Synthesis Element 1:

Water Temperature Effects on Fisheries and Stream Health in Nontidal Waters
(Discussion Draft pending additional warmwater information)

Abstract

A limited review of relevant scientific literature related to temperature sensitivities of fish species, stream health indicators, and any related geospatial information was conducted. Rising stream temperatures will have a range of impacts on nontidal aquatic ecosystems. Cold headwaters and associated species like brook trout and sculpin are especially vulnerable to higher stream temperatures. Efforts should be taken to identify and protect high quality resilient cold headwater brook trout habitat. More information is needed on groundwater impacts on stream temperatures and ecologically relevant temperature thresholds for species of concern. A vulnerability assessment would be valuable to better understand the drivers and stressors of rising stream temperatures, their effects on aquatic resources, and the risk to fish and other aquatic species. Developing and fully vetting a complete list of cold/cool water benthic macroinvertebrate taxa and freshwater mussel taxa that are vulnerable to temperature change in the Chesapeake watershed is a research priority.

Note: See Addendum 1 for additional attachments

A. Contributors

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B. Resources

The synthesis was developed through a limited review of the scientific literature and informal solicitation of expert opinion to formulate the overall approach and provide supporting science.

C. Approach

We conducted a limited review of the relevant scientific literature and developed a questionnaire requesting information related to temperature sensitivities of fish species, stream health indicators, and any related geospatial information. This was sent to a selected group of researchers, natural resource professionals, and other stakeholders in the Chesapeake Bay Watershed (CBW). Further informal discussions were held with an engaged group of the few respondents that included recommended publications to include in this review.

D. Synthesis

Stream temperature has direct and indirect effects on many biological, physical, and chemical processes in the freshwater environment including significant impacts on fish metabolism, physiology, and behavior (Clark and Johnston, 1999). Climate change can also shift species ranges, distribution, phenology, and productivity modifying the emergent properties of an ecosystem with divergent preferences for habitat for cool-water and warm-water species (Staudinger et al. 2021; Weiskopf et al. 2020). Conservation and management decisions regarding aquatic systems face new challenges as future temperature are projected to rise markedly and flow timing is projected to shift for many watersheds in the Northeast under climate change impacts (Isaak et al. 2015; Paukert et al. 2021).

Synthesizing the effects of water temperature on stream health in nontidal waters of the CBW is a complicated undertaking given the wide diversity of habitats, species, potential responses, and the limited number of studies directly measuring the effects of water temperature. The myriad of cool and coldwater fish communities are facing unique threats due to increasing water temperatures in conjunction with other stressors (Frumhoff et al. 2007). While not covered in this chapter, similar temperature-related impacts have been documented for amphibians (Blaustein et al. 2010; Polo-Cavia et al. 2017; Miller et al. 2018) and lake ecosystems (Breeggermann et al. 2016).

Fish

Temperature effects on freshwater fish have been studied in earnest since the 1940's (Eaton et al. 1995) across a range of different aspects including lethal limits (Hart, 1947), reproduction (Gaston et al. 2017), physiology (Alfonso et al. 2020), and life stage (Turschwell et al., 2017). However, linking broad implications from general principles or mensurative studies to more specific relationships that can inform Chesapeake Bay management and mitigation decisions is more difficult. Every species has a thermal optimum and maximum, but specific responses vary by life stage, length of exposure, and interactions with other stressors (Timm et al., 2020) and data specific to Chesapeake Bay species are limited. Few previous studies have focused on how climate change may impact headwater systems, despite the importance of these areas for aquatic refugia.

The paucity of species/taxa-specific studies has resulted in the majority of climate impact assessments focusing on conservation of ecological systems at broad levels with results that aren't readily translatable into useful and actionable information for managers/practitioners on the ground. A recent literature review of multiple stressors driving biological impairment of CBW freshwater streams found that only about half of the studies reviewed (34) included temperature and it was identified as an important stressor in about 30% of those studies (Fanelli et al., in preparation).

The U.S. Environmental Protection Agency surveys streams and rivers and compiles the information, including stream temperatures, in the National Rivers and Streams Assessment (hereafter NRSA) (USEPA, 2020). As part of a larger fish habitat assessment within the CBW, Krause et al. (2021a) collated species occurrence data from a suite of natural resource agencies and other stakeholders. This was cross-referenced to the EPA NRSA data set to identify the stream temperature classification of Chesapeake Bay freshwater species. Brown trout, brook trout, and rainbow trout are the only species identified as coldwater (Table 1). Checkered sculpin (*Cottus* sp. cf. *girardi*), an undescribed global endemic species, also is limited to cold groundwater-fed streams in the Chesapeake Bay headwaters (central Potomac River basin). Krause et al. (2021b) have developed species occurrence maps for the species of primary importance, sculpin and brook trout. This provides a scalable geospatial map resource to identify where the species occur in the watershed and can be linked to other data, e.g., HUC classification, climate change scenarios, necessary to identify areas vulnerable to increasing water temperatures (Fig 1.).

Brook trout are specifically identified as one of the four indicator species in the Chesapeake Bay Executive Order 13508 because "they reflect the habitat health and hold great ecological, commercial and recreational significance". They rely on clean, cold stream habitat and are sensitive to rising stream temperatures, thus providing a potential early warning of detrimental changes in water quality. Brook trout are also highly prized by recreational anglers and have been designated as the state fish in many eastern states. They are an essential part of the headwater stream ecosystem, an important part of the upper watershed's natural heritage and a valuable recreational resource. The decline of brook trout serves as a warning about the health of local waterways and the impact of activity on lands draining to them. More than a century of declining brook trout populations has led to lost economic revenue and recreational fishing opportunities in the Bay's headwaters.

