Shading Effects of Photovolatic Panels on the Evapotranspiration Process in Extensive Green Roofs

Effets d'ombrage par les panneaux photovoltaïques sur le processus d'évapotranspiration des toitures végétalisées extensives

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RÉSUMÉ

Le développement à faible impact est une approche novatrice et alternative de l'aménagement de terrain pour les méthodes traditionnelles de drainage des eaux pluviales. Les toitures végétalisées extensives (TVE) sont une technologie de développement à faible impact qui peut être mise en œuvre pour réduire le ruissellement généré par la pluie sur les toits des bâtiments. Lorsqu'une TVE est intégrée à un système photovoltaïque (PV), on peut réduire la température ambiante localisée via l'évapotranspiration (ET). La baisse de la température de fonctionnement des cellules photovoltaïques augmente le rendement de conversion et la durée de vie utile des panneaux photovoltaïques. L'ombre provoquée par les panneaux photovoltaïques peut bloquer partiellement le rayonnement solaire sur les TVE, ce qui peut influer les taux d'ET. L'objectif de cette étude est d'étudier le processus d'ET dans les zones ombragées et non ombragées de systèmes combinés (TVE-PV). Deux lysimètres ont été modifiés pour mesurer l'ET de deux modules de TVE, l'un dans une zone ombragée (sous les panneaux photovoltaïques) et l'autre dans une zone non ombragée. En période d'été (irriguée), l'ET mesurée pour le module ombragé a été inférieure de 81% à celle mesurée pour le module non ombragé. En période d'automne (non irriguée), l'ET pour le module ombragé a été inférieure de 38% par rapport au module non ombragé. Les différences de rayonnement solaire entre l'été et l'automne pourraient expliquer ce résultat distinct.

ABSTRACT

Low impact development (LID) is an innovative and alternative land-development approach to traditional stormwater drainage. Extensive green roofs (GR) are an LID technology that can be implemented to reduce the runoff generated by rainfall on building rooftops. When a GR is integrated with a photovoltaic system (PV), it may lower localized ambient temperature through evapotranspirarion (ET). Lowering the operating temperature of PV cells increases the conversion efficiency and useful lifetime of PV panels. PV panel shading may block solar radiation on GR partially, which may affect ET rates. The goal of this study is to investigate the ET process in shaded and unshaded areas of combined system (GR-PV). Two Smart Field Lysimeters were modified to measure the ET of two GR modules, one in a shaded area (under the PV panels) and the other one in an unshaded area. The measured ET for the shaded GR module was 81% and 38% lower than the measured ET for the unshaded GR module for summer-irrigated and fall-non-irrigated periods, respectively. Differences in solar radiation in summer and fall, could explain this distinct ET pattern.

KEYWORDS

Evapotranspiration, Green roof system, Photovoltaic system, PV Shading

1 INTRODUCTION

Low impact development (LID) is an innovative and alternative land-development approach to traditional stormwater drainage. Extensive green roofs (GR) are an LID technology that can be implemented to reduce the runoff generated by rainfall on building rooftops. A GR structure includes a vegetation layer, a growing medium, a drainage layer, a root barrier, and in some cases, an irrigation system. The depth of an extensive GR is typically 20 cm or less.

Recently, the French parliament passed legislation that requires all new commercial buildings to be partially outfitted with either GR or photovoltaic (PV) systems. Although the implementation of both systems is growing worldwide seldom do rooftop designers apply both technologies on the same roof area. An integrated system provides both climate change mitigation and adaptation strategies as they supply renewable energy. Additionally, GRs provide secondary benefits such as water retention and increased urban habitat. When a GR is integrated with a PV system (GR-PV), it may lower localized ambient temperatures through evapotranspiration (Chemisana & Lamnatou, 2014). Lowering operating temperature of PV cells increases the conversion efficiency and useful lifetime of PV cells.

It is noteworthy that PV panel shading partially blocks direct solar radiation onto an underlying GR, which may affect evapotranspiration (ET) rates (Bousselot et al., 2013). To the best of our knowledge, the measurement and estimation of ET in shaded GRs has not been previously considered. However, the effect of canopy shadow on vegetation and soil (understory vegetation) in terms of ET has received some, albeit limited, attention from researchers (Feng et al., 2014; Raz-Yaseef et al., 2010; Moller & Assouline, 2007; Liu et al., 2003; Wallace et al., 1999).

