Photosynthetic and Transpiration Rates of Three *Sedum* Species Used for Green Roofs

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*Sedum* species, which utilize crassulacean acid metabolism (CAM) photosynthetic pathway, have been the most commonly used plants in extensive green roofs. Previous investigations on *Sedum* green roofs have focused on their establishment and survival under drought conditions. Several *Sedum* species have been described as “inducible type of CAM” plants, suggesting that their photosynthetic and transpiration rates under wet conditions might greatly affect the carbon sequestration and the cooling effect of a *Sedum* green roof. Therefore, we investigated the photosynthetic and transpiration rates of three *Sedum* species (*Sedum japonicum* Siebold ex Miq., *Sedum lineare* Thunb., and *Sedum sarmentosum* Bunge) under wet and dry treatments. All three *Sedum* species exhibited CO\(_2\) uptake only during the light period under wet conditions as well as under dry treatment for several days after irrigation. Moreover, in the wet treatment, their photosynthetic and transpiration rates were found to be similar to those of the other green roof plants, *Zoysia matrella* (L.) Merr. and *Ophiopogon japonicus* (Thunb.) Ker Gawl. Thus, we suggest that the carbon sequestration and the cooling effect of the *Sedum* green roofs are equivalent to those of the green roofs utilizing the other plant under wet conditions from the standpoint of physiological traits.

Keywords: extensive green roof, inducible type of CAM, irrigation, *Sedum japonicum* Siebold ex Miq., *Sedum lineare* Thunb., *Sedum sarmentosum* Bunge

INTRODUCTION

*Sedum* species are the most commonly used vegetative plants in extensive green roofs worldwide. Green roof technology provides several environmental benefits, for example, cooling and insulation of buildings (Wong et al., 2003; Sailor, 2008), mitigation of the urban heat-island effect (Susca et al., 2011), stormwater management (Villarreal and Bengtsson, 2005; Getter et al., 2007; Rowe, 2011), carbon sequestration and reduction of air pollution (Yang et al., 2008; Getter et al., 2009), and habitat provision for other organisms (Kadas, 2006). These benefits result from the presence of living plants and growth medium on green roofs. Studying the physiological traits of green roof plants is the key to understanding the environmental benefits of green roofs.

*Sedum* species use the crassulacean acid metabolism (CAM) photosynthetic pathway, which plays a crucial role in their growth under drought conditions (Yamori et al., 2014; Way and Yamori, 2014). In addition, several *Sedum* species have been described as “inducible” CAM plants (Lee and Griffiths, 1987; Gravatt and Martin, 1992). They are actually C\(_3\) plants with an ability to switch their carbon metabolism to the CAM pathway in response to drought stress (Sayed, 2001). This suggests that the physiological responses of *Sedum* species to soil water regimes severely affect the carbon sequestration and the cooling effect of a *Sedum* green roof. However, the investigation of *Sedum* species in green roofs has tended to focus primarily on their drought tolerance (Monterusso et al., 2005; VanWoert et al., 2005; Nagase and Dunnett, 2010; Thuring et al., 2010), and less attention has been paid to their physiological traits in wet conditions.

The aim of the present study was to investigate the physiological responses of three *Sedum* species to different soil water regimes, and compare their photosynthetic and transpiration rates with those of two other commonly used green roof plants. In addition, we discuss the influence of soil water regimes on the environmental benefits of the *Sedum* green roofs.

MATERIALS AND METHODS

**Plant material**

Three *Sedum* species, *S. japonicum* Siebold ex Miq., *S. lineare* Thunb., and *S. sarmentosum* Bunge, were selected for this study. In addition to the three *Sedum* species, we used other two green roof plants — *Zoysia matrella* (L.) Merr. and *Ophiopogon japonicus* (Thunb.) Ker Gawl. — for comparison.

All plants in this study were propagated at the same time as cuttings in plug flats (128 cells/tray) filled with seedling propagation soil (Metro Mix; Sun Gro Horticulture, Agawam, MA, USA). After approximately a month, we planted these plugs in 0.2-L polyethylene pots — for comparison.
(44 cm$^2$ surface area) filled with commercial artificial soil for green roofs including the following nutrients, NO$_3$-N: 114 mg kg$^{-1}$; NH$_4$-N: 323 mg kg$^{-1}$; P$_2$O$_5$: 159 mg kg$^{-1}$; K$_2$O: 32 mg kg$^{-1}$; CaO: 41 mg kg$^{-1}$; and MgO: 2 mg kg$^{-1}$.