Because of their importance to the region and sensitivity to higher stream temperatures, brook trout and the headwater streams they occupy have been the subject of intensive research with a focus on understanding the effects of air temperature on water temperature and resultant impact on brook trout habitat (Flebbe et al. 2006; Snyder et al. 2015). There are, however, other factors that can mitigate the impact and response of simple changes in air temperature including land use (Merriam et al. 2019; Maloney et al. 2020), landform features (Johnson et al. 2017), flow (Merriam et al. 2017), and fine-scaled groundwater inputs (Snyder et al. 2015; Briggs et al. 2018). In addition, spatial grain or scale is an important aspect affecting the results and interpretations. For example, Flebbe at al. (2006) used a watershed model approach, which assumes one uniform value of thermal sensitivity for the entire watershed, and predicted a nearly 80% loss of suitable brook trout habitat under a 3.0°C temperature increase. Snyder et al. (2015) used a reach model incorporating fine-scaled groundwater inputs which reduced the loss of suitable brook trout habitat under a 3.0°C temperature increase to approximately 20% from the 2012 baseline. Introduced fishes also may compete with and displace native brook trout (Fausch and White 1981 ; Wagner et al. 2013) and such effects are exacerbated with elevated stream temperature (Hitt et al. 2017).

There are a number of models developed to predict stream temperatures and brook trout occupancy to provide managers and researchers the tools needed to predict impacts to brook trout from changes in climate and land use (Fig 2). Letcher et al. (2016) have developed a Bayesian model to predict daily stream temperature based on catchment characteristics and climate conditions. That temperature model underpins a dynamic interactive data visualization tool, the Interactive Catchment Explorer (ICE), for exploring catchment characteristics, model predictions, and identifying priority catchments (Walker et al. 2020) (Fig 3). Predictions in ICE should be viewed as a first cut for locations without stream temperature data as it is difficult to incorporate local drivers with insufficient data in regional temperature models (e.g., the buffering effects of groundwater-surface water interactions).

Table 1. Adapted National Rivers and Streams Assessment (NRSA) classification of cold (CD) and cool (CL) water temperature Chesapeake Bay freshwater fish species (adapted from EPA, 2020)

Common Name	NRSA Classification		Common Name	NRSA Classification	Common Name	NRSA Classification
SLIMY SCULPIN	CD		SHORTHEAD REDHORSE	CL	BLUEBACK HERRING	CL
BROWN TROUT	CD		POTOMAC SCULPIN	CL	ALEWIFE	CL
BROOK TROUT	CD		BLUE RIDGE SCULPIN	CL	AMERICAN PICKEREL	CL
RAINBOW TROUT	CD		REDSIDE DACE	CL	BRIDLE SHINER	CL
SHIELD DARTER	CL		CHAIN PICKEREL	CL	MOUNTAIN REDBELLY DACE	CL
ROSYFACE SHINER	CL		SWALLOWTAIL SHINER	CL	BANDED SCULPIN	CL
MOTTLED SCULPIN	CL		ALLEGHENY PEARL DACE	CL	ROANOKE HOG SUCKER	CL
RAINBOW DARTER	CL		STONECAT	CL	LONGFIN DARTER	CL
LOGPERCH	CL		BLACKNOSE SHINER	CL	RIVERWEED DARTER	CL
FANTAIL DARTER	CL		BROOK STICKLEBACK	CL	CANDY DARTER	CL
TONGUETIED MINNOW	CL		AMERICAN EEL	CL	NEW RIVER SHINER	CL
LONGHEAD DARTER	CL		YELLOW PERCH	CL	CHANNEL DARTER	CL
BLACKSIDE DARTER	CL		BANDED KILLIFISH	CL	APPALACHIA DARTER	CL
W. BLACKNOSE DACE	CL		WALLEYE	CL	KANAWHA MINNOW	CL
VARIEGATE DARTER	CL		MUSKELLUNGE	CL	BLACKCHIN SHINER	CL

BANDED DARTER	CL		SEA LAMPREY	CL	NORTHERN REDBELLY DACE	CL
SILVER SHINER	CL		NORTHERN PIKE	CL	RUDD	CL
MIMIC SHINER	CL		AMERICAN SHAD	CL	HICKORY SHAD	CL
FALLFISH	CL		EMERALD SHINER	CL	BLUEFISH	CL
COMELY SHINER	CL		NORTHERN BROOK LAMPREY	CL		
SPOTFIN SHINER	CL		TROUT-PERCH	CL		
SPOTTAIL SHINER	CL		GLASSY DARTER	CL		
REDBREAST SUNFISH	CL		SWAMP DARTER	CL		