Feng et al., (2014) indicated that neglecting the shadows cast by sparse vegetation may lead to evaporation and ET overestimation up to 66% and 24%, respectively. In another study, Raz-Yaseef et al., (2010) observed up to 92% higher evaporation rates in a sun-exposed area in comparison with a tree shaded area in a semi-arid pine forest. Liu et al., (2003) estimated that transpiration from the understory of a forest in Canada was 8% of total ET. Wallace et al., (1999) modeled the soil evaporation with and without tree shade. Their model illustrated that tree shade can reduce the annual soil evaporation by an average of 35%. Beard et al., (1974) showed that shading decreases plant density and quality as leaf width decreases, leaf moisture increases and stomatal density decreases.

Improving the understanding the ET process in shaded and unshaded areas of GR-PV system is the goal of this study. In this regard, ET in shaded and unshaded areas on a GR is compared with respect to solar radiation, soil temperature, and soil moisture.

2 METHODS

Two Smart Field Lysimeters were modified to measure the ET of two GR modules, one in a shaded area (under the PV panels) and one in an unshaded area. The lysimeters were placed on the roof of the Daniels Faculty Building at the University Toronto located in downtown Toronto, ON. The Daniels roof houses the UofT Green Roof Innovation Testing Laboratory (gritlab) and contains four arrays of PV panels. The lysimeters contain the unit of drainage box, 150 mm substrate layer and vegetative cover. Figure 1 illustrates schematic view of one lysimeter. The substrate mixture is comprised of 70% porous inert aggregate, 25% compost and 5% fine sand. Mature green roof vegetation (a mix of native meadow species) was transplanted to the GR modules from a one-year old extensive green roof, also located in the gritlab.

The GR module was positioned on a tray collecting the drained water from the GR module and conveying it to the water container by gravity. The lysimeter was situated on the top of the balance (PL-50, UMS Inc.). The precision of PL-50 is ±7 gm.

Soil moisture sensors (5TE, Decagon Devices) and temperature sensors (MPS-2, Decagon Devices) were installed evenly spaced within the soil layer of each lysimeter at three different locations. The lysimeters measure continuously the weight of GR modules at 1-min intervals. Soil moisture and temperature were recorded at 10-min intervals.

The experimental tests took place from July 18 to October 20, 2015. The GR modular weights in shaded and unshaded areas were measured continuously with irrigation during the summer (July 18 to Sep. 8) and without irrigation during the fall (Sep. 9 to Oct. 20).

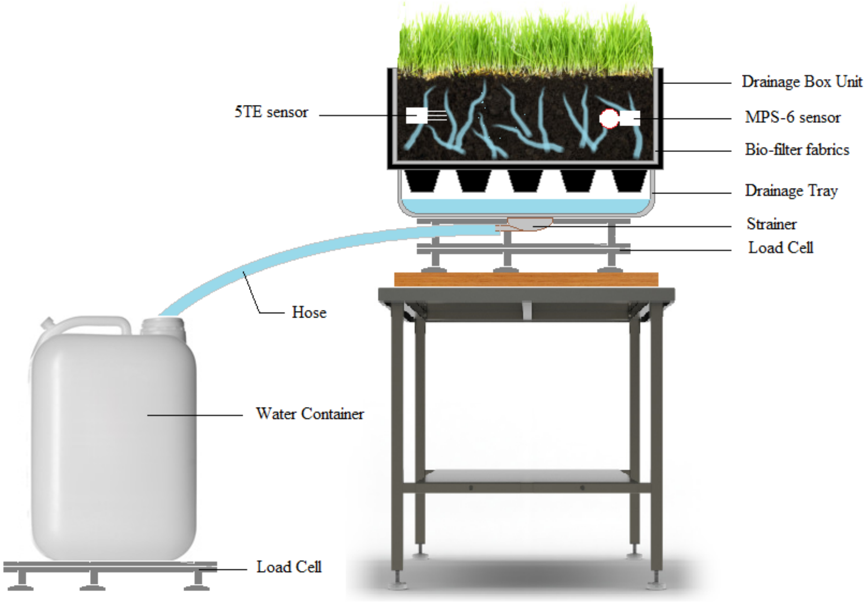

Figure 1. Weighing lysimeter and water container

The change in soil moisture (ΔS) can be calculated as the change in the weight of lysimeter (ΔW):

$$\Delta S_{daily} = \frac{\Delta W_{daily}}{\rho \times A} \qquad [1]$$

where ΔW_{daily} (kg) is the net daily differential weight of GR module which is calculated as the difference between the maximum weight at the beginning of the day, and the minimum weight at the end of the day, ρ (kg/m^3) is the density of the stored water and A (m^2) is the surface area of the GR module.

