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Comparison of irrigation efficiency and plant health of overhead, drip, and sub-irrigation for extensive green roofs

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ABSTRACT

This study was conducted in two phases in a greenhouse in green roof modules. In Phase I, five commercial substrate types or systems were subjected to three irrigation methods (overhead, drip, and sub-irrigation) to determine substrate water distribution and retention. Substrates subjected to overhead irrigation or those with a moisture retention fabric (MRF) retained the greatest amount of water. Sub-irrigation resulted in the least amount of water retention and the most wastewater, except when a MRF was present. Substrate volumetric moisture content exhibited similar results. The MRF was effective in retaining water, but for sub-irrigation a visible water front was not visible as water did not reach the surface via capillary action. Differences can be attributed to the fact that overhead irrigation distributed water over 100% of the area, whereas in many cases the water front radiating from the drip or sub emitters never merged leaving dry areas in between emitters. In Phase II these irrigation methods were assessed to see how they influenced plant growth and health of *Sedum album* and *Sedum floriferum*. Repeated measurements were recorded for plant survival, growth index, chlorophyll fluorescence, and substrate volumetric moisture content. Results show that overhead was the most favorable for plant growth and health. Plant dry weights averaged 1.00 g, 0.78 g, 0.40 g, and 0.09 g for *Sedum album* subjected to overhead, drip, sub- and no irrigation, respectively, when no MRF was used. The inclusion of MRF generally improved results for drip and sub-irrigated plants. Chlorophyll fluorescence values were generally highest for plants subjected to overhead irrigation. Because green roof substrates tend to be coarse to allow adequate drainage, water does not move laterally to a great extent as it would in finer substrates. For this reason, drip and sub-irrigation may not be the most efficient irrigation methods.

1. Introduction

Green roofs impact environmental, economic, and social issues of sustainable urban sites and serve as urban ecosystems that can partially offset negative impacts of urban areas (Clark et al., 2008; Oberndorfer et al., 2007; Rowe and Getter, 2010). Establishing plant material on rooftops provides numerous benefits including stormwater management, energy conservation, mitigation of the urban heat island, carbon sequestration, increased longevity of roofing membranes, habitat for wildlife, noise and air pollution mitigation, and a more healthy and esthetically pleasing environment in which to work and live (Clark et al., 2008; Getter et al., 2007, 2011; Getter and Rowe, 2006; Rowe, 2011; US EPA, 2009).

However, obtaining these benefits on a roof can sometimes be difficult. Healthy, actively growing plants are necessary to achieve optimal benefits, but extremes in temperature and drought due to shallow highly porous substrates make this a challenge. Green roof substrates differ from commercial growing mixes used in the nursery industry or natural soils as they must be stable enough to last for the life of the building. It is both impractical and cost ineffective to continuously add substrate to a green roof because decomposition of organic matter has decreased substrate depth. Instead, stable aggregates such as heat expanded slate, shale, or clay are often the main component. In addition, because depths are shallow, there must be adequate pore space to allow for drainage which translates to less water holding capacity and little if any capillary movement of water (Beattie and Berghage, 2004; Friedrich, 2005). Therefore, water does not move laterally to a great extent as it would in finer substrates. For this reason, there are challenges to utilizing drip and sub-irrigation despite the increasing trend to specify these for green roofs.

Although succulents such as *Sedum* spp. are often used on green roofs because they can usually survive without supplemental irrigation, there is a major international movement to use plants other than succulents such as native herbaceous perennials, grasses, and vegetable gardens. However, unless substrate

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depths can be increased, these plants require supplemental water to survive and remain esthetically pleasing on a roof and irrigation is a must if one desires to grow vegetables (Whittinghill and Rowe, 2012). The inclusion of irrigation also provides an opportunity for more biodiversity in plant selection. Limited moisture also negatively impacts growth and survival of some *Sedum* spp. (Monterusso et al., 2005; Getter and Rowe, 2009; Rowe et al., 2006, 2012). Increasing substrate depth can alleviate some of these problems, but shallow depths are often desirable because buildings must be structurally strong enough to support the added weight of the green roof.

Succulents such as *Sedum* spp. are ideal for extensive green roofs due to their method of photosynthetic carbon metabolism and their ability to store water. Most succulents are categorized as Crassulacean acid metabolism (CAM) plants, one of three mechanisms for plant uptake of CO_2. CAM plants have the ability to fix CO_2 in the dark for later use in photosynthesis. By opening their stomata at night for the uptake of CO_2, they limit water loss due to transpiration (Ting, 1985). Facultative CAM plants possess a variation of CAM and are able to shift between C_3 metabolism and CAM depending on soil moisture conditions (Lee and Kim, 1994). Staats and Klett (1995) found that *S. acre* required less irrigation to maintain a pleasing leaf color when compared with C_3 and C_4 plants and in one green roof experiment, a mix of *Sedum* spp. was able to survive for 88 days without irrigation (VanWoert et al., 2005).

