EFFECT OF CLIMATE CHANGE ON BROWN TROUT THERMAL HABITAT SHIFTS ALONG THE RIVER CONTINUUM

JOSÉ M. SANTIAGO

DIEGO GARCÍA DE JALÓN

CARLOS ALONSO

JOAQUÍN SOLANA

Laboratory of Hydrobiology. Universidad Politécnica de Madrid, ETSI Montes, Avda. Ramiro de Maeztu S/N, Madrid 28040, Spain

JAIME RIBALAYGUA

Fundación para la Investigación del Clima. C/ Tremps 11. Madrid 28040, Spain

Water temperature is a central issue in freshwater ecology because it influences on physical, chemical and biological processes and, therefore, on organisms that live all the time or part of this in water. Therefore, climate change might drive the availability of suitable habitat for many fish species including brown trout. This paper deals with the mechanics of the effects of Climate Change on thermal performance in two streams in the centre of the Iberian Peninsula (Duero basin) and its consequences on brown trout (*Salmo trutta*) distribution. Water temperature data were collected by means of 11 thermographs located along the altitudinal gradient of the trout range in the streams. Trout abundance was studied using electrofishing samplings conducted at 37 sites. A high resolution spatio-temporal model was developed to reconstruct the temperature regime of the streams in the past and to simulate its behaviour in the future, using air temperature as the independent variable. The thermal behaviour simulations of the streams were based on the most recent climate change scenarios used in the 5th Assessment Report of the Intergovernmental Panel on Climate Change. According to observations in this study, climate warming might drive a retraction up to 56% of the current brown trout thermal habitat in the studied streams.

1 INTRODUCTION

Water temperature is one axis of brown trout's (*Salmo trutta*) multidimensional niche space. Together with natural obstacles, water temperature sets the limits of brown trout’s distribution within a river. Moreover, temperature has a strong influence on the biological success of fish and others aquatic organisms, acting as a fundamental driver affecting fish’s energy budget, growth and other physiological functions.

Stream temperature is strongly correlated with air temperature, and an increase in temperature due to global warming could disturb aquatic ecosystems dramatically. Climate change may affect habitat availability for many species by increasing or reducing stream temperature. The native range of cold water species such as brown trout is likely to shift to higher altitudes and latitudes. Simulation of climate scenarios can help us assess the magnitude of this loss of suitable range not only in terms of distribution but also physiologic efficiency. These effects are more likely to be noticed at the limits of the thermal axis of a species' ecological niche. This is the case with some Iberian populations of brown trout, which live at the southern edge of their native distribution.

The aim of this study is to quantitatively describe the influence of temperature on trout distribution along the river continuum and determine the temperature range that does not support trout survival with the aim of forecasting the potential habitat shifts in brown trout populations under the recent climate change scenarios established in Taylor et al. [1] and used in the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC [2]).

Table 1. Altitude in meters above sea level (henceforth, m a.s.l.) of electrofishing sites (C*n* and P*n*). *n* is the site number.

Site	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19
Altitude	1610	1320	1258	1150	1106	1044	995	966	961	944	934	921	910	898	885	866	845	805	798

Site	C20	C21	C22	C23	C24	C25	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
Altitude	788	780	778	762	748	730	1620	1337	969	908	879	858	856	835	822	810	804	786

2 MATERIAL AND METHODS

2.1 Study site and field work

Field work was conducted in two tributaries of the Duero River (Cega and Pirón streams, [40º59'N; 3º50'W], Central Spain). These streams are 135 km and 92 km long, respectively. Water temperature was registered every two hours by Hobo® Water Temperature Pro v2 (Onset®) thermographs at 6 Cega sample sites (Ct1 to Ct6) and 5 Pirón sites (Pt1 to Pt5) between April 2011 and October 2012. These loggers were located along the altitudinal trout range at both streams. Maximum and minimum air temperatures were obtained from the AEMET (Spanish Meteorological Agency) station no. 2516 in Ataquines. This meteorological station was selected because it is the closest to temperature sites (average 69 km), with the best data series to fit models and to simulate local climate change scenarios. Data recorded before 1955 were discarded to achieving a homogeneous time-series before its climatic use by applying an homogeneity test (based by a Kolmogorov-Smirnov goodness-of-fit test) that marks years as possible candidates of heterogeneous data, and, in a second phase, it matches the marked years against the distribution of the whole series for determining if they have not true homogeneities.

Electrofishing samplings were conducted at 37 sites (C1 to C25 sites from 1610 m a.s.l. to 730 m a.s.l. in Cega stream, and P1 to P12 sites from 1620 m a.s.l. to 786 m a.s.l. in Pirón stream, Table 1) in August of two consecutive years (1997 and 1998), to characterise trout populations.