3 RESULTS

Figure 2 illustrates a sample of the GR storage change in unshaded (continuous line) and shaded (dashed line) GR modules from Oct. 1 to Oct. 20 when the modules were not irrigated. The presence of PV panels could affect the GR in two ways: the first is via the shading of the GR, which reduces the rate of ET. From Oct. 1 to 20, the weight of the shaded GR module decreased by 20.2%, while the weight of the unshaded GR module reduced by 25.4%. The second way PV panels affect the GR is via a reduction in the rainfall input to the GR surface because PV panels intercept rainfall. The weight of the lysimeter for the unshaded GR module (continuous line) peaked several times because of rainfall, while shaded GR module (dashed line) did not receive rainfall.

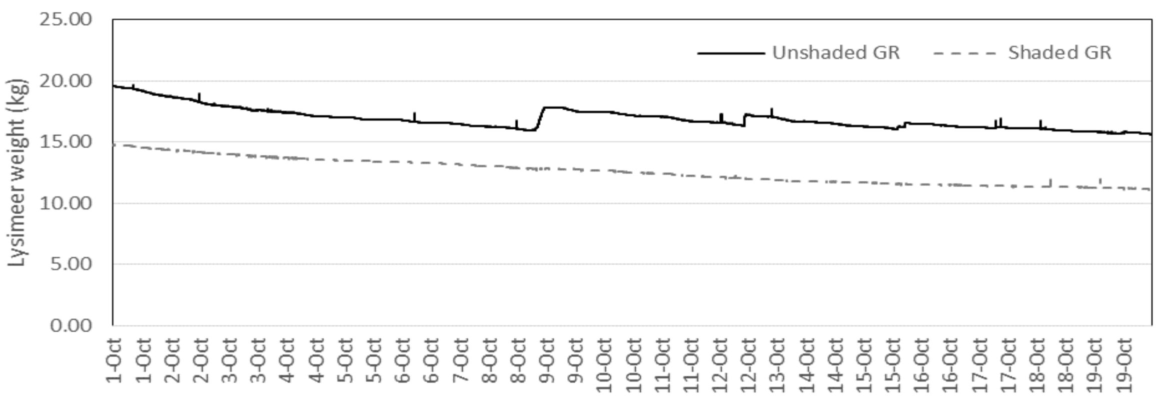

Figure 2. Weight change in lysimeters for shaded and unshaded GRs

Figure 3 illustrates daily ET rates of shaded versus unshaded modules during both summer-irrigated (Figure 3a) and fall-non-irrigated periods (Figure 3b). Considering the lower and upper bounds, the standard deviation of the ET ratio between shaded and unshaded GRs ($ET_{shaded}/ET_{unshaded}$) for both periods has been obtained based on the Three-Sigma Rule (Duncan, 2000). In the summer-irrigated period, the ET ratio between shaded and unshaded GRs was 0.2 with the standard deviation of 0.06, while in the fall-non-irrigated period, this ratio was 0.62 with the standard deviation of 0.05. This indicates that ET in shaded GR is lower than unshaded Grin both periods.

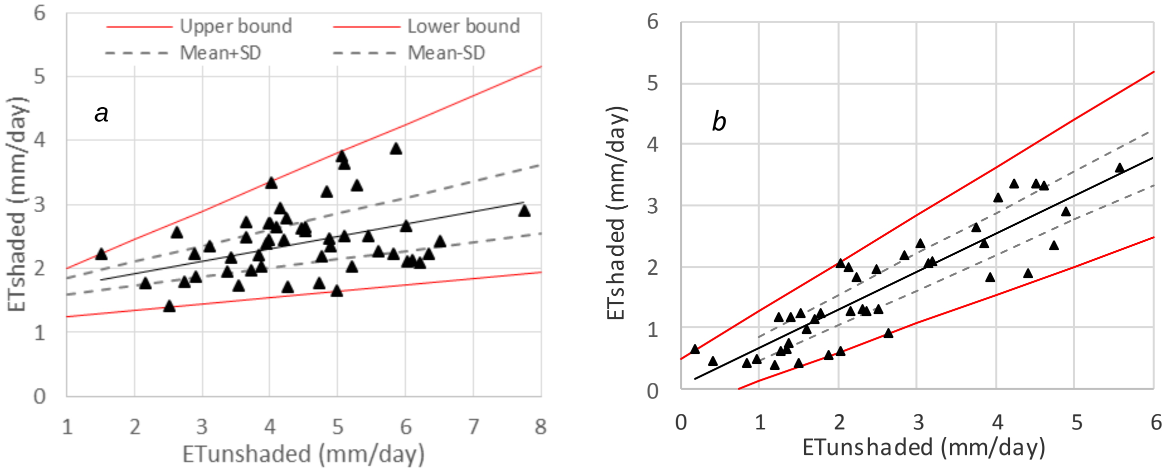

Figure 3. ET in shaded versus unshaded GR in irrigated situation, a) Summer-Irrigated b) Fall-Non-irrigated

Table 1 lists the range of ET in mm/day for shaded and unshaded GRs in both summer-irrigated and fall-non-irrigated periods.

