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Variability in ecosystem structure and functioning in a low order stream: Implications of land use and season

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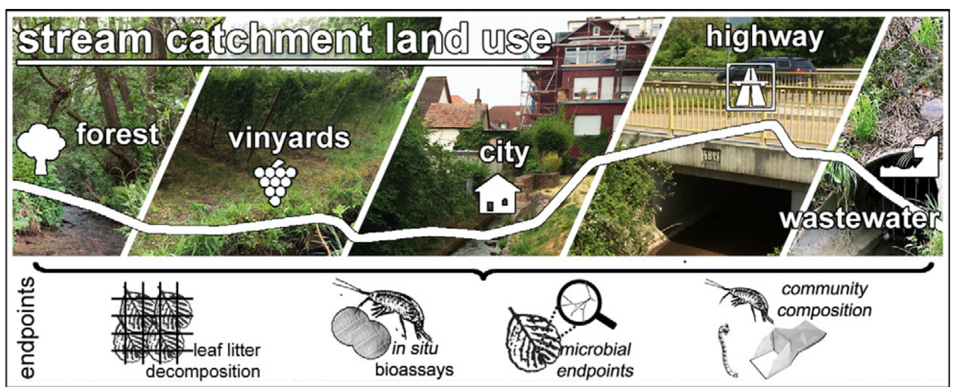
HIGHLIGHTS

- Successive land uses substantially modified stream ecosystem structure and function.
- Adverse effects increased along the stream channel and hence with land uses.
- The impact of land use deviated substantially among seasons.
- In situ bioassays indicated changes in water quality as driving force.

GRAPHICAL ABSTRACT



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ABSTRACT

Human activity can degrade the habitat quality for aquatic communities, which ultimately impacts the functions these communities provide. Disentangling the complex interaction between environmental and anthropogenic parameters as well as their alteration both along the stream channel, over the seasons, and finally their impact in the aquatic ecosystem represents a fundamental challenge for environmental scientists. Therefore, the present study investigates the implications of successive land uses (i.e., vineyard, urban area, highway and wastewater treatment plant (WWTP)) on structural and functional endpoints related to the ecosystem process of leaf litter breakdown during a winter and summer season in a five km stretch of a second-order stream in southern Germany. This sequence of the different land uses caused, among others, a downstream decline of the ecological status from “high” to “bad” judged based on the $SPEAR_{pesticides}$ index together with significant shifts in the macroinvertebrate community composition, which coincided with substantial impairments (up to 100%) in the macroinvertebrate-mediated leaf decomposition. These effects, seem to be mainly driven by alterations in water quality rather than morphological modifications of the stream's habitat since the key shredder *Gammarus* was not in direct contact with the local habitat during in situ bioassays but showed similar response patterns than the other endpoints. While the relative effect size for most endpoints deviated considerably (sometimes above 2-

Abbreviations: ANOVA, analysis of variance; CI, confidence interval; EU WFD, European Water Framework Directive; NMDS, non-metric multidimensional scaling; PERMANOVA, permutational multivariate analysis of variance; SIMPER, similarity percentage analysis; $SPEAR_{pesticides}$, SPEcies At Risk index; WWTP, wastewater treatment plant.

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fold) among seasons, the general response pattern pointed to reductions in energy supply for local and downstream communities. Although the present study focused on a single low-order stream with the main purpose of describing the impact of different land uses on various levels of biological organization, which limits the direct transferability and thus applicability of results to other stream ecosystems, the findings point to the need to develop adequate management strategies mitigating land use specific exposures during all seasons to protect ecosystem integrity.

1. Introduction

Freshwater ecosystems provide a variety of highly valuable services for humans, which include abstraction of clean water as well as the disposal of wastewater (Costanza et al., 1997). However, most stream catchments worldwide are substantially influenced by anthropogenic land uses (Foley et al., 2005) ultimately modulating the morphology of the stream channels or water quality, which degrades the habitat quality for aquatic communities and consequently impacts the functions these communities provide (Malmqvist and Rundle, 2002). These effects are, due to the strong dependence on the land use of adjacent terrestrial habitats, particularly important in low order streams (Bundschuh and McKie, in press).

Moreover, land uses vary along the stream and might cause independent but, if located in close proximity to each other, also cumulative implications on the structure and functioning of aquatic ecosystems. Also seasonal shifts in land use – or more precisely in its intensity – alter among others the pattern of contamination (Bundschuh et al., 2014; Hallberg et al., 2007; Helmreich et al., 2010). At the same time, various environmental factors show seasonal cycles with implications on the aquatic ecosystems and their functioning (e.g., Linke et al., 1999). Disentangling the complex interaction between environmental parameters and land use patterns, their shifts both along the stream channel and over seasons and finally their impact in the aquatic ecosystem represent a fundamental challenge for environmental scientists. A more detailed understanding of these interactions is crucial for the prioritization and implementation of stream restorations or effect mitigation measures to achieve the goals of, for instance, the European Water Framework Directive (EU WFD; European and Commission, 2000) aiming for a “good ecological status” of all surface water bodies in Europe.

