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Hydrologic and water-quality rehabilitation of environments for suitable fish habitat

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SUMMARY

Aquatic ecological rehabilitation is attracting increasing public and research attention, but without knowledge of the responses of aquatic species to their habitats the success of habitat restoration is uncertain. Thus efficient study of species response to habitat, through which to prioritize the habitat factors influencing aquatic ecosystems, is highly important. However many current models have too high requirement for assemblage information and have great bias in results due to consideration of only the species' attribute of presence/absence, abundance or biomass, thus hindering the wider utility of these models. This paper, using fish as a case, presents a framework for identification of high-priority habitat factors based on the responses of aquatic species to their habitats, using presence/absence, abundance and biomass data. This framework consists of four newly developed sub-models aiming to determine weightings for the evaluation of species' contributions to their communities, to quantitatively calculate an integrated habitat suitability index for multi-species based on habitat factors, to assess the suitable probability of habitat factors and to assess the rehabilitation priority of habitat factors. The framework closely links hydrologic, physical and chemical habitat factors to fish assemblage attributes drawn from monitoring datasets on hydrology, water quality and fish assemblages at a total of 144 sites, where 5084 fish were sampled and tested. Breakpoint identification techniques based on curvature in cumulated dominance along with a newly developed weighting calculation model based on theory of mass systems were used to help identify the dominant fish, based on which the presence and abundance of multiple fish were normalized to estimate the integrated habitat suitability index along gradients of various factors, based on their variation with principal habitat factors. Then, the appropriate probability of every principal habitat factor was estimated and graded, and the priority of habitat factors for rehabilitation was determined. Application of the model to Jinan City, a pilot city for the construction of a civilized and ecological city in China, proved effective, revealing that carbonate is the poorest habitat factor and has the highest priority for ecological rehabilitation. This was tested using two methods: alternative priority models and a dataset of all habitat factors in place of only the principal habitat factors. We also found that hydrological factors have higher priority than the water quality factors at the levels of both the whole city and its subordinate eco-regions and therefore that hydrological factors deserve special attention in the future ecosystem rehabilitation. Further, the current habitat state makes nearly half of the habitats in Jinan City undesirable for fish communities, largely due to long-term agricultural practices. Spatially, rivers in the mountainous region south of Jinan city and adjacent to the urban area and rivers in the agricultural region north of the city should be emphasized in future habitat rehabilitation. All of these findings have substantial ramifications for the rehabilitation of aquatic ecosystems in Jinan City as a reference for river ecological remediation in rivers with scarce ecological data worldwide.

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1. Introduction

Globally, climate change and human activities have strongly influenced the world in terms of land use, soil characteristics, hydrological regime, water quality, and biota in aquatic ecosystems (Xu, 2015). In particular, intensive human activities have been changing riverine environments in terms of their hydrology, pollutant loads and habitat attributes (Walters et al., 2009). Environmental variation can exert direct or indirect effects on species arranged along a gradient from proximal to distal attributes (Austin, 2002; Guisan and Thuiller, 2005). In aquatic ecosystems, species that are intolerant of these changes can decline or disappear and are replaced by organisms that are more tolerant (Fraker et al., 2002; Helms et al., 2005; Morgan and Cushman, 2005; Kemp, 2014). Biodiversity in aquatic ecosystems is thus negatively influenced, and degradation of aquatic ecosystems is therefore unavoidable (Svirčev et al., 2014).

Over the past several decades, water habitat restoration has been utilized as a strategy for recovering and conserving threatened and endangered species (Bernhardt et al., 2005) by which to recover the biodiversity and even the aquatic ecosystem health. However, the success of habitat restoration without knowledge of the response of aquatic species to their habitats is uncertain (Wissmar and Bisson, 2003; Bellmore et al., 2012). Hydrology and water quality are two principal attributes of aquatic habitats. Suitable habitats are very important for species survival and diversity in aquatic ecosystems. Improvement or at least maintenance of habitats is therefore necessary for the recovery of aquatic ecosystems (Bellmore et al., 2012). River restoration thus requires the identification of environmental and pressure gradients that affect river systems, especially in terms of hydrology and water quality, as well as the selection of suitable indicators to assess habitat quality before, during and after restoration (Hughes et al., 2010).

