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Bundles of stream restoration measures and their effects on fish communities

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ABSTRACT

At the global scale, substantial numbers of stream restoration projects have been carried out in the last decades, utilizing significant investment. Yet comparative studies on the effectiveness of stream restorations are rare, and the few existing studies show inconsistent results. A common flaw in these studies is that the restoration projects investigated often include widely varying sets of restoration measures, which may lead to contradictory findings on restoration outcomes. To overcome this flaw we propose an approach to identify, bundles of restoration measures based on cluster analysis. We applied our approach to a comprehensive dataset of 61 Central European stream restoration projects and compare the restoration effects of these different bundles of restoration measures on fish communities. Restoration projects concentrating on stream bank restoration measures led to improvements in fish diversity. By contrast, complex reconfigurations of entire watercourses led to less diverse fish communities, at least within the first ten years after restoration. In general, changes in species diversity and species turnover depended on the age of a restoration project, and support evidence that the effects of restoration should be monitored more than ten years after restoration. Streams often suffer from recurring syndromes of hydromorphological deficits, relating to different forms of human land use, and analogously, recurring bundles of restoration measures are applied to overcome these deficit syndromes. Thus, our strategy to statistically identify, describe and evaluate bundles of effective restoration measures for similar stream types can help to better inform restoration practice.

1. Introduction

In many parts of the world, streams are strongly transformed by humans (Vörösmarty et al., 2010). Streams are straightened and their floodplains drained for agricultural use, instream and riparian structures altered for floating and towing, and dams and retention areas built for flood management. These engineering activities alter, and most often, homogenize geomorphological and hydraulic stream features (Lepori et al., 2005). Ecological restoration is primarily aimed at reinstating the physical heterogeneity of a habitat. Kauffman et al. (1997) define ecological restoration as the re-establishment of processes, functions and related biological, chemical and physical linkages between the aquatic and associated riparian ecosystems. However, in current stream restoration projects the linkages to riparian ecosystems are still often ignored, in part because in areas with intensive land use options are limited due to conflicts with land owners in floodplain areas. As a consequence, restoration projects are often limited to the stream channel (Kauffman et al., 1997).

Even though hydromorphological restoration projects with the mandate to improve the ecological conditions of streams have become increasingly common in the last thirty years (Bernhardt and Palmer, 2007; Jähnig et al., 2009), comparative reports on restoration outcomes have only appeared recently (Baldigo et al.,

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2010; Miller and Kochel, 2010; Bernhardt and Palmer, 2011; Kail et al., 2015), and are inconsistent in their findings: Most studies on stream restoration effects using stream invertebrate communities as indicators conclude that restoration projects failed to reach their targets (Palmer et al., 2010; Louhi et al., 2011; Violin et al., 2011; Sundermann et al., 2011a; Haase et al., 2013; but see Miller et al., 2010). By comparison, reported restoration effects on fish are much more variable. Some studies did not observe major effects on fish communities (Pretty et al., 2003; Lepori et al., 2005; Vehanen et al., 2010; Haase et al., 2013; Stoll et al., 2013, 2014; Nilsson et al., 2015) while others found that fish abundances, species richness and diversity are increased following stream restoration (Näslund, 1989; Scully et al., 1990; Schmutz et al., 1994; Zika and Peter, 2002; Roni et al., 2008; Whiteway et al., 2010; Lorenz et al., 2013). A potential explanation for the contradicting results of stream restoration projects is poor definition of restoration types, and analyses averaging over different kinds of restorations, potentially obscuring response patterns.

A more careful selection of restoration projects for comparative analyses will be helpful in identifying the effects of different restoration approaches, and thereby help restoration managers to choose those restoration measures which promise the best ecological outcomes. A challenge in analyzing restoration effects is that restoration projects typically do not only apply one but a whole suite of restoration measure simultaneously, preventing straightforward analyses on which individual restoration measure will result in the greatest biological recovery (Stoll et al., 2013). However, stream degradation often comes in recurring syndromes of symptoms that relate to different types of land use, e.g. drainage of floodplains for agricultural use is typically achieved by ditching and stream straightening, which leads to increased flow velocity in the channel. This in turn leads to a removal of bed material and incision of the stream. Hence, straightened and incised streams with deficits in bed material form one syndrome that is caused by floodplain drainage. Based on this thought, we assume here that also restoration measures should be applied in a clustered manner, reflecting the degradation syndromes they are meant to alleviate. Describing such bundles of restoration measures might be a useful approach to group restoration projects and to structure comparative analyses on restoration outcomes.

