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Research article

Proposing priorities of intervention for the recovery of native fish populations using hierarchical ranking of environmental and exotic species impact

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ABSTRACT

The freshwater populations of native fish species (Ns) have reached critical levels in many parts of the world due to combined habitat deterioration by human interventions and exotic fish species (Es) invasions. These alarming conditions require combined and well-designed interventions for restoring environmental quality and restricting Es invasion. The aim of the study is to propose a method to design spatially explicit priorities of intervention for the recovery of Ns populations in highly impacted freshwater systems by exotic multi-species invasion and water quality (WQ) degradation. WQ and Es are used as Ns descriptors, which require intervention. The method uses gradient analysis (ordination method of Canonical Correspondence Analysis) for assessing the weights of Ns descriptors' effects, which are further used to develop weighted severity indices; the severity index of WQ (*Swq*) and Es invasion (*Se*), respectively. *Swq* and *Se* are further merged to one combined total severity index *St*. The proposed method provides a) a ranking of the sites, based on the values of S_t, which denotes the priority for combined intervention in space and can be visualized in maps, b) a ranking of the most important Ns descriptors for each site to perform site-specific interventions, and c) Es rankings based on their potential threat on Ns for species-specific interventions. WQ, Es and Ns data from 208 sampling sites located in the Emilia-Romagna Region (Northern Italy) were used as a case study for the presentation of the proposed method. The application of the method showed that the north and northwestern lowland areas of Emilia-Romagna region presented the higher priority for intervention since the Ns of these areas are the most impacted from combined Es invasions and WQ degradation. Specific Es belonging to cyprinids, which are mostly responsible for the decline of aquatic vegetation and the increase of water turbidity, and a top Es predator (Wels catfish) were mostly present in these areas. Additionally, the most important WQ stressors of Ns were found to be COD, BOD and temperature that are all connected to oxygen depletion. The aforementioned conditions in the areas described by high priority for intervention can be used as a basis for the development of specific Ns conservation practices targeting the containment of the most harmful Es, the restoration of aquatic vegetation and the improvement of oxygen conditions.

1. Introduction

The decline in native fish species (Ns) populations of freshwater systems have reached critical levels globally (IUCN, 2016). The most important causes are habitat degradation (flow modification, pollution) (Gehrke et al., 1995; Lee et al., 2016), invasions of exotic fish species (Es) (Strayer, 2010; Trumpickas et al., 2011; Castaldelli et al., 2013a), overfishing (Allan et al., 2005; Aschonitis et al., 2017) and the interaction of these causes (Dudgeon et al., 2006; Light and Marchetti, 2007).

Habitat degradation due to pollution (Carpenter et al., 1998; Khun et al., 2012), destruction of aquatic vegetation, damming, river bed and flow modification (Nilsson et al., 2005; Elosegi and Sabater, 2013) have led to reduction or complete loss of both lateral and longitudinal connectivity of streams (Jansson et al., 2007). These conditions have also led to a consequent reduction

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Abbreviations[*]

A1	Group of sites with no fish presence due to severe human impact
A2	Group of sites with no fish presence due to severe natural conditions
B	Group of sites only with exotic fish species present
C	Group of sites with both native and exotic fish species present
CCA	Canonical Correspondence Analysis
D	Group of sites only with native fish species present
DCA	Detrended Correspondence Analysis
EQD	Environmental Quality Degradation
Es	Exotic species
IDW	Inverse Distance Weighted interpolation method
Kr	Kriging interpolation method
N	Total number of sampling sites
Ns	Native species
Nwq	Number of WQ variables used in Eq. (1)
Ne	Number of Es variables used in Eq. (1)
RDA	Redundancy Analysis
Pd	Priority ranking of all Ns descriptors (i.e. both Es and WQ variables) for intervention in a specific site (integer ordinal values 1,2,3…) (the lower values denote higher priorities)
Ps	Priority ranking of Es variables for intervention considering all sites (integer ordinal values 1,2,3…) (the lower values denote higher priorities)
Pt	Priority ranking of sites for combined interventions on both Es and WQ variables (integer ordinal values 1,2,3…) (the lower values denote higher priorities)
SC	Severity class
Se	Severity index of sites based only on Es impact (higher values denote higher severity)
Sd	Severity index of an Ns descriptor for a specific site (higher values denote higher severity)
Ss	Severity index of an Es variable considering all sites (higher values denote higher severity)
St	Total or combined severity index of sites based on both Es and WQ impact (higher values denote higher severity)
Swq	Severity index of sites based only on WQ impact (higher values denote higher severity)
W	Weight of Ns descriptors (equivalent to λ-1 from the CCA analysis)
WQ	Water Quality
i	Sequence number of sampling sites
j	Sequence number of WQ variables
k	Sequence number of Es variables
n	Sequence number of all Ns descriptors (i.e. both Es and WQ variables)
λ-A	Conditional effects of Ns descriptors obtained by an ordination method (e.g. CCA or RDA)
λ-1	Marginal effects of Ns descriptors obtained by an ordination method (e.g. CCA or RDA)

