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Restoring fish ecological quality in estuaries: Implication of interactive and cumulative effects among anthropogenic stressors

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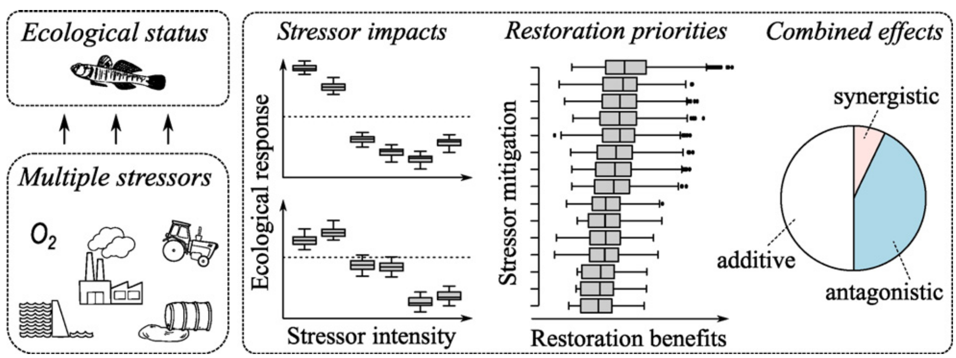
HIGHLIGHTS

- Impact of multiple stressors on fish ecological status was investigated in estuaries.
- Mitigation of water pollution and oxygen depletion yield the largest benefits.
- Non-additive effects represented half of pairwise interactions among stressors.
- Antagonisms are widespread in estuaries for predicting fish ecological status.
- Managers can use these findings in prioritizing restoration measures.

GRAPHICAL ABSTRACT



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ABSTRACT

Estuaries are subjected to multiple anthropogenic stressors, which have additive, antagonistic or synergistic effects. Current challenges include the use of large databases of biological monitoring surveys (e.g. the European Water Framework Directive) to help environmental managers prioritizing restoration measures. This study investigated the impact of nine stressor categories on the fish ecological status derived from 90 estuaries of the North East Atlantic countries. We used a random forest model to: 1) detect the dominant stressors and their non-linear effects; 2) evaluate the ecological benefits expected from reducing pressure from stressors; and 3) investigate the interactions among stressors. Results showed that largest restoration benefits were expected when mitigating water pollution and oxygen depletion. Non-additive effects represented half of pairwise interactions among stressors, and antagonisms were the most common. Dredged sediments, flow changes and oxygen depletion were predominantly implicated in non-additive interactions, whereas the remainder stressors often showed additive impacts. The prevalence of interactive impacts reflects a complex scenario for estuaries management; hence, we proposed a step-by-step restoration scheme focusing on the mitigation of stressors providing the maximum of restoration benefits under a multi-stress context.

1. Introduction

Aquatic systems subjected to multiple anthropogenic disturbances are widespread because of their attractiveness for human activities (Halpern et al., 2008b). The advantageous location of estuaries and coastal zones for maritime exchanges and their large diversity of

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exploitable resources have encouraged the extensive development of urban, agricultural and industrial areas which threaten their ecosystems (Elliott and Whitfield, 2011; Halpern et al., 2007; Lotze, 2010). Over the last century, the estuarine structure and functioning had dramatically changed because of anthropogenic stressors, such as resource overexploitation, habitat fragmentation or pollution (Aubry and Elliott, 2006; Lotze et al., 2006). The expanding degradation of estuarine conditions worldwide has pushed the environmental authorities to develop platforms aiming at assessing the ecological status of transitional waters (i.e. estuaries and lagoons) and managing ambitious conservation and restoration programs (reviewed in Borja et al. (2008)). As an example, the European Water Framework Directive (WFD; 2000/60/EC) required the establishment of methods to quantify the ecological status of water bodies, based upon long-term monitoring data. Among the biological quality elements considered in the WFD, fishes provide a good indication of estuarine health or condition through their sensitivity to environmental disturbances at various levels of biological organization (Borja et al., 2012; Minier et al., 2015), integrating ecological quality at a high ecological level, producing a "system response" when exposed to a range of anthropogenic pressures. Fish-based assessment indices were thus developed by Member States, often on the basis of the aggregation of independent biological metrics reflecting assemblage composition or functional attributes (Perez-Dominguez et al., 2012). The biological assessments are expressed as an 'ecological quality ratio' (EQR) to ensure comparability of monitoring systems providing useful and understandable indicators for environmental managers (Heiskanen et al., 2004).

The WFD has the objective of achieving the 'good ecological status for the surface waters in Europe and to prevent any further degradation. Nevertheless a high number of transitional waters currently failing to achieve the 'good ecological status', highlighting the urgent requirement of restoration measures for the most impacted water bodies (EEA, 2012). Local stressors can be handled directly by management, but it is essential to identify previously the dominant anthropogenic stressors and their impacts. Then, restoration priorities can be determined by focusing on the mitigation of stressors providing the maximum of expected ecological benefit, because they are the most impacting stressors.