In this study we aimed at (1) identifying bundles of restoration measures that are often used simultaneously to address degradation syndromes and (2) investigating whether these bundles of restoration measures differ in their effects on fish communities. To address these questions, we make use of a large dataset of 61 stream restoration projects in Central Europe. We apply a clustering method to determine frequently used bundles of restoration measures and compare their effects on fish communities. Fish are regarded as excellent indicators of reach scale hydromorphological changes and therefore ideal indicators for which restoration measures would be most successful (e.g. Welcomme, 1995; Jungwirth et al., 2002).

2. Materials and methods

2.1. Dataset

We analyzed the outcome of 61 reach-scale stream restoration projects in 50 streams, in Germany, Switzerland and Liechtenstein. All German fish data were sampled based on the German EU Water Framework Directive compliant protocol for fish community assessment (Diekmann et al., 2005; Stoll et al., 2013). Fish data from Switzerland and Liechtenstein were sampled by similar protocols and data were provided by administrative authorities and extracted from scientific works (Thomas et al., 2015).

Streams in which the restoration projects were carried out ranged from slow flowing streams in the German lowlands (7 m a.s.l.) to fast flowing streams in the pre-alpine regions of Switzerland (572 m a.s.l.). The width of the evaluated streams varied between 1.5 m and 57 m, with the majority having a width of less than 15 m. The catchment areas ranged from 0.2 km^2 to 2902 km^2 and the mean size was 535 km^2. Restored section lengths varied between 100 and 12,000 m (average 700 m). The sites were restored between the years1990–2009. The time since the implementation of the restoration actions and evaluation of outcome ranged from 0.5 to 19 years (average 4.9 years). Nine evaluation protocols compared fish communities prior and after restoration, all others used space for time substitution, sampling a restored and a nearby unrestored control site, both after the restoration was implemented. Each restoration project was assessed once.

Restoration measures aimed at restoring habitat diversity and recreating connectivity in a longitudinal or lateral way with the ultimate goal to bring biotic stream communities to a natural status. We identified 16 individual measures that restoration projects used. These restoration measures included removing bank fixations, opening up culverts or creating new channels, re-braiding, re-meandering, stream widening, restoring riffle-pool sequences, raising stream bed levels, installing flow deflectors, introducing large woody debris, adding boulders and stones, restoring riparian vegetation, removing weirs and dams, re-connecting the stream to the floodplain, removing channel floor fixations, adding artificial bed loads, and restoring connectivity at stream confluences. A minimum of one and a maximum of nine individual measures (average 3.6) were used per restoration project.

2.2. Statistical analyses

In order to assess the similarity between restoration projects based on the set of restoration measures that was used, we performed a cluster analysis. Following the recommendation of Clarke and Warwick (2001) to use cluster analysis based on Bray–Curtis distances for community presence–absence data, as also used this approach for the presence–absence data of individual restoration measures of each project. To cluster the restoration projects based on continuous stream characteristics, Euclidean distance was used. All data were $\log(x+1)$-transformed and normalized on forehand. The available site variables were stream width, elevation and catchment size. A similarity profile test was performed on the null hypothesis that a specific sub-cluster can be recreated by permuting the entry sites. Significant branches (SIMPROF, $p < 0.05$) were then used to define clusters of restoration measures and stream characteristics.

Restoration outcomes were compared between the different clusters of restoration measures. Four metrics of restoration effects on fish communities were analyzed: change in diversity, change in density (individuals per hectare), species turnover, and change in species richness. Fish diversity was calculated based on abundance data standardized to sampling area, using the Brillouin index (Pielou, 1975). The Brillouin index was calculated once for the restored and once for the unrestored control condition of each restoration project and the difference in Brillouin index (i.e. score of restored reach minus score of unrestored reach) was used in analyses. The Brillouin index is particularly suitable for electrofishing data, as it considers methodological differences in sampling efficiency (Pelz and Luebbers, 1998). Fish diversity was examined in 50 restoration projects for which fish abundance data was available (not only presence–absence data) and more than one species was present both at restored and unrestored control conditions. To calculate the change in fish density (total fish abundance at restored reach minus total fish abundance at unrestored reach) abundance data were first standardized to one hectare of area