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Establishment and performance of an experimental green roof under extreme climatic conditions

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HIGHLIGHTS

- Native plant species established more readily than exotic succulents under extreme conditions.
- In mixed community establishment, *Bouteloua gracilis* proved to be the most dominant species.
- Green roof temperatures and buoyancy fluxes at 1.5 m tended to be lower than over a concrete roof.
- Higher net radiation over the green roof was compensated by higher evapotranspiration rates.

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ABSTRACT

Green roofs alter the surface energy balance and can help in mitigating urban heat islands. However, the cooling of green roofs due to evapotranspiration strongly depends on the climatic conditions, and vegetation type and density. In the Southern Central Plains of the United States, extreme weather events, such as high winds, heat waves and drought conditions pose challenges for successful implementation of green roofs, and likely alter their standard performance. The National Weather Center Experimental Green Roof, an interdisciplinary research site established in 2010 in Norman, OK, aimed to investigate the ecological performance and surface energy balance of green roof systems.

Starting in May 2010, 26 months of vegetation studies were conducted and the radiation balance, air temperature, relative humidity, and buoyancy fluxes were monitored at two meteorological stations during April–October 2011. The establishment of a vegetative community trended towards prairie plant dominance. High mortality of succulents and low germination of grasses and herbaceous plants contributed to low vegetative coverage. In this condition succulent diversity declined. *Bouteloua gracilis* and *Delosperma cooperi* showed typological dominance in harsh climatic conditions, while *Sedum* species experienced high mortality. The plant community diversified through volunteers such as *Euphorbia maculate* and *Portulaca maculate*. Net radiation measured at a green-roof meteorological station was higher than at a control station over the original, light-colored roofing material. These findings indicate that the albedo of the green roof was lower than the albedo of the original roofing material. The low vegetative coverage during the heat and drought conditions in 2011, which resulted in the dark substrate used in the green roof containers being exposed, likely contributed to the low albedo values. Nevertheless, air temperatures and buoyancy fluxes were often lower over the green roof indicating that higher evapotranspiration rates compensated for the higher net radiation at the green roof.

1. Introduction

City air temperatures are typically higher than in surrounding rural areas, a phenomenon described as the urban heat island (Arnfield, 2003; Grimmond et al., 2010; Oke, 1982). Heat stress for urban populations is thus often exacerbated during heat waves, which are predicted to become more frequent and intense due to the increase of greenhouse gas emissions (Patz et al., 2005). The elevated urban air temperatures can be explained by changes in the surface energy and radiation balance in built-up areas. Compared to natural, vegetated environments, cities have different aerodynamic and thermal properties, a lower albedo (i.e. they absorb more solar radiation), and are typically impermeable surfaces that retain less water. Several cities have launched programs to increase urban vegetation as measures for improving urban climate and air quality (e.g. Pincetl, 2010). Bowler et al. (2010) conducted a systematic review of empirical evidence about cooling effects of urban

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vegetation. They concluded that on average urban parks are about 1 °C cooler than nearby, built-up areas. Shading effects of trees and other taller vegetation along with increased evapotranspiration (ET) appear to contribute to these cooling effects. While there is evidence that urban vegetation can play an important role in sustainable urban development and in mitigating urban heat islands, further research is needed to successfully implement urban greening initiatives (Bowler et al., 2010; Gago et al., 2013). The scale of the cooling effects beyond the green spaces is still an open question. This is particularly true for vegetated roof systems. Berardi and GhaffarianHoseini (2014) present a comprehensive review of the environmental benefits of green roofs. They were shown to reduce heating and cooling loads of buildings, mitigate storm water run-off, and improve air quality in cities (Baik et al., 2012; Berndtsson, 2010; Jaffal et al., 2012; Rowe, 2011; Oberndorfer et al., 2007), but the scale of their microclimate benefits is still not well defined.

A number of recent studies have discussed the performance of vegetated roofs under different climate conditions (Dvorak and Volder, 2013b; Farrell et al., 2012; Fioretti et al., 2010; Lin et al., 2013; Olivieri et al., 2013; Ouldboukhitine et al., 2012; Coutts et al., 2013) and for different types of roof insulations (D'Orazio et al., 2012). Temperatures at the surface and below the substrate of vegetated green roof systems were found to be significantly lower than surface temperatures of traditional roofs (Dvorak and Volder, 2013b; Gaffin et al., 2009; Susca et al., 2011). While some studies reported that the surface temperatures decreased by as much as 60 °C (Saadatian et al., 2013), much more moderate average reductions (18 °C) and even an increase in surface temperatures under drought conditions were observed for green roof systems using dark substrates and low-lying groundcover-type plants with limited surface cover (Hien et al., 2007). The overall thermal performance of green roofs appears to be strongly dependent on climatic conditions, particularly the rainfall and irrigation amounts, and it also varies diurnally (Coutts et al., 2013; Lin et al., 2013; Zinzi and Agnoli, 2012).