By attempting to address this knowledge gap, the present study characterized the implications of different successive land uses (i.e., vineyard, urban area, highway and wastewater treatment plant (WWTP)) on structural and functional endpoints during two seasons, namely winter 2011/12 and summer 2012, along a five km stretch of a second-order stream in southern Germany. Although the strong focus on one stream may limit the transferability to other stream ecosystems, this procedure allowed for a detailed investigation of the effects caused by different land uses at different levels of biological organization broadening our general understanding on ecosystem level responses to anthropogenic stress. In this context, the decomposition of allochthonous organic matter (e.g., leaf litter), mediated by decomposing microorganisms (i.e., fungi and bacteria) and detritivorous invertebrates (i.e., shredders), represents an essential ecosystem process providing energy (in the form of fine particulate organic matter such as feces) for local as well as downstream aquatic communities (i.e., collectors; Vannote et al., 1980). Hence, the microbial and macroinvertebrate-mediated leaf litter decompositions were used as functional measures whereas endpoints related to the leaf-associated microbial community (bacterial cell numbers, fungal biomass) as well as the macroinvertebrate community composition at the sampling sites served as structural estimates. This suit of endpoints was supplemented by in situ bioassays investigating the effects on the feeding rate of the leaf-shredding amphipod *Gammarus fossarum*. As these gammarids experienced exclusively an exposure via the water phase (but not the sediment) confounding effects arising from, for instance, habitat alterations are excluded and the effects can be related to the site-specific water quality. Moreover, due to the standardized food source (i.e., leaf discs) these assays display only direct – not food quality related (cf. Bundschuh et al. (2011a)) – implications of environmental conditions on a sublethal behavioral response of a key species in the leaf decomposition process (Englert et al., 2013; Piscart et al., 2011). Thus, these bioassays represent a valuable amendment to the response variables covered in the present study. It was finally hypothesized that the effects increase in their magnitude (i.e., accumulate) from upstream to downstream sites, and thus with increasing disturbances in the upstream catchment. In addition, the responses were expected to be modulated by seasonal conditions (e.g., differences in stream water levels; cf. Englert et al. (2013)).

2. Materials & methods

2.1. Study site

The present study was performed in a second-order stream (i.e., Triefenbach; Fig. 1) flowing through the city of Edenkoben (Rhineland-Palatinate, Germany). An upstream reference site (ED1; 49.281′N; 8°093′E) within this stream was located directly at the edge of the palatinate forest upstream of any settlement and agricultural activity. After passing a rather small catchment area used for wine production (~1.2 km in length), the Triefenbach flows through the city of Edenkoben (population: ~7000) and is subsequently crossed by a highway. Approximately 500 m further downstream, the municipal WWTP of Edenkoben releases wastewater of a population equivalent of roughly 25,000 (Verbandsgemeindewerke Edenkoben, 2015) into the Triefenbach. At the inflow point, the wastewater contributed approximately 25% to the Triefenbach's discharge during winter (see Appendix 1.1), while its share may be somewhat higher during lower stream water levels during summer. Using the methods described below, ecotoxicological implications on functional (macroinvertebrate- and microorganism-mediated leaf mass loss, feeding rate of *G. fossarum*) and structural endpoints (shifts in the macroinvertebrate community structure, bacterial cell numbers, fungal biomass) were assessed at sampling sites within the vineyards (ED2; 49°281′N; 8°109′E; after a 600 m stream stretch flowing through vineyards), below the city of Edenkoben (ED3; 49°285′N; 8°152′E), 100 m downstream of the highway (ED4; 49°284′N; 8°154′E) as well as 100 m upstream (ED5; 49°284′N; 8°155′E) and 100 m downstream (ED6; 49°283′N; 8°157′E) of the WWTP effluent relative to the upstream references site (ED1), during winter 2010/11 and summer 2011. For the sake of completeness, the information about precipitation and ambient temperature during the experiments performed in both seasons is presented in the Appendix (Table A.1).

2.2. Water quality parameters

At all sites, oxygen saturation, temperature, pH and conductivity were measured in situ weekly during both seasons with a WTW Multi 340i/SET (Wissenschaftlich Technische Werkstätten GmbH, Weilheim, Germany). Current velocity was measured with a Höntzsch instrumentals flow meter (type μO-TAD; Waiblingen, Germany). Ammonium, nitrate, nitrite, phosphate, chloride, and sulfate concentrations as well as hardness were quantified using Macherey-Nagel visocolor® kits (Macherey-Nagel, Düren, Germany; Table 1).