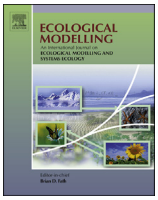
Ecological Modelling 313 (2015) 1–12

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel



A spatial modelling framework for assessing climate change impacts on freshwater ecosystems: Response of brown trout (*Salmo trutta* L.) biomass to warming water temperature

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ARTICLE INFO

Article history:
Received 4 November 2014
Received in revised form 13 June 2015
Accepted 16 June 2015

Keywords:
Spatial modelling
Biogeography
Hindcasting
Swiss Alps
Artificial Neural Network (ANN)
Regional Climate Model (RCM)

ABSTRACT

Mountain regions worldwide are particularly sensitive to on-going climate change. Specifically in the Alps in Switzerland, the temperature has increased twice as fast than in the rest of the Northern hemisphere. Water temperature closely follows the annual air temperature cycle, severely impacting streams and freshwater ecosystems.

In the last 20 years, brown trout (*Salmo trutta* L.) catch has declined by approximately 40–50% in many rivers in Switzerland. Increasing water temperature has been suggested as one of the most likely cause of this decline. Temperature has a direct effect on trout population dynamics through developmental and disease control but can also indirectly impact dynamics via food-web interactions such as resource availability.

We developed a spatially explicit modelling framework that allows spatial and temporal projections of trout biomass using the Aare river catchment as a model system, in order to assess the spatial and seasonal patterns of trout biomass variation. Given that biomass has a seasonal variation depending on trout life history stage, we developed seasonal biomass variation models for three periods of the year (Autumn–Winter, Spring and Summer). Because stream water temperature is a critical parameter for brown trout development, we first calibrated a model to predict water temperature as a function of air temperature to be able to further apply climate change scenarios. We then built a model of trout biomass variation by linking water temperature to trout biomass measurements collected by electro-fishing in 21 stations from 2009 to 2011.

The different modelling components of our framework had overall a good predictive ability and we could show a seasonal effect of water temperature affecting trout biomass variation. Our statistical framework uses a minimum set of input variables that make it easily transferable to other study areas or fish species but could be improved by including effects of the biotic environment and the evolution of demographical parameters over time. However, our framework still remains informative to spatially highlight where potential changes of water temperature could affect trout biomass.

1. Introduction

Mountain regions worldwide are particularly sensitive to ongoing climate change (Rebetez and Reinhard, 2008). Water temperature closely follows the annual air temperature cycle (Pilgrim et al., 1998; Morrill et al., 2005), severely impacting stream and freshwater ecosystems if temperature increases (Carpenter et al., 1992; Hari et al., 2006; Woodward et al., 2010). Freshwater communities are particularly vulnerable to this change because freshwater is (i) already exposed to numerous anthropogenic stressors (Ormerod et al., 2010) and (ii) naturally fragmented into stream networks and water bodies and because (iii) many species have limited dispersal ability to cope with habitat changes (Felipe et al., 2013; Roberts et al., 2013; Woodward et al., 2010; Daufresne and Boët, 2007; Hermoso et al., 2011).

In Switzerland, the trend in air temperature increase over the last three decades reached 0.58 K/decade and was more than twice

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http://dx.doi.org/10.1016/j.ecolmodel.2015.06.023
0304-3800/

as high as the average temperature increase trend in the rest of the Northern Hemisphere (Rebetez and Reinhard, 2008), with temperature having increased the most in Spring and Summer. Additionally, over the last 20 years, brown trout (*Salmo trutta* L.) catch has declined by approximately 40% to 50% in many rivers in Switzerland (Burkhardt-Holm et al., 2002; Zimmerli et al., 2007). Increasing water temperature has been suggested as one of the most likely cause of this decline (Burkhardt-Holm et al., 2002). Temperature has a direct effect on trout population dynamics through developmental and disease control (e.g., proliferative kidney disease (PKD); Wahli et al., 2002) but it can also indirectly impact dynamics via food-web interactions such as resource availability (Brodersen et al., 2011). Previous studies have mostly focused on the impact climate change may have on macro-invertebrates (e.g., Adrian et al., 2006; Jacobsen et al., 2012). Less effort has been put into the assessment of the effects of climate change on secondary consumers such as the brown trout (Milner et al., 2008; Brodersen et al., 2011; Bærum et al., 2013), although young-of-the-year fish may strongly structure the community and processes in aquatic ecosystems (Hansson et al., 2007). Aside from the impacts of climate change on the biotic components of streams, physical components are also particularly vulnerable because these linear structures are already relatively isolated and physically fragmented within a largely terrestrial landscape (Woodward et al., 2010). Rivers and streams may behave differently than terrestrial ecosystems because they can be linearly distributed across an elevation range, such that their heat balance is influenced by a corresponding range of elevation-dependent air temperatures along with other climatic drivers (Hari et al., 2006). Additionally, physical barriers restrict the longitudinal migration of organisms in mountain river catchments; therefore, upward habitat shifts followed by habitat reduction and overall population decreases are expected in mountain ranges with unfavourable hypsometry (Hari et al., 2006).

