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Environmental drivers of seasonal variation in green roof runoff water quality

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ABSTRACT

Green (vegetated) roofs provide many beneficial environmental services but can also pose a disservice by leaching nutrients and metals, via storm water runoff, to downstream aquatic ecosystems. Current estimates of water quality impacts rely on limited samples (snapshots in time) and may not accurately reflect the true influence of green roof ecosystems, which likely vary temporally as do natural ecosystems. Using a 46 m^2 green roof in Cincinnati, OH, we analyzed runoff from >80 events over two years for pH, conductivity, and concentrations of dissolved nutrients, base cations, and metals. We related the variation in water chemistry to environmental variables including air temperature, storm event magnitude, and estimated antecedent moisture. We observed strong seasonal patterns in bioactive elements, with carbon, nitrogen, phosphorus, and base cation concentrations highest in the summer, and positively correlated with temperature. This suggests temperature-mediated processes such as microbial mineralization of organic matter, desorption or weathering, rather than plant uptake or hydrologic variation among storms, are the major controlling mechanisms for runoff water quality in this newly constructed green roof. The large temporal variation in green roof effluent water quality supports the need for long-term studies to characterize the complexity of these engineered ecosystems and their responsiveness to environmental variation.

1. Introduction

Green roofs (roofs with vegetation and soil-like substrate overlain on a waterproof membrane) now comprise more than 20% of the flat roof area in cities like Stuttgart, Germany, and are expected to continue to proliferate in the near future with stated goals of 20% coverage of large buildings in Washington, D.C. by the year 2025 and 50–70% coverage of city owned buildings in Toronto and Portland (Carter and Laurie, 2008; Deutsch et al., 2005). The increasing implementation of green roofs can be explained in large part by the ecosystem services they provide. Green roofs provide reduced heating and cooling costs, improved air quality (Clark et al., 2008), noise reduction (Van Renterghem and Botteldooren, 2009) and wildlife habitat (Brenneisen, 2006). They also reduce stormwater runoff, often by 50% or more relative to impervious surfaces (Mentens et al., 2006), a crucial service for many cities dealing with combined sewer overflow problems.

However, despite their ability to reduce runoff water amount, green roofs may degrade local water quality by leaching out nutrients and metals during storm events. Previous studies have identified green roofs as sources of phosphorus (P), organic carbon (C), nitrogen (N) copper, and iron (Berndtsson et al., 2006; Buffam and Mitchell, 2015; Monterusso et al., 2004). The dynamics of phosphorus in runoff are of particular concern, since excess phosphorus in receiving water bodies can result in eutrophication (Carpenter et al., 1998). At this point, little is known about the temporal dynamics of this leaching from full-scale green roofs, since most studies of green roof water quality have involved snapshots in time with only a few samples (reviewed in Buffam and Mitchell, 2015). These studies may not accurately reflect the water quality impacts of green roof ecosystems, which are likely to vary temporally as natural ecosystems do among events and across seasons, in response to variation in precipitation and temperature. Because of the limited understanding of these dynamics in green roof ecosystems, it is not known how the potentially large-scale implementation of green roofs in urban watersheds could impact regional water quality.

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Although some green roof studies have noted variations in runoff water quality among rain events and across seasons, very little is known or understood about these patterns or the processes underlying them. One study found lower levels of conductivity in green roof runoff following larger precipitation events while another found higher concentrations of total phosphorus and PO_4^{3-} and lower NO_3^- in green roof runoff during large events (Berghage et al., 2009; Teemusk and Mander, 2007). A study of a Connecticut green roof, on the other hand, found no effect of event size on total phosphorus concentrations (Gregoire and Clausen, 2011). Researchers have also observed seasonal variability. One study observed increased copper and nitrate concentrations in the summer months compared to fall and winter samples (Van Seters et al., 2009). Other studies have found higher levels of phosphorus in snowmelt vs. rain event runoff (Gregoire and Clausen, 2011), annually variable NO_3^- concentrations in green roof runoff attributable to shifting pollution input levels (Teemusk and Mander, 2007), and reduced green roof retention of heavy metals such as copper and lead during the Fall and Winter seasons (Steusloff, 1998). With more long-term observation, the seasonal patterns and key mechanisms that are controlling these patterns may become apparent.

Like natural vegetated ecosystems, green roof ecosystems may be expected to exhibit seasonal fluctuations in runoff water chemistry due to variation in plant productivity, microbial activity, and other temperature or light-dependent processes. While little is known about the mechanisms controlling green roof ecosystems and runoff water quality, seasonal patterns in stream water chemistry in runoff from natural ecosystems have been attributed to physical processes including hydrologic variability (Agren et al., 2008; Welter et al., 2005) physicochemical processes including weathering (Likens et al., 1977), chemical processes including heightened reaction rates (Freeman et al., 2001; Gardner and Jones, 1973), and biological processes including enhanced mineralization and uptake (Likens et al., 1977; Wang et al., 2012). Determining the seasonal patterns of green roof water quality runoff and the primary mechanisms responsible for these patterns will improve green roof runoff models, green roof design and management, and our understanding of how these systems will impact urban water quality and respond to impending changes in temperature and precipitation patterns.

