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Effects of instream restoration measures on the physical habitats and benthic macroinvertebrates in an agricultural headwater stream

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ABSTRACT

The effectiveness of instream restoration measures in improving habitats has been extensively examined; however, the evidence is inadequate to infer that these measures have positive effects on benthic macroinvertebrates. In this study, we compared the effects of the instream wetland (IW), groin (GR), artificial drop (AD) and boulder placement (BP) measures on the physical habitat and benthic macroinvertebrates. On a five-year scale (two to six years after the implementation of the restoration project), the sample sites treated with the four restoration measures and the unrestored upstream control sample site were compared. The results show that the instream restoration measures had significant positive effects on the physical habitat and benthic macroinvertebrates in the agricultural headwater stream, that the physical habitat quality was a key factor affecting the restoration of the benthic macroinvertebrates, and that the restorative effects were affected by the interaction between the restoration measure and time. The five-year observation period showed continuous improvement in the habitat quality as well as a continuous increase in the taxon richness and diversity of the benthic macroinvertebrates at the restored sample sites. The AD and BP measures had the most significant positive effects on the richness and diversity of the benthic macroinvertebrates. The density of the benthic macroinvertebrates in the habitat at the sample site treated with the IW continuously remained at a high level. The benthic macroinvertebrates in the habitat at the sample site treated with the GR exhibited outstanding durability against and resilience to a flood. Schemes involving densely placed instream restoration measures had continuous positive effects on the physical habitat and benthic macroinvertebrates in agricultural headwater streams on a medium time scale (six years).

1. Introduction

Intensive agriculture is one of the main causes of ecological degradation in streams worldwide (Allan, 2004; Riseng et al., 2011; Vörösmarty et al., 2010), particularly in China (Liu et al., 2003; Sun et al., 2012). Streams in agricultural watersheds are facing many grave problems, such as excess fine-grained sediment and changes in hydrological conditions (e.g., Murphy et al., 2015; Wagenhoff et al., 2011). How to scientifically cope with the degradation of agricultural streams is a challenge around the world (Hering et al., 2015; Robertson and Swinton, 2005).

To cope with ecological degradation in streams, ecological restoration is widely conducted across the world to repair river and stream ecosystems (Bernhardt et al., 2005; Wortley et al., 2013). Streambed substratum conditions play a pivotal role in the life cycle of numerous aquatic species and the maintenance of their diversity (Geist, 2011; Palmer et al., 1997). Therefore, physical habitats have become one of the core targets of ecological stream restoration projects (Pander et al., 2015). Recent years have seen a continuous increase in financial investment and time spent on streambed substratum habitat restoration projects (e.g., Pander et al., 2013; Pulg et al., 2011). Changes in natural flow conditions (Mueller et al., 2011) and increases in fine sediment (Dudgeon et al., 2006) caused by agricultural activity are a major cause of degradation of streambed substratum habitats in agricultural

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watersheds. However, most research on the restoration of degraded physical habitats focuses on channelized streams (e.g., Baumgartner and Robinson, 2017; Erwin et al., 2017) and, in regard to ecological targets, this research concerns mainly fish (Kurth and Schirmer, 2014; Louhi et al., 2016) and special species (e.g., endangered, threatened, or native species). Because there are few types of fish of special economic value and ecological significance in agricultural headwater streams, most research investigating the management and restoration of agricultural streams focuses on the nitrogen, phosphorous, pesticides, agricultural activity management, and land-use efficiency (e.g., Flavio et al., 2017; Williams et al., 2015). Research on the degradation and restoration of physical habitats in agricultural headwater streams is severely lacking.

Physical streambed substratum conditions in a stream are one of the major factors that affect the aquatic community (Sheldon, 1968) and, particularly, have a significant direct impact on the benthic macroinvertebrates (Mazão and da Conceição, 2016). Benthic macroinvertebrates are the middle link of the food chain and the integral components of food webs in stream ecosystems. By playing a central role in energy flow and matter circulation (e.g., decomposition of organic matter), macroinvertebrates directly influence the survival and reproduction of other taxa and are regarded as the foundation of a stable stream ecosystem (Covich et al., 2004; Townsend et al., 1998). They are sensitive to environmental changes such as disturbance, deterioration, and improvement (Sharley et al., 2008; Townsend et al., 2009). Different macroinvertebrate taxa have different sensitivities and tolerance capabilities to environmental conditions (Milošević et al., 2016; Murphy et al., 2014). Meanwhile, their life cycles are relatively longer than algae, but their migration ability is relatively weaker than fish (Balderas et al., 2016; Bonada et al., 2006). Therefore, macroinvertebrates can reflect the comparatively long-term temporal and spatial changes of stream ecosystems and can predict future problems (Herman and Nejadhashemi, 2015; Karr, 1999; Koperski, 2011).

