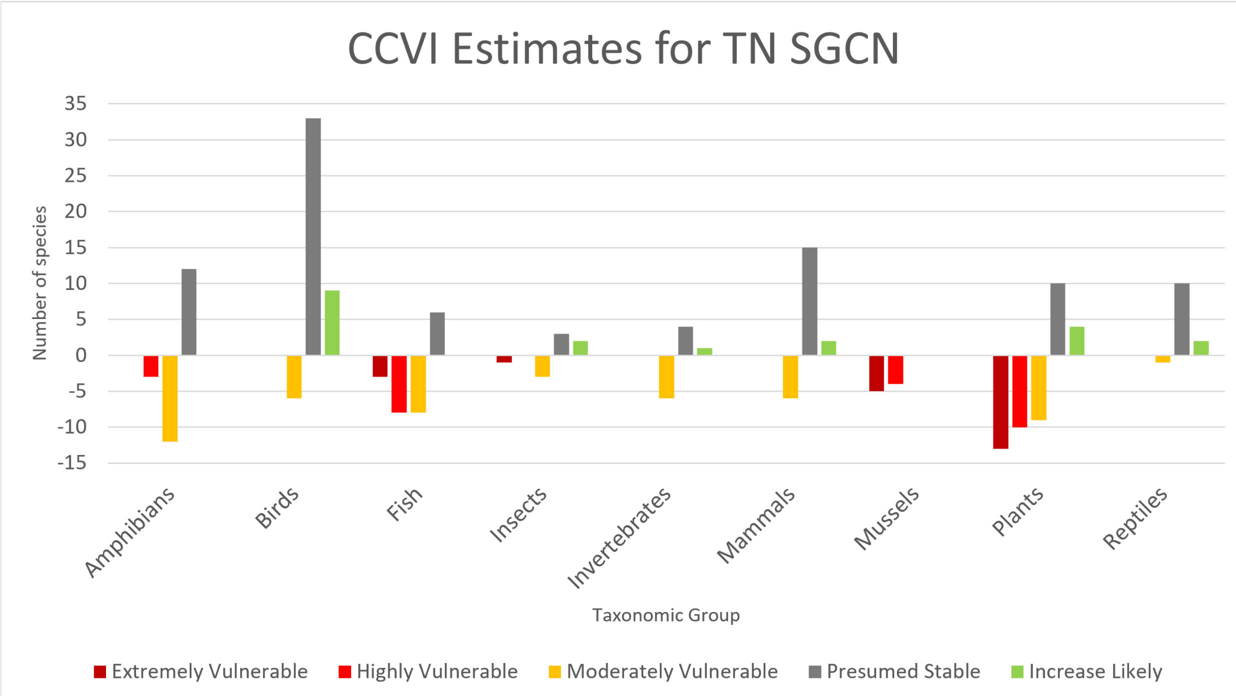

Figure 4. Tennessee species of greatest conservation need (SGCN) that are considered vulnerable, stable, or may increase in population based on available NatureServe Climate Change Vulnerability Index (CCVI) estimates from southeastern association of fish and wildlife agencies (SEAFWA) states (i.e., in their 2015 SWAPs) and other sources compiled by Armsworth et al. (2025a).

Summary of available ecological niche models

For Tennessee, 126 SGCN have been modeled via ecological niche models (i.e., species distribution models) to date (Armsworth et al., 2025b; Yoon et al., 2024). Figure 5 summarizes the combined results for these ecological niche models, which show that all assessed taxa have some SGCN for Tennessee that may experience decreases in their environmentally suitable landscape. However, Tennessee's amphibian SGCN that have been modeled show the largest numbers (19 species) potentially facing a large decrease of suitable habitat (Figure 5).

