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Climate-driven synchrony in growth-increment chronologies of fish from the world's largest high-elevation river

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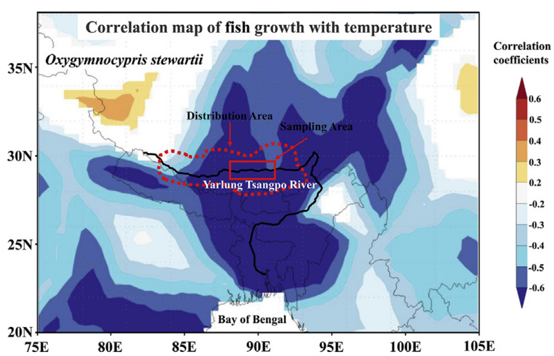
HIGHLIGHTS

- Fish growth-environment relations were established in a river fed by glacial water.
- Growth chronologies of fish were established using dendrochronological methods.
- Fish chronologies were negatively correlated with air temperature.
- Higher trophic level (TP) fish were more sensitive to climate than lower TP fish.

GRAPHICAL ABSTRACT



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ABSTRACT

Understanding how sensitive aquatic ecosystems respond to climate change is essential for effective biodiversity conservation and management. The Tibetan Plateau (TP) is one of the most globally sensitive areas to climate change with potentially serious implications for resident fish populations and aquatic food webs. However, how the growth of TP fish responds to climate change, and how this response varies with the trophic level of different species remain unknown. We established growth-increment chronologies of two important Schizothoracinae fishes that are endemic to the TP (e.g., the omnivorous *Schizopygopsis younghusbandi* and the carnivorous *Oxygymnocypris stewartii*) from the Yarlung Tsangpo River, using otolith increment width measurements and dendrochronological methods. These growth chronologies were correlated with key indicators of environmental variation (temperature, precipitation, and river discharge) to examine the potential effects of climate change. The two chronologies displayed synchronous responses to recent climate change. In this glacial-fed river, the growth of both fish species was significantly and negatively correlated with the mean annual air temperature, while it was positively but not significantly correlated with precipitation and discharge. The higher trophic level species *O. stewartii* was more sensitive to climate than was the lower trophic level species *S. younghusbandi*, with temperature variables explaining a higher proportion of growth variability in *O. stewartii* (64.6%) than in *S. younghusbandi* (46.4%). The results collectively indicate that both species are highly sensitive to climate change, which may affect fish growth by altering water environment, fish physiological fitness and food availability. This study provides further empirical evidence of the utility of growth-increment

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chronologies for investigating the effects of climate change on aquatic ecosystems across different basins and water body types of the TP. These findings can inform conservation and management actions related to addressing climate change on the TP and other high-elevation temperate systems found worldwide.

1. Introduction

Climate change and its environmental consequences have been widely observed and acknowledged (Walther et al., 2002; Parmesan, 2006; IPCC, 2014). Understanding how sensitive ecosystems respond to climate change is essential for effective conservation and management, and can provide sentinels for changes in other ecosystems (Adrian et al., 2009). The Tibetan Plateau (TP), which is commonly known as the third pole because of its massive size and high altitude (total area 2,500,000 km^2, average elevation >4000 m a.s.l.), is one of the most sensitive areas in the world to climate change (Kang et al., 2010; Tao et al., 2015; Tao et al., 2018). The warming rate of this region was twice that of the global average during the period of 1960–2012 (IPCC, 2014; Tibet Regional Innovation Team, 2015). The TP stores and cycles vast amounts of water resources in various forms, such as rivers, lakes, glaciers, snow cover and permafrost (Ma et al., 2011; Yao et al., 2012; Cuo et al., 2014). Climate warming has intensified the global water cycle (Huntington, 2006), thereby resulting in substantial environmental changes in the extent and characteristics of aquatic ecosystems (i.e., lakes and rivers) in this area. For example, >80% of lakes increased in area between the 1970s and 2010 (Zhang et al., 2014a). The flow regimes (i.e. magnitude, timing, frequency, and duration of flow events) of all major rivers have been affected by climate change to varying degrees (Cuo et al., 2014).