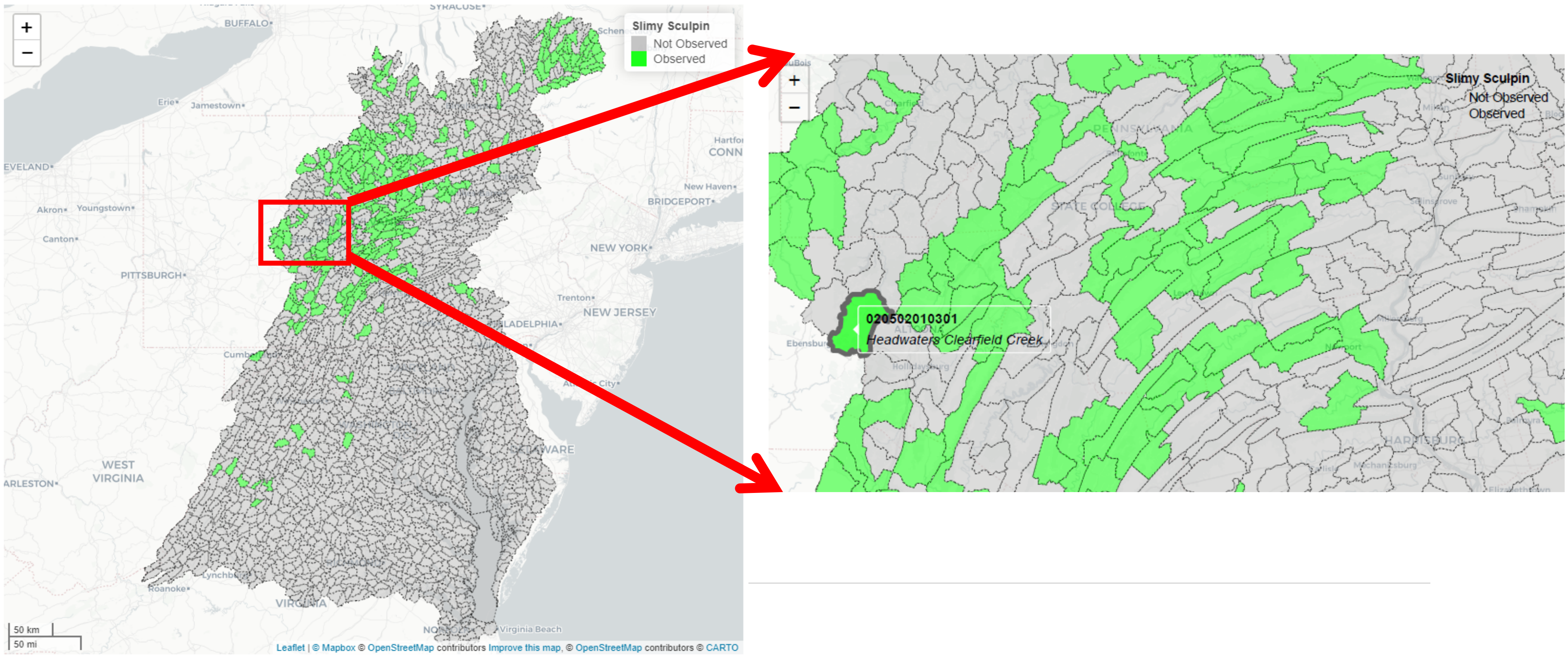
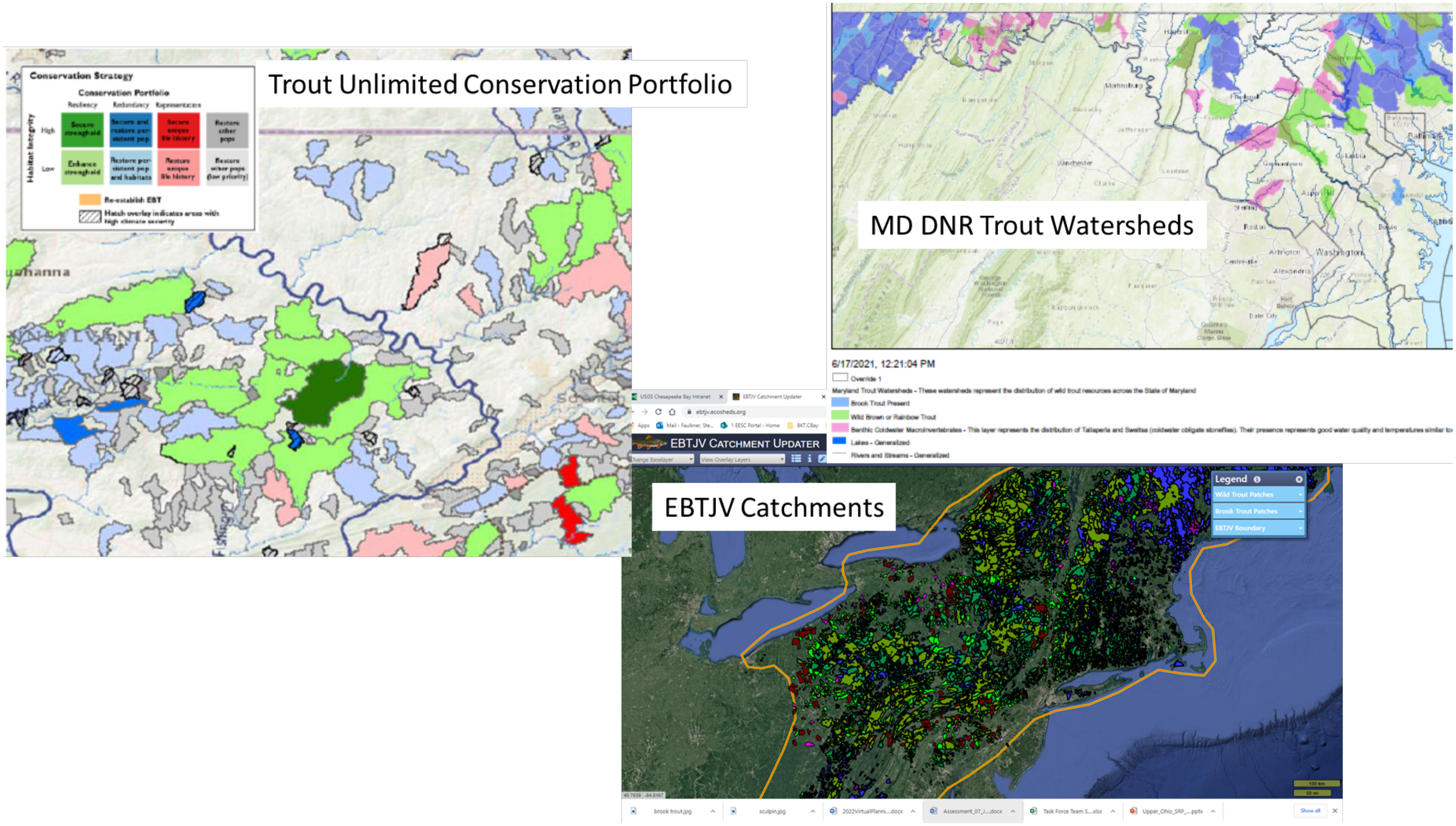


