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Crop species selection effects on stormwater runoff and edible biomass in an agricultural green roof microcosm

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ABSTRACT

Green roofs reduce urban stormwater runoff and are increasingly being designed for food production. However, studies of the effects of plant composition on green roof rainwater capture and runoff properties have yielded conflicting results and many domesticated crop species may be unsuitable to the harsh environmental conditions found on green roofs. In this study, we evaluated the interactive effects of plant species and growth medium selection on rainwater capture, nitrogen and phosphorus content of runoff, and production of edible biomass. In a full factorial experiment, four plant species, *Portulaca oleracea* L., *Amaranthus tricolor* L., *A. cruentus* L. 'Kerala Red,' and *A. dubius* Mart. Ex Thell. 'Klaroen Groot' were grown in three types of growing media (GaiaSoil, Extensive Mix, and Potting Soil) in microcosms with lysimeters to capture runoff. Forty days after planting, a rain event was simulated. Plants were harvested 45 days after planting. Species effects on edible biomass, runoff volume, and the concentration of total dissolved phosphorus (TDP) in runoff differed among growing media. Crops grown in Potting Soil yielded 45 times more edible biomass than GaiaSoil and three times more than Extensive Mix. In Extensive Mix, all plant species reduced runoff volume (22–69%), compared to the control, and *P. oleracea* produced three to 14 times more edible biomass compared with the *Amaranthus* spp., yet reduced runoff volume (29–61%) and TDP (21–39%) less than the *Amaranthus* spp. These results indicate that crop species selection results in trade-off effects among ecosystem functions highlighting the role of species selection on green roofs.

1. Introduction

Stormwater mitigation is one of the most widely studied environmental benefits of green roofs (Carter and Rasmussen, 2006; Teemusk and Mander, 2007; Gregoire and Clausen, 2011; Carson et al., 2013; Graceson et al., 2013), yet, the role of green roof plant composition on rainwater retention and runoff properties remains unclear and debated (Monterusso et al., 2004; VanWoert et al., 2005; Berndtsson et al., 2009; Gregoire and Clausen, 2011; Whittinghill et al., 2014). Some studies indicate the bare growing medium can reduce runoff volume equal to or more than succulent and non-succulent plants on green roofs (Monterusso et al., 2004; Dunnett et al., 2008a; Nagase and Dunnett, 2012). Further, while agricultural green roofs have inceased in popularity (Mandel, 2013), early evidence suggests that many crop species may be unsuitable for the harsh environmental conditions of green roofs (Kortright, 2001; Whittinghill and Rowe, 2011; Whittinghill et al., 2013). Accordingly, the effect of crop selection on stormwater mitigation properties may help elucidate possible ecosystem multifunctionality of agricultural green roofs.

Plant community effects on stormwater retention by green roofs may vary with both composition (Wolf and Lundholm, 2008) and the density of plant cover (Teemusk and Mander, 2007). For example, Nagase and Dunnett (2012) observed that some non-succulent polycutures and monocultures significantly decreased volume of runoff more than bare growing medium. In that study, runoff volume decreased as plant biomass increased, suggesting that maximizing crop yield on green roofs could substantially reduce runoff volume, while adding food production services. However, the use of fertilizers for enhancing food production on green roofs, and even the composition of the growing medium itself, may lead to increased pollution in runoff, offsetting the beneficial effects of green roofs on runoff volume.

Green roofs are generally thought of as a source of nitrogen and phosphorous in runoff because of leaching from the growing medium (Berndtsson, 2010). Previous research suggests both growing medium type (Teemusk and Mander, 2007; Berndtsson et al.,

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2009; Gregoire and Clausen, 2011) and the amount of vegetation (Gregoire and Clausen, 2011) affect the concentrations of nitrogen and phosphorous in runoff from green roofs. Given species selection affects the volume of runoff from green roofs, species selection may also affect nutrient concentrations in runoff; however, the effects of species selection and plant biomass on the concentrations of nitrogen and phosphorus in runoff from green roofs have not been studied.

Succulents are the most widely used group of plants used on green roofs (VanWoert et al., 2005; Oberndorfer et al., 2007), because they are pre-adapted to grow in xeric environments, which are the typical conditions of green roofs (Beattie and Berghage, 2004). These conditions tend to reduce survivorship in non-succulent plants (Dunnett et al., 2008b, Butler et al., 2012), and reduce yields of common domesticated crops (Kortright, 2001, Whittinghill et al., 2013). However, some crop species are pre-adapted to xeric conditions and could potentially increase food production on agricultural green roofs. For example, *Portulaca oleracea* L. forms succulent prostrate clumps and is drought tolerant via a combination of C_4 and crassulacean acid metabolism (CAM) photosynthesis (Koch and Kennedy, 1980). An additional drought tolerant family with forb species that exhibit C_4 photosynthesis and diverse morphology is the Amaranthaceae (Brenner et al., 2000). Therefore, *P. oleracea* and *Amaranthus* ssp., representing morphologically distinct and drought-tolerant plants, may be suitable for use as test species for agricultural green roofs.