Table 1. Average of ET for shaded and unshaded GRs in irrigated and non-irrigated periods

Time period	Range of ET for Shaded GR (mm/day)	Range of ET for Unshaded GR (mm/day)	Mean of $ET_{shaded}/ET_{unshaded}$	Standard dev. of $ET_{shaded}/ET_{unshaded}$
Summer-irrigated	3.87-0.88	7.75-1.5	0.2	0.06
Fall-non-irrigated	3.62-0.39	5.58-0.2	0.62	0.05

Figure 4 demonstrates the soil temperature of the unshaded GR (continues line) and the shaded GR (dashed line), averaging the temperature data between three MPS-2 sensors for each module. Vertical dashed line separated irrigated and non-irrigated periods. The soil temperature in the summer-irrigated period ranged between 18 to 29°C for both GR modules, but the soil temperature of the unshaded GR was mostly higher than the shaded GR. In the fall-non-irrigated period, the soil temperature for both GR modules ranged between 3 to 25°C, but it is higher in shaded GR than in the unshaded GR.

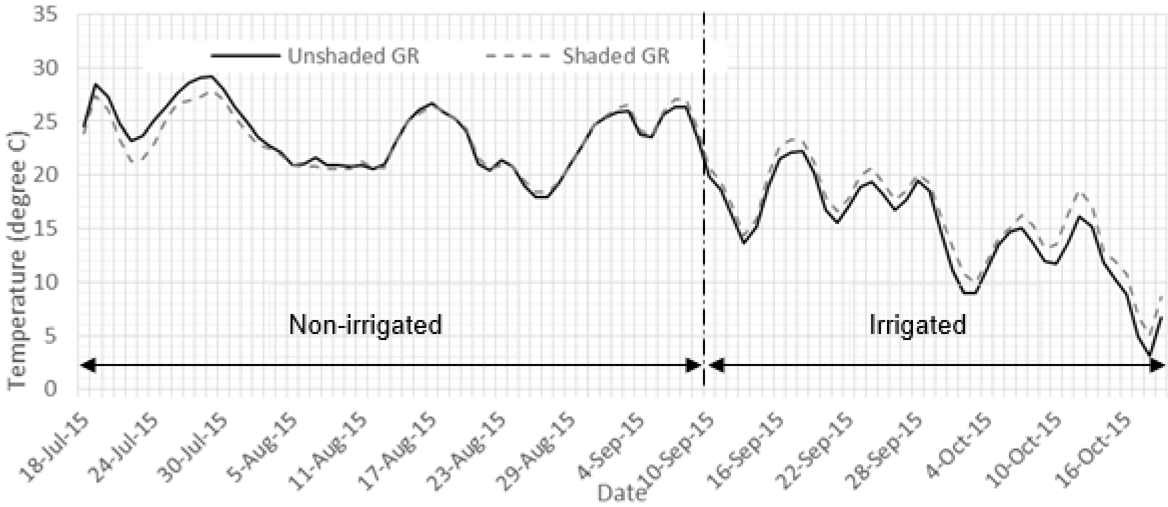

Figure 4. Soil temperature in shaded GR versus unshaded GR

Figure 5 demonstrates the soil moisture of the unshaded GR and the shaded GR, averaging the moisture data between three 5TE sensors for each module. Vertical dashed line separated irrigated and non-irrigated periods. The difference between shaded and unshaded GRs moisture data may be on the grounds of the fact that PV panel intercepted the rainwater and the shaded GR beneath the PV panel did not receive any rainwater, while the moisture of unshaded GR increased from rainwater infiltration.