Figure 1. Slimy sculpin fish occurrence map (Krause et al. 2021b)



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☐ Override 1

Maryland Trout Watersheds - These watersheds represent the distribution of wild trout resources across the State of Maryland

🟦 Brook Trout Present

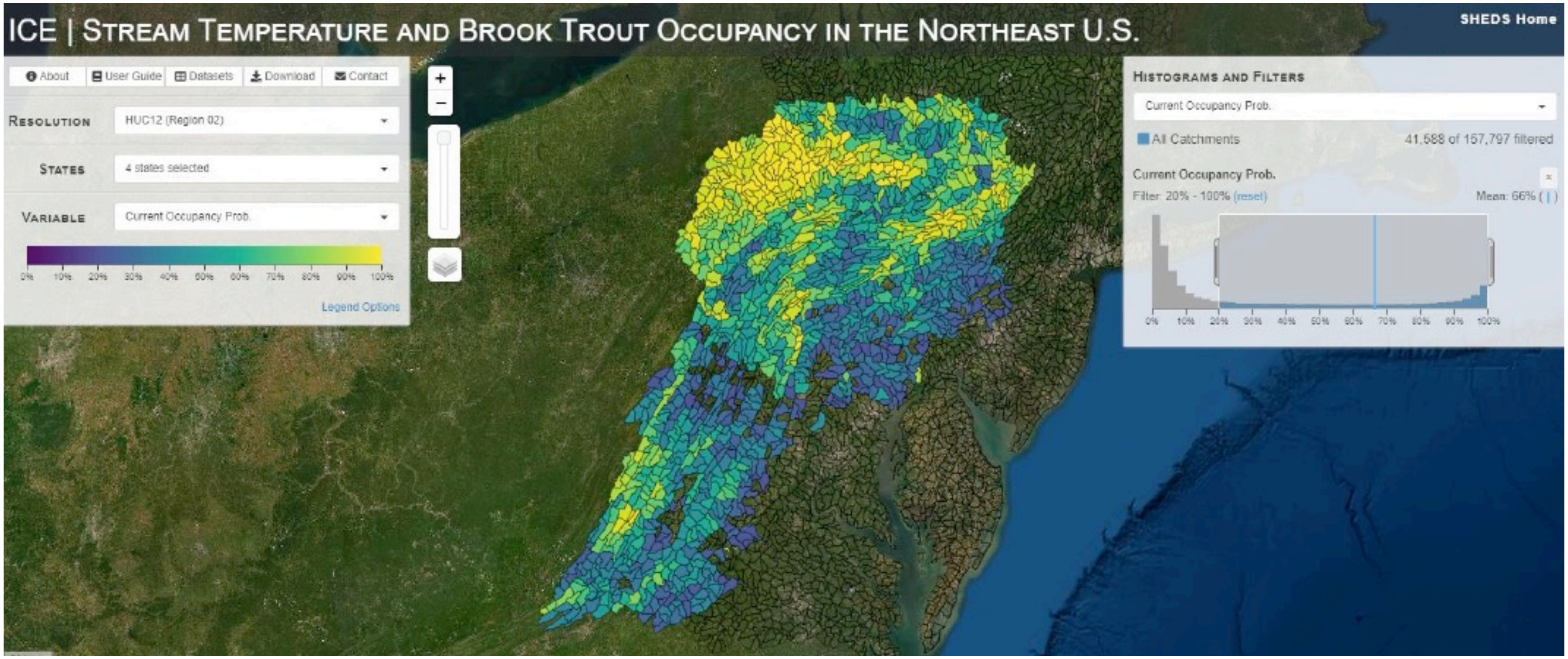
🟩 Wild Brown or Rainbow Trout

🟪 Benthic Coldwater Macroinvertebrates - This layer represents the distribution of Tallaperla and Sweltsa (coldwater obligate stoneflies). Their presence represents good water quality and temperatures similar to

🟦 Lakes - Generalized

— Rivers and Streams - Generalized

Figure 2. Spatially explicit brook trout decision support tools.



ICE | STREAM TEMPERATURE AND BROOK TROUT OCCUPANCY IN THE NORTHEAST U.S.

RESOLUTION HUC12 (Region 02)

STATES 4 states selected

VARIABLE Current Occupancy Prob.

