Experimental study on the stomatal resistance of green roof vegetation of semiarid climates for building energy simulations

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ABSTRACT

Current modelling approaches for energy simulations in green roofs use a range of values for parameters such as stomatal resistance ($r_s$) of the vegetation. $r_s$ reflects the capability of a plant to transpire, thus it has a direct relation to the cooling potential of green roofs in buildings. Therefore, $r_s$ values need to be revised based on differences among species and contrasting environmental conditions, considering anatomical and physiological characteristics among species and their changes throughout the day. In order to provide real data on species commonly used for green roofs in semiarid climates, this paper aims to evaluate the stomatal resistance of nine species of groundcovers and to compare this data with current models. $r_s$ was measured for each species at 8:00 h, 12:00 h, 16:00 h and 20:00 h during day and nighttime in winter in a leaf located at the middle of the stem. The results of this study showed that $r_s$ varies significantly among species, throughout the day and between the side of the leaf (adaxial or abaxial). The lowest $r_s$ values for species was at noon ranging from 264 to 807 s m$^{-1}$ and the highest $r_s$ was at night ranging from 568 to 973 s m$^{-1}$. Sedum spurium red, Sedum hybrid, and white and pink Verbena sp. had the largest $r_s$ variation in the day-night cycle. The results of $r_s$ are higher than those values recommended for some energy simulation models.

KEYWORDS

Cooling potential, plant physiology, Sedum, stomatal conductance,

INTRODUCTION

As a component of green infrastructure, green roofs have become more relevant in recent years because of the ecosystem services they provide, including the reduction of energy consumption in buildings (Tabares-Velasco and Srebric 2011; Zhao et al. 2014) and Urban Heat Island (UHI) (Gill et al. 2007). The cooling service of green roof vegetation relies on the abilities of different species to transpire, provide shade, reflect radiation back to the atmosphere or absorb it through photosynthesis (Cook-Patton and Bauerle 2012; Blanusa et al. 2013; Vaz Monteiro et al. 2017). Transpiration relates to the water vapour movement from the plant to the atmosphere through stomata, which are pores distributed in the epidermis of leaves that allows CO$_2$ and O$_2$ exchange. The stomatal resistance ($r_s$) corresponds to the rate of transpiration of water vapour by the leaves through opening and closing of stomata based on the environmental conditions. In nature $r_s$ relates to the species, their morphology and anatomy of the leaves, such as stomatal density on the adaxial and abaxial side and also temperature, water availability and photosynthetic active radiation (PAR) present, among other characteristics. In models of heat and mass transfer from green roofs to buildings, $r_s$ is one of the most relevant parameters that defines them (Jaffal et. al, 2012; Sailor, 2008) and although its importance, $r_s$ information comes mainly from research performed in agricultural
crops, but not from species commonly used in green roofs (Cook-Patton and Bauerle, 2012). That is why in green roof modelling, selected \( r_s \) values come from the literature available and the researcher’s criteria and not from empirical data that acknowledges species variability. In this study, \( r_s \) values were obtained throughout the day in nine species of ground covers commonly used in green roofs, to check for interspecific variation. Secondly, these \( r_s \) values were compared to those ranges proposed in the heat and mass transfer models from green roofs to buildings, to check whether these values were under or over estimating the true cooling potential of a green roof, according to a species.

**METHODS**

Seven succulent species _Aptenia cordifolia_, _Basella sp._, _Sedum hybrid_, _Sedum palmeri_, _Sedum spurium_ red, _Sedum spurium_ green, _Sedum spurium_ variegated and two herbaceous species _Verbena sp_. white and _Verbena sp_. pink grown in a heated greenhouse were used in this study. The experiment consisted in a completely randomized design (DCA), with three replicates, each consisting of four pots with one plant. The parent plant material was obtained from commercial nurseries and then propagated using four cm long cuttings, with three to four leaves, dipped in a mixture of indole butyric acid (IBA) plus Captan (Anasac Garden®). Cuttings were placed in a greenhouse for four weeks until transplant into 1.4 L pots filled with a mixture of peat and perlite 2:3 (v:v). Plants were irrigated to container capacity, every two days and five weeks after transplant, \( r_s \) was measured with a calibrated Leaf Porometer (model SC-1, Decagon Devices, USA) throughout the day at 8:00, 12:00, 16:00 and 20:00 hours during the fall. Measurements were taken in a marked leaf located in the middle of the stem, on its adaxial and abaxial side during six consecutive days with sky clear conditions. PAR and temperature were recorded. Data was analysed by ANOVA and mean separation was carried out by Fisher’s Least Significance Test (LSD) when differences were significant.

