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Surface energy balance of an extensive green roof as quantified by full year eddy-covariance measurements

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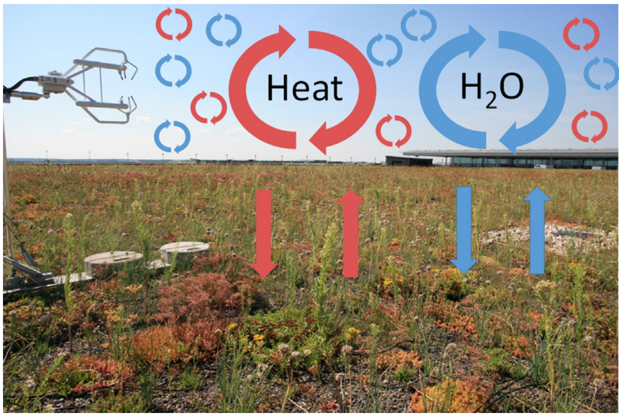
HIGHLIGHTS

- First eddy-covariance measurements on extensive green roof
- Analysis of surface energy balance during dry and wet periods
- High daytime Bowen ratios prevailed during warm, dry periods.
- Green roof revealed significant nocturnal cooling potential.
- Maximum daily evapotranspiration ration of green roof was 3.3 mm.

GRAPHICAL ABSTRACT



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ABSTRACT

Green roofs are discussed as a promising type of green infrastructure to lower heat stress in cities. In order to enhance evaporative cooling, green roofs should ideally have similar Bowen ratio (β = sensible heat flux/latent heat flux) characteristics such as rural sites, especially during summer periods with high air temperatures. We use the eddy-covariance (EC) method to quantify the energy balance of an 8600 m^2 extensive, non-irrigated green roof at the Berlin Brandenburg Airport, Germany over a full annual cycle. To understand the influence of water availability on green roof-atmosphere energy exchange, we studied dry and wet periods and looked into functional relationships between leaf area, volumetric water content (VWC) of the substrate, shortwave radiation and β. The surface energy balance was dominated by turbulent heat fluxes in comparison to conductive substrate heat fluxes. The Bowen ratio was slightly below unity on average but highly variable due to ambient meteorology and substrate water availability, i.e. β increased to 2 in the summer season. During dry periods mean daytime β was 3, which is comparable to typical values of urban instead of rural sites. In contrast, mean daytime β was 0.3 during wet periods. Following a summer wet period the green roof maximum daily evapotranspiration (ET) was 3.3 mm, which is a threefold increase with respect to the mean summer ET. A multiple regression model indicated that the substrate VWC at the present site has to be >0.11 m^3 m^{-3} during summer high insolation periods (>500 W m^{-2}) in order to maintain favourable green roof energy partitioning, i.e. mid-day $\beta < 1$. The microclimate benefit of urban green roofs can be significantly optimised by using sustainable irrigation approaches.

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1. Introduction

Urban green roofs and green infrastructure provide a number of ecosystem services, such as microclimate regulation, air purification, carbon sequestration, storm water retention, and increase of biodiversity (Oberndorfer et al., 2007; Coutts and Hahn, 2015; Gómez-Baggethun et al., 2013). Recently, a growing number of studies assessed and evaluated ecosystem services of urban green across cities in different cultures and climate zones (e.g. Derkzen et al., 2015; Haase et al., 2014). Green infrastructure is particularly important in reducing excess heat in cities (Bowler et al., 2010). This is of specific interest during periods of increased temperatures, i.e. hot summer conditions and heat waves. The need to reduce urban heat stress is urgent, given ongoing climate change with an increasing frequency of heat waves (e.g. Mazdiyasni and AghaKouchak, 2015; Russo et al., 2014).

Urban excess heat, e.g. the urban heat island, is a result of the three-dimensional urban fabric with a higher fraction of sealed surfaces, increased surface runoff and less vegetated areas compared to the rural environment (Oke, 1982). Consequently, the urban area experiences a modified surface energy balance and heat storage characteristics. The urban energy balance is dominated by sensible heat fluxes (Q_H) in comparison to latent heat fluxes (Q_E) during daytime, which results in Bowen ratios ($\beta = Q_H/Q_E$) larger than unity. Typical average urban β can reach daytime values of 1.4 in Oberhausen, Germany (Goldbach and Kuttler, 2013), 2.6 in Basel, Switzerland (Christen and Vogt, 2004), 4.4 in Marseille, France (Grimmond et al., 2004), and 5 in Phoenix, USA or Melbourne, Australia (Chow et al., 2014; Coutts et al., 2007).

