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Climate change risks, extinction debt, and conservation implications for a threatened freshwater fish: Carmine shiner (*Notropis percobromus*)

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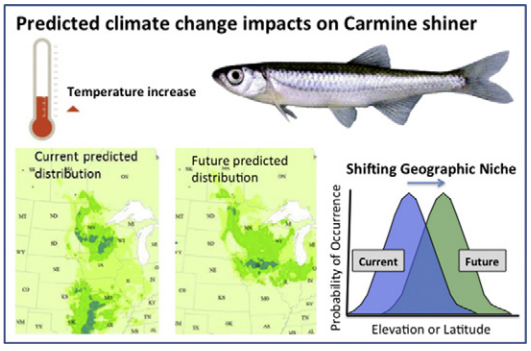
HIGHLIGHTS

- Climate change is hypothesized to disproportionately impact freshwater fishes.
- Species distribution modeling was used to predict range shifts in Carmine shiner.
- Thermally suitable habitat may decrease by half of current by the 2050s.
- This suggests climate driven extinction-debt from isolation in unsuitable habitat.
- Assisted migration may be needed to ensure this species doesn't remain in hot water.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change is affecting many freshwater species, particularly fishes. Predictions of future climate change suggest large and deleterious effects on species with narrow dispersal abilities due to limited hydrological connectivity. In turn, this creates the potential for population isolation in thermally unsuitable habitats, leading to physiological stress, species declines or possible extirpation. The current extent of many freshwater fish species' spatio-temporal distribution patterns and their sensitivity to thermal impacts from climate change — critical information for conservation planning — are often unknown. Carmine shiner (*Notropis percobromus*) is an ecologically important species listed as threatened or imperilled nationally (Canada) and regionally (South Dakota, United States) due to its restricted range and sensitivity to water quality and temperature. This research aimed to determine the current distribution and spatio-temporal variability in projected suitable habitat for Carmine shiner using niche-based modeling approaches (*MaxEnt*, *BIOCLIM*, and *DOMAIN* models). Statistically downscaled, bias-corrected Global Circulation Models (GCMs) data was used to model the distribution of Carmine shiner in central North America for the period of 2041–2060 (2050s). Maximum mean July temperature and temperature variability were the main factors in determining Carmine shiner distribution. Patterns of projected habitat change by the 2050s suggest the spatial extent of the current distribution of Carmine shiner would shift north, with >50% of the current distribution changing with future projections based on two Representative Concentrations Pathways for CO_2 emissions. Whereas the southern extent of the distribution would become unsuitable for Carmine shiner, suitable habitats are predicted to become available further north, if accessible. Importantly, the majority of habitat gains for Carmine shiner would be in areas currently inaccessible due to dispersal limitations, suggesting current populations may face an extinction debt within the next half century. These results provide

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evidence that Carmine shiner may be highly vulnerable to a warming climate and suggest that management actions - such as assisted migration - may be needed to mitigate impacts from climate change and ensure the long-term persistence of the species.

1. Introduction

Climate change is considered to be a major global threat to biodiversity (Chen et al., 2011; Solomon et al., 2007; Walther et al., 2002) primarily through biological effects including latitudinal and elevational species distribution range shifts (see Bellard et al., 2012; Devictor et al., 2012), alterations to species composition (Bellard et al., 2012; Pereira et al., 2010) or phenology (Bernardo et al., 2007; Huey et al., 2012). The magnitude of these threats is predicted to be larger in sensitive environments such as freshwater ecosystems where organisms are restricted in their movement capacity to the river channel as compared with terrestrial ecosystems (Dudgeon, 2010). For species with limited dispersal abilities and specialized ecological niches - like many small-bodied freshwater fishes - the impacts of climate change can be intensified (Gaston, 1994; Schloss et al., 2012). Accordingly, elucidating how species distributions may be altered in response to climate change remains an important question for freshwater ecosystem conservation and management.

A common response of animals to thermal impacts is to disperse into novel, thermally-suitable habitats. Generally, these novel habitats are found by moving towards differing latitudinal or elevational gradients where thermal habitat is more suitable (Chen et al., 2011; Devictor et al., 2012). However, due to hierarchical and dendritic river networks, freshwater organisms may not be able to migrate or adapt fast enough to keep pace with a warming climate (Brook et al., 2008; Tingley et al., 2009). For example, connectivity is often limited in freshwater ecosystems by both natural and anthropogenic factors (e.g., waterfalls, dams, road crossings; Januchowski-Hartley et al., 2013; Maitland et al., 2016), which have historically acted as dispersal barriers to fish and have helped shape current species' distributions (Rahel, 2007). Although many studies have documented range expansions and contractions from shifting thermal habitats in freshwater systems, few studies have documented whether there is sufficient dispersal ability to reach these habitats, or whether such shifts may represent a form of extinction debt that may leave fish stranded in unsuitable habitats (Fausch et al., 2002; Olden et al., 2010). In fact, many species with narrow habitat ranges are of special concern as they may be unable to adapt or disperse at a rate that is sufficient to track climate change, and are consequently a priority for conservation management.