Irrigated green roofs also increase evapotranspiration, reduce building energy requirements, and increase carbon sequestration. Plant species vary in their capacity to transpire and most plants with high transpiration rates need ample water. Some succulents can survive drought, but dry substrates provide limited cooling from evapotranspiration (Voyde et al., 2010), and up to 30% of roof cooling is due to transpiration (Takakura et al., 2000). In addition to moderating internal building temperatures, irrigation may also be a cost effective method of temperature control. This is because water needed to produce electricity is a significant portion of the cost. To obtain the same cooling effect, Mankiewicz et al. (2009) showed that the energy required to irrigate a green roof in New York was 41–93 times less than what was required to operate air conditioners. Limiting substrate moisture also reduces the amount of carbon stored as evidence suggests that under drought conditions, levels of soil organic carbon decline (Harte et al., 2006). Green roofs frequently experience drought conditions which could represent a significant barrier to sequestering carbon on green roofs.

Despite the benefits of reasonable irrigation practices, there is a concerted movement to limit irrigation on green roofs to drip or sub-irrigation or ban irrigation altogether. For example, the Bureau of Environmental Services in Portland, OR, has adopted laws that limit irrigating any green roofs receiving incentives from the city (Schroll et al., 2011). Banning or limiting irrigation on all roofs is problematic. For example, when rainwater is collected and recycled back to the roof for irrigation purposes there is no strain on the municipal water supply. Also, banning overhead irrigation in favor of drip or sub-irrigation because of perceived water conservation, regardless of the source, may be shortsighted and actually result in wasting water. Drip irrigation has been shown to be more efficient when growing individual plants (Goodwin et al., 2003; Weatherspoon and Harrell, 1980), but one is generally irrigating a vast area of groundcovers on an extensive green roof, not individual plants. Spacing drip tubes closer together just adds to installation and maintenance costs.

Our overall objective was to determine irrigation efficiency of overhead, drip, and sub-irrigation methods on coarse aggregate substrates utilized on green roofs and to measure plant establishment, growth, and health for various substrate types subjected to these irrigation methods. Specific objectives included: (1) determine effectiveness of application method (overhead, drip, and sub-irrigation) on irrigation efficiency when applied to several substrate types and green roof systems, (2) determine the impact of the presence of Sedum vegetation with a mature root system on water retention compared to the same substrate without vegetation, (3) quantify plant stress by measuring chlorophyll fluorescence, and (4) quantify biomass and carbon sequestration among treatments.

2. Materials and methods

The study was conducted in the Michigan State University Plant Science Greenhouses (East Lansing, MI) in LiveRoof, LLC (Spring Lake, MI) green roof modules (30.5 cm × 61 cm × 10 cm) placed on flat greenhouse benches and consisted of two phases: (1) determining if irrigation method and physical properties of various substrates and systems influenced water distribution and retention and (2) quantifying plant growth and health when subjected to different irrigation methods.

2.1. Phase I: water distribution and retention in substrates

Five commercial substrate types or systems were subjected to three irrigation methods (overhead, drip, and sub-irrigation). Measurements included volume of runoff (wasted water), substrate volumetric moisture content, and water dispersal (distance surface water front moves horizontally from emitter).

Irrigation treatments included (1) overhead (fixed spray heads with four 152 cm quarter circle (90°) matched precipitation rate nozzles on each corner and two 152 cm half circle (180°) matched precipitation rate nozzles; Rain Bird Corp., Azusa, CA), (2) drip irrigation (pressure compensating 3.78 L/h emitter; Antelco Corp., Longwood, FL), and (3) sub-irrigation (pressure compensating 600 series (16 mm) dripper line, spacing = 30 cm, flow rate = 3.78 L/h; Agrifim Irrigation Products, Fresno, CA). For the drip and sub-irrigation treatments, emitters were located on two lines down the length of each module with two emitters on each line (four emitters per module). Closeup views of the drip and sub-irrigation emitters and the layout of the overhead irrigation system are shown in Fig. 1. Application rates varied among the irrigation methods as all four drip and sub-irrigation emitters were located within the modules, whereas much of the overhead spray landed outside the modules. Actual water applied as calculated from measured quantities of water retained and water runoff for each module averaged 4.2 L, 9.6 L, and 8.5 L for overhead, drip, and sub-irrigation, respectively.

Irrigation treatments were applied to five commercial substrate types or systems: (1) Renewed Earth green roof substrate (Renewed Earth, Kalamazoo, MI) with no vegetation, (2) LiveRoof green roof substrate (LiveRoof, LLC, Spring Lake, MI) with no vegetation, (3) LiveRoof green roof substrate covered with an established (100% cover) vegetation mix of six *Sedum* spp. (*Sedum acre* 'Aureum', *Sedum album* 'Coral Carpet', *Sedum floriferum* 'Weihenstephaner Gold', *Sedum rupestre* 'Angelina', *Sedum sexangulare*, *Sedum spurium* 'Fuldaglut', and *Sedum takesimense* "Gold Carpet'), (4) Renewed Earth green roof substrate with no vegetation but with a moisture retention fabric (MRF) (0.75 cm thick) laid underneath (XeroFlor America, LLC, Durham, NC) with the capacity to hold up to 5.69 kg/m^2 of water, and (5) Fafard 3B Professional Formula Potting Mix (Fafard Horticultural Services, Agawam, MA) with no vegetation consisting of sphagnum peat moss (50%) and processed pine bark, perlite, and vermiculite. Physical and chemical properties of the Renewed Earth, LiveRoof, and Fafard substrates are shown in Table 1. The Farfard potting mix is excellent for potted plant production and is not generally considered suitable