of habitat availability for growth and reproduction of Ns (Castaldelli et al., 2013a). Conversely, it seems that these conditions may promote the success of many invasive Es (Bunn and Arthington, 2002; Didham et al., 2005; Leprieur et al., 2008; Alexander et al., 2014).

The increase of Es invasions is alarming (Leprieur et al., 2008; Marr et al., 2013) creating an important threat for freshwater ecosystems. Es can promote a) habitat deterioration/alteration through consumption of aquatic vegetation, b) increase of turbidity and nutrients release due to sediment resuspension that promote phytoplankton blooms and eutrophication, c) genetic alterations within populations, d) spreading of pathogens and parasites, e) competition with and replacement of native species (Crivelli, 1983, 1995; Crivelli and Maitland, 1995; Dibble and Kovalenko, 2009; Leprieur et al., 2009; Leunda, 2010; Badiou et al., 2011; Ribeiro and Leunda, 2012; Ilhéu et al., 2014).

Although, both environmental and biotic factors (e.g. exotic fishes) regulate Ns river communities (Godinho and Ferreira, 1998, 2000), the majority of survey studies consider only a group of explanatory variables (biotic or abiotic) or even a single factor for analyzing Ns responses (Meffe, 1984; Meffe and Sheldon, 1988; Harvey, 1987; Osborne and Wiley, 1992; Poff and Allan, 1995; Woodford et al., 2005; Pelicice and Agostinho, 2009; Alexandre et al., 2010 Pavlova and Rabadjiev, 2014). On the other hand, very few studies have explicitly related the response of Ns communities to both Es and environmental variables (e.g. water quality, aquatic vegetation, hydromorphological conditions, climate, topography, land uses of the surrounding environment) (Godinho and Ferreira, 1998, 2000; Moyle et al., 2003; Giannetto et al., 2012; Ilhéu et al., 2014; Carosi et al., 2015) analyzing the relative weight of Ns descriptors using ordination methods such as Canonical Correspondence Analysis (CCA) or Generalized Linear Models (GLMs).

The interactions among Ns and Es in combination with the effects of abiotic or other biotic environmental variables are extremely complicated and their description face several problems due to high covariation of anthropogenic and natural gradients, existence of complex scale-dependent mechanisms, non-linear responses, difficulty in separating present-day from past influences (e.g. past hydrological changes due to human intervention) (Rinne and Stefferud, 1999; Leprieur et al., 2008). These problems lead to significant limitations for planning management measures for the recovery of Ns populations, which require a) as a first step, the identification of abiotic (e.g. water quality) and biotic (e.g. Es) variables related to Ns community degradation and the assessment of their relative weight as Ns descriptors, and b) as a second step, the development of hierarchical ranking of priorities for interventions for improving the conditions of native fish species. Until now, there are only generalized proposals (Thom et al., 2016; Nguyen et al., 2016), either site-specific, event-specific or species-specific proposals (Rieman et al., 2003; Cooke et al., 2009; King et al., 2010; Woodford et al., 2011) without providing a method for prioritizing interventions based on a decision support protocol for designing management plans for Ns recovery. It is indicative that an integrated method for decision support purposes that can assist Ns recovery plans for large scale applications considering both multi-species invasion and human impact is still missing (Didham et al., 2007; Britton et al., 2011).

The aim of the study is to propose an integrated method that provides priority rankings for intervention facilitating management plans for Ns recovery in highly impacted freshwater systems by Es invasions and human activities. The method is based on gradient analysis for assessing the weight of Ns descriptors' effects,

[*] Abbreviations in italics denote mathematical/statistical variables.