In this study, we investigated the temporal dynamics of green roof runoff water quality to address the following questions: (1) is there seasonal variation in the concentrations of dissolved nutrients, cations and metals in runoff from a green roof ecosystem? if so, is the seasonal variation correlated with measurable environmental parameters (e.g., air temperature); (2) is there among-event variation in the concentrations of dissolved nutrients, cations and metals in runoff from a green roof ecosystem? if so, are these differences correlated with measurable event characteristics like precipitation amount, event duration and antecedent moisture conditions? (3) are seasonally-varying factors (e.g., temperature) or shorter-term event-related factors (e.g., amount of precipitation) stronger drivers of variation in green roof runoff water quality? We addressed these questions by analyzing water chemistry from incoming precipitation and runoff samples from a 46 m^2, sloped green roof and an adjacent, 37 m^2, sloped shingled roof, for the majority of the precipitation events from April 2011 to February 2013. We hypothesized that the concentrations of bioactive compounds (dissolved N, P, C and base cations) would be elevated in green roof runoff relative to precipitation and control roofs, due to the presence of these elements in green roof substrate; but would decrease during summer due to uptake by plants within the green roof ecosystem, particularly N which is commonly the limiting nutrient in terrestrial ecosystems (Chapin et al., 2011). We also expected that concentrations of all elements would be diluted during larger storm events.

2. Study site and methods

2.1. Location, climate and study site

The vegetated roof and non-vegetated, traditional roof used in this study are located at the Civic Garden Center in Cincinnati, Ohio. Cincinnati lies in a transition zone between the humid subtropical and humid continental climate zones, with a long-term (1961–1990) average high temperature of 31 °C in July and 4 °C in January (National Weather Service, Wilmington, Ohio). Precipitation averages 1080 mm per year and is typically relatively evenly distributed throughout the year, with slightly higher average precipitation amounts during spring and summer (March–August, 97–120 mm $month^{-1}$) than fall and winter (September–February, 67–84 mm $month^{-1}$). Short, intense thunderstorms are common during the warmer months. The climate during the 22-month sampling period for this study included one wetter than average year (1360 mm of precipitation during 2011) and one drier than average year (763 mm of precipitation during 2012).

The 46 m^2 extensive, 20° sloped vegetated roof was installed by Tremco Inc. (Cincinnati, OH) in April 2010 using Tremco's standard aggregate-based extensive green roof substrate, at a depth of 10 cm. A soil stabilization system was installed along with a pre-vegetated sedum mat with commonly used green roof plants including *Sedum album*, *S. sexangulare*, *S. acre*, *S. spurium*, *S. rupestre, S. floriferum*, *S. kamtschaticum*, *S. immergrunchen*, and *S. hispanicum.* Management of the roof includes occasional weeding by hand, and in May 2012, treatment with corn gluten meal, an organic weed preventer. The 37 m^2 traditional, 20° sloped roof is composed of asphalt shingles. Approximately 30% of the green roof is shaded by *Magnolia acuminata* and *Magnolia grandiflora* trees while approximately 10% of the traditional roof is shaded by *M. grandiflora* and *Fagus sylvatica* trees. Both roofs have gutters which direct roof runoff into a PVC pipe and ultimately into a 4.7 l high-density polyethylene (HDPE) runoff collection bucket positioned to overflow into a rain barrel.

2.2. Sampling

Runoff water samples for water quality analyses were collected from both roofs for the majority of precipitation events that induced green roof runoff from 4/12/2011 to 2/13/2013, using acid-washed 500 ml HDPE containers. Samples were either collected directly from the gutter downspout during the event or, if runoff had ceased, from the corresponding runoff collection bucket. Because samples were taken as grab samples at the end of runoff events, concentrations are instantaneous concentrations and do not necessarily capture the full behavior of each storm event or its contribution to local waterways. A pilot study was performed which confirmed that our measured end of event concentrations were on average approximately 10% different than the event mean concentrations (EMC) for all variables, and up to 30% for some analytes. An atmospheric deposition sample was also collected from each runoff-inducing rain event using a 19 l HDPE collection bucket positioned on a nearby flat conventional roof located 45 m from the vegetated and traditional test roofs. These samples are termed "precipitation" samples but include both wet deposition from the event, as well as dry deposition from the between-event time period. Since the green roof frequently generated no runoff following small rain events, in practice the sampling regime involved a cutoff where we only sampled events of >ca. 5 mm precipitation, depending on antecedent conditions. This approach resulted in samples taken from a total of 88 unique events (defined in Section 2.4 below), including 88 green