The minimum and maximum \( r_s \) values obtained in this study were compared to those reported by Sailor (2008) and Zhao et al. (2014). In Sailor (2008), the user can choose an \( r_s \) value between 50 to 300 s m\(^{-1}\), which are values found in different plant species. On the other hand, \( r_s \) values proposed by Zhao et al. (2014) ranged from 225 to 1125 s m\(^{-1}\) and were derived from studies on desert plants by Tabares-Velasco and Srebric (2011).

**RESULTS**

_Stomatal resistance (\( r_s \))_

Stomatal resistance (\( r_s \)) was significantly higher (P<0.01) in five species at the adaxial side compared to the abaxial side of leaves. In addition, the mean \( r_s \) was species dependent (P<0.01) (Fig. 1). Herbaceous species such as white and pink _Verbena sp_. had on average, an \( r_s \) value of 417 s m\(^{-1}\), while succulent species, such as _Basella sp_. had the highest \( r_s \) with 880 s m\(^{-1}\). On the other hand, _Sedum_ species \( r_s \) ranged between 536 to 692 s m\(^{-1}\).

\( r_s \) changed within the species across the day (P<0.001) and was lower at 12:00, compared to 20:00 h, with the exception of _S. spurium var._ that had no significant differences. _S. spurium_ red, for example had a 71% higher value of \( r_s \) at 20:00 than at 12:00, while _Basella sp._ had the lowest variations of \( r_s \) across the day (15%). Although PAR radiation was highest at noon, all species showed their lowest \( r_s \) values at midday while the highest values were found at night (PAR values of 0.0 µmol m\(^{-2}\) s\(^{-1}\)). In general, \( r_s \) values at 8:00 h and 16:00 h were similar across species.
**Stomatal resistance ($r_s$) comparison with current models**

When comparing the $r_s$ values obtained on this study (Table 1) with those proposed in the heat and mass transfer models from green roofs to buildings of Sailor (2008), only the mean $r_s$ values at 20:00 of the herbaceous White and Pink *Verbena sp.* and *S. spurium* red were within the range. On the other hand when comparing the $r_s$ values obtained with the ones proposed for desert plants by Zhao et al., (2014), all species had values within that range.

![Photosynthetic active radiation (PAR) (µmol m$^{-2}$ s$^{-1}$) and mean (white), adaxial (grey) and abaxial (black) stomatal resistance ($r_s$) (s m$^{-1}$) on of (A) Aptenia cordifolia, (B) Basella sp., (C) Sedum hybrid, (D) Sedum palmeri, (E) Sedum spurium red, (F) Sedum spurium green, (G) Sedum spurium variegated (H) Verbena sp. White and (I) Verbena sp. Pink, at 8:00 h, 12:00 h, 16:00 h and 20:00 h.](image)
Minimum and maximum $r_s$ values obtained in this study were higher than the ones proposed by Sailor (2008), and they were closer to the $r_s$ values proposed by Zhao et al. (2014) (Table 1).

Table 1. Minimum (min) and maximum (max) stomatal resistance ($r_s$ s m$^{-1}$) of the nine species of groundcovers of this study and $r_s$ values proposed by the simulation models of Sailor (2008) and Zhao et al. (2014).

<table>
<thead>
<tr>
<th>Species</th>
<th>$r_s$ min</th>
<th>$r_s$ max</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Aptenia cordifolia</em></td>
<td>589</td>
<td>914</td>
</tr>
<tr>
<td><em>Basella sp.</em></td>
<td>807</td>
<td>948</td>
</tr>
<tr>
<td><em>Sedum hybrid</em></td>
<td>358</td>
<td>834</td>
</tr>
<tr>
<td><em>Sedum palmeri</em></td>
<td>471</td>
<td>703</td>
</tr>
<tr>
<td><em>Sedum spurium</em> red</td>
<td>266</td>
<td>923</td>
</tr>
<tr>
<td><em>Sedum spurium</em> green</td>
<td>440</td>
<td>973</td>
</tr>
<tr>
<td><em>Sedum spurium</em> var.</td>
<td>624</td>
<td>784</td>
</tr>
<tr>
<td><em>Verbena sp.</em> white</td>
<td>282</td>
<td>568</td>
</tr>
<tr>
<td><em>Verbena sp.</em> pink</td>
<td>264</td>
<td>643</td>
</tr>
<tr>
<td>Sailor (2008)</td>
<td>50</td>
<td>300</td>
</tr>
<tr>
<td>Zhao et al. (2014)</td>
<td>225</td>
<td>1125</td>
</tr>
</tbody>
</table>

