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

Rocío Arriola-Cepeda[1], Sergio Vera[2], Francisco Albornoz[1] and Ursula Steinfort[1*]

[1] Facultad de Agronomía e Ingeniería Forestal, Pontificia Universidad Católica de Chile, Vicuña Mackenna 4860, Macul, Santiago, Chile.
[2] School of Engineering, Department of Construction Engineering and Management, Pontificia Universidad Católica de Chile, Vicuña Mackenna 4860, Macul, Santiago, Chile.

[*]*usteinfo@uc.cl*

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 night-time 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 obtain throughout the day in nine species of groundcovers commonly used in green roofs, to check for interspecific variation. Secondly, these r_s values were compare 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.

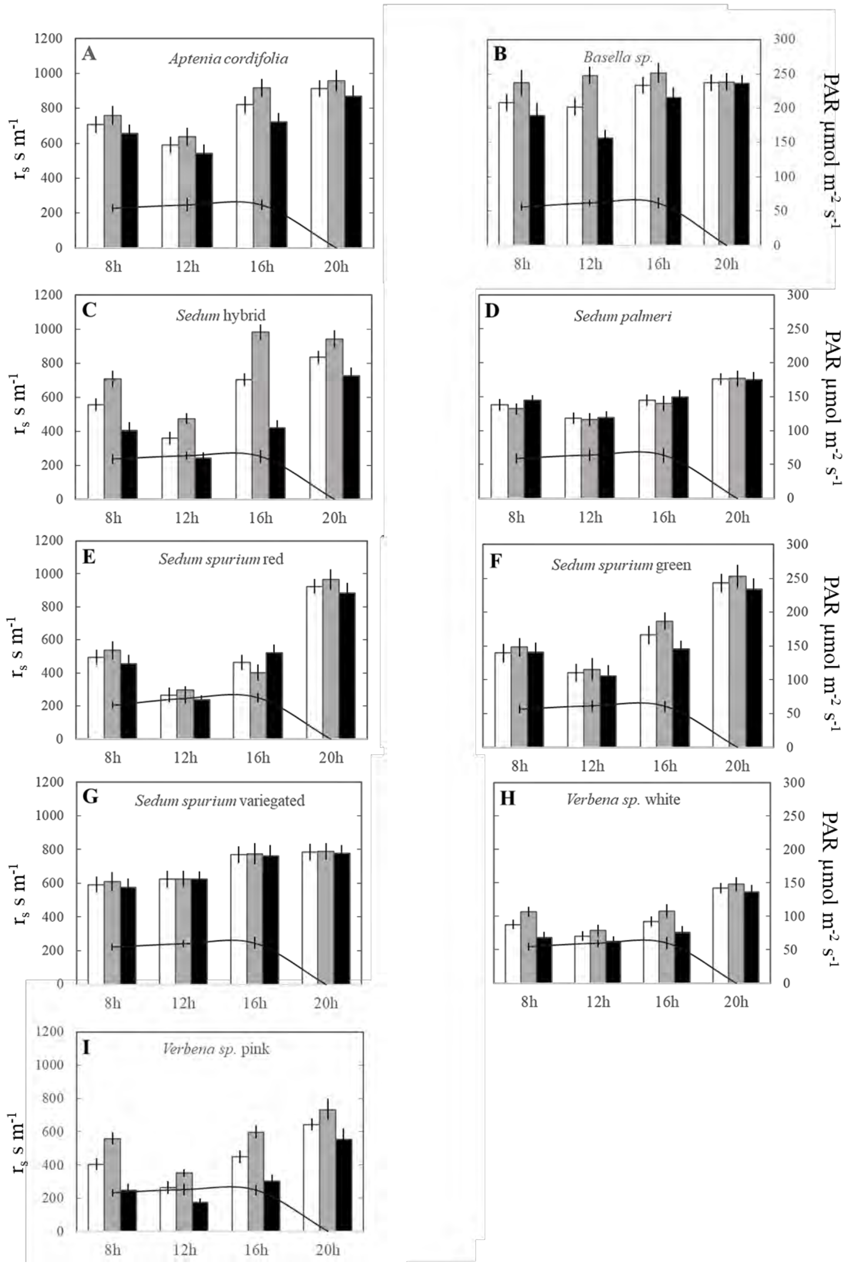

Figure 1. Photosynthetic active radiation (PAR) (µmol m^{-2} s^{-1}) and mean (white), adaxial (grey) and abaxial (black) stomatal resistance (r_s) (s m^{-1}) on of (A) *Aptenia cordifolia,* (B) *Basella sp.,* (C) *Sedum* hybrid, (D) *Sedum palmeri,* (E) *Sedum spurium* red, (F) *Sedum spurium* green, (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.

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).

	r_s (s m^{-1})	
Species	**r_s min**	**r_s max**
Aptenia cordifolia	589	914
Basella sp.	807	948
Sedum hybrid	358	834
Sedum palmeri	471	703
Sedum spurium red	266	923
Sedum spurium green	440	973
Sedum spurium var.	624	784
Verbena sp. white	282	568
Verbena sp. pink	264	643
Sailor (2008)	**50**	**300**
Zhao et al. (2014)	**225**	**1125**

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.

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