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Fish thermal habitat current use and simulation of thermal habitat availability in lakes of the Argentine Patagonian Andes under climate change scenarios RCP 4.5 and RCP 8.5

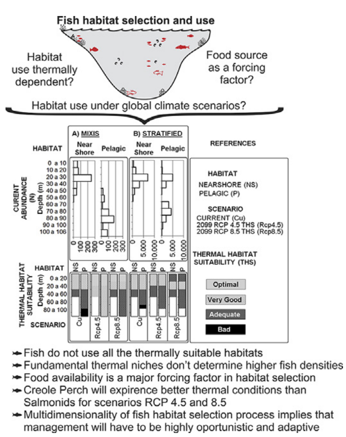
Pablo H. Vigliano [a,*], Magalí M. Rechencq [a], María V. Fernández [a], Gustavo E. Lippolt [b], Patricio J. Macchi [a]

[a] INIBIOMA, CONICET-Universidad Nacional del Comahue, Quintral 1250, R8400FRF Bariloche, Río Negro, Argentina
[b] Centro Regional Universitario Bariloche, Universidad Nacional del Comahue, Quintral 1250, R8400FRF Bariloche, Río Negro, Argentina

HIGHLIGHTS

- Fish do not use the best thermally suitable habitats currently available to them.
- Higher fish densities are not constrained to their fundamental thermal niches.
- Food availability is a major forcing factor in fish habitat selection and use.
- Creole perch will probably benefit from warmer waters due to climate change.
- Salmonids will probably retract from small size shallow lakes and nearshore waters.

GRAPHICAL ABSTRACT



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ABSTRACT

Habitat use in relation to the thermal habitat availability and food source as a forcing factor on habitat selection and use of *Percichthys trucha* (Creole perch), *Oncorhynchus mykiss* (rainbow trout), *Salmo trutta* (brown trout) and *Salvelinus fontinalis* (brook trout) were determined as well as future potential thermal habitat availability for these species under climate change scenarios Representative Concentration Pathways 4.5 and 8.5. This study was conducted in three interconnected lakes of Northern Patagonia (Moreno Lake system). Data on fish abundance was obtained through gill netting and hydroacoustics, and thermal profiles and fish thermal habitat suitability index curves were used to identify current species-specific thermal habitat use. Surface air temperatures from the (NEX GDDP) database for RCP scenarios 4.5 and 8.5 were used to model monthly average temperatures of the water column up to the year 2099 for all three lakes, and to determine potential future habitat availability. In addition, data on fish diet were used to determine whether food could act as a forcing factor in current habitat selection. The four species examined do not use all the thermally suitable habitats currently available to them in the three lakes, and higher fish densities are not necessarily constrained to their "fundamental thermal niches" sensu Magnuson et al. (1979), as extensive use is made of less suitable habitats. This is apparently brought about by food availability acting as a major forcing factor in habitat selection and use. Uncertainties related to the multidimensionality inherent to habitat selection and climate change imply that fish resource

* Corresponding author.
E-mail address: pablo.vigliano@gmail.com (P.H. Vigliano).

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management in Patagonia will not be feasible through traditional incremental policies and strategic adjustments based on short-term predictions, but will have to become highly opportunistic and adaptive.

1. Introduction

It is now widely accepted that the atmospheric accumulation of greenhouse gases such as CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, CO and VOCs due to anthropogenic activities leads to global climate warming (Schneider, 1989; Meinshausen et al., 2011; Smith et al., 2011). It is also acknowledged that climate change represents one of the major threats to biodiversity in the near future on global, regional and local scales, with 15–37% of terrestrial species and up to 75% of fish riverine species possibly becoming extinct (Thomas et al., 2004; Xenopoulos et al., 2005). Furthermore, one must also take into account that "predictions indicate that global climate change will continue even if greenhouse gas emissions decrease or cease" (Ficke et al., 2007). In relation to inland water fish, it is widely acknowledged that climate change, whether acting as a direct or indirect driver, is and will be responsible for a variety of responses, ranging from the individual level (Whitney et al., 2016), to populations, assemblages and aquatic communities (Lynch et al., 2016). So far, the identified responses of inland fishes include changes in abundance, growth and recruitment, shifts in migration timing, hybridization, novel species interactions and shifts in species distributions (Lynch et al., 2016). Shifts in species spatial distributions due to temperature change are considered among the most dramatic responses documented on continental, regional and local scales (Alofs et al., 2014; Babaluk et al., 2000; Comte et al., 2013; Comte and Grenouillet, 2013; Eby et al., 2014; Heino et al., 2009; Johnson and Evan, 1990; Lynch et al., 2016). So far, it is generally accepted that warm water species will increase their present distributional ranges as air temperature continues to rise over the years, whereas cold water species will experience a decrease in their distributional ranges.

