Drivers of organic matter decomposition of headwater streams in an urbanizing region

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Key Points

- Headwater streams often constitute >75 percent of stream networks and are critical for the integrity of downstream waters. Despite this, we lack an understanding of how their key ecosystem processes, such as organic matter decomposition, vary across landscapes.
- Studying Australia's diverse and globally distinctive headwater streams will help researchers understand how flow intermittence and aquatic-terrestrial linkages influence traits and processes within headwater stream environments.
- We conducted organic matter decomposition experiments at four headwater stream sites in the Melbourne region to understand how surface and subsurface environments influence rates of decomposition.
- We found organic matter decomposition was, on average, nine times faster beneath the surface of our study headwater streams than at the streambed.
- Our results suggest that subsurface regions of headwater streams can be active zones for organic matter decomposition, sustaining this key ecosystem process even without persistent surface flow.

Abstract

Headwater streams often constitute >75 percent of natural stream networks and are critical for the integrity of downstream waters. These environments are experiencing increasing stress and degradation from agriculture and urbanization, yet we lack a detailed or quantified understanding of how their key ecosystem processes, such as organic matter decomposition, vary across the landscape. We conducted organic matter decomposition experiments at four headwater streams in the Melbourne region to understand how surface and subsurface environments influence rates of decomposition. A main study of 40 sites, varying in catchment land cover, temperature, rainfall, geology and vegetation, will follow. We used cotton strips as a standardized proxy for organic matter, leaving them to decompose in the stream for four weeks in early summer 2020. We found organic matter decomposition was, on average, nine times faster beneath the surface than on the streambed of our headwater streams despite lower average temperatures beneath the surface. Ongoing research is assessing how flow intermittency and other physical and chemical parameters influence decomposition and the diversity of microbial communities across the landscape. Our results suggest that subsurface regions of headwater streams can be active zones for organic matter decomposition, sustaining this key ecosystem process even without persistent surface flow.

Keywords

Headwater streams, ecosystem health, organic matter decomposition

Introduction

Headwater streams substantially influence the health of downstream waters (U.S. EPA, 2015), forming the majority of the stream network (Barmuta et al., 2009; Allan and Castillo, 2007). They are major suppliers of freshwater, nutrients, and organic material (Barmuta, et al., 2009), can be biodiversity hotspots (Clarke, et al., 2008; Meyer et al., 2007), and are areas of active biogeochemical processing (Hotchkiss et al., 2015). Impacts from urbanization and agriculture continue to threaten headwaters (Meyer and Wallace, 2001), but we lack knowledge of how fundamental ecosystem processes in headwater stream vary across the landscape and under urbanizing conditions.

Headwater stream environments

The characteristics of headwater streams vary with ecoregion, topology, and local environmental conditions. While much of the literature has focused on perennial headwaters in temperate forested catchments, there is now a recognition that streamflow in these regions can cease to flow for parts of the year. Australia's "unusual environmental conditions" (Lake, et al., 1985) warrant further study, due to the continent's high inter-annual flow variability, low runoff, and substantial presence of non-perennial streams.

This research focuses on the smallest and most upstream segments of the stream network. We define headwaters as the most upstream reaches of a catchment, where surface runoff is sufficiently concentrated to scour the catchment surface and create distinct banks, or where there are identifiable aquatic and semi-aquatic habitats. Examples of headwater streams in the greater Melbourne region are provided in Figure 1.

Figure 1. Examples of headwater streams across Melbourne

Threats to headwater streams

Across the river system, headwater streams often receive the least protection. Effective management is hindered in part by the shortage of current information on the recognition of non-perennial headwaters (Larned, et al., 2010), as well as the lack of effective mapping of small headwater streams (Acuña et al., 2014; Barmuta et al., 2009; Buttle et al., 2012; McDowell, 2009). As a consequence, headwater streams are often lost from the landscape or drastically altered (Meyer & Wallace, 2001). More specifically, these streams are typically subject to agricultural or forestry impacts in the first instance, before being further threatened through urban development, where traditional engineering approaches frequently bury or channelize headwater streams to create efficient drainage pathways to deal with urban stormwater (Elmore & Kaushal, 2008; Kaushal & Belt, 2012).

An important question is, what do we stand to lose? Given their large contribution to stream network lengths (Allan & Castillo, 2007; Barmuta et al., 2009) and fundamental ecosystem processes (U.S. EPA, 2015), incremental loss of headwater streams may have severe, far-reaching ecological impacts. To help answer this question, we must understand their ecosystem processes.