**DISCUSSIONS**

In nature, most species have hipo-stomatic leaves, meaning that stomatal density is higher on the abaxial compared to the adaxial side of the leaf (Lallana, 2003), which is also related to differences on cells of inner tissues on both sides (Fukushima and Hasebe, 2014). This anatomical and morphological characteristic of leaves is considered to be part of the plant adaptive response to avoid water loss through excessive transpiration on the adaxial side, which is directly exposed to solar radiation (Clements, 1905). In the case of the nine species evaluated in this study, stomatal density on the abaxial versus the adaxial side of the leaves was also higher (unpublished data) in line with previous information, which could be responsible for the lower $r_s$ values on the abaxial side. It is also possible that the stomatal size, could increase or decrease $r_s$ values together with the characteristics of the epidermis and accessory elements in leaves.

In this study, succulent species commonly grown in green roofs showed higher $r_s$ values compared to non-succulents. Succulent species have fewer stomata per unit of area (Sayed, 1998). The opening and closing of stomata relates not only to $r_s$, but also with CO$_2$ assimilation for photosynthesis and environmental limiting factors such as vapour pressure, radiation, relative humidity, water availability and temperature (Farquhar and Sharkey, 1982), which explains the broad variability of $r_s$ during the day, between species and in the same species. Succulents species adapted to open their stomata for CO$_2$ uptake during night times and close them during the day to limit water loss, do not showed crassulacean acid metabolism performance in their $r_s$ behaviour through the day. All this morphological and anatomical traits have evolved in succulents as an adaptive response to water deficit and high temperatures, leading to higher $r_s$ values in these species.
Irrigated plants, usually have higher transpiration rates due to the opening of stomata and, therefore, $r_s$ is lower compared to plants under water stress. In this study though, $r_s$ was higher compared to the values proposed in the heat and mass transfer models from green roofs to buildings of Sailor (2008) and were within the range proposed by Zhao et al. (2014). Sailor (2008) is overestimating the cooling potential of the species, by means of using $r_s$ values commonly found in agricultural crops, while the values proposed by Zhao et al. (2014) are based on desert plants (Tabares-Velasco & Srebric, 2011), similar to the ones used in this study. Nevertheless, it is worth mentioning that $r_s$ measurements were carried out at the end of fall under irrigated conditions, when $r_s$ values are naturally lower, however, the cooling potential of plants and $r_s$ values are more important over summer, when temperatures are higher. This information could be useful in green roof design, where the principal consideration should be to maximize transpiration in plants with low levels of irrigation. In addition, we think that specifically in the case of Sedum spurium red, the lowest $r_s$ at noon could be related with the red pigmentation in both sides of the leaves, could be increasing the capacity to transpire even in hours with high temperature and irradiation.

CONCLUSIONS
This study has denoted a broad variability of $r_s$, both within species across the day and between species of common use in green roofs. Also, the results showed that the values currently used in heat and mass transfer models of green roofs are in some cases underestimating $r_s$. This emphasizes the need of empirical data to support species selection in green roofs in order to maximize the energy savings in buildings by means of supporting greater transpiration of plants, with the use of species with lower $r_s$ values especially at noon, when temperatures outside buildings are higher.

It is essential to create a biological database of species commonly used in green roofs and their parameters values, such as $r_s$, that will support designers and modellers to improve species selection to maximize energy savings in buildings. On the other hand, a common criteria, that includes the species natural variation and their behaviour across the day is relevant to design methodologies that will aid to standardize the data collection. Also, we expect that this results will raise awareness on the biological diversity that exists in green roof vegetation, in order to identify further parameters that are currently used in green roofs from data extracted from agricultural crops which would bring greater benefits to the area of sustainable construction.

ACKNOWLEDGEMENT
We would like to thank the Department of Plant Science of the Faculty of Agriculture and Forestry from the Pontificia Universidad Católica de Chile, for partially providing the resources to develop this research. Also, this project was partially funded by research grants FONDECYT 1150675 and FONDECYT 1181610. We thank professor Jorge Gironás from the Department of Hydraulic and Environmental Engineering for facilitating the Leaf Porometer used in this research.

REFERENCES