The primary goal of this research was to evaluate the performance of four different crop species for their potential to produce edible biomass and to estimate their effect on runoff properties utilizing a microcosm in a rooftop environment. We compared the response among different growing media types using a two-way factorial experimental design with three different growing media. We hypothesized that (a) crop species edible and dry biomass would differ among species and depend on growing medium type because of morphological variation. We predicted that the edible succulent *P. oleracea* would produce the greatest biomass compared to *Amaranthus* spp. We hypothesized that (b) the presence of plants would result in lower growing medium moisture content over the course of the growing season and that (c) there would be variation among species within each growing medium type. We hypothesized that (d) runoff volume and the concentrations of total dissolved nitrogen (TDN) and total dissolved phosphorous (TDP) in runoff in the presence of crop species would be reduced compared to the runoff of bare growing medium. We hypothesized that (e) increased plant biomass would decrease the volume and concentration of TDN and TDP in runoff in each growing medium type. Species-specific hydrologic responses were further analyzed in Extensive Mix. We hypothesized that (f) plant biomass would affect the volume and concentration of TDN and TDP in runoff and would depend on species selection.

2. Methods

2.1. Experimental design

This study was conducted on the rooftop of the Fordham University parking garage located at Fordham's Rose Hill campus, in the Bronx, NY, USA (40.85906 N–73.881706 W). The roof is located on the 5th level (top floor), 15 m above the ground level entrance and 51 m above sea level. Surrounding buildings or trees do not shade the roof.

We created custom microcosms with zero tension lysimeters (Fig. 1a), constructed from 49 cm dia plastic containers (Model: 0417WMRBKDC.08, Home Products International, Chicago, IL), and installed them on elevated platforms on the Fordham roof. A 2 cm dia hole was drilled in the center of the base of each container. The lysimeter was a 3.8 cm dia PVC pipe with four 1 cm drainage holes located 3.8 cm above the base of the container. The lysimeter was glued (Model: 150011, Eclectic Products, Inc., Eugene, OR) into the center of each container (Fig. 1b). Window screening (2 mm mesh) was used to prevent coarse growing medium from seeping through the lysimeter. Drainage holes were set at 3.8 cm to allow for water retention in the container to support plant growth during prolonged periods without water inputs.

Each microcosm was filled to a depth of 11 cm with one of three types of growing medium (Extensive Mix, GaiaSoil, and Potting Soil). Extensive Mix (LI Compost Inc., Yaphank, NY) meets German Landscape Research, Development and Construction Society (FLL) guidelines for green roof growing media (Schulze-Ardey and Schroder, 2008), has high porosity, low nutrient content, and low cation exchange capacity (CEC), and is composed of 80% mineral components, while the remaining 20% or less is organic material, such as compost or woodchips. GaiaSoil (Gaia Institute, City Island, NY) is specifically engineered for rooftops that have limited load capacity. It is composed of ~90% small polystyrene foam balls (3–10 mm in diameter), ~10% compost, and trace amounts of clay (to improve CEC) and pectin (to make the polystyrene hydrophilic). This system also utilizes a coconut jute fabric layer on top of the polystyrene to prevent wind erosion and mulch to provide a constant source of organic material. Potting Soil (Hamptons Estate Professional Potting Mix, LI Compost Inc., Yaphank, NY, USA) differs from Extensive Mix in a number of ways including high nutrient concentrations, fertilizer amendment, high organic content (peat, compost, and wood chips), high water holding capacity, and little pore space.

The four plant species used in this study were *P. oleracea* L., *Amaranthus tricolor* L. (PI 604669), *A. cruentus* L. 'Kerala Red' (PI 566897), and *A. dubius* Mart. Ex Thell. 'Klaroen Groot' (PI 642737). *P. oleracea* was grown from seeds obtained from around New York City, while the *Amaranthus* spp. were grown from seeds obtained from United States Department of Agriculture (USDA) National Plant Germplasm System. Seeds were sown in 4 cm cells using Potting Soil at the Louis Calder Center, Armonk, NY, USA, greenhouse in mid-April 2011 and watered daily by hand. Twenty-one days after sowing, a two-way (growing medium × plant species) 3^4 factorial design was established. Seven replicate microcosms of each treatment combination contained two individuals of a single species ($n = 84$, Fig. 1b). Six additional microcosms of each growing medium were kept plant-free by weeding (unplanted control), and six microcosms had no growing media or plants ((−) media control), for a total of 24 control microcosms.

2.2. Sampling

Growing medium water content was measured every other day (Model CD620, Campbell Scientific Inc., Logan, UT). Plant colonists were hand-removed weekly. Plants were watered to maintain moist growing media and to prevent wilting but always equally among all microcosms. Natural rain events were not sufficiently large for the Potting Soil treatment to release runoff. Therefore, a 3-h rain simulated rain event (70 mm) was applied 40 days after planting using a flow-metered hose.

Runoff collection containers were rinsed three times with deionized water immediately prior to the simulated rain event. After the simulated rain event, runoff quantity was measured in the collection container and multiplied by the ratio of the area of the bottom of the collection container versus the area of the bottom of the growth container to estimate runoff depth (mm) in terms of the growth area ($0.188\ m^2$). After the simulated rain event, runoff pH was measured in the field (Model 230A, Orion Research Inc., Beverly, MA, USA), and 45 ml of runoff was then immediately filtered