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Original Research Article

Microbial biofilms as one of the key elements in modulating ecohydrological processes in both natural and urban water corridors

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ABSTRACT

Fluvial corridors such as streams and urban canals are critical components of the landscape and are key ecohydrological assets. They are essential to landscape function and are vulnerable to anthropogenic pressures. Energy and nutrient budgets in such corridors are dominated by processes associated with detrital organic matter and are mediated by microorganisms that mainly reside in biofilms. Here, we review the major hydrologic factors shaping biofilms in natural and urban water corridors, and propose the integration of single-cell visualization techniques with other broad-scale approaches (genomics) to better understand structure–function coupling in such complex microbial communities. We, further, provide evidence that it is possible to visualize specific bacterial clusters and autotrophic microorganisms within the matrix of natural biofilms from urban canals. This can then guide the development of ecohydrological approaches and management interventions to harness ecological services mediated by biofilms, with enormous implications also by a sanitary point of view.

1. Introduction

Fluvial corridors, such as streams and urban concrete canals, are dominant features in both natural and human-dominated landscapes. They facilitate the flow of energy and materials between patches on the landscape, thereby exerting a strong influence over landscape functions beyond what their spatial footprint would suggest (Puth and Wilson, 2001; Naiman and Décamps, 1997). As elements of larger networks and interfaces between different landscape patches, such corridors are also key ecohydrological assets. The benthic ecosystem, inherent within such corridors, is a driver of crucial ecosystem processes and is vulnerable to anthropogenic pressures.

The dynamism in natural riverine environments arise from variations in geomorphology, edaphic properties, precipitation patterns, land-cover and anthropogenic influences (Puth and Wilson, 2001; Naiman and Décamps, 1997; Amalfitano et al., 2008). However, such corridors have either been lost, transformed or designed across many regions. These transformations have disrupted the natural flow regime that previously occurred within such

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natural hydrosystems (Puth and Wilson, 2001). This can, in turn, affect fluxes of carbon and contribute to climate change. For instance, globally, riverine environments have been observed to contribute around 0.4 Pg C yr^{-1} in both inorganic and organic carbon (Richey, 2004). Carbon and energy budgets in such fluvial corridors are mainly dominated by processes associated with degradation of allochthonous and autochthonous organic matter, mediated by microbes that mainly reside in biofilms. In these biofilms, the tight physical association among autotrophic and heterotrophic microorganisms enhance the efficiency of the C cycling. Microbial degradation of dissolved and particulate organic matter prevail in headwaters, and the ensuing detritus based food webs are critical to headwater functioning and affect the overall ecology and nutrient cycles of even the lowest stream reaches (Findlay et al., 2002). As light exposure increases, proceeding downstream, rapid development of microbenthic algae resulting from nutrient enrichment improves the nutritional quality of benthic biofilms (Zalewski et al., 1998). Light may limit primary production affecting food web structure and energy flow (Hill et al., 1995; Ceola et al., 2013).

On the other hand, urban water transfer networks, comprising concrete canals and drains represent the built counterparts of natural streams in highly urbanized environments such as well-managed modern cities. They serve a multitude of purposes including water storage, flood conveyance and a sense of place (Grimm et al., 2008), key to sustaining an ever-increasing urban population. Flow regime in such networks are controlled by virtue of their design, as opposed to the dynamic nature of flow in natural streams (Elliott et al., 2004). Such altered conditions have few precedents (Grimm et al., 2008) and thus limit the application of principles governing biofilm ecology in other natural flow environments (Battin et al., 2003). Contrary to natural streams and rivers, the aquatic habitat in such hydro-systems is poorly understood. Benthic biofilms are thought to drive key nutrient and energy transformations, thereby contributing to the self-purification capacity of such systems (Battin et al., 2003). Ultimately, the hydro-resilience of modern cities to global environmental change will depend on the stability and sustainability of such networks.

In this article, we highlight how hydrological factors shape biofilms in natural streams and urban water corridors in order to integrate the processes they drive in an ecohydrological approach. One of the major challenges that needs to be immediately addressed is to link microscale biofilm functions to landscape level ecosystem processes (Findlay et al., 2002). An ecohydrological approach to stream quality assessment, restoration and management, therefore, cannot disregard the analysis of the dynamics of microbial biofilms by long term monitoring tools. Quantitative insights into biofilm ecology can be combined with existing detailed hydrological models to make mechanistic predictions. We finally suggest the integration of single-cell visualization techniques with other broad-scale approaches to better understand the coupling between structure–function of such microbial communities.

2. Microbial biofilms

Across most natural and urban water corridors, interface-bound matrix-enclosed biofilms dominate microbial life. They exert a strong influence over energy and nutrient fluxes, thereby effecting critical ecosystem services (Battin et al., 2003). Biofilms in most environments comprise complex self-organized microbial communities with a distinctive spatial architecture. Their development usually consists of incremental biomass accumulation in the nascent stages while three-dimensional structural differentiation marks their maturation (Neu et al., 2010; Watnick and Kolter, 2000).

The significance of coupled biofilm structure and function and hydrology, at microbial relevant scales, have been reported (Battin et al., 2003). In particular, biofilms bring hydrodynamic retention and biochemical processing into close spatial proximity and influence biogeochemical processes and patterns in streams. Its structure highly depends on the hydrological context, with biofilm thickness ranging from 300 μm to 100 μm and biofilm density from 0.03 g cm^{-3} to 0.01 g cm^{-3} when grown in slow- and fast-flow mesocosms respectively (Neu et al., 2010). Working in a Mediterranean river, subject to high flow variation, Osorio et al. (2014) found that after a flood event, the accrual of biofilm biomass (calculated as the increase of chlorophyll-a in time) were significantly reduced, passing from 0.44 to 0.5 μg Chla cm^{-2} day^{-1} to 0.02–0.25 μg Chla cm^{-2} day^{-1}.

Reproducible spatial patterns have been observed at the millimetre scale, which highlight their possible significance to their functioning (Webster, 2007). Yet, we know little about the influence of such microscale dynamics on landscape level ecosystem processes (Neu et al., 2010). Therefore, a mechanistic understanding of such spatial clustering and compartmentalization is a key requirement in order to elucidate the specificity, stability and functional implications of such microbial associations (Fazi et al., 2013).

Our understanding of stream biogeochemistry has indeed benefitted much from decades of research, with theories such as spiralling down the river continuum becoming a unifying paradigm describing the coupled transport and transformation of materials in such ecosystems (Webster, 2007; Ensign and Doyle, 2006). However, a comprehensive framework that describes biogeochemistry of urban water corridors still needs to be developed. Although flow affects the transport of material and biofilms regulate reaction rates, researchers and policy makers treat corridors and the ecosystems they harbour, as separate unrelated features, missing the relationship between flows and biofilms and *vice versa.* Biofilm function in corridors depends much on its regional context, with flow and energy gradients imposing important controls. Studying biofilm ecology in the context of the critical components of stream flow that regulate ecohydrological processes (*i.e.* flow regime) can also help to identify how alterations of streamflow regime due to habitat fragmentation or other anthropogenic factors affect the stream ecosystem (Ceola et al., 2013).