2.2 Modelling temperature

Modelling was necessary to reconstruct the streams' thermal data because stream temperature measurements and fishing samplings did not coincide in time. In general, water temperature lags air temperature with a short delay. Commonly, weekly average stream temperatures are used for modelling stream temperature behaviour, because they generally exhibit a stronger correlation than daily averages. On the other hand, the established time for determining thermal tolerance usually is 7 consecutive days (Elliott and Elliott [4]). However, using weekly average could induce errors like overestimate the importance of a threshold, since a determined weekly average does not mean that every considered daily average was equal or higher than the weekly average. Consequently, in this study daily mean temperature was used, because it reflects better the average conditions that trout must bear for short time periods. In addition, studying events in which a threshold was exceeded for 7 consecutive days was preferred over a 7-day average because it reflects better passing a threshold.

To improve the correlation between daily air and water temperatures, a modified Mohseni et al.'s [3] model was used. This modified model includes a one-day temperature differential to introduce a time lag. Non-linear regression was used to estimate the model parameters for each thermal sampling station, and bootstrap techniques were used to ensure parametric significance from a slight residual autocorrelation found. Calculations were made with R software (R Core Team 2013). A 95% confidence interval was calculated for each parameter. A high correlation was detected between annual average daily mean water temperature and altitude in both streams (R^2= 0.986 and 0.985). Thus, altitudinal interpolation was undertaken to estimate the parameters at each electrofishing site; and altitudinal extrapolation was performed for sites C23, C24 and C25 at Cega stream, and for P11 and P12 at Pirón stream. From the obtained thermal models for the electrofishing sites, the day–number exceeding various daily mean temperature thresholds between 1997 and 1998 was quantified. Time-number exceeding the thresholds for

7 consecutive days and maximum consecutive days above those thresholds also was quantified. The same models were used to forecast thermal behaviour at every electrofishing site for each climate scenario.

Two climate change scenarios, RCP4.5 (a Representative Concentration Pathways stable scenario) and RCP8.5 (which included a stronger increase in CO_2 concentrations) (Taylor et al. [1]), were locally simulated using a two-step analogue/regression statistical downscaling (Ribalaygua et al. [5]). Both concentration scenarios were then applied to a set of nine different global climate models (BCC-CSMI-1, CanESM2, CNRM-CM5, GFDL-ESM2M, HADGEM2-CC, MIROC-ESM-CHEM, MPI-ESM-MR, MRI-CGCM3 and NorESM1-M). Finally, the two predicted thermal trajectories were obtained by averaging the nine models considered.

3 RESULTS

Brown trout were not detected downstream of the C24 Cega site and the P8 Pirón site. They were also absent in intermediate sites, such as the C14 and P3 sites, in the first year. At the C15 site, only one trout was captured each year. At the C24 site, one and six trout were caught in the first and second samplings, respectively. A drought occurred during the second year; as a consequence, C7, C11, C14, C22, C23, P3, and sites downstream of P10 were dry at the time of the second electrofishing sampling.

All estimated parameters of stream temperature models were significant ($p<0.025$), and root mean square errors for thermal samples ranged from 1.08ºC to 1.93ºC. Pt2 (1335 m a.s.l.) and Pt3 (905 m a.s.l.) were the only sample sites that showed anomalous thermal behaviour. Torrecaballeros dam is altering the natural thermal regime upstream of the Pt2 sample site (Santiago et al. [6]), and a spring and catchment for drinking water also produced an anomalous prediction of the thermal model close to the Pt3 site.

The 7-consecutive-day temperature thresholds for trout distribution were detected to be 18.7ºC (Cega stream) and 18.1ºC (Pirón stream) for both sampling time. In addition, simulations considering both trout thresholds in the context of climate change scenarios showed that the frequencies of high daily mean temperatures increase with time in both scenarios. These frequencies were significantly higher in RCP8.5 than RCP4.5, as expected. The frequency of high temperature for intervals of 7 or more consecutive days similarly increased. A maximum of 56 consecutive days above 18.7ºC in RCP8.5, was reached at C6, C7 and C25 Cega sites. The same scenario at Pirón sample sites P11 and P12, predicts maximum of 59 consecutive days with water temperatures above 18.1ºC.

The current lower limits of the altitudinal range of brown trout are approximately 730 m a.s.l. in Cega stream and 820 m a.s.l in Pirón stream. The RCP4.5 scenario forecasts that 7 consecutive days above the thresholds will occur at 785 m a.s.l. and 830 m a.s.l., at Cega and Pirón streams respectively. In the RCP8.5 scenario, using simulations averaged over the period of 2090-2099, these altitudinal boundaries are predicted to be 830 m a.s.l. and 831 m a.s.l. A warm window in the intermediate reach, characterized by Ct3 site (1043 m a.s.l.) in Cega stream, would also open as consequence of climate change. In this sense, warmer waters could extend to 941 m a.s.l. (RCP4.5) or 913 m a.s.l. (RCP8.5) downstream. The upstream boundary of this window was identified by a water infiltration area from approximately 1050 m a.s.l. to downstream.

