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Projection of invertebrate populations in the headwater streams of a temperate catchment under a changing climate

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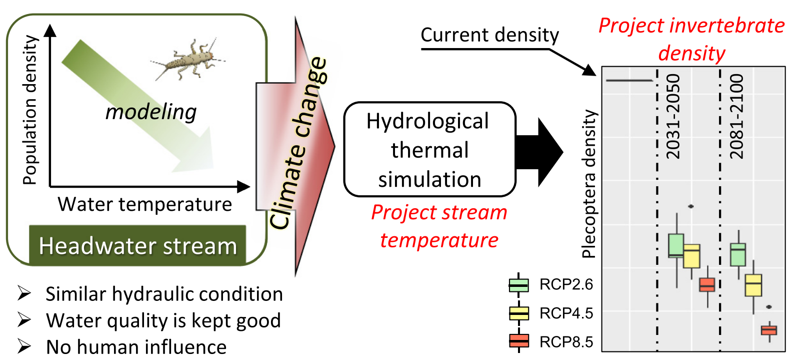
HIGHLIGHTS

- Anticipated climate changes might alter the habitat of stream animals.
- Hydrological and climate models were used to project future stream temperature.
- Invertebrate density was projected by future stream temperature.
- Spatial distribution of density reduction was projected in a catchment.
- Partial taxa in Plecoptera family were sensitive indicator of climate change.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change places considerable stress on riverine ecosystems by altering flow regimes and increasing water temperature. This study evaluated how water temperature increases under climate change scenarios will affect stream invertebrates in pristine headwater streams. The studied headwater-stream sites were distributed within a temperate catchment of Japan and had similar hydraulic-geographical conditions, but were subject to varying temperature conditions due to altitudinal differences (100 to 850 m). We adopted eight general circulation models (GCMs) to project air temperature under conservative (RCP2.6), intermediate (RCP4.5), and extreme climate scenarios (RCP8.5) during the near (2031–2050) and far (2081–2100) future. Using the water temperature of headwater streams computed by a distributed hydrological-thermal model as a predictor variable, we projected the population density of stream invertebrates in the future scenarios based on generalized linear models. The mean decrease in the temporally averaged population density of Plecoptera was 61.3% among the GCMs, even under RCP2.6 in the near future, whereas density deteriorated even further (90.7%) under RCP8.5 in the far future. Trichoptera density was also projected to greatly deteriorate under RCP8.5 in the far future. We defined taxa that exhibited temperature-sensitive declines under climate change as cold stenotherms and found that most Plecoptera taxa were cold stenotherms in comparison to other orders. Specifically, the taxonomic families that only distribute in Palearctic realm (e.g., *Megarcys ochracea* and *Scopura longa*) were selectively assigned, suggesting that Plecoptera family with its restricted distribution in the Palearctic might be a sensitive indicator of climate change. Plecoptera and Trichoptera populations in the headwaters are expected/anticipated to decrease over the considerable geographical range of the catchment, even under the RCP2.6 in the

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near future. Given headwater invertebrates play important roles in streams, such as contributing to watershed productivity, our results provide useful information for managing streams at the catchment-level.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) anticipated that air temperature would increase by ~4 °C in the end of the 21st century (IPCC, 2007), with wide-ranging consequences that include fluctuating precipitation. Changing climatic conditions are expected to cause major stress to stream organisms, through altering flow regimes and elevating water temperature (Sala et al., 2000; Van Vliet et al., 2013). However, climate change-related impacts on stream organisms remain poorly understood (Durance and Ormerod, 2007; Moritz and Agudo, 2013). In addition, the extinction rate in freshwater ecosystems is faster than that in marine and terrestrial ecosystems (Jenkins, 2003; Revenga et al., 2005; Xenopoulos et al., 2005; Strayer and Dudgeon, 2010). Therefore, it is essential to evaluate how future temperature increases due to global warming will affect freshwater ecosystems.

Stream invertebrates are generally poor dispersers that strongly depend on local environments; thus, the relationship between local environments, including water quality and invertebrates, have been frequently studied (e.g., Kerans and Karr, 1994; Glendell et al., 2014). Of the local environmental factors in rivers, water temperature is the primary factor constraining the growth, metabolism, and survival of stream invertebrates (Sweeney and Vannote, 1986; Brittain, 1991; Robinson and Minshall, 1998). Several studies (e.g., Gaufin and Hern, 1971; Quinn et al., 1994) have attempted experimental approaches to understand biological response of invertebrate changes to water temperature, but such research is limited to a few taxonomic groups and cannot inform us about ecological responses at a community level. Researchers (e.g., Statzner and Higler, 1986; Tsuruishi, 2006; Duggan et al., 2007) have explored thermal influences on invertebrates through field monitoring; however, habitats of stream invertebrates are determined by complex environmental factors, including flow velocity, substrate, and water quality. Consequently, it is difficult to detect the specific impact of water temperature on the invertebrate community of streams.