HISTOGRAMS AND FILTERS

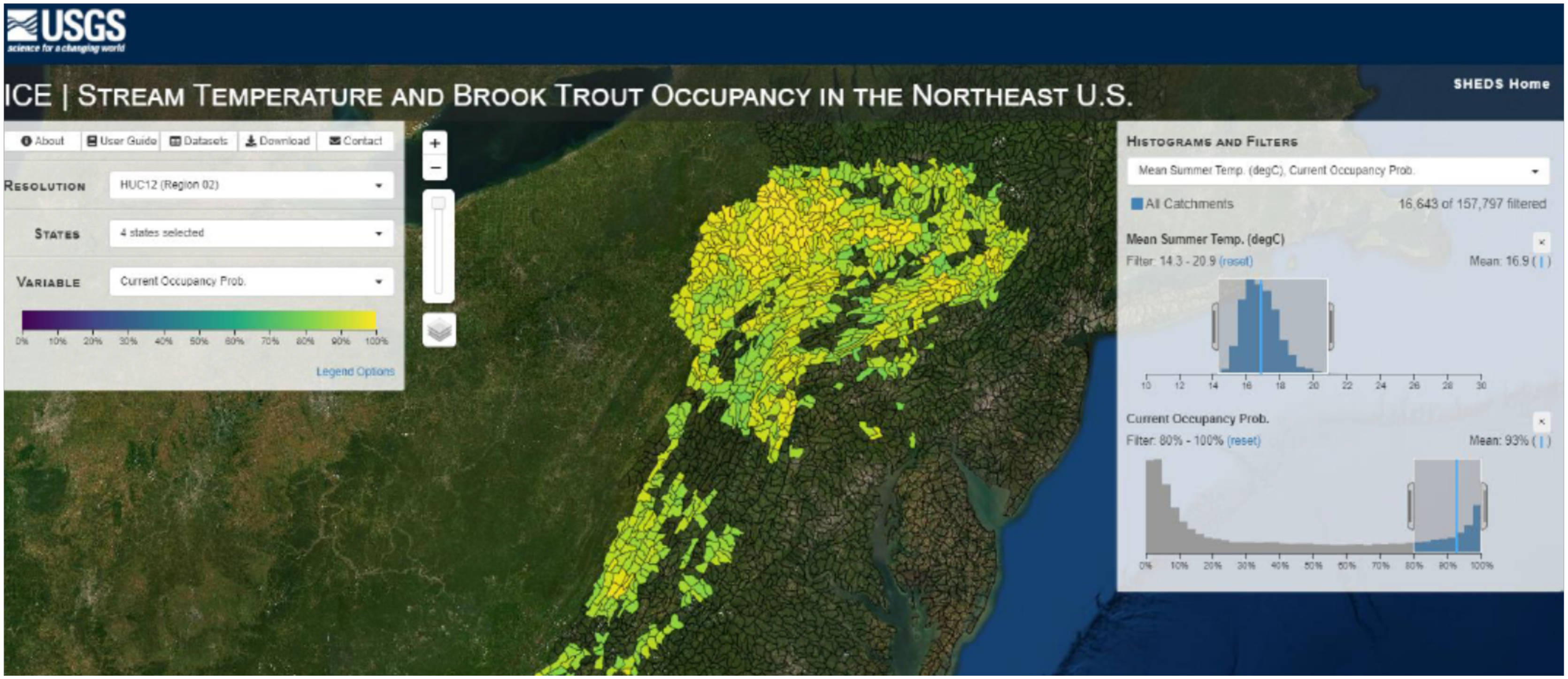
Current Occupancy Prob.

All Catchments 41,588 of 157,797 filtered

Current Occupancy Prob.

Filter: 20% - 100% (reset) Mean: 66% (|)

Catchments in MD, PA, WV, VA with 80-100% Occupancy Probability



RESOLUTION: HUC12 (Region 02)

STATES: 4 states selected

VARIABLE: Current Occupancy Prob.

Mean Summer Temp. (degC), Current Occupancy Prob.

All Catchments 16,643 of 157,797 filtered

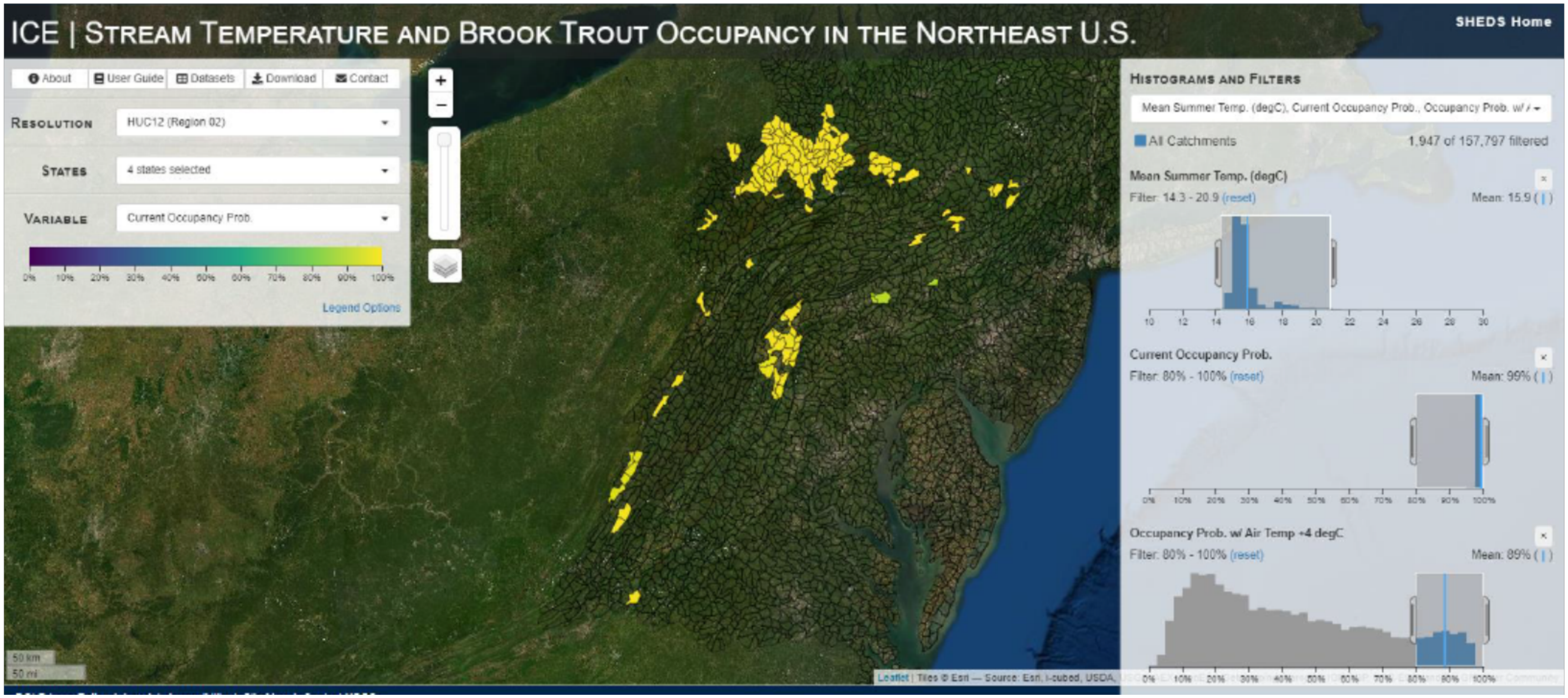
Mean Summer Temp. (degC)

Filter: 14.3 - 20.9 (reset) Mean: 16.9

Current Occupancy Prob.