The artificial soil composition was 75% perlite, 22% bark and peat, and 3% zeolite. Subsequently, these potted plants were placed in a phytotron (Seedling Terrace; Mitsubishi Plastics Agri Dream, Japan) and were allowed to grow for three weeks under the following conditions: 25°C (light period) and 20°C (dark period), 400 ppm CO$_2$, 65% relative humidity, 14 h light (225 25/mol m$^{-2}$s$^{-1}$), and 10 h dark. Density of planting in the phytotron was approximately 55 pot m$^{-2}$.

In order to investigate the photosynthetic and transpiration rates of the three Sedum species under wet and dry conditions, they were randomly assigned to wet or dry treatments, and then acclimatized to each treatment for three weeks. Plants subjected to the wet treatment were watered every day, and plants subjected to the dry treatment were watered once per week. An irrigation system was used to supply a nutrient solution (NO$_3$-N: 72 ppm; NH$_4$-N: 11 ppm; P$_2$O$_5$: 100 ppm; K$_2$O: 167 ppm; CaO: 71 ppm; and MgO: 17 ppm) for 30 min by bottom watering in each treatment. Z. matrella and O. japonicus received only the wet treatment in accordance with general cultivation practice.

**Photosynthetic and transpiration rates of three Sedum species under wet and dry conditions**

To measure the photosynthetic and transpiration rates of the three Sedum species using a photosynthesis system (LI-6400; LI-COR, Lincoln, NE, USA) with an LED light source (Yamori et al., 2012), the fully expanded leaves on the 8th to 10th nodes were selected, and the upper and lower leaves of those nodes were removed. The photosynthetic and transpiration rates of five plants under each treatment were measured every 10 min for 4 h (light period: 2 h and 25°C; dark period: 2 h and 20°C). The photosynthetic and transpiration rates and soil water content were measured for the plants subjected to the dry treatment every day for one week (Time after irrigation: 0, 1, 2, 3, 4, 5, and 6 d). The measurements with photosynthesis system were conducted under the assumed roof conditions: 400 ppm CO$_2$ concentration, 50% 10% relative humidity, and 1,000/TypeOne0 mol m$^{-2}$s$^{-1}$ PPFD. The soil water content was determined using a soil moisture sensor (EC-5 and ProCheck; Decagon, Pullman, WA, USA).

**Comparison of photosynthetic and transpiration rates under wet treatment**

For all the five species subjected to the wet treatment, the photosynthetic and transpiration rates of five plants per species were measured at 15, 25, and 35°C. All measurement conditions, except temperature, were the same as above.

**Statistical analysis**

Analysis of variance (ANOVA) was used to assess the effects of different treatments and species using an IBM SPSS Statistics software version 22.0 (IBM Japan, Tokyo, Japan). In addition, differences in the mean values were estimated with multiple comparisons (Tukey-b, homoscedasticity assumed or Dunnett-T3, homoscedasticity not assumed).

**RESULTS**

**Photosynthetic and transpiration rates of three Sedum species under wet and dry conditions**

Representative values of sequential photosynthetic rates of the three Sedum species are shown in Fig. 1. All species and samples in the wet treatment exhibited CO$_2$ uptake only during the light period. In contrast, none of the plants in the dry treatment showed any CO$_2$ uptake during either light or dark periods at 6 d after irrigation.

For the three Sedum species, photosynthetic rates in the dry and wet treatments are shown in Fig. 2. Sedum
japonicum plants exhibited CO₂ uptake only during the light period from 0 to 3 d after irrigation, and their photosynthetic and transpiration rates during that time were not significantly different from those of the wet-treatment plants and the dry-treatment plants from 4 to 6 d after irrigation (Fig. 2A and Table 1). Likewise, from 0 to 2 d after irrigation, S. lineare plants exhibited CO₂ uptake only during the light period. In addition, their photosynthetic and transpiration rates in the dry treatment during that time were not significantly different from those of the wet-treatment plants, while no significant differences were observed in the photosynthetic rates among the dry-treatment from 1 to 6 d after irrigation (Fig. 2B and Table 1). Similarly, the photosynthetic rates of S. sarmentosum plants subjected to the dry treatment from 0 to 3 d after irrigation were not significantly different from those of the wet-treatment plants (Fig. 2C). Moreover, there were no significant differences in the photosynthetic rates among the dry-treatment from 3 to 6 d after irrigation. However, the daily transpiration rates of all S. sarmentosum plants subjected to the dry treatment were significantly lower than those subjected to the wet treatment (Table 1).

