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Water-quality impacts in semi-arid regions: can natural ‘green filters’ mitigate adverse effects on fish assemblages?

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ABSTRACT

The effective aridity in riparian areas is increasing from climate change and from human water consumption, which exacerbates the impacts of effluents from wastewater-treatment plants and from catchment run-off in rivers. The potential of natural riparian areas to act as ‘green filters’ has long been recognized, but the possible ecological benefits of natural riparian areas over large-scale environmental gradients on fish have not been explored in detail. Using an extensive data-set from northeastern Spain (99,700 km^2, 15 catchments, 530 sites), ours is the first study to ask whether natural riparian vegetation can mitigate the effects of pollution on fish in rivers experiencing water scarcity. We used multimodel inference to explore the additive and interactive effects of riparian vegetation with nutrient pollution and water conductivity, which are among the world's worst river stressors, on multiple fish guilds, including widely distributed species and highly invasive alien fish species. Most models (54%) supported the additive effects of water-quality factors on fish, after having accounted for the influence of geography and hydrological alterations. Although many fewer models (7%) included riparian vegetation as an important predictor, riparian vegetation modulated the forms of the associations between fish and pollution. The relationship of nutrient pollution with native and alien fish richness changed from negative to positive with greater riparian structure or species richness. However, we found the opposite effect for the mean body size of sedentary fish, and only positive additive effects of riparian richness for the probability of occurrence of pelagic fish. Ammonium and nitrite concentrations adversely affected fish in these rivers up to 10 years after the enforcement of the implementation of the Water Framework Directive by the European Union. High conductivity also much affects fish, having negatives associations with migratory, pelagic, invertivorous and native fish, and positive associations with sedentary, benthic, omnivorous and alien fish. Therefore, the current status of natural riparian areas is unlikely to fully mitigate water-quality impacts on fish. The conservation of freshwater resources in semi-arid regions, such as north-eastern Spain, requires improved waste-water treatments and better agriculture practices.

1. Introduction

The management of freshwater resources is one of the major challenges for humanity. Freshwater scarcity affects two-thirds of the global population (>4 billion people), and half a billion people in the world face severe water scarcity year round (Mekonnen and Hoekstra, 2016). Sewage discharges exacerbate this crisis of freshwater availability, with as many as 2.4 billion people at risk of acquiring water-borne diseases (W.H.O., 2017). Although developing countries are most at-risk, water-pollution issues occur in developed countries, especially in semi-arid regions, where the low dilution ability of rivers makes standard wastewater treatment plants (WWTP) less able to fully mitigate pollution stress (Prat and Munné, 2000; E.P.A., 2013). If most of the world's population are to be living in water-stressed areas by 2025 (W.H.O., 2017), then there is an urgent need to search for improved water-treatment

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strategies for these regions, ideally sensitively integrated with natural ecosystem processes (Hering et al., 2013).

Current technologies allow the purification of WWTP effluents to high water-quality standards (e.g. García-Ivars et al., 2017; Talvitie et al., 2017; Yang et al., 2017). However, these treatments are not always cost-effective (Rosal et al., 2010; Grant et al., 2012) and do not necessarily have the benefits of WWTP when integrated into natural systems, such as constructed wetlands (Hering et al., 2013; García-Rodríguez et al., 2014). Constructed wetlands provide habitats for wildlife alongside water purification (Kadlec, 1979; Higgins et al., 1993), and they have been used more often in recent decades as a cheaper alternative to technologically advanced WWTPs (Cole, 1998; Dan et al., 2017). Some limitations are that constructed wetlands may occupy large surface areas (Cole, 1998; Kadlec, 1979) and that their performance depends on climate and river flow, which may limit their efficacy in semi-arid regions (but see Cerezo et al., 2001; Puigagut et al., 2007). Moreover, other major pathways of pollution in rivers than point sources (WWTP effluents) need to be considered, such as agricultural runoff (Krause et al., 2008, Fig. 1).

Run-off and effluents from WWTPs carry many compounds, which can act as subsidies (nutrients) or pollutants (chemicals and high nutrient levels) for riverine ecosystems (Wagenhoff et al., 2011; Aristi et al., 2015). The benefits of intact riparian vegetation for river-ecosystem functioning long have been recognized (Broadmeadow and Nisbet, 2004; Feld et al., 2011; Melcher et al., 2016), as are 'buffer strips' that reduce the nutrient influx from agricultural areas (Peterjohn and Correll, 1984; Krause et al., 2008; Collins et al., 2012). However, the potential of an intact vegetation continuum to attenuate in-stream pollution in rivers have not yet been examined in detail (Fig. 1). The relatively few studies addressing this question in semi-arid regions have shown in-stream attenuation of inputs from urban and industrial WWTPs (e.g. Aristi et al., 2015; Acuña et al., 2015; Colin et al., 2016) or after experimental nutrient additions (e.g. Sabater et al., 2000; Bernal et al., 2015). Sabater et al. (2000) reported that removal of riparian vegetation affects in-stream nutrient retention, which supports other studies that have shown experimentally the ability of several plant species (e.g. *Phragmithes australis*, *Typha latifolia*) to purify pollutant mixtures (Kumari and Tripathi, 2015). Nonetheless, chemicals also can be toxic to many organisms, including plants, and affect their growth, abundance and diversity (e.g. Barbour et al., 1999; Colin et al., 2016). Moreover, the structure of riparian areas differs depending on geography and human activities, and their benefits can be plant-specific (e.g. Pozo et al., 1997). Therefore, more comprehensive studies assessing the potential of riparian vegetation to attenuate pollution than these spatially limited studies are necessary before one can develop appropriate mitigation strategies for dealing with riverine water pollution in semi-arid regions.