Filter: 80% - 100% (reset) Mean: 93%

Occupancy Probability with +4 °C Air Temperature



RESOLUTION HUC12 (Region 02)

STATES 4 states selected

VARIABLE Current Occupancy Prob.

Mean Summer Temp. (degC), Current Occupancy Prob., Occupancy Prob. w/ A

All Catchments 1,947 of 157,797 filtered

Mean Summer Temp. (degC)
Filter: 14.3 - 20.9 (reset) Mean: 15.9

Current Occupancy Prob.
Filter: 80% - 100% (reset) Mean: 99%

Occupancy Prob. w/ Air Temp +4 degC
Filter: 80% - 100% (reset) Mean: 89%

Figure 3. Interactive Catchment Explorer (ICE) www.usgs.gov/apps/ecosheds/ice-northeast (Walker et al. 2020).

Macroinvertebrates/Mussels

Like fishes, macroinvertebrates are partially structured by temperature where species occupy niches under thermal optima and threshold constraints. While water temperature controls basic metabolic processes and dissolved oxygen availability, it also effects the timing of important life history stages in both larval and adult development, emergence, egg laying, and overall population recruitment and maintenance. Further, a myriad of direct and indirect ecosystem-level processes and stressors can be affected by climate change, thereby altering macroinvertebrate community structure. Thus, while cold water stenotherms and warmwater eurytherms have evolved mechanisms to proliferate differently under both narrow and wide physiologic temperature ranges, other environmental stressors will be exacerbated leading to further assemblage alteration. In the Chesapeake Bay watershed, stream size, latitude, and elevation exert overarching spatial controls on natural thermal regimes and the resulting macroinvertebrate fauna. Predictably, we would expect shifts in macroinvertebrate assemblages to occur with increased warming. Hypothetically, coldwater and coolwater specialists could face inhospitable future conditions and local extirpation where stenothermic taxa would be forced to shift toward other habitats along the river continuum (e.g., higher elevation or smaller groundwater-fed streams).

One key problem in monitoring and assessing the effects of temperature change is in assigning definitive thermal traits to macroinvertebrate taxa. States like MD have identified several coldwater specialist taxa, mainly mayflies, stoneflies, and caddisflies (or EPT) via continuous temperature data where others have often used other modeling methods or best professional judgment. Existing trait-based assignments for genera (e.g., Vieria et al. 2006; Poff et al. 2006, Fritz, EPA unpublished database) are helpful resources but species-level identification is needed among some genera (USEPA 2016). However, out of the >650 genera compiled for the Chesapeake Bay watershed (Smith et al. 2017), nearly 100 genera are listed as coldwater stenotherms (Fritz, EPA unpublished); this list provides a potential means to design appropriate analyses to track climate change and predict outcomes. In comparing MD, PA, and Fritz (EPA unpublished) trait-based thermal designations, some disparity exists (Table X). In this list below, many other Mid-Atlantic taxa (e.g., additional EPT, Chironomidae and other Diptera, aquatic beetles, and crustaceans) are not listed. Developing and fully vetting a more complete list of cold/cool water taxa that are vulnerable to temperature change in the Chesapeake watershed is a research priority. Going forward, monitoring for individual indicator taxa will be critical, but whole assemblage assessments will provide stronger evidence of shifting spatial patterns.

Table 2. Comparison of thermal trait-based assignments for macroinvertebrate taxa in MD and PA (adapted from USEPA 2016), and Fritz, EPA unpublished.

Order	**Genus**	**MD**	**PA**	**EPA (Fritz unpubl.)**
Diptera	*Bittacomorpha*	Cold		Cold
Diptera	*Dixa*	Cold		Cold/Cool
Diptera	*Heleniella*	Cold		Cold
Diptera	*Prodiamesa*	Cold		Cold
Ephemeroptera	*Ameletus*		Cold	Cold
Ephemeroptera	*Cinygmula*	Cold	Cold	Cold
Ephemeroptera	*Diphetor*	Cold	Cold	Cold/Cool
Ephemeroptera	*Drunella*		Cold	Cold/Cool
Ephemeroptera	*Epeorus*	Cold	Cool	Cold
Ephemeroptera	*Ephemera*	Cold		Cold/Cool
Ephemeroptera	*Ephemerella*		Cold	Cold/Cool
Ephemeroptera	*Eurylophella*		Cold	Cold/Cool
Ephemeroptera	*Habrophlebia*	Cold	Cool	Cold
Ephemeroptera	*Paraleptophlebia*	Cold		Cold/Cool
Plecoptera	*Alloperla*	Cold	Cold	Cold
Plecoptera	*Amphinemura*		Cold	Cold/Cool
Plecoptera	*Diploperla*		Cold	Cold
Plecoptera	*Haploperla*		Cold	Cold/Cool
Plecoptera	*Isoperla*		Cold	Cold/Cool
Plecoptera	*Leuctra*	Cold		Cold/Cool
Plecoptera	*Malirekus*		Cold	Cold
Plecoptera	*Peltoperla*		Cold	Cold/Cool
Plecoptera	*Pteronarcys*		Cold	Cold/Cool
Plecoptera	*Remenus*		Cold	Cold
Plecoptera	*Sweltsa*	Cold	Cold	Cold/Cool
Plecoptera	*Tallaperla*	Cold	Cold	Cold/Cool
Plecoptera	*Yugus*		Cold	Cold
Trichoptera	*Diplectrona*	Cold		Cold
Trichoptera	*Wormaldia*	Cold	Cold	Cold/Cool

Like fishes and macroinvertebrates, freshwater mussels are partially structured by temperature where species occupy niches under thermal optima and threshold constraints. Nearly 70% of the 297 species of the freshwater mussel family Unionidae in North America are extinct or vulnerable to extinction (Bogan, 1993). Several factors (habitat degradation, water quality, temperature, etc.) are playing role in the decline of the freshwater mussels. Recent findings suggest that many freshwater mussel species in the Southeastern United States are already living close to their upper thermal tolerances (Pandolfe et al. 2012; Martin 2016).