Vegetation density in cities is negatively correlated with β due to the stronger effect of evaporative cooling with increased surface green fractions (Grimmond and Oke, 2002; Christen and Vogt, 2004). The implementation of roof greening is one promising way to enhance vegetation density in cities. Taking Germany as example, green roofs cover an average area of 1.4×10^6 m^2 (1.5 m^2 per capita) in the cities of Munich, Karlsruhe and Stuttgart (Ansel et al., 2015). Increasing urban green density on rooftops has the advantage that this strategy is not in space competition with the surface built environment, in contrast to other types of greening, e.g. urban parks. Green roofs are defined into extensive and intensive types. Intensive green roofs consist of herbaceous plants, shrubs and single trees, making irrigation and large substrate depths necessary (Pfoser et al., 2014). The extensive type consists of mosses, *Sedum* species and herbaceous plants, which are not considered to need irrigation for survival. Typically, substrate depths of extensive roofs are between 0.02 m and 0.15 m (Berndtsson, 2010). Currently, >90% of green roofs in Germany are extensive and non-irrigated (Zinco GmbH and Optigrün international AG, pers. communication).

Green roofs show positive characteristics considering their UHI mitigation potential (Smith and Roebber, 2011), air quality aspects (Yang et al., 2008), retention performance (Stovin et al., 2013) and energy consumption of buildings (Sailor et al., 2011). However, in order to lower warming of cities by evaporative cooling, green roofs ideally should have similar β characteristics such as rural sites (i.e. $\beta \ll 1$), especially during hot periods. We hypothesise that non-irrigated, extensive green roofs show unfavourable heat flux partitioning due to low substrate water availability during hot summer conditions and rainless periods. Hence, green roofs may lose their positive effects on local climate, i.e. evaporative cooling. Tabares-Velasco and Srebric (2011) measured a decrease of Q_E with declining substrate moisture in laboratory green roof experiments whereas Q_H increased. Consequently, the Bowen ratio is affected. Coutts et al. (2013) measured Bowen ratios >4 on a green roof that dropped to <1 after irrigation.

Although green roof models are available (e.g. Kumar and Kaushik, 2005; Sailor, 2008), a lack of validation data is evident (Sailor, 2008). This especially holds for the green roof energy exchange as a function of various meteorological conditions. To the knowledge of the authors, direct measurements of the complete energy balance of green roofs have not been published, yet. Up to now, only individual terms of the green roof energy balance, e.g. evapotranspiration and latent heat fluxes were quantified (e.g. Ayata et al., 2011; Coutts et al., 2013; DiGiovanni et al., 2012; Marasco et al., 2015; Sherrard and Jacobs, 2011; Tabares-Velasco and Srebric, 2011; Voyde et al., 2010; Wolf and Lundholm, 2008). Rates of evapotranspiration were estimated by lysimetry, chamber measurements, substrate heat flux measurements combined with meteorological measurements, and laboratory experiments. In the cited studies at least one term of the energy balance was calculated as a residual or needed to be parameterized.

In this study, we use the state-of-the-art micrometeorological approach to measure surface-atmosphere exchange, i.e. the eddy-covariance (EC) method (Baldocchi, 2014). The advantage of the EC method is that it is a direct method to quantify turbulent exchange of heat and mass without assumptions about the turbulent state of the atmosphere (Lee et al., 2006). The motivation of the present study is to analyse heat flux partitioning of an extensive green roof by surface energy balance measurements over a full annual cycle. We studied dry and wet periods and looked into functional relationships between leaf area, substrate water content, shortwave radiation and β to understand the influence of these variables on green roof-atmosphere energy exchange and heat flux partitioning.

2. Material and methods

2.1. Study area and study period

The green roof is situated on top of a multi-storey car park at the Berlin Brandenburg airport (BER), Germany. The car park is built of a porous mesh façade and a flat roof. The height of the car park is 18 m, which roughly equals the mean building height at the airport. The green roof has a size of about 8600 m^2 and was constructed in May 2012.

The vegetation of the non-irrigated extensive green roof is dominated by *Sedum* species and complemented by herbaceous plants (e.g. *Allium schoenoprasum*, *Trifolium* sp., Fig. 1). The vegetation height varies between 0.1 and 0.3 m. Similar to other green roofs our study site is not completely covered by plants (cf. Section 2.2). The substrate has a depth of 0.09 m and is a homogeneous mix composed of expanded shale, pumice and compost (substrate type “M-leicht”, manufactured by Optigrün AG). Substrate laboratory analysis was conducted to determine substrate parameters not specified in the manufacturer datasheet (Table 1). The green roof substrate is followed by a 3 mm protection mat, a 50 mm insulation layer, and a 160 mm layer of ferroconcrete. The roof has a slope of 2%. Gardeners maintain the roof approximately

Fig. 1. The BER green roof in the summer period showing parts of the eddy covariance setup (sonic anemometer and open-path gas analyser). The photograph was taken on 22 July 2014. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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