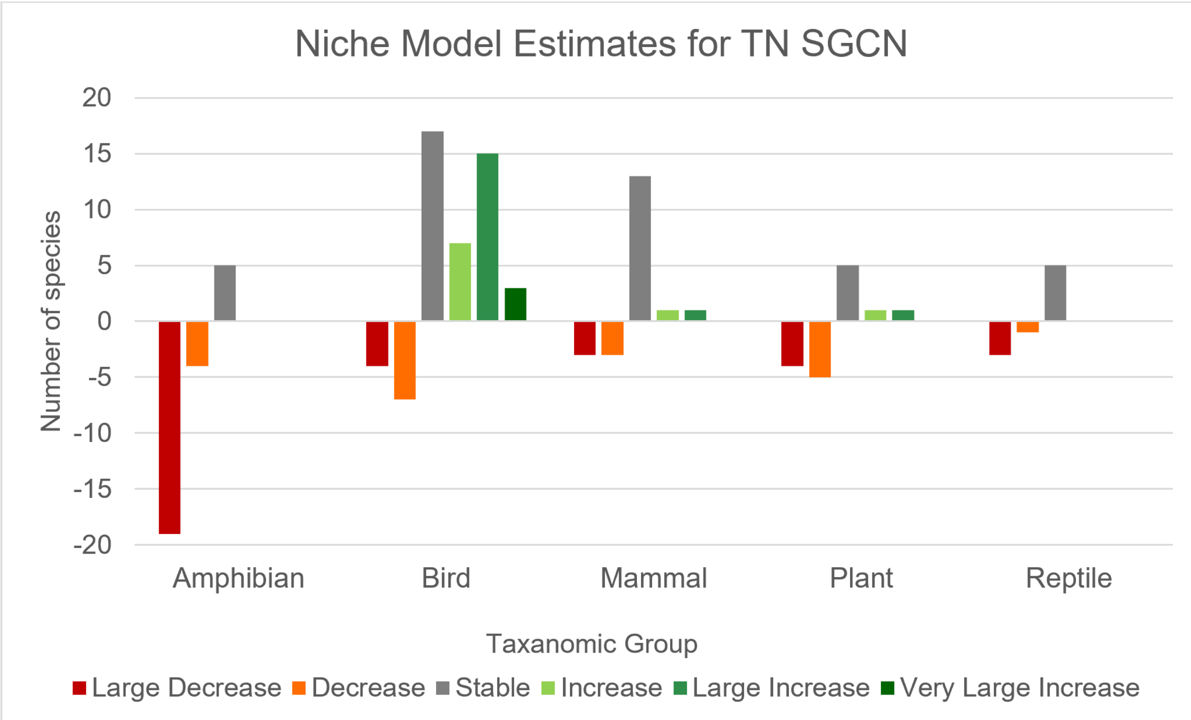

Figure 5. Tennessee species of greatest conservation need (SGCN) that may decrease, remain stable, or increase based on available niche model estimates for eastern North America ranges from the literature compiled by Armsworth et al. (2025b) and from Yoon et al. (2024).

Like the CCVI assessments, most niche models examined herein have focused on birds, finding many bird species may experience increases in their environmentally suitable landscape within the Southeast region as a result of changing environmental conditions. All assessed taxa have some SGCN that are projected to experience decreases (i.e. a decrease or large decrease) in climatically suitable landscape across the Southeast region (Figure 5). These estimates suggest that amphibian and reptile SGCN are projected to have the greatest proportion of species that have been evaluated and may experience reductions in environmentally suitable land area with changing environmental conditions (Figure 5). However, more assessments need to be conducted for more species and taxa not included (e.g., fish, other invertebrates) (Figure 5).

Comparing CCVI and available ecological niche model results

Comparing the results of the ecological niche models to the CCVI estimates for SGCNs within Tennessee reveals similar trends for taxa that were evaluated using both methods. For example, we see that all Tennessee's evaluated taxa have SGCN that have been assessed as vulnerable (i.e., moderately, highly, extremely vulnerable) and some are projected to experience decreases in their suitable habitat ranges (i.e., decrease or large decrease) (Figures 4 & 5). Birds have the greatest number of SGCN with predicted stable or increasing populations across both ecological niche model and CCVI approaches, partially due to how many more bird SGCN have been evaluated compared to other taxa (Figures 4 & 5).

Currently, few species have been evaluated by both the CCVI and ecological niche model approaches, which limits the scope of comparisons across methods. However, looking beyond birds, results from both CCVI and niche models suggest that amphibian and plant SGCN in Tennessee are projected to have many species that are vulnerable to changing environmental conditions (Figures 4 & 5). Niche model estimates are not yet available for many aquatic species, such as fishes, which the scientific literature suggests may be some of the most vulnerable to changing environmental conditions in Tennessee and the Southeast region (Halpern and Kappel 2012; Poff et al. 2012; Ingram et al. 2013). However, the available CCVI for these aquatic taxa suggest that many fish and mussels SGCN of Tennessee are predicted to be extremely vulnerable to changing environmental conditions (Figure 5).

A Closer Look – Changing Environmental Conditions and Impacts to Mussels in Tennessee

North America hosts a significant diversity of freshwater mussels with over 290 species, mostly residing in the southeastern US (Williams et al. 2017). Freshwater mussels are critically important species that provide important ecosystem services (e.g., biofiltration, habitat engineering, nutrient recycling and storage) and function as indicators of overall ecosystem health (Aldridge et al. 2022, Vaughn 2018). Approximately 65% of freshwater mussel species in the US are considered either endangered, threatened, or vulnerable and over 25 extinctions have been reported in the past century (Hopper et al 2023).

Tennessee's many freshwater rivers and streams make the state a hotspot for freshwater mussel diversity, with 140 species occurring throughout the state, many of which are rare (Table 4, Dinkins et al. 2020; Womble and Rosenberger 2025). For example, the only two remaining populations of the White Wartyback (*Plethobasus cicatricosus*), exist below the Wilson and Pickwick Dams on the lower Tennessee River, despite the species having once been distributed across the Ohio, Cumberland, and Tennessee drainages (US Fish and Wildlife South Atlantic-Gulf Region 2022). As seen in Table 4, this once widespread species is now listed as Endangered under the federal Endangered Species Act (ESA) and considered critically endangered by other sources such as the IUCN Red List. In another case, the Littlewing Pearly Mussel (*Pegias fabula*), another Endangered mussel species, is now found only in six streams where previously they had existed throughout tributaries of the Tennessee and Cumberland Rivers in multiple states across 24 streams (NCWildlife.gov). Another example is the Finelined Pocketbook (*Hamiota altilis*), which is found in Tennessee in the small portion of the Conasauga River which briefly meanders into the southeastern part of the state (Tennessee Department of Environment

& Conservation (Williams et al. 2022). The Finelined Pocketbook is listed as Threatened under the ESA and of concern by other metrics shown in Table 4.