Uncertainties also remain concerning the benefits of green roofs in reducing air temperatures above roofs and improving the microclimate in nearby streets. Experimental studies have shown that air temperatures above green roofs are reduced compared to traditional roofs but the influence is limited to just a couple of meters above the roof surface (Wong et al., 2003). Ouldboukhitine et al. (2014a) measured air temperatures in scaled-down street canyons with traditional and green roofs and found that the vegetation reduced the air temperature of the street canyon by 0.8 °C. However, green roof systems with dark substrates and limited vegetation cover can also lead to an increase in air temperatures (Hien et al., 2007). Some modeling studies also suggest that green roofs can reduce air temperatures in nearby streets: Peng and Jim (2013) found that the observed temperature reductions were quite small ($\approx$10 °C or less) while Alexandri and Jones (2007) reported that greening of roofs can reduce average street-canyon temperatures by as much as $\approx$10 °C in hot, dry climates. A number of studies have also focused on the potential of using different roof materials, which can include both cool (reflective materials with high-albedo) and green roofs, as city-wide heat-island mitigation strategies (Berardi and GhaffarianHoseini, 2014; Santamouris, 2014). Cool roofs primarily alter the radiation balance of the surface with the higher albedo leading to lower net radiation, which reduces the amount of energy available for partitioning into sensible and latent heat (Li et al., 2014). Green roofs, on the other hand, are known to increase latent heat fluxes due to higher ET rates (Santamouris, 2014). Scherba et al. (2011) found that replacing black roofs by white or green roofs drastically reduces the sensible heat flux to the environment. Li et al. (2014) investigated city-scale impacts of green and cool roofs using numerical simulations with the Weather Research and Forecasting (WRF) model and an urban canopy model. Green roofs with abundant surface moisture were found to lead to comparable reductions in urban surface and air temperatures as cool roofs, whereby the reduction of surface temperatures was much more pronounced than the reduction in 2-m air temperatures. Oleson et al. (2010) studied the influence of cool roofs on urban temperatures using global-scale models and found that urban maximum temperatures decreased by 0.6 °C. In a recent review of green roof and cool roof studies, Santamouris (2014) concluded that an increase in the albedo of roofing materials can lead to decreasing ambient urban air temperatures with an average reduction rate of $\approx$2 °C per 0.1 increase in roof albedo. The same paper points out that the effectiveness of green roofs in reducing air temperatures is more variable and also depends on the height of the buildings.

One variable influencing green roof benefits is its vegetation where the conventional approach is to install a relatively uniform palette of plants possessing low height, spreading growth habit, and shallow rooting depths, such as species from the *Sedum* genus (Dunnett and Kingsbury, 2004; Snodgrass and Snodgrass, 2006). *Sedums*, the most common green roof plant, show strong adaptability to roof conditions where they tolerate the harsh environmental conditions of cold, heat and drought. In temperate regions *Sedums* have been shown to outperform North American natives in shallow roof soils (Monterusso et al., 2005). However, these species have not been proven adaptable in all geographic locations. *Sedums* common to the nursery trade, may be unfit for hot dryland locations. Although some members of the genus can adapt to water and temperature changes by changing their photosynthetic pathways, many members of *Sedum* genus possess limitations in high temperatures (Williams et al., 2010). Additionally, Dvorak and Volder (2013a) argue that using exotic sedums exclusively ignores ecoregional context and could put new roofs at risk of failure or operation at underperforming levels. Consequently, an alternative approach gaining interest is the use of the prairie vegetation as analog for vegetative roof plant community. A review of nearly two dozen green roofs deduced that the prairie biome is highly adaptive, offers greater diversity and taps context for green roofs in new locations (Sutton et al., 2012).

One of the challenges is achieving vegetative community stability on new roofs. Vegetation is often installed as plugs, but *Sedums* are often propagated by sowing leaf cuttings or installed as pregrown mats. Mats are optimal for coverage but lack diversity. Meanwhile, native plants are most commonly plugged, but can also be seeded (Brenneisen, 2005; Sutton, 2013). Because *Sedums* tend to behave as stress tolerators with slower growth, it is possible that they could complement the rapid establishment of pioneering prairie species. *Sedums* have nursed native North American wildflowers during establishment in roof settings (Butler and Orians, 2009). In addition, it has been suggested that planting multiple species that possess varying growth forms could optimize water loss and roof surface cooling (Wolf and Lundholm, 2008). Thus, increasing plant diversity at installation could positively impact plant coverage and community stability, while secondarily improving temperature and hydrologic benefits.

As several studies suggest, questions remain concerning the performance of green roof systems, particularly for green roofing systems with low-lying plants and under variable climatic conditions. In the Central Plains of the United States, climatic conditions vary widely during the different seasons including periods of extreme temperatures and drought in the summertime. In the spring and fall thunderstorms can lead to intensive rainfall events. Ambient wind speeds typically remain quite high and pose further challenges for green roof maintenance and performance. Obtaining further knowledge about the feasibility and environmental impacts of green roof systems under such conditions motivated this research study. The location, at the University of Oklahoma in Norman, Oklahoma is particularly interesting as Oklahoma has strong north–south oriented temperature gradients while the moisture gradients are in east–west direction. Thus, the study in Norman, which is located in the central part of the state, allows assessing the cooling efficiency of green roofs for a wide range of thermodynamic environments.