In general, field studies of invertebrate in this line of inquiry have focused on midstream to downstream zones because of the relative ease of entry to a watercourse for sampling. However, midstream to downstream water quality is generally impaired by point and nonpoint source pollution, which might obscure the link between water temperature and invertebrates. In the upland forests, stream water is mainly composed of intermediate flow filtered through forested soil (Neary et al., 2009), with consumption and canopy interception reducing direct runoff (Hewlett, 1982). Typically, water quality is higher in the headwaters of such rivers than downstream, while water temperature varies depending on the altitude and season in temperate catchments (Sponseller et al., 2001). Furthermore, headwater streams are generally free of thermal pollution caused by industrial effluents (Caissie, 2006). Such environments are therefore suitable study areas for improving our understanding of ecological responses to water temperature gradients (Arai et al., 2015).

To date, researchers have modeled the impact of climatic-change on stream invertebrates using general circulation models (GCMs). Li et al. (2013) used invertebrate data collected throughout South Korea and predicted the habitat distribution of invertebrates under future climates by introducing GCM-projected air temperatures. However, this study assumed negligible effects from other habitat conditions (e.g., current velocity). In addition to air temperature, other reports have used precipitation and topographic variables to project the distribution of stream invertebrates under changing climate scenarios (Bálint et al., 2011; Domisch et al., 2011; Domisch et al., 2013). Although previous studies succeeded in integrating GCMs into habitat models, challenges remain. First, surrogates of water temperature measures (e.g., annual maximum air temperature) were used because air temperature variables are easily accessible. Li et al. (2013, 2014) projected habitat distribution of stream invertebrates by water temperature although the water temperature used was estimated by GCM-projected air temperature using a linear regression model. Second, projection uncertainty under different GCMs (Wilby and Harris, 2006) is rarely taken into account, with only one or two GCMs generally being used. This uncertainty could lead to bias when attempting to project stream invertebrate responses. Thus, the number of GCMs should be increased for a more objective evaluation of means and deviations.

We aimed to develop a predictive model of stream invertebrate density under different climatic change scenarios using multiple GCMs, biological field data from headwater streams, and a hydrological simulation (see conceptual study flow in Fig. 1). We used existing quantitative sampling data of stream invertebrate and water temperature (Arai et al., 2015) in the headwater streams of a temperate catchment in northeast Japan. The headwater streams selected for the current study had similar hydraulic and geomorphic conditions and was free of human-induced impacts. In addition, stream invertebrates are well known to respond to environmental changes. Thus, these data are useful for projecting fate of headwater invertebrates in response to the water temperature rise while minimizing the effects of driving factors other than water temperature on invertebrates. We adopted eight GCM types and three RCP (Representative Concentration Pathways) scenarios to check model uncertainty and assess climate-change effects on stream invertebrate density. By inputting GCM-projected air temperature into an existing distributed hydrological-thermal model (hereafter hydrothermal model), we computed stream water temperatures for the studied headwaters. Finally, regression models were developed to project invertebrate density at the study catchment under different climate change scenarios (based on water temperature). Our results are expected to identify invertebrate groups appropriate for use as thermal-sensitive indicators of climate change, which could then be used in the predictions of climate-change effects over much broader scales.

2. Materials and methods

2.1. Study area

We studied headwater streams in the Natori River catchment (939 km^2), northeast Japan. The annual mean air temperature and annual precipitation were 9.8 °C and 1593.5 mm at the Nikkawa Meteorological Station (265 m above sea level [a.s.l.]), 12.7 °C and 1179.5 mm at the Sendai Meteorological Station (39 m a.s.l.), and 11.2 °C and 1257.5 mm at the Zao Meteorological Station (112 m a.s.l.), respectively (Fig. 2). Surface air temperature and precipitation seasonally varies (Fig. S1). Gunawardhana and Kazama (2012) reported that air temperature increased by about 1.8 °C from 1947 to 2007, while precipitation exhibited no specific trend over the same period.

Ten headwater sites in the catchment were selected (Fig. 2) according to four criteria: stream order = 1, similar hydraulics (e.g., water depth) and catchment area, presence of broadleaf riparian forests, and the lack of human influence and artificial structures in the watershed. Water quality was similar with small fluctuations (Arai et al., 2015). Because water temperature fluctuates with season and altitudinal gradients (100–850 m), biological surveys in this environment facilitate the analysis of ecological responses to thermal variation.