Tennessee's abundant freshwater sources include several sites that are of particularly high conservation value for mussels. The Duck River, one of the most biodiverse rivers in North America contains over 50 extant mussel species several of which are federally listed (Ahlstedt et al 2017). To monitor this delicate and biologically diverse system, several programs have been deployed by Tennessee Wildlife Resource Agency (TWRA) biologists over the last two decades. A capture-mark-recapture study was initiated in 2022 and uses colored and numbered individually unique tags to study the population structure at three different locations. A long-term monitoring program also exists at five locations and includes snorkel surveys with quadrats every five years to monitor population shift through time. Governor Bill Lee signed a bill in 2024 to conserve the Duck River and surrounding watershed (TN GOV 2025).

Another well-known hotspot for freshwater mussel diversity is the Clinch River in the upper Tennessee River Basin. The Clinch River supports roughly 50 extant species, of which 24 are federally listed as Endangered (Cope et al. 2021). Ongoing efforts to conserve mussel species in the Clinch River region include the Kyles Ford Preserve, which was established in this watershed to aid in mussel conservation and contains at least 35 species, some of which are unique to this section of the Clinch River (Tennessee Wildlife Resources Agency n.d.; Tennessee Department of Environment & Conservation n.d.). A long-term monitoring program initiated and continued by the Virginia Polytechnic Institute and State University (Virginia Tech) has also been monitoring mussel population health for multiple decades.

The State of Tennessee's Mussels

Along with setting aside protected regions for conservation, significant work has gone into Species Status Assessments (SSAs), produced by the U.S. Fish and Wildlife Service, to determine a species resiliency, redundancy, and representation (collectively known as the "3 Rs") (USFWS). Of the finalized SSAs, 16 species of mussels are also included in the Tennessee SGCN list. For example, a recent SSA for the Tennessee Heelsplitter (*Lasmigona holstonia*) evaluated its current range, preferred habitat, and resiliency to threats (US Fish and Wildlife Service 2022). Forty-one mussel species on Tennessee's SGCN list are Endangered under the ESA (Table 4) and increased climatic and anthropogenic threats have raised concern for mussel populations across the country where declines have been observed (Haag 2012).

The reasons for these declines are multifaceted. Although it is common for land-dwelling species to move toward more suitable habitat as temperatures rise, aquatic freshwater mussels are unable to do so, one reason being lack of habitat connectivity due to dams or impoundments (Inoue and Berg 2016). Freshwater mussel populations are negatively impacted by several anthropogenic disturbances, including the construction of impoundments and canals, the introduction of invasive and non-native species, and over-harvesting (Aldridge et al. 2023). The Tennessee Riffleshell (*Epioblasma propinqua*) is one mussel that is now extinct due to habitat loss and degradation (Haag 2012). Changing environmental conditions pose an additional challenge for these mussel species and may interact with these existing anthropogenic disturbances, amplifying mussel declines. Warming water temperatures, declining water and sediment quality, natural disasters, host species declines, and drought are commonly cited negative impacts on mussel population persistence. In addition, up to 94% of mussel species may exclusively use native fish species as hosts for larvae. Even if they are not identified as SGCN, host species are indispensable for the role they play in ensuring native mollusks thrive in Tennessee's waterways, and host fish are likewise vulnerable to changes in water quantity (Modesto et al. 2018).

Vulnerability and Risk Assessments

Table 4 lists Tennessee's updated list of mussel SGCN. The Table includes summary indicators of species overall status from [NatureServe Explorer] and [IUCN Red List of Threatened Species] assessments. The Table also indicates whether the species is listed under the Endangered Species Act, again reflecting the species overall conservation status. Finally, the table shows results of two different approaches to evaluating a species vulnerability to future conditions, an emergent driver of threats for mussel species and other groups.

The first of these assessment approaches for climate vulnerability are CCVI assessments (Lyons et al. 2024). CCVI assessments combine a worksheet-based exercise informed by expert judgment about species traits and environmental factors with physical climate data. The second set of climate vulnerability assessments comes from ecological niche models, which project whether climatically suitable conditions may become more widespread or more restricted in the future. The niche model results shown in Table 4 are based on the predicted range changes for each species within the 55 watersheds of Tennessee. These predictions come from an analysis that considers both impoundments and environmental impacts in evaluating how species-specific climate suitable areas might change over time (Yoon et al. 2024). Many of Tennessee's SGCNs are also regional species of greatest conservation need (RSGCNs), meaning that other states in the Southeast also consider mussels to be a priority, and are indicated as such in Table 4.

Table 4. Tennessee mussel species of greatest conservation need (SGCN) conservation and vulnerability assessments to date. Y's for the regional SGCN column indicate whether the species is a regional SGCN. Conservation statuses (per NatureServe Explorer and IUCN Red List) and species status (per the Endangered Species Act) are listed in the next three columns. Available assessments of vulnerability based on NatureServe climate change vulnerability index (CCVI) calculations from southeastern states summarized by Armsworth et al. (2024a) and labeled as "NatureServe CCVI by SE States". The niche model results shown in the table are based on the predicted range changes for each species within the 55 watersheds of Tennessee and come from an analysis where both impoundments and climate impacts were considered in evaluating how species-specific climate suitable areas might change over time (Yoon et al. 2024).