Processes in headwater streams

An important ecosystem process that occurs in headwater streams is organic matter decomposition. Organic matter is a fundamental input into freshwater ecosystems, and its decomposition provides food resources in heterotrophic ecosystems (e.g. Allan & Castillo, 2007), contributes to global carbon cycles (Elosegi & Pozo, 2016), and influences nutrient retention and transformation (Elosegi & Pozo, 2016; Mulholland & Webster, 2010). Organic matter also provides a range of other ecological functions, including providing habitat for aquatic biota and influencing invertebrate productivity (Cross et al., 1997).

Headwater streams, perhaps more than any other stream type, warrant detailed study of organic matter dynamics for three reasons: (1) in many headwater streams, food webs are supported by detritus; (2) as the first flow points in the catchment, headwater streams provide storage, processing and act as conduits of allochthonous material to the downstream river network (Barmuta et al., 2009; Elosegi & Pozo, 2016; U.S. EPA, 2015); (3) due to their extent, the influence of headwater streams on the ecosystem integrity of downstream waters can be substantial (U.S. EPA, 2015).

Study aims

This study aims to increase our understanding of the importance of protecting and restoring headwater streams from human impacts. Specifically, we aim to understand how site and catchment characteristics influence rates of decomposition and microbial communities (see Figure 2).

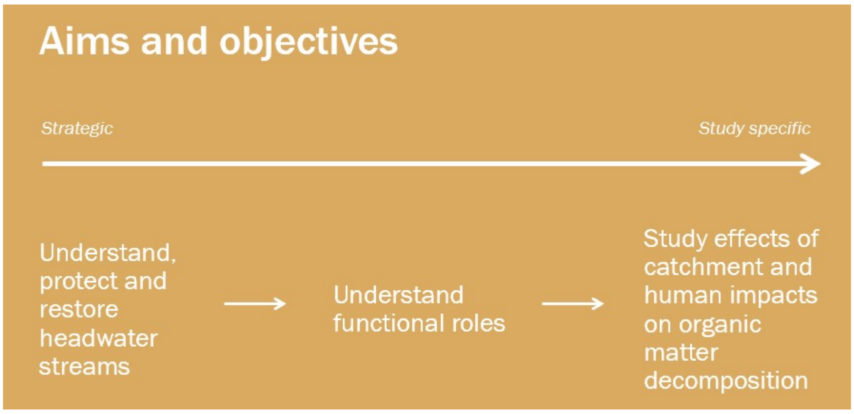

Figure 2. Aims and objectives

Methods

Pilot study

We conducted organic matter decomposition experiments at four “reference” sites (streams whose catchment remains in their natural state) in Melbourne’s west. Pilot study sites varied in geology, temperature, and vegetation. These sites were selected to trial the experimental method.

We used cotton strips as a proxy for organic matter, leaving them to decompose in the stream for four weeks at the start of summer 2020 (as per the standardized method by Tiegs et al., 2013). Two sets of temperature loggers (HOBO Pendant Data Logger Temp/Light) and three cotton strips were deployed at each site: one set at the surface of the stream bed and the other buried 25cm below stream sediments to measure activity in the hyporheic zone. We also measured temperature continuously over the experiment.

We investigated differences in the mean rates of organic matter decomposition between subsurface (n=4) and surface (n=4) environments using Kruskal-Wallis test by ranks.

Main study

In Spring 2021, we propose to conduct organic matter decomposition experiments at 40 sites in the greater Melbourne region (see Figure 3). The selected sites vary in catchment land cover, temperature, rainfall, geology, and vegetation. This is to represent the diversity of streams and human impacts across the region, particularly capturing variation across the key drivers in organic matter decomposition rates as highlighted during our literature review: nutrient concentrations, temperature, and flow permanence. We selected sites using GIS analysis, which will be verified through site visits.

We selected sites across five general sub-regions of greater Melbourne: west, north, north-east, the Dandenong Ranges, and Mornington Peninsula. Each sub-region consisted of three to four forested (reference) catchments, and four to five cleared catchments. Cleared catchment land uses include vineyards, cropping, and peri-urban (i.e., “lifestyle properties”).