Modeling is a useful and valuable approach to simulate the improvement of ecological quality after reducing a disturbance, which can be defined by the difference between the current ecological state and that expected after restoration (Downs et al., 2011; Hermoso et al., 2011; Maire et al., 2015). However, consideration of the complex relationships between the ecological response and stressors acting simultaneously is essential to improve the predicted outcomes of restoration actions, because of non-linear and interactive effects of stressors (Brown et al., 2013; Halpern et al., 2008a). Current challenges include using the large biological databases generated through the WFD monitoring surveys to identify and predict the effects of multiple stressors on estuarine ecosystems, in order to assist water managers prioritizing measures of restoration (Hering et al., 2015; Reyjol et al., 2014).

Systems with multiple stressors are complicated matter for management because stressors can have additive, but also interactive effects on organisms, populations and communities (Crain et al., 2008; Nõges et al., 2015). The combined effect of multiple stressors was commonly assumed to be additive, i.e. equal to the sum of individual effects acting in isolation. However, this model is not always prevalent in ecological systems where antagonistic and synergistic interactions may dominate (Crain et al., 2008). Stressors act in synergy when the combined effect of stressors is greater than the sum of the impacts of individual stressors, whereas antagonistic interactions occur when the combined effect of stressors is less than expected based on their individual effects (Folt et al., 1999). In these conditions, the ecological benefit resulting from efforts to reduce any stressors acting additively can be predicted on the basis of the knowledge of its individual effect, whereas interactive effects could produce some 'ecological surprises' (Paine et al., 1998). Although synergic interactions are expected to be more harmful for ecosystem because of accelerating system degradation, they also represent cost-efficient opportunities of restoration yielding larger overall benefits than additive or antagonistic effects (Crain et al., 2008; Piggott et al., 2015). Conversely, the efforts to mitigate stressors often not yield proportional benefits in systems where antagonistic interactions are prevalent, which is often considered as the "worst-case" scenario for ecosystem management (Brown et al., 2013; Folt et al., 1999; Piggott et al., 2015). The development of scheme for prioritizing management actions should thus consider the type and the strength of interactions (Halpern et al., 2008a), which can act differently depending on the water types (Nõges et al., 2015).

The present study investigated the influence of multiple stressors on fish ecological quality in European estuaries, with the aim of assisting environmental managers to develop efficient strategies for restoration. We used a random forest algorithm to detect the dominant stressors in estuaries and their effects on the EQR (defined by the fish indices in use) in the North East Atlantic countries. Model simulations were undertaken to evaluate the ecological benefits resulting from reducing the intensity of stressors on EQR, and investigate the type of pairwise interaction between stressors (i.e. additive, synergistic and antagonistic). Finally, a step-by-step scheme of restoration was proposed for the studied stressors, on the basis of an iterative process maximizing the ecological benefit at each step (i.e. mitigation of one stressor).

2. Material and methods

2.1. Estuaries locations and fish assessments

The ecological status of 90 European estuaries, from the North East Atlantic (NEA) (Fig. 1) was assessed according to their EQR calculated on fish communities. The EQR values were calculated according to the seven multimetric indices used as part of the WFD for the area covered by this study (Borja et al., 2004; Breine et al., 2007; Cabral et al., 2012; Coates et al., 2007; Delpech et al., 2010; Harrison and Kelly, 2013; Scholle and Schuchardt, 2012). These indices for transitional waters are usually based on fish communities, but in one method the demersal assemblage includes also crustaceans. They are computed from a number of independent metrics among which the most commons rely on species richness-composition, habitat guild, trophic guild, or abundance and condition of fish (Perez-Dominguez et al., 2012). As assessment methods differ across Europe, a great effort of intercalibration was made to harmonize the results obtained from the different national assessment methods, trying to ensure comparability between the different countries, within the NEA (Lepage et al., 2012; Poikane et al., 2014). The resulting assessments take into account the regional environmental particularities in their reference conditions and provide comparable EQR values at the European scale for transitional waters. The EQR value represents the ratio between the value of the observed biological parameter and the expected value under reference conditions. It ranges between zero and one, with high ecological status represented by values close to one and bad ecological status by values close to zero, after the WFD. A total of 272 EQR values were used to evaluate the ecological status of estuaries. EQR data were obtained from the intercalibration task ($n = 188$), plus some other available evaluations for French and Belgian estuaries ($n = 84$). Assessments were performed for samples taken between 1989 and 2014, allowing to record from one to eleven EQR values per water body.

2.2. Stressor evaluation

A total of 17 stressors, merged into 9 stressor categories, were selected to assess the disturbance intensity affecting estuaries (Table 1). Data availability about stressors in estuaries is often limited and the choice of relevant stressors is restricted to the ones assessed with similar resolution in all locations (Vasconcelos et al., 2007). Some stressor categories