Mussel Species		Broad Risk Assessment Measures				Climate Vulnerability Measures	
Common Name	Scientific Name	Regional SGCN	NatureServe State Rank	ESA Status	IUCN Red List	Niche Model Output	NatureServe CCVI by SE States
Alabama Clubshell	*Pleurobema troschelianum*			Not Listed	Extinct	Not Assessed	Not Assessed
Alabama Creekmussel	*Strophitus connasaugaensis*	Y	Critically Imperiled	Not Listed	Near Threatened	Not Assessed	Moderately Vulnerable
Alabama Lampmussel	*Lampsilis virescens*	Y	Critically Imperiled	Endangered	Critically Endangered	Not Assessed	Not Assessed

Mussel Species		Broad Risk Assessment Measures				Climate Vulnerability Measures	
Common Name	Scientific Name	Regional SGCN	NatureServe State Rank	ESA Status	IUCN Red List	Niche Model Output	NatureServe CCVI by SE States
Alabama Moccasinshell	*Medionidus acutissimus*	Y	Critically Imperiled	Threatened	Endangered	Not Assessed	Not Assessed
Alabama Pigtoe	*Pleurobema johannis*			Not Listed	Extinct	Not Assessed	Not Assessed
Alabama Rainbow	*Cambarunio nebulosa*	Y	Imperiled	Not Listed	No Data	Not Assessed	Not Assessed
Alabama Spike	*Elliptio arca*	Y	Imperiled	Not Listed	Data Defecient	Not Assessed	Not Assessed
Appalachian Elktoe	*Alasmidonta raveneliana*	Y	Critically Imperiled	Endangered	Critically Endangered	Not Assessed	Not Assessed
Appalachian Monkeyface	*Quadrula sparsa*	Y	Critically Imperiled	Endangered	Critically Endangered	Not Assessed	Not Assessed
Barrens Bankclimber	*Lasmigona sp. 1 cf. holstonia*			Not Listed	No Data	Not Assessed	Moderately Vulnerable
Birdwing Pearlymussel	*Lemiox rimosus*	Y	Critically Imperiled	Endangered	Critically Endangered	Not Assessed	Not Assessed
Black Sandshell	*Ligumia recta*		Secure	Not Listed	Near Threatened	Stable	Extremely Vulnerable
Caney Fork Rainbow	*Cambarunio simus*			Not Listed	No Data	Not Assessed	Not Assessed
Clubshell	*Pleurobema clava*	Y	Possibly Extirpated	Endangered	Critically Endangered	Not Assessed	Highly Vulnerable
Coosa Creekshell	*Villosa umbrans*	Y	Imperiled	Not Listed	No Data	Not Assessed	Not Assessed
Coosa Moccasinshell	*Medionidus parvulus*	Y	Critically Imperiled	Endangered	Endangered	Not Assessed	Not Assessed
Cracking Pearlymussel	*Hemistena lata*	Y	Critically Imperiled	Endangered	Critically Endangered	Not Assessed	Not Assessed
Creeper	*Strophitus undulatus*		Secure	Not Listed	No Data	Decrease	Presumed Stable
Cumberland Bean	*Villosa trabalis*		Critically Imperiled	Endangered	Critically Endangered	Not Assessed	Not Assessed
Cumberland Elktoe	*Alasmidonta atropurpurea*	Y	Critically Imperiled	Endangered	Endangered	Not Assessed	Not Assessed
Cumberland Moccasinshell	*Medionidus conradicus*	Y	Critically Imperiled	Proposed Endangered	Near Threatened	Not Assessed	Moderately Vulnerable
Cumberland Monkeyface	*Quadrula intermedia*	Y	Critically Imperiled	Endangered	Endangered	Not Assessed	Not Assessed

Mussel Species		Broad Risk Assessment Measures				Climate Vulnerability Measures	
Common Name	Scientific Name	Regional SGCN	NatureServe State Rank	ESA Status	IUCN Red List	Niche Model Output	NatureServe CCVI by SE States
Cumberland Papershell	*Anodontoides denigratus*	Y	Critically Imperiled	Not Listed	No Data	Not Assessed	Not Assessed
Cumberland Pigtoe	*Pleurobema gibberum*	Y	Critically Imperiled	Endangered	Critically Endangered	Not Assessed	Not Assessed
Cumberlandian Combshell	*Epioblasma brevidens*	Y	Critically Imperiled	Endangered	Critically Endangered	Not Assessed	Not Assessed
Delicate Spike	*Elliptio arctata*	Y	Imperiled	Not Listed	No Data	Very Large Increase	Not Assessed
Dromedary Pearlymussel	*Dromus dromas*	Y	Critically Imperiled	Endangered	Critically Endangered	Not Assessed	Not Assessed
Elktoe	*Alasmidonta marginata*		Apparently Secure	Not Listed	Least Concern	Stable	Moderately Vulnerable
Fanshell	*Cyprogenia stegaria*	Y	Critically Imperiled	Endangered	Critically Endangered	Not Assessed	Moderately Vulnerable
Fat Pocketbook	*Potamilus capax*	Y	No Status Rank	Endangered	Vulnerable	Not Assessed	Highly Vulnerable
Fatmucket	*Lampsilis siliquoidea*		Imperiled	Not Listed	Least Concern	Not Assessed	Not Assessed
Finelined Pocketbook	*Hamiota altilis*	Y	Critically Imperiled	Threatened	Endangered	Very Large Increase	Not Assessed
Finerayed Pigtoe	*Fusconaia cuneolus*	Y	Critically Imperiled	Endangered	Endangered	Not Assessed	Not Assessed
Fluted Kidneyshell	*Ptychobranchus subtentum*	Y	Imperiled	Endangered	Near Threatened	Not Assessed	Not Assessed
Georgia Pigtoe	*Pleurobema hanleyianum*		Critically Imperiled	Endangered	Critically Endangered	Not Assessed	Moderately Vulnerable
Green Floater	*Lasmigona subviridis*	Y	Imperiled	Proposed Threatened	Least Concern	Not Assessed	Highly Vulnerable
Hickorynut	*Obovaria olivaria*		Imperiled	Not Listed	Least Concern	Stable	Moderately Vulnerable
Little Spectaclecase	*Cambarunio lienosa*		Apparently Secure	Not Listed	No Data	Not Assessed	Not Assessed
Littlewing Pearlymussel	*Pegias fabula*	Y	Critically Imperiled	Endangered	Critically Endangered	Not Assessed	Not Assessed
Longsolid	*Fusconaia subrotunda*	Y	Vulnerable	Threatened	Vulnerable	Not Assessed	Highly Vulnerable
Mountain Creekshell	*Villosa vanuxemensis*	Y	Apparently Secure	Not Listed	No Data	Decrease	Highly Vulnerable