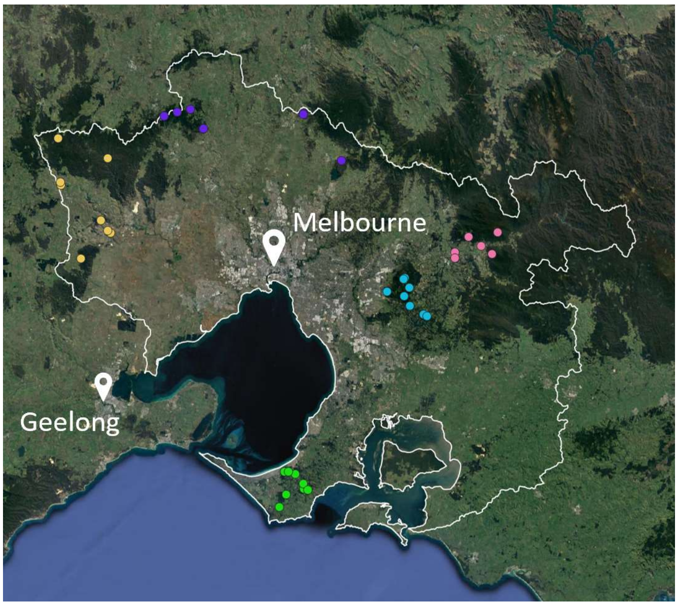

Figure 3. Study sites and their sub-regions: west (yellow), north (purple), north-east (pink), Dandenong Ranges (blue), Mornington Peninsula (green)

Following the method from the pilot study, we will deploy cotton strips at the surface and buried 25cm below stream sediments at each site for four weeks in spring 2021. As well as measuring temperature, we will also collect measurements of hydrology using surface water level sensors (developed by the University of Melbourne), water quality, and microbial diversity. Temperature and water level will be measured continuously over the experiment, while water quality will be measured using in-stream YSI multiprobe instrumentation and grab sampling for laboratory analysis (once at the start and once at the end of the study).

Results

Our results from the pilot study showed that organic matter decomposition was, on average, nine times faster beneath the surface of our study headwater streams than at the streambed (Figure 4; Chi-squared = 5.3, p-value = 0.02). In subsurface environments, percent tensile strength-loss per degree day ranged on average from 0.038 to 0.091 with an average of 0.072. By comparison, in surface environments, the average percent tensile strength-loss per degree day was 0.0080, with a range from 0.0032 to 0.016. This is despite lower average temperatures beneath the surface (see Figure 2).

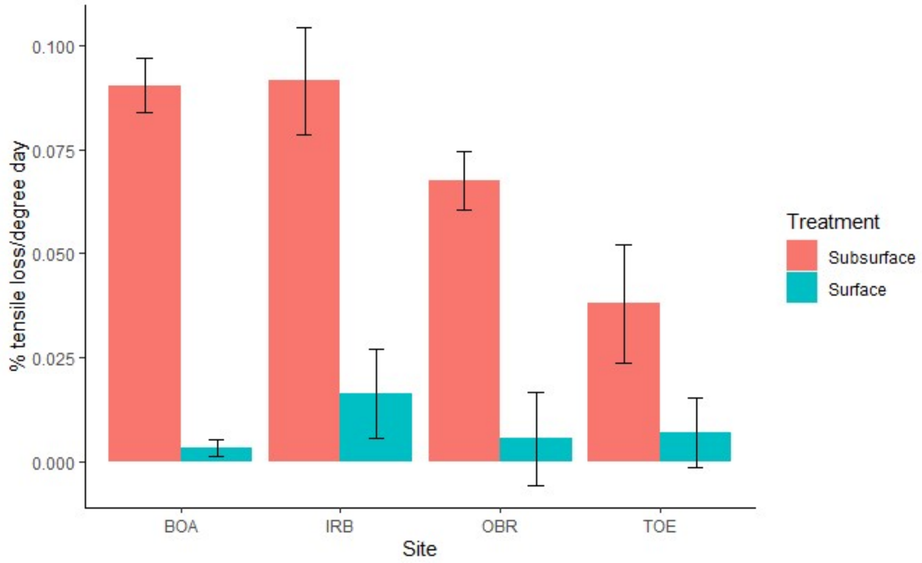

Figure 1: Percent tensile-strength loss per degree day (mean +/- 1 SD) of cotton strips for four pilot study sites in Melbourne's west. The plot shows subsurface and surface results at each site. Mean percent tensile strength loss per degree day was higher for subsurface regions than at the surface across all four sites. Note: The limit of detection of the tensiometer used is 1.660 volts. One sample each taken from the surface of TOE and OBR measured breaking tension above 1.660 volts (beyond the limit of detection), suggesting that gains in tensile strength at the surface for TOE and OBR are unlikely to be a product of cementation (see French, 1988) and rather are associated with the uncertainty of the instrument.