One key problem in monitoring and assessing the effects of temperature change is in assigning definitive thermal traits to freshwater mussel taxa. A need exists to develop a strategy to obtain and classify the thermal tolerance information on the resident freshwater mussels within the Chesapeake Bay watershed as this information is currently limited. Wood et al. (2021) has summarized the status and distribution of the freshwater mussels of the Chesapeake Bay watershed (Table 3). The next step is to review the scientific literature and assign upper thermal limits for each species within the Chesapeake Bay watershed. Martin (2016) has started the process that could be used. A similar effort was convened by the Ohio River Valley Water Sanitation Commission (ORSANCO) to assign temperature criteria limits to the 160 species of fishes in the Ohio River. A similar effort could be completed for the freshwater mussels.

Table 3. Status and Distribution of the Freshwater Mussel of the Chesapeake Bay watershed.

Genus	Species	Common Name	Federal Status	VA	MD	DC	DE	WV	PA	NY
Alasmidonta	*heterodon*	Dwarf Wedgemussel	🟥	YES	YES	YES	YES	NO	YES	NO
Alasmidonta	*undulata*	Triangle Floater		YES	YES	YES	YES	YES	YES	YES
Alasmidonta	*varicosa*	Brook Floater		YES	YES	YES	YES**	YES	YES	YES
Alasmidonta	*marginata*	Elktoe		NO	NO	NO	NO	NO	YES	YES
Utterbackiana (previously Anodonta)	*implicata*	Alewife Floater		YES	YES	YES	YES	NO	YES	NO
Anodontoides	*ferussacianus*	Cylindrical Papershell		NO	NO	NO	NO	NO	YES	YES
Elliptio	*complanata*	Eastern Elliptio		YES	YES	YES	YES	YES	YES	YES
Elliptio	*congaraea*	Carolina Slabshell		YES	NO	NO	NO	NO	NO	NO
Elliptio	*fisheriana*	Northern Lance		YES	YES	YES	YES	YES	YES	NO
Elliptio	*Icterina*	Variable Spike		YES	NO	NO	NO	NO	NO	NO
Elliptio	*lanceolata*	Yellow Lance	🟨	YES	YES	NO	NO	NO	NO	NO
Elliptio	*producta*	Atlantic Spike		YES	YES	NO	NO	NO	NO	NO
Elliptio	*roanokensis*	Roanoke Slabshell		YES	NO	NO	NO	NO	NO	NO
Elliptio	*angustata*	Carolina Lance		YES	NO	YES	NO	NO	NO	NO
Fusconaia	*masoni*	Atlantic Pigtoe		YES	NO	NO	NO	NO	NO	NO
Lampsilis	*cardium/ovata*	Pocketbook		YES	YES	NO	NO	NO	YES	NO
Lampsilis	*cariosa*	Yellow Lampmussel		YES	YES	YES	YES	YES	YES	YES
Lampsilis	*radiata*	Eastern Lampmussel		YES	NO	YES	YES	YES	YES	YES
Lasmigona	*compressa*	Creek heelsplitter		NO	NO	NO	NO	NO	NO	YES
Lasmigona	*subviridis*	Green Floater		YES	YES	YES	YES**	YES	YES	YES
Leptodea	*ochracea*	Tidewater Mucket		YES	YES	YES	YES	NO	NO	NO
Ligumia	*nasuta*	Eastern Pondmussel		YES	YES	YES	YES	YES	NO	NO
Margaritifera	*margaritifera*	Eastern pearlshell		NO	NO	NO	NO	NO	NO	YES
Pleurobema	*collina*	James Spinymussel	🟥	YES	NO	NO	NO	YES	NO	NO

Pyganodon	*cataracta*	Eastern Floater		YES	YES	YES	YES	YES	YES	YES
Pyganodon	*grandis*	Giant floater		NO	NO	NO	NO	NO	NO	YES*
Strophitus	*undulatus*	Creeper		YES	YES	YES	YES	YES	YES	YES
Utterbackia	*imbecillis*	Paper Pondshell		YES	YES	YES	NO	YES	YES	YES
▨	: Expected Extinct		**Bay Watershed**	**VA**	**MD**	**DC**	**DE**	**WV**	**PA**	**NY**
🟥	: Endangered	TOTAL:	28	23	16	15	11	12	15	13
🟨	: Threatened									

E. Evaluation

Given the limited data at present for specific mitigation efforts and uncertainty of future climate scenarios and impacts, the conceptual framework developed by Foden et al. (2013) provides a framework for identifying the species most vulnerable to extinction from a range of climate change induced stresses (Fig 4.). The framework guides users to independently measure three dimensions of climate change vulnerability, namely sensitivity (the lack of potential for a species to persist in situ), exposure (the extent to which each species' physical environment will change) and low adaptive capacity (a species' inability to avoid the negative impacts of climate change through dispersal and/or microevolutionary change). The three dimensions can then be used to allocate species to one of four classes of climate change vulnerability, each with different implications for conservation (Figure 1). Species are considered to be highly vulnerable to climate change if they qualify as highly sensitive, highly exposed and of lowest adaptive capacity.

Ultimately, a vulnerability assessment (sensu Hare et al. 2016) is needed to better understand the drivers and stressors of rising stream temperatures, their effects on aquatic resources, and the risk to fish and other aquatic species (Fig 5).

