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Taxon-specific physico-chemical change points for stream benthic invertebrates

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ABSTRACT

Freshwater organisms face numerous stressors, such as nutrient enrichment, contaminant pollution, sedimentation and alterations in stream hydrology and habitat structure. One of the most significant and widespread stressors in European freshwaters is expected to be water pollution from intensive land use. However, the information on critical threshold concentrations at which taxa decline or increase in frequency and abundance is missing for the large majority of river benthic invertebrate taxa. The main aim was to determine ecological change points for benthic invertebrate taxa at which rapid alterations in species frequency and abundance occur as a consequence of relatively small changes in the environmental gradient. These change points can be interpreted as critical threshold concentrations. A total of 468 river benthic invertebrate taxa and nine physico-chemical variables describing the daytime dissolved oxygen, chloride, nutrient concentrations and organic load were analyzed. We selected 751 river sites from a nationwide range of locations in Germany for this investigation. Depending on the physico-chemical variable, between 20.6% and 48.8% of the total number of tested taxa were assigned with a valid change point. All taxa were assigned to negative or positive response groups depending on the response direction. Except for daytime dissolved oxygen, negative responding taxa are referred to as decreasers and positive responding taxa as increasers, respectively. In total, 25.8–100% of the decreasers' change points were below (and above in the case of daytime dissolved oxygen) the background values defined as quality criteria for German rivers by the water authorities. This indicates that stricter quality criteria may need to be set to reach the good ecological status according to the European Water Framework Directive. The calculated daytime dissolved oxygen change points were essentially in line with the species saprobic values and taxon-specific change points for physico-chemical variables fit well with the data provided in other international studies. We deliver valuable knowledge about the sensitivities and response schemes of river benthic invertebrate species. This information is especially useful for the development of efficient management and policy tools to predict the likelihood of occurrence of individual species under different levels of anthropogenic impact.

1. Introduction

Freshwater organisms face numerous stressors, such as nutrient enrichment, contaminant pollution, sedimentation, river fragmentation and alterations in stream hydrology and habitat structure (Allan, 2004; Walsh et al., 2005; Wenger et al., 2009) as well as the impact of climate change (Domisch et al., 2011; Palmer et al., 2009). This issue found its way into legislative debates with the implementation of the European Water Framework Directive (WFD) and the Clean Water Act (CWA) in the United States; these management plans aim to monitor and preserve freshwater ecosystem health (Copeland, 2010; EU Commission, 2000). Besides the above mentioned stressors it has been stated that one of the most significant and widespread stressor in European freshwaters is expected to be water pollution (EU Commission, 2007). These pressures cause systematic changes in the composition and abundance structure of freshwater communities, with taxa successively dropping out with rising stressor levels (Pautasso and Fontaneto, 2008).

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Consequently, freshwater communities are used as indicators of river health (USEPA, 2002) with benthic invertebrates most frequently used for river bioassessment (De Pauw and Hawkes, 1993; Rosenberg and Resh, 1993) as they are e.g., relatively easy to collect and highly diverse. Systems assessing river health consider quantitative changes in various aggregating metrics, e.g., the number of Ephemeroptera, Plecoptera and Trichoptera (Álvarez-Cabria et al., 2010; Böhmer et al., 2004; Brabec et al., 2004; Lücke and Johnson, 2009; USEPA, 2002; Vlek et al., 2004). These metric-based approaches are widely accepted and can deliver some information regarding general human impacts on the community. However, they do not provide direct information about which stressors might affect the community. Assessment systems which explicitly focus on species' differential responses to gradients in water pollution are less common until now. The reason is that the information on stressor levels and the critical concentrations at which, for example, sensitive taxa decline is missing for the large majority of freshwater organisms.

Despite the information gap on critical concentrations, it has often been shown that the response patterns of species to a multitude of environmental stressors (e.g., nutrient load and many other factors) are non-linear. Species have specific habitat requirements and show distinct responses if environmental conditions are beyond their tolerance ranges. These responses often follow a change point or threshold principle (Clements et al., 2010; Gido et al., 2010; Scheffer et al., 2001; Scheffer and Carpenter, 2003; Wang et al., 2007). In our study, the change point is understood as a critical concentration at which rapid alterations in species frequency and abundance occur as a consequence of relatively small changes in the environmental gradient (see also Andersen et al., 2009; Dodds et al., 2010; Groffman et al., 2006; Kail et al., 2012; Muradian, 2001; Sonderegger et al., 2009). This change point is consistent with the idea of a taxon-specific threshold response (*sensu* Groffman et al., 2006).