4 DISCUSSION

The observed limits of the brown trout's summer distribution are linked to daily mean stream temperature thresholds between 18.1ºC and 18.7ºC. These limits are lower than the critical feeding temperature for brown trout (19.4ºC) (Elliott and Elliott [4]). Additionally, they are below the upper critical temperature range (i.e. 20-30ºC) and the incipient lethal temperature; brown trout can tolerate 24.7ºC for up to 7 days. The difference between the thresholds observed in this study and those previously suggested for brown trout may be related to long periods of physiological inefficiency which make trout less competitive, thereby favouring their exclusion from warmer sites. However, these limits may be influenced by other constraints such as low summer flow, which could be reducing the suitable habitat. In this sense, we observed very low flow downstream P5 site in Pirón stream in summer. On the other hand, high summer temperatures (up to 20ºC but less than 7 consecutive days) in the piedmont zone were estimated, coinciding with karst geology, which supports a healthy trout population. Moreover, trout can tolerate very low temperatures under the lower growth threshold in the headwaters of these streams, possibly because competition with other species and hypoxic stress do not exist.

On the basis of climate change forecasts, the thermal habitat is expected to induce decreases in brown trout range by the year 2100. These reductions would affect up to 38% of the length of Cega stream that was occupied by brown trout and 11% of Pirón stream, as estimated from the 1997 and 1998 samplings. The thermal window detected at the piedmont zone could open increasing habitat loss up an additional 18%. Thermal habitat losses are important but not as dramatic as other studies forecast even for higher latitudes in the Iberian Peninsula (i.e., almost the whole stream length in Almodóvar et al. [7], and 57% of reaches in Filipe et al. [8]). The differences between our assessment and those of other authors may be due to we use more recent climate models and more precise methods for downscaling and modelling stream temperature. The expected high summer temperatures might disconnect the population at the middle reaches of Cega stream. This fragmentation would exacerbate the predicted decrease in the trout population.

5 ACKNOWLEDGMENTS

We are grateful to the Consejería de Medio Ambiente y O.T. of the Government of Castilla y León, especially to Mariano Anchuelo, Fabián Mateo and the forest ranger team of Navafría. Ignacio Martín, Pablo Cobos and José Ramón Molina contributed crucially to electrofishing fieldwork. The World Climate Research Programme's Working Group on Coupled Modelling is responsible for the 5th Coupled Model Intercomparison Project (CMIP5), and we thank the climate modelling groups for producing and making available their model output. Electrofishing samplings were part of the projects titled "Estudio de las poblaciones piscícolas del río Cega (Segovia)" and "Segundo muestreo piscícola en la cuenca del río Cega (Segovia)" funded by the Government of Castilla y León. Climate change study was partially funded by the Ministrerio de Agricultura, Alimentación y Medio Ambiente through the Fundación para la Investigación del Clima (http://www.ficlima.org/).

REFERENCES

[1] Taylor, K.E, Stouffer. R.J. and Meehl G.A., *A summary of the CMIP5 experiment design*. PCDMI Rep., 33 pp. [http://cmip-pcmdi.llnl.gov/cmip5/docs/Taylor_CMIP5_design.pdf]. (2009)

[2] IPCC, *Climate Change 2013. The physical science basis* (*Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*). Geneva, pp 2216. (2014)

[3] Mohseni, O., Stefan, H.G. and Eriksson, T.R., A nonlinear regression model for weekly stream temperatures. *Water Resources Research* Vol. 34, No. 10, (1998), pp 2685-2692.

[4] Elliott, J.M. and Elliott, J.A., Temperature requirements of Atlantic salmon *Salmo salar*, brown trout *Salmo trutta* and Arctic charr *Salvelinus alpinus*: predicting the effects of climate change. *Journal of Fish Biology* Vol. 77 (2010), pp 1793–1817. doi 10.1111/j.1095-8649.2010.02762.x

[5] Ribalaygua, J., Torres, L., Pórtoles, J., Monjo, R., Gaitán, E. and Pino, M.R., Description and validation of a two-step analogue/regression downscaling method. *Theoretical and Applied Climatology*, Vol. 111 (2013). doi 10.1007/s00704-013-0836-x

[6] Santiago, J.M., García de Jalón, D., Alonso, C. and Solana, J., Comportamiento térmico de dos tramos fluviales de cabecera del sistema central: impacto del embalse de Torrecaballeros (Segovia). *Proc. III Jornadas del Ingeniería del Agua*, Valencia, Vol. 1 (2013), pp 153–160.

[7] Almodóvar, A., Nicola, G.G., Ayllón, D. and Elvira, B., Global warming threatens the persistence of Mediterranean brown trout. *Global Change Biology* Vol. 18 (2011), pp 1549–1560. doi 10.1111/j.1365-2486.2011.02608.x

[8] Filipe, F., Markovic, D., Pletterbauer, F., Tisseuil, C., De Wever, A., Schmutz, S., Bonada, N. and Freyhof, J., Forecasting fish distribution along stream networks: brown trout (*Salmo trutta*) in Europe. *Diversity and Distributions* Vol. 19, No. 8 (2013), pp 1059-1071. doi: 10.1111/ddi.12086