The fate of Swiss trout populations in a changing climate will depend on (i) the persistence of suitable sites for trout, (ii) the creation of new suitable sites generated by shifting and rising temperature and (iii) the ability of trout to track suitable areas, which are expected to shift toward higher elevations in rivers.

Species distribution models (SDMs; also often designated as ecological niche models, ENMs; Guisan and Thuiller, 2005) that empirically estimate relationships between the spatial distribution of species and aspects of the environment, have commonly been used to address a broad variety of issues including the risk of local and global extinctions. SDMs serve to alert decision makers but also anticipate change to activate adaptive management strategies (see e.g., Cianfrani et al., 2011). Crude estimates of range shifts and extinctions, available early from climatic SDMs applied to many species, have yielded alarming projections, especially for several species in mountain areas (e.g., Thuiller et al., 2005; Jaberg and Guisan, 2001). Although evidence of range expansions and contractions corroborate these projections (Pauli et al., 2007; Pauli et al., 2012; Milner et al., 2008), further developments, particularly regional and high-resolution assessments, are still required to provide safer projections (Randin et al., 2009). The coarse spatial scales of most published assessments (e.g., typically at a 1 km resolution) failed to capture topography and its ability for climatic buffering (Dobrowski, 2011), and several recent studies indicate that taking these factors into consideration can seriously alter model predictions (see review in Willis and Bhagwat, 2009). Although SDM projections remain informative, such predictions based exclusively on projected changes in availability of suitable habitat may be insufficient. Predictions of habitat quality should be derived from proximal species' biological and physiological requirements and explicitly linked to key demographic features (Thomas and Kunin, 1999; Schurr et al., 2012).

As a step forward, we developed a spatially explicit modelling framework that allows projections of trout biomass variation under changing climate conditions. Considering that biomass has a seasonal variation depending on trout life history stage, our frameworks aims at predicting the variation of biomass for three periods of the year (Autumn–Winter, Spring and Summer). Because stream water temperature is a critical parameter for the development of brown trout and other widespread stream fishes, we based our model on water temperature as a function of air temperature, which allowed us to further apply climate change scenarios and aimed to answer the following questions:

(1) What are the spatial and seasonal patterns of trout biomass variation under current environmental conditions?
(2) How will predicted temperature change for the 21st century affect this seasonal biomass variation and how will changes in trout biomass be spatially distributed in the future?

2. Methods

Our modelling framework was applied to the Aare river catchment, which is a tributary of the Rhine River. We studied the main segment between the Lake of Thun and the city of Bern and its tributaries (Fig. 1): a linear extension of approximately 433 km. The analytical framework was organized into three consecutive modelling stages. In the first stage, we computed the air temperature modelling. We used daily mean air temperature measurements to spatially project air temperature in the locations where water temperature was measured. Then we computed the water temperature modelling. For that we used the projected air temperature in the water temperature stations coming from the previous stage to predict daily water temperature for all streams in the study area. Finally we used water temperature together with others variables as explanatory variables for building the seasonal trout biomass variation model (Fig. 2). Models were re-projected under climate change scenarios for two future time periods (2032–2036 and 2057–2061) driven by the following two socio-economic scenarios: the A1B scenario, which was the most extreme assuming no mitigation, and the RCP3PD, which was the mildest (CH2011 2011) (Fig. 2). Each methodological step of the analytical framework is further detailed in the following sections.

2.1. Air temperature modelling

2.1.1. Air temperature measurements

We used 129 climate stations located in a 100-km buffer around the study area. We sought to have enough stations to calculate robust temperature lapse rates and to capture regional variations adequately without any border effects during the interpolation stage.

2.1.2. Air temperature interpolation technique

To spatially project air temperature measurements carried out in the 129 stations (see previous paragraph) in the locations were water temperature measurements were carried out, we first calculated the adiabatic lapse rates of daily mean 2-m air temperature along elevations using linear least-square regressions for the 2007–2011 time periods taken from weather stations of the Swiss national meteorological networks (MeteoSwiss). Next, daily temperature values for each weather station were projected to 0 m.a.s.l., using the regression-based adiabatic lapse rate coefficients previously calculated. These projected sea-level temperature correspond to the intercept of the regression with each local residual, thus reflecting regional characteristics such as