Comparison of photosynthetic and transpiration rates under wet treatment
For all five species subjected to the wet treatment, the photosynthetic rates at three different temperatures are shown in Fig. 3A. The photosynthetic rates of the three Sedum species were not significantly different from those of O. japonicus at all temperatures. In contrast, Z. matrella exhibited significantly higher photosynthetic rates at 25 and 35°C than the other species.

No significant differences were observed in the transpiration rates of all five species at 25 and 35°C (Fig. 3B).

DISCUSSION
In this study, we sought to determine whether the physiological response of Sedum species to different water regimes affects their effectiveness as green roof plants. Because of a large error range, S. japonicum plants subjected to the dry-treatment did not exhibit significant differences in the photosynthetic and transpiration rates among the dry-treatment (Fig. 2 and Table 1). Likewise, no significant differences were observed in the photosynthetic rates of S. lineare among the dry-treatment from 1 to 6 d after irrigation, and in those of S. sarmentosum among the

Table 1 Transpiration rates of three Sedum species (S. japonicum, S. lineare, and S. sarmentosum) under dry and wet conditions.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Time after irrigation</th>
<th>Transpiration rate (mmol H₂O m⁻² s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>S. japonicum</td>
</tr>
<tr>
<td>dry</td>
<td>0 d</td>
<td>1.79 ± 0.42 a</td>
</tr>
<tr>
<td></td>
<td>1 d</td>
<td>2.03 ± 0.38 a</td>
</tr>
<tr>
<td></td>
<td>2 d</td>
<td>0.98 ± 0.21 a</td>
</tr>
<tr>
<td></td>
<td>3 d</td>
<td>0.73 ± 0.20 a</td>
</tr>
<tr>
<td></td>
<td>4 d</td>
<td>0.24 ± 0.09 b</td>
</tr>
<tr>
<td></td>
<td>5 d</td>
<td>0.28 ± 0.08 b</td>
</tr>
<tr>
<td></td>
<td>6 d</td>
<td>0.21 ± 0.05 b</td>
</tr>
<tr>
<td>wet</td>
<td>-</td>
<td>1.33 ± 0.21 a</td>
</tr>
</tbody>
</table>

Data represented by Means ¤ SE (n = 5).
* Significant differences among means of dry and wet treatment are indicated by different letters based on Dunnett-T3 at P < 0.05.
* Significant differences among means of dry and wet treatment are indicated by different letters based on Tukey-b test at P < 0.05.
The photosynthetic rates of vegetation plants have a close relationship with carbon sequestration (Yamori et al., 2016). In addition, previous studies have demonstrated that evapotranspiration is the most important contributing factor toward the cooling effect in green roofs (Takakura et al., 2016). In addition, previous studies have demonstrated that the Sedum green roof plants use the C3 photosynthetic pathway (Durhman et al., 2006; Butler and Orians, 2011). Our results for the plants subjected to the wet and dry treatments are consistent with this photosynthetic response occurring in green roofs. In contrast, the plants exhibiting CO2 uptake during the dark period were not observed in any of the Sedum species. Accordingly, for the three Sedum species, the comparisons of the photosynthetic and transpiration rates between C3 and CAM plants require further investigation.

The photosynthetic rates of vegetation plants have a close relationship with carbon sequestration (Yamori et al., 2016). In addition, previous studies have demonstrated that evapotranspiration is the most important contributing factor toward the cooling effect in green roofs (Takakura et al., 2000; Oberndorfer et al., 2007; Feng et al., 2010). The photosynthetic rates of the three Sedum species in wet treatment were similar to that of O. japonicus (Fig. 3A), and their transpiration rates were not significantly different from those of Z. matrella and O. japonicus (Fig. 3B). From the standpoint of physiological traits, these results suggest that the carbon sequestration and the cooling effect of the Sedum green roofs are likely equivalent to those of the green roofs employing other commonly used plant species under wet conditions.

Moreover, when the soil water content decreased below approximately 10 to 15%, the photosynthetic and transpiration rates of the three Sedum species subjected to the dry treatment were found to be significantly lower than those subjected to the wet treatment (Fig. 2 and Table 1). These observations suggested that keeping the soil water content above 10 to 15% might improve the environmental benefits of Sedum green roofs.

Although previous investigations of the application of Sedum species in green roofs have primarily focused on their drought tolerance, our study indicated that the appropriate soil water regime could elevate the carbon sequestration and the cooling effect of the Sedum green roofs as a result of their physiological response. We believe that our results will contribute to the improvement of the environmental benefits of green roofs through more suitable design and maintenance of vegetation.

REFERENCES

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