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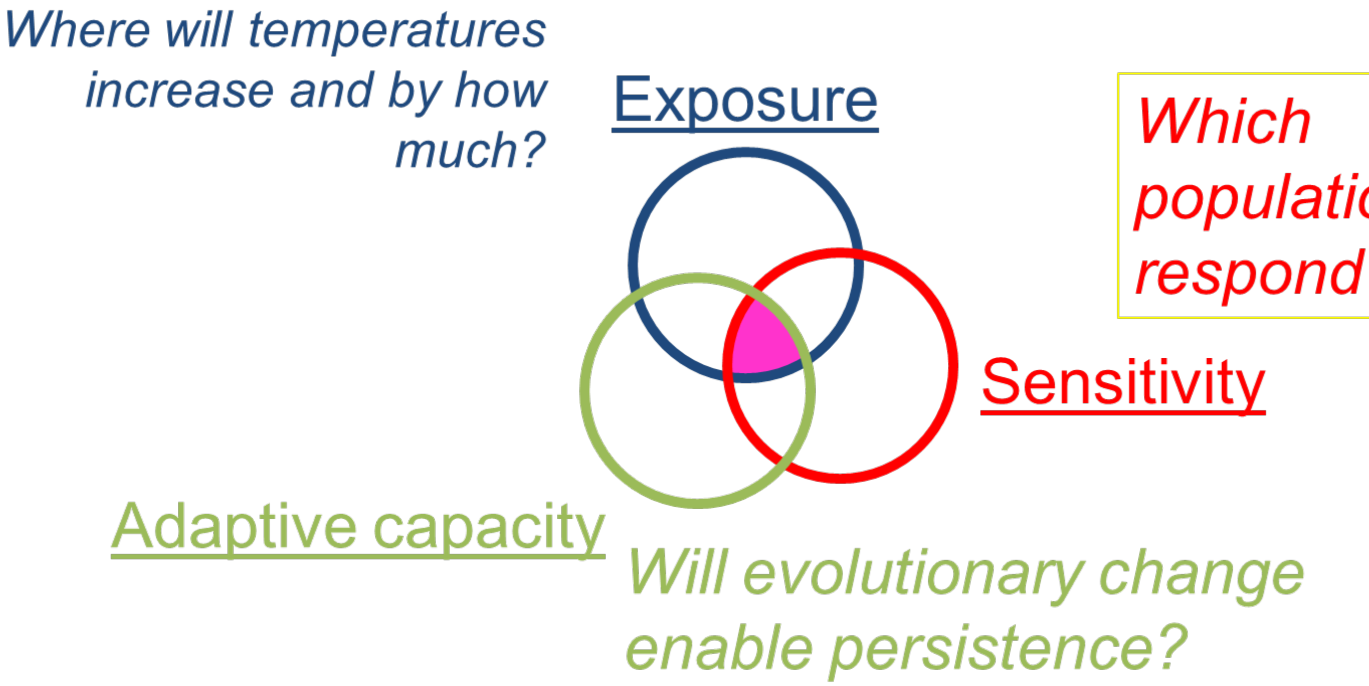
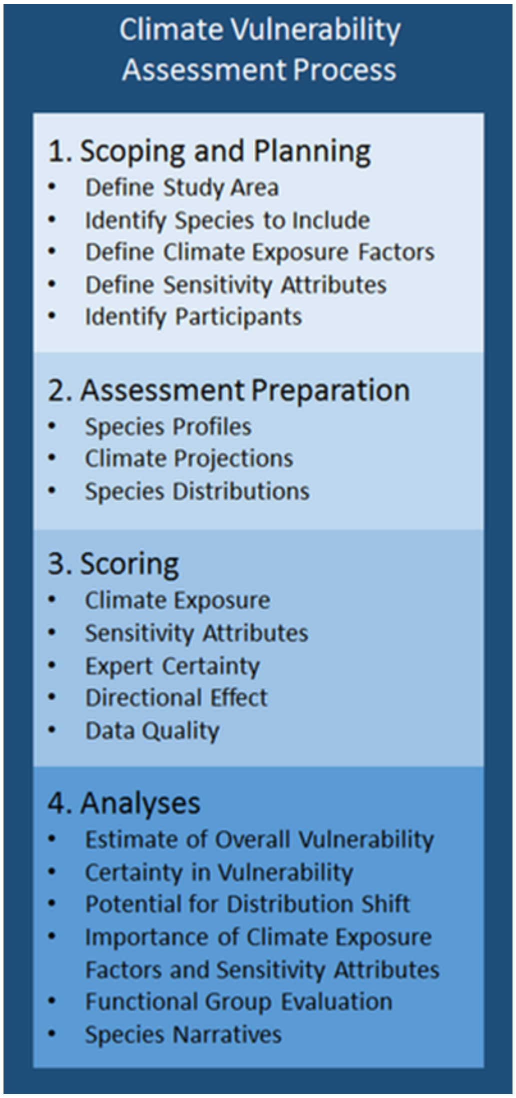


Figure 4. Conceptual model to assess effects of rising water temperatures on aquatic organisms (Adapted from Foden et al. 2013)



Climate Vulnerability Assessment Process

1. Scoping and Planning
- Define Study Area
- Identify Species to Include
- Define Climate Exposure Factors
- Define Sensitivity Attributes
- Identify Participants

2. Assessment Preparation
- Species Profiles
- Climate Projections
- Species Distributions

3. Scoring
- Climate Exposure
- Sensitivity Attributes
- Expert Certainty
- Directional Effect
- Data Quality

4. Analyses
- Estimate of Overall Vulnerability
- Certainty in Vulnerability
- Potential for Distribution Shift
- Importance of Climate Exposure Factors and Sensitivity Attributes
- Functional Group Evaluation
- Species Narratives

Figure 5. Climate vulnerability assessment process (From Hare et al. 2016)