Mussel Species		Broad Risk Assessment Measures				Climate Vulnerability Measures	
Common Name	Scientific Name	Regional SGCN	NatureServe State Rank	ESA Status	IUCN Red List	Niche Model Output	NatureServe CCVI by SE States
Mucket	*Actinonaias ligamentina*		Apparently Secure	Not Listed	Least Concern	Stable	Not Assessed
Ohio Pigtoe	*Pleurobema cordatum*		Vulnerable	Not Listed	Near Threatened	Not Assessed	Moderately Vulnerable
Orangefoot Pimpleback	*Plethobasus cooperianus*	Y	Critically Imperiled	Endangered	Critically Endangered	Not Assessed	Highly Vulnerable
Ovate Clubshell	*Pleurobema perovatum*		Possibly Extirpated	Endangered	Extinct	Not Assessed	Not Assessed
Oyster Mussel	*Epioblasma capsaeformis*	Y	Critically Imperiled	Endangered	Endangered	Not Assessed	Not Assessed
Painted Clubshell	*Pleurobema chattanoogaense*			Not Listed	Critically Endangered	Not Assessed	Not Assessed
Painted Creekshell	*Villosa taeniata*	Y	Vulnerable	Not Listed	Least Concern	Not Assessed	Highly Vulnerable
Pale Lilliput	*Toxolasma cylindrellus*	Y	Critically Imperiled	Endangered	Critically Endangered	Not Assessed	Not Assessed
Pheasantshell	*Actinonaias pectorosa*	Y	Apparently Secure	Not Listed	Near Threatened	Not Assessed	Moderately Vulnerable
Pink Mucket	*Lampsilis abrupta*	Y	Imperiled	Endangered	Vulnerable	Not Assessed	Moderately Vulnerable
Purple Bean	*Villosa perpurpurea*			Endangered	Critically Endangered	Not Assessed	Not Assessed
Purple Catspaw	*Epioblasma obliquata*	Y	Critically Imperiled	Endangered	Endangered	Not Assessed	Not Assessed
Purple Lilliput	*Toxolasma lividum*		Critically Imperiled	Not Listed	Least Concern	Not Assessed	Moderately to Extremely Vulnerable
Pyramid Pigtoe	*Pleurobema rubrum*	Y	Critically Imperiled	Not Listed	Near Threatened	Not Assessed	Moderately Vulnerable
Rabbitsfoot	*Quadrula cylindrica*		Vulnerable	Threatened	Near Threatened	Not Assessed	Moderately Vulnerable
Rainbow	*Villosa iris*		Secure	Not Listed	No Data	Decrease	Highly Vulnerable
Rayed Bean	*Villosa fabalis*		Critically Imperiled	Endangered	Endangered	Not Assessed	Highly Vulnerable
Rayed Kidneyshell	*Ptychobranchus foremanianus*	Y	Critically Imperiled	Not Listed	No Data	Not Assessed	Not Assessed