Carmine shiner (*Notropis percobromus*, Cope, 1871) has been listed as a threatened or imperilled species nationally (Canada) and regionally (South Dakota, United States). A restricted range and sensitivity to changes in water temperature and habitat quality (avoiding temperature over 27.2 °C; Stauffer et al., 1975) could be the primary reasons for the species' designation (Fisheries and Oceans Canada, 2013). Carmine shiner is a small minnow of the genus *Notropis*, where many species are difficult to distinguish, and in some cases where phylogenetic relationships among species are still unresolved (Fisheries and Oceans Canada, 2013). Carmine shiner, in particular, has recently been assessed as a valid species from a formerly widespread and variable species, Rosyface shiner (*N. rubellus*). Several other taxa were also identified within the former distribution of Rosyface shiner, but the exact definition and distribution of these taxa remain somewhat uncertain and are an area of active research (Berendzen et al., 2008; Berendzen et al., 2009). An omnivore, Carmine shiner is a low to mid-tropic level consumer, typically inhabiting warm-water environments (Lyons et al., 2009). The species is native to the Midwestern United States and to southern Manitoba in Canada. It prefers clear pool and riffle habitat in large creeks and small rivers. Because water temperature and river flow can be limiting factors for the species' survival (Stauffer et al., 1975), some populations (e.g., those found in Ohio) have already experienced declines to the point of extirpation during the last 50 years (COSEWIC, 2001; Trautman, 1981).

Understanding how suitable habitats for species may be impacted by climate change is the first step in determining appropriate recovery actions. In North America, evidence has shown that climate change has resulted in shorter winters, more ice-free days, increases in annual average temperatures, and heavier precipitation events (Cherkauer and Sinha, 2010). Climate change models have predicted increases in air temperatures between 1 °C and 7 °C in winter and 3 °C to 11 °C in summer by the 2050s (Christensen et al., 2007; Poesch et al., 2016). In areas where Carmine shiner are currently found, mean annual air temperatures have risen by 2 °C and evaporation rates have increased by 30% within a 20 year period (1960s to mid-1980s; Schindler et al., 1990). Although Carmine shiner is a warm-water species, climate change could be a significant threat to its persistence (Tanentzap et al., 2008) as it may alter stream thermal structure through direct changes in meteorological variables such as air temperature (Keller et al., 2005; Solomon et al., 2007; Tanentzap et al., 2008). For example, Urban (2015) suggests that future global temperature increases will be a major contributing factor towards accelerating extinctions risks, possibly threatening up to one in six species under current regulatory policies. Given the extent of potential habitat loss and species extirpations from a warming climate, particularly for threatened species such as Carmine shiner, there is a pressing need to elucidate the characteristics of species' current climatic niches, and how they may change in the future. This information can be helpful in identifying conservation goals and actions that will allow the species to persist in a changing climate.

The objectives of this study were to 1) predict current and future spatial distribution patterns of Carmine shiner, and 2) estimate how variations of climatic variables affect future spatio-temporal distribution patterns. Specifically, we evaluated the potential effects of climate change on Carmine shiner's distribution, and determined the rate of latitudinal shifting of the species' distribution in response to climate change under both low (RCP2.6) and high (RCP8.5; see Methods) CO_2 emission scenarios. Because fish are ectotherms, we hypothesized that predicted future climate change will have a significant impact on the distribution of this species. Specifically, we predict that the spatial distribution of Carmine shiner will become truncated with respect to the current southern extent and will expand with respect to the current northern extent with warming climatic conditions. This hypothesis was examined using three species distribution model (SDM) approaches (*MaxEnt*, *BIOCLIM*, *DOMAIN*), which are fundamentally different in terms of their theoretical assumptions, but rely on presence-only occurrence records.

2. Methods

2.1. Data acquisition

A total of 964 occurrence records of Carmine shiner in North America were compiled from a variety of sources including the primary literature, Canadian Species at Risk reports (Fisheries and Oceans Canada, 2013), the Global Biodiversity Information Facility (http://www.gbif.org), FishBase (http://www.fishbase.org), Minnesota Department of Natural Resources (http://www.dnr.state.mn.us), Wisconsin