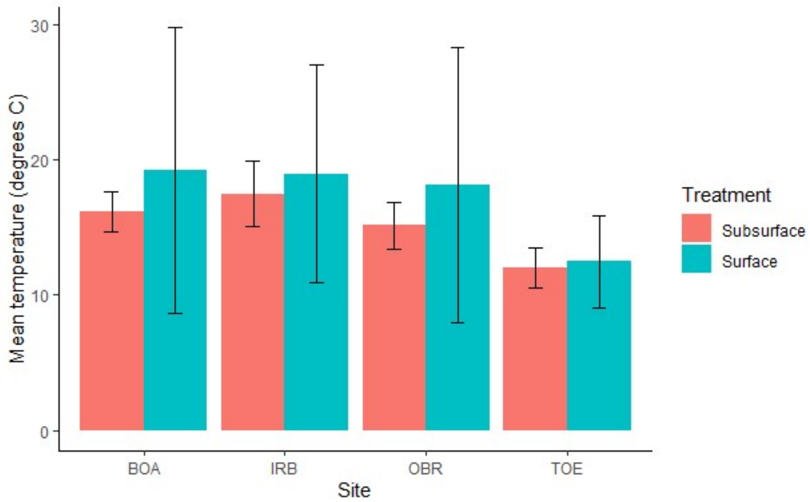

Figure 2: Mean temperature (mean +/- 1 SD) at the four pilot sites in Melbourne's west. The plot shows subsurface and surface temperatures at each site. Mean temperature was higher for surface regions than subsurface regions at all four sites. The average subsurface temperature across all four sites was 15.2 degrees C, compared with an average of 17.2 degrees C across the surface environments.

Discussion

Our results suggest that subsurface regions of headwater streams can be highly active zones for organic matter decomposition, sustaining this key ecosystem process even without persistent surface flow. Our current hypothesis is that the subsurface environment of the pilot study sites was wetter than the surface during the study period. While this was visually observed at each visit, we do not have hydrologic data for the pilot study to confirm this. This will be evaluated in the wider Melbourne study. Previous research has shown that flow intermittence and moisture availability fundamentally influence organic matter decomposition rates (Larned et al., 2010; Datry et al., 2011). In a study of larger non-perennial streams in humid subtropical eastern Australia, Burrows et al. (2017) observed similar results, indicating that groundwater induced effects on sediment moisture content was likely a key driver of elevated decomposition rates beneath the surface.

Our findings have important implications for the management of headwater streams in rapidly urbanizing environments. Research shows that urbanization alters stream hydrology, changing surface flow patterns and groundwater flow paths (Walsh et al., 2005; Bonneau et al., 2018). This change in hydrology and moisture availability within the stream environment will likely influence organic matter breakdown rates, with flow on implications for carbon cycles, nutrient retention and transformation, and aquatic food webs. Minimising the effects of urbanization on headwater stream environments will require careful management of stormwater runoff and stream hydrology.

While our results to-date highlight the importance of hydrology and moisture availability, the broader study across the Melbourne region will help identify other key catchment variables which influence decomposition and the diversity of microbial communities across the landscape; further highlighting management approaches which facilitate the protection of headwater stream ecosystem structure and function.

Conclusions

Headwater streams clearly influence the integrity of downstream waters in terms of hydrology, biodiversity, and biogeochemical processes. Australia is predominately drained by non-perennial headwaters, and while the study of non-perennial headwater streams is rapidly growing, local research is lacking, especially in the study of organic matter decomposition.

This project supports much needed research into the ecological function of headwater streams across varying flow environments. Importantly, it contributes to the cataloguing of decomposition rates in headwater streams, which is a critical step in better understanding the ecological value of headwater streams and to enable managers to use organic matter processing as an indicator of ecosystem health in Australia.

Our results to-date highlight the importance of hydrology and saturated hyporheic zones to the decomposition of organic matter in headwater streams, including streams that may look mostly terrestrial and otherwise be considered unlikely to contribute to downstream aquatic ecosystem structure and function. This has important implications for the management of headwater stream hydrology in urbanizing environments.

Acknowledgments

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