Mussel Species		Broad Risk Assessment Measures				Climate Vulnerability Measures	
Common Name	Scientific Name	Regional SGCN	NatureServe State Rank	ESA Status	IUCN Red List	Niche Model Output	NatureServe CCVI by SE States
Ring Pink	*Obovaria retusa*	Y	Critically Imperiled	Endangered	Critically Endangered	Not Assessed	Extremely Vulnerable
Rough Pigtoe	*Pleurobema plenum*	Y	Critically Imperiled	Endangered	Critically Endangered	Not Assessed	Extremely Vulnerable
Rough Rabbitsfoot	*Quadrula strigillata*	Y	Imperiled	Endangered	Endangered	Not Assessed	Not Assessed
Round Hickorynut	*Obovaria subrotunda*	Y	Imperiled	Threatened	Endangered	Not Assessed	Highly Vulnerable
Round Pigtoe	*Pleurobema sintoxia/rubrum*		Apparently Secure	Not Listed	Least Concern	Decrease	Presumed Stable
Salamander Mussel	*Simpsonaias ambigua*		Critically Imperiled	Proposed Endangered	Vulnerable	Not Assessed	Highly Vulnerable
Scaleshell	*Leptodea leptodon*	Y	Critically Imperiled	Not Listed	Near Threatened	Not Assessed	Not Assessed
Sheepnose	*Plethobasus cyphyus*	Y	Imperiled	Endangered	Endangered	Not Assessed	Highly Vulnerable
Shiny Pigtoe	*Fusconaia cor*	Y	Critically Imperiled	Endangered	Critically Endangered	Not Assessed	Not Assessed
Slabside Pearlymussel	*Pleuronaia dolabelloides*	Y	Imperiled	Endangered	Endangered	Not Assessed	Moderately Vulnerable
Slippershell Mussel	*Alasmidonta viridis*	Y	Vulnerable	Not Listed	Least Concern	Not Assessed	Moderately Vulnerable
Snuffbox	*Epioblasma triquetra*	Y	Vulnerable	Endangered	Endangered	Not Assessed	Extremely Vulnerable
Southern Acornshell	*Epioblasma othcaloogensis*		Presumed Extirpated	Not Listed	Critically Endangered	Not Assessed	Not Assessed
Southern Clubshell	*Pleurobema decisum*	Y	Possibly Extirpated	Endangered	Endangered	Very Large Increase	Not Assessed
Southern Fatmucket	*Lampsilis straminea*			Not Listed	No Data	Very Large Increase	Not Assessed
Southern Hickorynut	*Obovaria jacksoniana*	Y	Critically Imperiled	Not Listed	Vulnerable	Not Assessed	Not Assessed
Southern Pigtoe	*Pleurobema georgianum*	Y	Critically Imperiled	Endangered	Critically Endangered	Not Assessed	Not Assessed
Southern Rainbow	*Cambarunio vibex*		Imperiled	Not Listed	No Data	Not Assessed	Not Assessed
Spectaclecase	*Cumberlandia monodonta*	Y	Imperiled	Endangered	Endangered	Not Assessed	Not Assessed

Mussel Species		Broad Risk Assessment Measures				Climate Vulnerability Measures	
Common Name	Scientific Name	Regional SGCN	NatureServe State Rank	ESA Status	IUCN Red List	Niche Model Output	NatureServe CCVI by SE States
Tan Riffleshell	*Epioblasma walkeri*	Y	Critically Imperiled	Endangered	Critically Endangered	Not Assessed	Not Assessed
Tapered Pondhorn	*Uniomerus declivis*		Imperiled	Not Listed	No Data	Not Assessed	Not Assessed
Tennessee Clubshell	*Pleurobema oviforme*	Y	Imperiled	Proposed Endangered	Vulnerable	Not Assessed	Highly Vulnerable
Tennessee Heelsplitter	*Lasmigona holstonia*	Y	Imperiled	Not Listed	Least Concern	Not Assessed	Moderately Vulnerable
Tennessee Pigtoe	*Pleuronaia barnesiana*	Y	Imperiled	Proposed Endangered	Least Concern	Not Assessed	Moderately Vulnerable
Triangular Kidneyshell	*Ptychobranchus greenii*			Endangered	Endangered	Not Assessed	Not Assessed
Upland Combshell	*Epioblasma metastriata*		Possibly Extirpated	Not Listed	Critically Endangered	Not Assessed	Not Assessed
Warrior Pigtoe	*Pleurobema rubellum*			Not Listed	Critically Endangered	Not Assessed	Not Assessed
White Heelsplitter	*Lasmigona complanata*		Secure	Not Listed	Least Concern	Decrease	Presumed Stable
White Wartyback	*Plethobasus cicatricosus*	Y	Critically Imperiled	Endangered	Critically Endangered	Not Assessed	Not Assessed
Winged Mapleleaf	*Quadrula fragosa*	Y	Critically Imperiled	Endangered	Critically Endangered	Not Assessed	Not Assessed

Forty-one of the 89 species are listed as Endangered under the ESA and nearly all species are considered by NatureServe to be Critically Imperiled, Imperiled, or Vulnerable. Risk designations concur for some species such as the Shiny Pigtoe (*Fusconaia cor*), Clubshell (*Pleurobema clava),* Ring Pink (*Obovaria retusa)*, and Rough Pigtoe (*Pleurobema plenum)* (Table 4). Impacts from changing environmental conditions may exacerbate existing stressors for mussel species (Tarter et. al 2022). Some species have been evaluated by IUCN, NatureServe and USFWS (through ESA review) as being in critical condition and are projected to also be highly vulnerable to future environmental conditions like the Ring Pink (*Obovaria retusa*) and Rough Pigtoe (*Pleurobema plenum*). Even for species that are currently of least concern, niche model projections suggest their suitable range might decrease in the future, as in the case of the Rainbow mussel (*Villosa iris*)*,* White Heelsplitter (*Lasmigona complanata*), and Round Pigtoe (*Pleurobema sintoxia*). In contrast, for other species like the Finelined Pocketbook (*Hamiota altilis*), niche models suggest the impacts of changing environmental conditions may not be as substantial with a predicted increase in climatically suitable area.

There are some discrepancies in the estimates of climate vulnerability of species between the niche model outputs and the CCVI method, such as with the Elktoe (*Alasmidonta marginata*). There may be different reasons for this, not least that the two methods include different kinds of information. It may also be due to the niche models representing the projected trend for the whole region due to climate and impoundment effects, whereas CCVI assessments were conducted at the state level (Table 4). Additionally, to date, many species have either not been assessed using the CCVI tool or have been the subject of regional ecological niche modeling efforts as is indicated by the gray "Not Assessed" boxes in Table 4.