Such environmental changes not only threaten the water supply for 1.4 billion people on and around the TP (Immerzeel et al., 2010) but also alter aquatic ecosystems at all levels of organisms, and across the entire food web. More specifically, warming can stimulate increases in primary production (including the growth of benthic algae and phytoplankton) in lakes and rivers (Allan and Castillo, 2007; Adrian et al., 2009). Lake area expansion and increasing surface runoff from precipitation or melting water can also increase the input and availability of allochthonous organic matter (e.g., terrestrial plants and arthropods) in lakes and rivers (Vannote et al., 1980; Doi, 2009). These terrestrial carbon sources are an important subsidy to aquatic food webs and may increase due to the warming and wetting of the TP (Xu et al., 2007; Chen et al., 2013). In recent decades, the combination of changes in the temperature and precipitation regimes significantly increased net riparian primary production in the TP region (Fan et al., 2010; Zhang et al., 2014b). Consequently, the increasing of primary production could accelerate the growth of aquatic consumers such as fish. At present, it is largely unknown how climate-induced changes in aquatic primary production and terrestrial carbon subsidies to aquatic food webs will affect fish growth in the TP.

Growth chronologies of fish derived from regular growth increments (i.e. annuli) in carbonate body parts (e.g. scales and otoliths) have increasingly been used to study fish responses to climate change (Black et al., 2005; Morrongiello et al., 2012; Doubleday et al., 2015). Growth chronologies can provide a long-term continuous record of environmental changes which is often lacking from traditional biological monitoring data (Gillanders et al., 2012). Two common dendrochronological techniques, i.e. crossdating and detrending, are critical in building growth chronologies. Crossdating assures that each increment is assigned to the right calendar year and provides a mean to assess the quality of dating (Black et al., 2016). Detrending aims to remove the intrinsic effects (e.g., from age or size) on increment width series from the extrinsic effects (i.e. from the environment) before establishing a growth chronology (Weisberg, 1993; Cyterski and Spangler, 1996; Weisberg et al., 2010). The annual increment width displays an intrinsic decreasing trend with age or size. Only once this intrinsic trend is eliminated (i.e., detrending) can the extrinsic effects on the annual increment width series or master growth chronology be examined. The established master growth chronology can not only be used to investigate the effects of environmental change on fish growth (Black et al., 2008; Rypel, 2009; Tao et al., 2015), but also be used for environmental reconstruction (Black et al., 2009), age validation (Black et al., 2005), detecting changes in reproductive phenology (Tao et al., 2018), and exploring synchronous responses across ecosystems (Black, 2009; Izzo et al., 2016; Ong et al., 2016). Climate change induces alterations in freshwater fish growth, and these can be habitat-specific (e.g., lotic vs lentic) alterations (Richard and Rypel, 2013; Tonkin et al., 2014); changes in fish growth can have distinct impacts based on the trophic level positioning of each species (Voigt et al., 2003; Thackeray et al., 2016). For example, climate change can decrease bottom-up trophic cascade effects along the food chain, and these effects can be delayed in higher predators (Thompson and Ollason, 2001; Frederiksen et al., 2006).

Here, we studied the climate change response of two endemic fish species in the world's highest elevation large river and one of the most climate-change sensitive catchments on the TP (You et al., 2007; Zhang et al., 2014b). Our specific objectives were to establish growth index chronologies of the omnivorous *Schizopygopsis younghusbandi* Regan, 1905 and the carnivorous *Oxygymnocypris stewartii* Lloyd, 1908 from the Yarlung Tsangpo River based on annual increment width measurements of otoliths and to investigate the effects of climate change on the growth of fish at different trophic levels over time. The outcomes of this study provide information on how riverine fish at different trophic levels respond to climate change on the TP and how these responses differ in fish from other water-body types (e.g., lakes) in this area. This study will provide essential insights for future aquatic ecosystem management and conservation to help cope with climate change on the TP and other high-elevation temperate systems around the world.

2. Methods

2.1. Study species

Schizopygopsis younghusbandi is one of the most important local commercial fishes and is only distributed in the middle reaches of the Yarlung Tsangpo River (Duan et al., 2014). During a fish survey conducted from 2004 to 2006, *S. younghusbandi* contributed to 30% of the total captures (Chen and Chen, 2010). This species is omnivorous and mainly feeds on periphyton algae and macrophytes, as well as on some invertebrates and their eggs (Ji, 2008). It can live up to 20 years (Chen et al., 2009; Duan et al., 2014), and males and females sexually mature at four and seven years of age, respectively (Duan, 2015).

Oxygymnocypris stewartii is the top predator fish in the Yarlung Tsangpo River. Due to rapid population degradation, this species was listed as an endangered species (Yue and Chen, 1998). During the survey (Chen and Chen, 2010), *O. stewartii* accounted for 8% of the total captures (Jia and Chen, 2011). The main food sources of *O. stewartii* are invertebrates as well as larvae and juveniles of other endemic or alien fish species, including *S. younghusbandi* and *Carassius auratus* (Ji, 2008). The longevity of *O. stewartii* is approximately 20 years, and males and females reach sexual maturity at five and seven years of age, respectively (Huo, 2014).