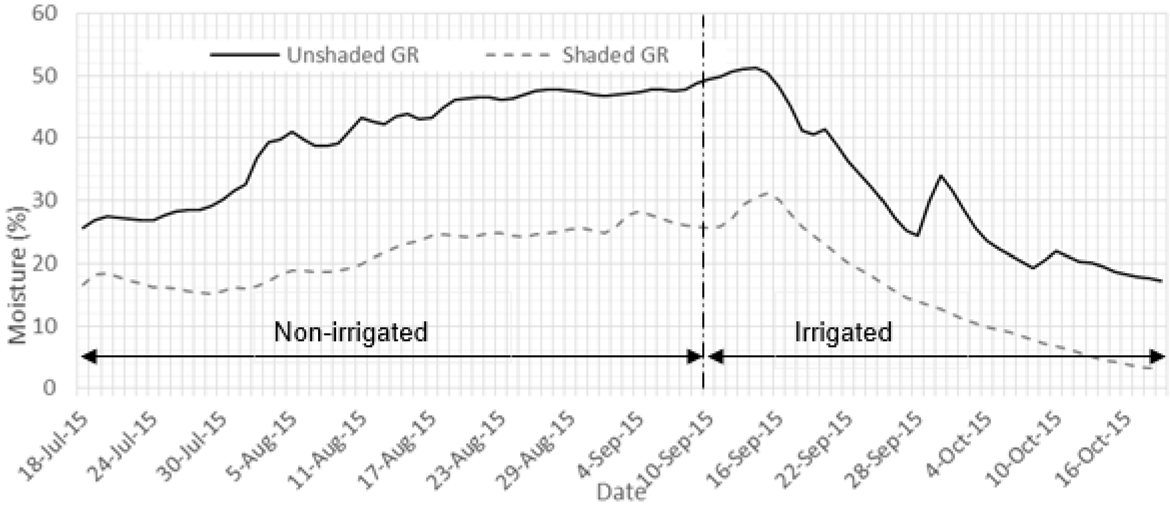

Figure 5.Soil moisture in shaded GR versus unshaded GR

4 DISCUSSION

Solar radiation influences ET rates from the soil and vegetation surface (Liu et al., 2003; Wallace et al., 1999; Hillel, 1998). Feldhake et al. (1985) stated that ET decreases linearly with solar radiation reduction. Solar radiation will be reduced by shade. This is consistent with Figure 3 in which the measured ET for GR under PV shadow was lower than measured ET for unshaded GR in both summer-irrigated and fall-non-irrigated periods.

In Toronto, the sunny daylight hours were 61% (39% cloudy daylight hours) in summer, whereas the sunny daylight hours were 46% in fall, 2015. Hence, the difference in solar radiation between shaded and unshaded GRs in summer was more significant than in fall. As a result, the difference between ET in shaded and unshaded GRs in summer is much greater than in fall (the average ratio of ET between shaded and unshaded GRs in summer and fall was 0.2 and 0.62, respectively).

Lower solar radiation beneath the PV panel resulted in variations in soil temperature between shaded and unshaded GRs (Figure 4). Villages et al. (2010) showed that surface temperature is also an important factor to identify the effect of shadows on ET. Feng et al., (2014) stated that two independent factors affect soil temperature in shaded areas: evaporative cooling and shadow cooling. When the soil is drying, shadow do not exert a significant influence on soil temperature, rather evaporative cooling is the dominant factor influencing soil temperature (Feng et al., 2014). As shown in Figure 4, in fall-non-irrigated period, the soil temperature in unshaded GR was lower than shaded GR (by the range between 0 and 2.6^{o}C) this is likely due to higher evaporative cooling in unshaded GR (by the range between 0 and 2.53 mm/day). In contrast, in summer-irrigated period, the soil temperature in unshaded GR is alternately higher and lower than shaded GR because soil temperature in shaded GR is influenced by both evaporative cooling and shadow cooling (Figure 4).

PV panel interception prevents precipitation below it. This process explains the higher soil water content in unshaded GR module during both irrigated and non-irrigated periods (Figure 5).

The variation of soil moisture among shaded and unshaded GRs play a significant role in ET processes (Raz-Yaseef et al., 2010). When water was abundantly available (summer-irrigated period), the ranges of ET for both shaded and unshaded GR modules were higher than during water limited periods (fall-non-irrigated) (Table 1). In addition, the averaged moisture of unshaded GR was higher than shaded GR in summer and fall periods by 46% and 51%, respectively (Figure 5), supporting higher overall ET in this module.

5 CONCLUSION

Use of weighing lysimeters during summer (July 18 to Sep. 8) and fall (Sep. 9 to Oct. 20) periods indicated a variability of ET in GRs integrated with a PV system. The measured ET for PV shaded GR was 81% and 38% lower than measured ET for unshaded GR in summer-irrigated and fall-non-irrigated periods, respectively. Differences in solar radiation in summer rather than fall can explain the distinct ET pattern.

Further studies are required to explain the effect of climatological factors on ET in both shaded and unshaded GRs. Using pyranometer beneath a PV panel, and comparing the measurements with unshaded pyranometer would be useful to observe the effect of shading on solar radiation, directly.

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