Some studies have indicated that benthic macroinvertebrates are ideal indicator organisms for research on the effectiveness of habitat restoration projects (Jähnig et al., 2010; Li et al., 2015). However, far less attention is paid to benthic macroinvertebrates than fish in research on the effectiveness of stream habitat restoration. The available research shows variable results with respect to the relations among stream restoration projects, changes in streambed substratum habitats, and benthic macroinvertebrate communities. Some studies find that stream habitats and benthic macroinvertebrate communities noticeably recovered after streambed substratum restoration projects were conducted (Frainer et al., 2018; Kail et al., 2015; Miller et al., 2010; Verdonschot et al., 2016), whereas more studies demonstrate that physical streambed substratum habitat restoration projects had limited positive effects on the benthic macroinvertebrate communities in the streams (e.g., Feld et al., 2011; Friberg et al., 2014; Jähnig et al., 2010; Lepori et al., 2005; Louhi et al., 2011; Negishi and Richardson, 2003; Palmer et al., 2010). The low effectiveness of restoration on macroinvertebrates can be attributed to insufficient restoration intensity (Suding, 2011), inappropriate design or measures (Lepori et al., 2005; Lorenz et al., 2009; Verdonschot et al., 2016), the limited scale (Bernhardt and Palmer, 2011; Jähnig et al., 2010; Sundermann et al., 2011), and a lack of geographically adjacent source populations for species colonisation (Brederveld et al., 2011; Kitto et al., 2015; Nilsson et al., 2015; Parkyn and Smith, 2011). While a wide variety of streambed substratum habitat restoration measures have been used extensively, they are mostly set up and implemented based on experience, and scientific evidence on their restorative effects is scant (Pedersen et al., 2009; Sarriquet et al., 2007). These apparent discrepancies in the results from empirical case studies limit our ability to understand the restoration process and improve the restorative effects. Therefore, studies of the various types of stream restoration cases and examinations of the effects of physical habitat restoration measures on biotic communities are necessary. Agricultural stream habitat restoration is the weak area of relevant research.

In this study, the effects of several instream restoration measures on the physical habitat quality and benthic macroinvertebrate community in a headwater stream in the black-earth agricultural region in Northeast China were analyzed. The black-earth agricultural region in Northeast China is a major commodity grain base in China. In this region, the pressure placed on river and stream ecosystems by agricultural activity is a prominent problem. The damage of a headwater stream flowing into a reservoir in the black-earth agricultural region was repaired within a 1-km range. The stream is a typical representative of agricultural headwater streams. An evaluation was conducted after the restoration project was implemented on a five-year scale (i.e., two to six years after the implementation of the restoration project). The objectives of this study were (1) to evaluate the restorative effects of densely placed instream restoration measures on the damaged agricultural headwater stream and (2) to compare the effects of four instream habitat restoration measures (instream wetland (IW), groin (GR), artificial drop (AD), and boulder placement (BP) measures) on the benthic macroinvertebrate community.

2. Material and methods

2.1. Study area

The Yinma River is a primary tributary of the Second Songhua River. The Shitoukoumen Reservoir situated in the middle reaches of the Yinma River. The stream restored in this study is a 3.2-km-long agricultural headwater stream (43°53′N, 125°45′E; Fig. 1) that flows from west to east into the Shitoukoumen Reservoir. Before restoration, the headwater stream had a longitudinal gradient of 5‰, a width of 1–2 m, and a water depth of 0.1–0.2 m in normal seasons. The small watershed of the headwater stream has a valley-alluvial floodplain-terrace landform, with black earth and leached soil as the main soil types. To the north bank of the stream are highways and residential areas; to the south bank of the stream is a sloping cornfield with some remaining forestland at the top. This area has a northern temperate semi-humid monsoon climate, with an annual average temperature of 4.8 °C and an annual average precipitation of 522–615 mm. Most precipitation in this area falls in summer, and the precipitation from July to September accounts for 75% of the total annual precipitation.

2.2. Restoration scheme

Our restoration scheme increased the instream flow dynamics and the diversity of flow patterns by implementing instream measures and achieved a redistribution of the substratum and habitat quality restoration by means of diversified water flows, thereby restoring aquatic communities, such as benthic macroinvertebrates, and eventually restoring stream ecosystem functions (e.g., the self-cleaning capability).

To address the existing problems facing the agricultural headwater stream (e.g., unstable banks, discontinuous hydrological conditions, physical habitat degradation and water quality deterioration; Fig. 1B), our research team designed a ecological stream restoration scheme and restored a 1000-m-long segment of the stream (3200 m in total length) in its middle reaches in 2008 (Table 1). Four instream measures—IW, GR, AD and BP measures—were implemented to help rehabilitate the stream to near-natural conditions relating to erosion, transport, and sedimentation, with a focus on improving its ecological conditions (hydrological and habitat quality) and a goal of ultimately increasing the diversity of the flow patterns, stream habitat quality, and biodiversity.

2.3. Restorative effects

The physical habitat quality and benthic macroinvertebrate communities in the microhabitats were monitored at the same time at five