Species status assessment (SSA) reports, produced by the U.S. Fish and Wildlife Service, provide another source of valuable information for enhancing the conservation of freshwater mussels in Tennessee. SSAs generally integrate population and demographic data, current and projected climate data (e.g., global climate models), and data quantifying a variety of potential risks (e.g., pollutant concentrations, land use change) to both assess the status of individual mussel populations and predict how this may change under future conditions. For example, in the 2022 SSA for the Snuffbox (*Epioblasma triquetra*), multifactor assessments of demographic condition and risk factors were combined to determine individual population statuses (delineated by USDA HUC8 units). Demographic condition was assessed on a scale from high to functional extirpation, based on demographic factors including population size, population extent, and reproduction and recruitment rates. Risk factors are assessed on a scale from high to low for five categories - water quality/contaminants, landscape, hydrological regime, connectivity, and invasive species presence. The SSA concludes that the five remaining contemporary populations in the Tennessee region are in moderate or low demographic condition with high to moderate risk of extirpation.

Increased water temperature and mussels

Freshwater mussels are experiencing thermal stress for longer periods as increases in average air and water temperatures extend the duration of the summer season (van Ee et al 2022). Freshwater mussel survival is negatively affected as elevated water temperatures have been shown to be associated with mussel die-offs (van Ee et al. 2022, Waller and Cope 2019). Moreover, as water temperatures increase, a timing mismatch between freshwater mussels and their fish hosts may occur, leading to further declines in abundance (Osterling 2014).

Mussels depend on host species populations to be relatively dense to achieve reproductive success. This is because most freshwater mussels reproduce by releasing larvae called glochidia, which embed in a host fish's gills until their juvenile phase, after which they are released back into the habitat (Lane et al. 2021). This is an obligate parasitic relationship, and freshwater mussels often specialize on specific fish hosts. Some mussels have highly specialized "lure" appendages that attract specific fish hosts, increasing the probability of a successful egg release (Lane et al. 2021). The Oyster Mussel (*Epioblasma capsaeformis*) is one such species, as female Oyster Mussels have colorful, expandable lures to entice their fish host (Lane et al. 2021). The mantle can inflate to keep its host species still so that its glochidia can implant successfully (Lane et al. 2021). As seen in Table 4, the Oyster Mussel is now listed as Endangered by the ESA and considered of significant concern by other metrics.

Host fish are also susceptible to climate-related threats, such as warming temperatures and extreme weather events (Aldridge et. al 2022). Loss of a fish host may lead to an extinction of the mussel species that relies on the obligate relationship to reproduce. Some freshwater mussels are long term brooders, rearing their glochidia in early summer, brooding over winter, and then releasing them late spring or early summer (Österling 2014). Warming temperatures may cause freshwater mussels to release their glochidia earlier in the year, prior to their host species population reaching suitable abundance in the same area to support an adequate amount of glochidia (Moore et al. 2018). This may lead to reduction in recruitment, especially in slower growing mussels (Moore et al. 2018). Therefore, host species declines and phenological mismatches due to warming temperatures are of concern to mussel conservation.

Increased extreme weather events and impacts on water quality and mussels

Changing environmental conditions are expected to alter disturbance regimes (e.g., flooding, storms) resulting in more frequent and extreme weather events, such as the destruction caused by Hurricane Helene in eastern Tennessee in 2024 (Tarter et al. 2022). These events may heavily impact both water and sediment quality, factors that are critical to mussel health. As benthic filter-feeders, mussels are particularly sensitive to pollution in the sediment and water column (Haag et al. 2019). Extreme weather events may also lead to increases in the levels of contaminants, which are often correlated to mussel declines (Cope et. al 2021). Studies have shown that mussel health is negatively affected by metals, ammonia, chlorine, and major ions from dissolved solids (Cope et al. 2021, Price et al. 2014). For example, at Ellejoy Creek in Blount County, Tennessee, the presence of nearby roads and an eroding stream bank have increased turbidity and levels of suspended sediment in the water, which are associated with notable declines in mussel density downstream (Schilling et al. 2017). Increased rainfall could lead to additional runoff from human populations and contribute to streambank erosion and bedload instability.

Extreme flooding and increased stormwater runoff are also projected to become more frequent in Tennessee (Lomardi & Davis 2023). For the Spectacle Case Mussel (*Cumberlandia monodonta*), prolonged increases in the stream velocity due to extreme flooding poses two major threats, (1) the spatial displacement and mortality of juvenile mussels and glochidia, and (2) the alteration of the streambed habitat, particularly due to the accumulation of debris (USFWS, 2022a). Spatial displacement in the wake of these extreme weather events may alter community composition in the long-term, with disturbance-tolerant species becoming more abundant (Tarter et al. 2022). The Spectacle case mussel tends to inhabit areas with variable stream velocity at the interface between swift and slow-flowing water. However, the magnitude and length of increased velocity expected with increases in extreme flooding events may likely exceed the tolerance range for this species (USFWS, 2022a). The fate of displaced mussels that have been relocated by flooding or extreme weather events remains unclear (Sotola et al. 2020). Habitat alteration has major consequences for mussel life history events, as it may prevent both mussels and their host fish from being able to persist or reestablish in each area post-flood.