Here, we use data from extensive fish surveys in rivers in northeastern Spain ($N = 530$ sampling sites, 15 catchments) to explore the effects of riparian vegetation and pollution on freshwater fish assemblages. Freshwater fish are very important resources for humans and are among the most-at risk biotic groups on Earth (Closs et al., 2015). Previous studies in northeastern Spain have shown that individuals' body condition and size, and the taxonomic and functional composition of fish assemblages, are affected by water pollution and by physical habitat degradation (e.g. Murphy et al., 2013; Maceda-Veiga et al., 2016; Colin et al.,

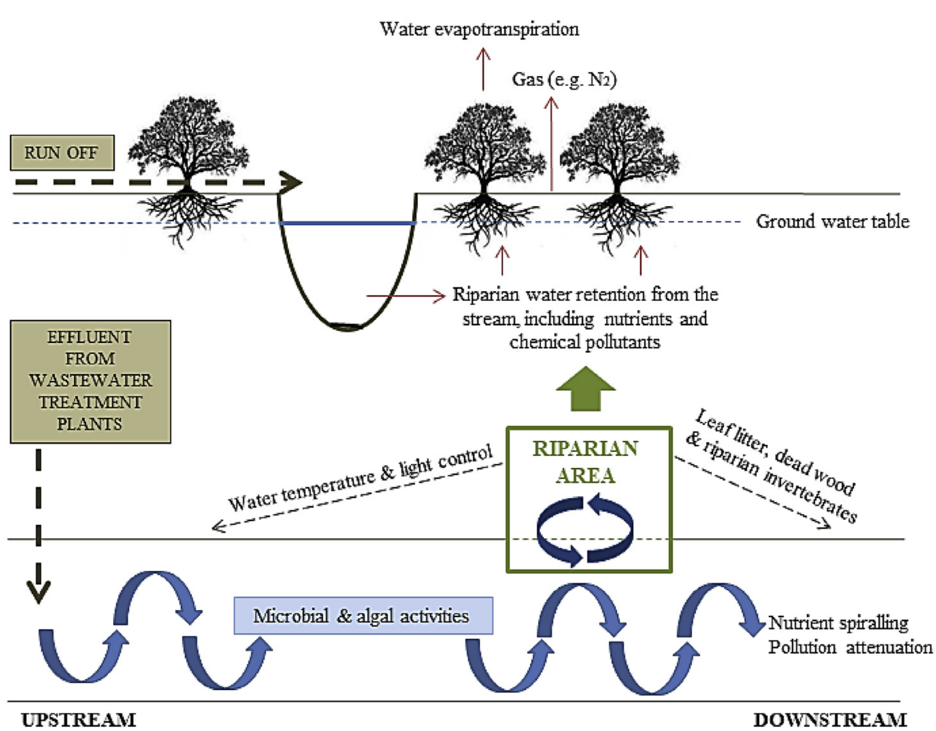

Fig. 1. Diffuse (terrestrial run-off) and point pollution (sewage discharges) are among the major sources of subsidies and chemicals to rivers. Subsidies (e.g. nutrients, essential trace elements) at high concentrations are pollutants. In-stream microbial and algal activities and physico-chemical processes are involved in the attenuation of pollution along the river channel (Sabater et al., 2000; Aristi et al., 2015; Acuña et al., 2015). Riparian areas may benefit rivers in many ways (Broadmeadow and Nisbet, 2004) and probably modulate the impacts of water pollution on fish: (1) shading reduces in-stream primary production and water temperature (Melcher et al., 2016), which in turn may reduce fish metabolism and reduce toxic effects (2) organic matter from riparian areas (e.g. leaf litter) boosts availability of fish prey (invertebrates, Lorion and Kennedy, 2009); (3) overhanging vegetation, dense root systems and large wood provide fish with shelter (e.g. Sievers et al., 2017); and (4) riparian evapotransporation moves water from streams to riparian areas, where subsidies and chemicals can be microbially transformed, retained in soils, volatized or absorbed by plants. Riparian water retention is particularly high in semi-arid regions during drought (Lupon et al., 2017).