A variety of statistical methods (including, e.g., nonparametric deviance reduction, piecewise regression, Bayesian changepoint, quantile piecewise constant, quantile piecewise linear approaches and significant zero crossings) have been used to detect and investigate ecological thresholds, whereas these thresholds have primarily been examined on the aggregate community level and not on the species level (Andersen et al., 2009; Brenden et al., 2008; Cardoso et al., 2013; Dodds et al., 2010; Sonderegger et al., 2009). A methodological approach to identify taxon-specific change points along environmental gradients was developed by Baker and King (2010). Their approach is called TITAN (Threshold Indicator Taxa Analysis) and is based on taxon-specific indicator species analysis (Dufrêne and Legendre, 1997). The advantage of this approach is that taxon-specific change points are detected and that the directionality of the taxon's responses is also provided. Specifically, the result of the analysis gives information on the critical intensity of a particular stressor variable at which a taxon either decreases or increases in frequency and abundance, and thus provides evidence for the presence of ecological thresholds.

In the present study, taxon-specific change points for benthic invertebrates were identified and compared with quality criteria for physico-chemical variables defined by the German water authorities. These are background values, understood as the minimum requirement for reference conditions and orientation values that can be regarded as minimum criteria to ensure ecosystem functioning (European Communities, 2005; LAWA, 2007). It has to be noted that background values as defined in our study do not equal natural background concentrations, characterizing loads at non-impacted river sites. Background and orientation values serve as an additional utility to confirm and validate the classification of river sites in the five ecological status classes (EU Commission, 2000) and are based on expert judgement rather than on empirical evidence. By comparing taxon-specific change points with background and orientation values, it is possible to test whether the latter are ecologically sound. This comparison allows an estimation of the need for future adjustments of quality criteria for physico-chemical variables. The same applies to a further approach presented here: a comparison of the identified taxon-specific change points for daytime dissolved oxygen with the species' saprobic values. The latter build the basic information for the saprobic index (Friedrich and Herbst, 2004; Rolauffs et al., 2004), which is one of many indices used in the European Union to assess the organic pollution of streams via the estimated sensitivity of benthic invertebrate species to decreases in oxygen concentrations (Sandin and Hering, 2004). Each taxon is assigned a saprobic value and an indicative weight, which specifies the taxon's association with particular conditions along the saprobity gradient. Both are based upon expert opinions rather than field-derived data (Walley et al., 2001). Thus, solid information about taxon-specific critical concentrations of oxygen is still missing.

Against the backdrop explained above, the main aim of our study was to derive change points for benthic invertebrate taxa and physico-chemical variables. We analyzed species occurrence and a comprehensive set of high quality and field-derived river survey data from a nationwide range of locations in Germany. Thereby, two questions were addressed: (i) do taxon-specific change points exceed the background and orientation values as defined by the water authorities? and (ii) do taxon-specific change points for daytime dissolved oxygen correlate with the taxon-specific saprobic value as assigned for the saprobic index?

With our current study, we meet the growing demand to provide information on taxon-specific requirements on environmental conditions. Our findings contribute to a better understanding and prediction of potential changes in taxon occurrence as a response to changes in physico-chemical variables. Moreover, we deliver valuable information for the development of a promising tool to estimate the potential occurrence of species under different levels of physico-chemical stress, including the question of which taxa occur if defined quality criteria are met.

2. Methods

In the present study, 468 river benthic invertebrate taxa and nine physico-chemical variables at 751 river sites from a nationwide range of locations were investigated (Fig. 1). The river sites lie at elevations between 1 and 924 m above sea level with catchment areas between 0.1 and 71,587 km^2. By including the full range of river sizes a long environmental gradient was covered by our data, which enlarges the chance to detect taxon responses to physico-chemical stress.

2.1. Benthic invertebrates

Benthic invertebrate samples of each site originated from routine surface water surveys according to the protocol for collecting samples in river monitoring programmes to assess the ecological status of rivers in Germany (Haase et al., 2004). The invertebrate samples were collected from March to October in 2004 to 2010. The sampling method is based on sampling microhabitats according to their coverage at the sampling site (multi-habitat sampling). All microhabitats in a 100-m-long stream section are recorded in 5% coverage intervals, and each 'sampling unit' (25 cm × 25 cm) is sampled using a handnet with a 25 × 25 cm opening and a tapering netbag with a mesh size of 0.5 mm. We applied the kick sampling method according to Barbour et al. (1999). A complete sample is comprised of 20 sampling units, which are pooled for further analysis (total sampling area of 1.25 m^2). The organisms are sorted from