Increased drought and mussels

The frequency and intensity of droughts is also projected to increase (IPCC 2022). These changes pose a particularly difficult challenge for sedentary organisms like mussels, which have a limited ability to track suitable climatic conditions in space. Stressors related to drought include emersion (periods of low water exposure), desiccation (complete drying or dehydration), and increased predation pressure. These stressors occur when water levels decrease, which leads to increases in water temperature and hypoxia, or lack of suitable oxygen in the waterway (Cushway et al. 2025). As water scarcity increases, the concentration of solutes, including pollutants, increases. These stressors disrupt mussel physiology (e.g., reduce the availability of lipids, proteins, and carbohydrates, slow ATP production) and hinder filter feeding, resulting in declines in body condition, energy availability, and slowed growth rates (Jeffery et al. 2018). Several studies have demonstrated that drought may lead to mass mussel mortality and increases the risk of population extirpation (Lombardi and Davis 2023). Some mussel species may be more heavily impacted due to unique niche partitioning such as those that are often found near banks or in shallow water or stranded more readily than those that live in the center of the river (i.e., thalweg). Drought may also alter mussel population structure, either due to impacts on host species availability or the increased vulnerability of juvenile mussels relative to adults (Jeffery et al. 2018).

As flow regimes change in the Southeast, predicting droughts is essential to inform conservation efforts. In 2019, the US Geological Survey in collaboration with the Gulf Coastal Plains and Ozarks Landscape Conservation Cooperative developed a model which simulates water availability in the Southeast based on historical and simulated climate records (LaFontaine et al. 2019). Tools that project stream flow, like this model, may be useful in helping managers to predict which streams could be suitable for freshwater mussel populations, which in turn may help guide restoration efforts.

Summary and Discussion

In summary, studies cited here document declines in mussel populations and impacts from changing environmental conditions, indicating ongoing ecological shifts relevant to conservation. The Tennessee Wildlife Resources Agency has several projects dedicated to mussel conservation, such as the partnership with Dale Hollow National Fish Hatchery to raise Endangered and Threatened mussels to nearly adult size before releasing them into the wild. Because mussels are mainly stationary organisms that reside in streams, reservoirs, and rivers, monitoring and maintaining favorable water conditions across Tennessee may also be fundamental to the survival of these species. For species with limited data as shown in Table 4, such as the Southern Fatmucket (*Lampsilis straminea)*, additional monitoring and sampling efforts could improve understanding of their potential responses to changing environmental conditions. These conservation efforts are needed to preserve these critically important species and understand how mussels may react to a changing climate and human impacts.

Adaptation strategies

Identifying adaptation strategies to address impacts and vulnerability is a step towards resiliency in a changing world. Adaptation to changing environmental conditions and mitigation come in various forms, and multiple frameworks have been built to support planning for and implementation of adaptation actions. Most adaptation frameworks for ecosystems and wildlife generally include:

1. Recognizing limitations to adaptation, such as the degree of natural resource management, availability of funding, or staffing capacity; and
2. Deciding which type(s) of adaptation approach(es) meet specific conservation goals.

Two well-known examples of frameworks include the 1) Resist-Accept-Direct (RAD) Framework developed by the US Geological Survey and partners and the 2) Resistance, Resilience and Transition (RRT) Framework developed by Colorado State University. There are also multiple sources for adaptation and mitigation strategies. The Adaptation Workbook, a compilation of resources developed by the Northern Institute of Applied Climate Science and its partners, provides an overview of strategies. The Adaptation Workbook is divided into sections, one of which being Adaptation Strategies and Approaches. In this section, adaptation strategies are listed in what are known as "menus"—categorized by focus areas—with the goal of the menus to provide specific, actionable adaptation options. The menus are not all encompassing, nor are they intended to serve as guidance for management decisions. They simply serve as a starting point for those interested in adaptation so as to not have to start from scratch. Adaptation menus and the recommended strategies and approaches that apply to the U.S. Southeast include:

- Agriculture
- Fire-Adapted Ecosystems
- Forests
- Forest Carbon Management
- Forested Watersheds
- Grasslands
- Non-Forested Wetlands
- Recreation
- Saltwater Coastal Ecosystems
- Tribal Perspectives
- Urban Forests
- Wildlife Management

Working in resilient landscapes

Regardless of the projected impacts from changing environmental conditions, some portions of the state are predicted to be more resilient than others. Focusing conservation action within resilient places can be a useful approach.

Terrestrial resilience

Much of Tennessee's natural landscape is considered a resilient terrestrial site. The Nature Conservancy (TNC) developed a data set called the Resilient Land Data that identifies areas with different landscape characteristics such an area's capacity to maintain species diversity and ecosystem function in the face of changing environmental conditions. It measures two factors that influence resilience.

1. Landscape biodiversity: Reflects the number of microhabitats and climatic gradients created by topography, elevation, and hydrology.
2. Local connectedness: Reflects the degree of habitat fragmentation and strength of barriers to species movement.

Highly resilient sites contain many different habitat niches that support biodiversity and allow species to move freely throughout the landscape to find suitable microclimates under changing environmental conditions. Resilience emphasizes diverse landscapes where species are likely to be able to move and adjust to changing conditions. While the species themselves may change, these areas are likely to be able to host a continued diversity of species into the future.

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