Many models, e.g., the most popular Maxent (VanDerWal et al., 2009) and ENFA (Vaclavik and Meentemeyer, 2012), link the response of species to the environmental habitat factors based on ecological niche. However, most are based only on either the presence/absence or biomass of species (Schroeder and Vangilder, 1997; VanDerWal et al., 2009), with a few based on the combination of presence and abundance (Ehrlén and Morris, 2015). These models have contributed greatly to the prediction of geographical spatial distribution of a few certain species. They can be generally classified into two categories inclusive of correlative and mechanistic models. Species distribution models, or SDMs, a set of correlative models also known as climate envelope models, habitat suitability models, niche models and resource selection functions (Elith and Leathwick, 2009; Elith et al., 2011; Araujo and Peterson, 2012), typically combine information about known locations where a species occurs with data about abiotic variables to predict the probability of occurrence of that species. The recently proposed dynamic range model (DRM), a set of mechanistic models simultaneously estimating population dynamics and dispersal, yields better niche estimates than state-of-the-art correlative SDMs (Schurr et al., 2012). However, the DRM has not yet been applied to real data, and its data requirements may be quite high (Ehrlén and Morris, 2015). Data collection and model construction require substantial knowledge about the biology of the study organism, and their parameterization for specific environments is typically labor-intensive (Holt, 2009; Schurr et al., 2012). The considerable effort required for the direct measurement of demographic responses and for the development of mechanistic niche models thus currently precludes the application of DRMs to large numbers of species (Schurr et al., 2012). Moreover, while very appealing at the species level, DRMs often require too much data to be of general use in nature management and biodiversity assessment (Guisan and Thuiller, 2005). More importantly, most previous models emphasized prediction of species-level indices instead of selecting the highest-priority habitat factors for rehabilitation.

By comparison, SDMs are easy to implement and are therefore more suitable for prioritizing habitat environmental factors and gradients for the sake of better maintenance or restoration of biodiversity and river ecosystems. "Distribution from place to place and abundance at different times are two aspects of the one fundamental problem." (Birch, 1953; Ehrlén and Morris, 2015). Abundance is a far better measure of the effects of a species on its local ecosystem than simply whether it is present (Ehrlén and Morris, 2015). Moreover, abundance reflects the number of individuals of a species, while biomass reflects the size of a species. The demands of a large species on the local ecosystem are markedly different from those of a small species. Both of them are important for the existence and health of any biological community (Zhao et al., 2012, 2014, 2015). SDMs provide the likelihood of occurrence of the species by associating occurrence records with a suite of environmental variables. If these factors also influence abundance, it follows that sites with high environmental suitability will support populations at high abundance. In fact, abundance is often highly variable among sites within the distribution of a species. To our knowledge, the relationship between local abundance and environmental suitability predicted from presence-only data has not been properly investigated (VanDerWal et al., 2009). It is also worth noting that consideration of only abundance or biomass in estimation of species response to the abiotic habitat environment inevitably biases the results and that therefore consideration of both factors is urgently required.

Among all SDMs, the habitat suitability index (*HSI*) is widely used to indicate the degree of preference of species to different habitats (Leclerc et al., 2003; Ahmadi-Nedushan et al., 2006). It is often used to quantify the response of a species to a set of habitat factors on the assumption that a species would choose its optimal habitat (Schamberger and O'Neil, 1986). Habitat suitability is defined as the preference of an aquatic organism for a particular set of habitat attributes (Vadas and Orth, 2001; Vismara et al., 2001). However, its estimation of the preference of an aquatic organism usually target a single species (Wakeley, 1988; Tikkanen et al., 2007; Gong et al., 2012; Zohmann et al., 2013) rather than multiple species, which precludes the extension of the traditional *HSI* to multiple species or a community. It is therefore difficult to estimate the synthetic effect of a habitat factor on the ecosystem community. Consideration of multiple species' responses to their abiotic habitat in the *HSI* is therefore crucial for the synthetic effect estimation of a habitat factor.

Among all of the communities in aquatic ecosystems, fish communities are effective ecosystem indicators as they are relatively easy to identify, and their position at the top of the food chain helps provide an integrative view of the environment (Wu et al., 2014). Habitat type and complexity, or habitat heterogeneity, influence resource use by many fish species (Okun and Mehner, 2005; Visintainer et al., 2006), along with biological interactions such as competition and predation (Coen et al., 1981; Danielson, 1991; Whitley and Bollens, 2014). Therefore, understanding the response of fish to habitat variation in terms of hydrology and water quality is important for habitat rehabilitation.

The objectives of this paper are to develop an effective framework for identifying the highest-priority habitat factors influencing the aquatic ecosystems based on the multiple fish responses in terms of presence/absence, abundance and biomass to their habitat environment. This framework is expected to require only basic information and expertise (fish assemblage: only the abundance and biomass of dominant fish species; fish names are