Although one may anticipate that climate change on continental and regional scales may induce expansion or contraction of a species range, it is much more difficult to foretell what consequences climate change will have on a local scale in terms of habitat use. Until now, most work on lake habitat use and global warming has dealt with the Northern hemisphere, and is related to shifts in the extent of available habitat within the thermal niche of particular species (Jansen and Hesslein, 2004; Magnuson et al., 1990; Cline et al., 2013). However, habitat selection and use is a multidimensional process that involves species preferences in relation not only to physico-chemical water characteristics but also to food and cover availability. Since fish exhibit temperature-dependent selection, preferred temperatures being at or close to the physiological optimum (Coutant, 1987; Tonn, 1990), it has been hypothesized that in any given water body, provided that food is available and competition for resources is not too high, higher species densities will occur in habitats within their thermal niches (Rudstam and Magnuson, 1985). Magnuson et al. (1979) defined the "fundamental thermal niche" as ± 2 °C of the median preferred temperature, but warned that under field conditions fish may occupy lower temperatures. In lentic water bodies local climate conditions determine thermal structure, and therefore for any given species, thermal habitat availability (Magnuson et al., 1979). However, as explained earlier, habitat use will also be dependent on other drivers such as reproduction, competition, and food and refuge availability. Consequently, even if we can easily measure the amount of suitable available thermal habitat for any given species according to its temperature preferences, this does not imply current thermal habitat use.

In Argentina, most published work considers generalizations regarding overall temperature effects, and consequently possible overall changes in fish distribution. Gonçalves et al. (2010) wrote a comprehensive review on the effects of ultra violet radiation and temperature-related climate change on both plankton and fishes of freshwater systems in temperate zones. These authors pointed out that "in the Southern Hemisphere, we should distinguish between species limited in their southward distribution by low temperatures and those limited in their northward distribution by high temperatures". In fact, they also provided evidence suggesting that fish fauna of Neotropical origin has in recent years extended its distribution into Andean and Patagonian icthiogeographical provinces ("sensu" Lopez et al., 2008) and argue that introduced salmonids in Patagonia will be adversely affected by climate change, whereas the native *Percichthys trucha* (Creole perch) will benefit. Becker et al. (2017) give a comprehensive analysis of the historical biogeography of Patagonian freshwater ichthyofauna that allows for better understanding of present adaptations and associated physiological ecology.

The two best-documented cases for Argentina explore the distribution of *Odontesthes bonaerensis* (silverside bonaerense) (Gomez et al., 2004; Gomez and Menni, 2005) and the distribution of native fish and salmonids in Patagonia (Aigo et al., 2008, 2014; Aigo, 2010). Silverside bonaerense populations have recently experienced an increase in numbers and expansion to formerly dry areas, now flooded due to increased precipitation runoffs, which allows greater connectivity and new habitat availability. In the second case, starting with Aigo et al. (2008), several authors have stated that in Patagonian lakes the relative abundance of native perch has seen an increase, whereas that of salmonids has experienced a significant decline. They have also proposed that salmonids have been excluded from the littoral zone of lakes due to an increase in water temperatures at the lake shores (Aigo et al., 2008; Aigo, 2010).

In Argentine Patagonia, in addition to future global climate changes, managers must deal with a complex scenario where two main management imperatives exist in relation to freshwater fish fauna. One is related to the conservation goals of the National Park System and Non-Governmental Conservation organizations, and the other is fostered by local, regional and national governments associated with development and enhancement of the economic movement based on salmonid sport fisheries (Rechencq et al., 2017). This has led to a "development vs conservation management debate" which has been documented by several authors (Cussac et al., 2016; Macchi and Vigliano, 2014; Pascual et al., 2009; Rechencq et al., 2017; Vigliano and Alonso, 2007), who all agree that this "debate" has hindered rather than helped current, sound, management practices. In addition to this complex scenario, there are other threats to the goals of both these management imperatives: the introgression of new exotics from Chilean aquaculture, damming, and urban development (Habit et al., 2010). These stressors, more often than not, act synergistically on a local or regional scale (Cussac et al., 2016; Macchi and Vigliano, 2014; Pascual et al., 2009; Vigliano and Alonso, 2007). Therefore, management of the fresh water fish fauna of continental Patagonia has to be viewed as a multidimensional problem extending over multiple spatial, temporal, biological and sociological scales, and influenced by climate change. Successful future management in relation to conservation goals or economic development of sport fisheries requires, among other things, knowledge of the influence of other forcing factors on current thermal habitat use. This would allow better understanding of possible future changes in habitat use due to climate warming.

Within this context, the goals of this paper are to investigate current fish habitat use in relation to thermal habitat availability and food source as a forcing factor in habitat selection as well as to model future thermal habitat availability under different climate change scenarios. Partial objectives of the present paper are: 1) to evaluate, for three Patagonian lakes, present habitat use by adults of the four top fish