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Effect of combined water and salinity stress factors on evapotranspiration of *Sedum kamtschaticum* Fischer in relation to green roof irrigation

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ABSTRACT

In dryland areas, secondarily treated municipal wastewater could be used in extensive green roof systems. In this study, the effects of water and salt stress on a crassulacean acid metabolism (CAM) plant, *Sedum kamtschaticum* Fischer, was evaluated under intermittent saline irrigation. The salinity of irrigation water varied from 6.0 to 18.0 dS m^{-1}. A reduction in soil water content and an increase in soil water electrical conductivity (EC) were observed during the irrigation interval (5–17 d) as a result of evapotranspiration (ET). The effect of soil water potential (SWP) on reduction of the ET ratio (ET$_r$) was successfully described with an equation that could be applicable to a wide range of soil salinities and water contents, to estimate ET. In this study, the stress factor was defined as the integration of solute potential, and matric potential less soil water content for optimum growth (less than −0.1 MPa) with elapsed time. The stress factor rapidly reduced total ET in CAM plants but effectively increased water-use efficiency (WUE). Thus, by using CAM plants for green roofs under intermittent saline irrigation, the need for irrigation water is reduced without a considerable loss of plant biomass.

Introduction

In recent years the use of green roofs has become widespread due to the variety of benefits they provide, including esthetic appeal, habitat preservation, storm water reduction, and energy savings (Sailor, 2008; Cameron et al., 2012; Jim and Peng, 2012). In addition to rainfall, most green roof systems receive tap-water irrigation during the dry season to maintain good visual quality (Nagasea and Dunnett, 2010). However, irrigation with portable water would not be sustainable where water shortages occur. Thus, an alternative water resource is required (e.g., secondarily treated municipal wastewater) particularly in dryland areas, if the use of green roofs is to be expanded (Ayers and Westcot, 1985; Al-Busaidi et al., 2007; MLIT, 2010). Under saline irrigation, it is expected that the salinity level of green roof soils may be higher than that of field soils because of the low amount of water available in the thin soil beds in green roof systems. To avoid the adverse effects of salinity on plant growth, the soil water potential (SWP) must be maintained at a high level by frequent irrigation and leaching (Smith and Hancock, 1986; Dehghanisanij et al., 2006). However, water management systems for frequent irrigation, as used in intensive green roofs, require a high-level of design (Emilsson and Rolf, 2005; Mentens et al., 2006). On the other hand, under the intermittent irrigation methods practiced on extensive green roofs, plants are likely to experience drought and salinity stress as a result of salt accumulation in the root zone (Yamamoto and Cho, 1978b). Under such conditions, evapotranspiration (ET) declines due to low SWP. Thus, SWP should be included when considering the stress factors that affect plant growth. The relationship between SWP and ET highlights the importance of properly designing irrigation schedules for green roof management systems; however, few detailed reports on this subject are available in the literature (Allen et al., 1998).

The purposes of this study were to (1) experimentally derive the relationship between the SWP and ET of green roofs plants, and (2) quantify the water and salinity stress factors. Through these objectives, we aimed to define suitable leaching requirements to minimize the amount of irrigation water used and to reduce salt accumulation in the soil. To achieve these purposes, an intermittent saline irrigation regime reflecting drought and salinity stresses was compared experimentally to commonly used, frequent irrigation methods.

Sedum species are commonly used for green roofs due to their drought tolerance (Nagasea and Dunnett, 2010; Farrell et al., 2012).

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Some sedums shift their method of photosynthesis from C_3 to crassulacean acid metabolism (CAM) in response to drought and/or salinity stress (Hanscom and Ting, 1978; Lee and Griffiths, 1987). The transpiration dynamics of *Sedum kamtschaticum* Fischer also change according to the degree of drought condition. For instance, sufficient transpiration occurs in this species during the day under normal conditions while a little transpiration occurs at night under drought condition (Tanaka et al., 2008). In this study, the C_3–CAM intermediate-type species *S. kamtschaticum*, registered under US patent, was used (Fujita, 2008).

Materials and methods

Soil and plants

The experiment was performed in a glass greenhouse (glasshouse) during the summer of 2007 at the Arid Land Research Center (ALRC) of Tottori University in Japan (lat 35°32′ N, long 134°13′ E). A manufactured soil consisting of Andosols (50%) mixed with bark compost (30%), leaf mold (10%), and fine coal (10%), was used in the experiment (Moritani and Yamamoto, 2007). The soil was dominated by gravel (48.9%) and sand (32.1%), with smaller proportions of silt (10.6%) and clay (8.4%). The soil bulk density and saturated hydraulic conductivity were $0.48\,\mathrm{Mg\,m^{-3}}$ and $3.6 \times 10^{-2}\,\mathrm{m\,s^{-1}}$, respectively. The EC and pH were $0.7\,\mathrm{dS\,m^{-1}}$ and 6.7, respectively. Cation exchange capacity (CEC) was $40.4\,\mathrm{cmol_{(+)}\,kg^{-1}}$. Green roofs are typically constructed in 2 layers: the drainage layer and a thin (20–200 mm) bed of soil (Johnston and Newton, 1993). To simulate practical irrigation for our experimental green roof, 10 cm of the manufactured soil was placed over a gravel drainage layer, in plastic pots with diameter and height of 0.16 m and 0.20 m, respectively. Phosphorous ($24\,\mathrm{kg\,ha^{-1}}$), nitrogen ($52\,\mathrm{kg\,ha^{-1}}$), and potassium ($45\,\mathrm{kg\,ha^{-1}}$) were applied as fertilizers before planting. Two bare-soil pots were prepared to determine the amount of initial soil water that remained after irrigation water was drained gravimetrically as described below.

Six *S. kamtschaticum* plants were transplanted into 24 pots in mid-June 2007. The planting density was determined based on construction specifications for an actual green roof at maximum plant coverage. All plants were grown for 1 mo under well-watered conditions prior to starting the experiment on August 1, 2007. The irrigation experiment was conducted for 2 mo during summer. All plants were well developed by the start of the experiment.

Experimental conditions

Air temperature and relative humidity were recorded with a thermohygrometer. Evapotranspiration and pan evaporation were measured, respectively, by weighing each of the 24 pots and a small open pan with internal diameter 0.20 m. An average pan evaporation of $4.4\,\mathrm{mm\,d^{-1}}$ was observed during the experiment. While temperatures higher than 50 °C were recorded in the glasshouse for a few days, the average temperature was 32 °C. The humidity ranged from 10% to 90%; the maximum humidity was recorded before sunrise and the minimum at noon; the average humidity was 62%.

The EC of the irrigation water ($\mathrm{EC_i}$) treatments was $0.7\,\mathrm{dS\,m^{-1}}$ (tap water), and 6, 12, and $18\,\mathrm{dS\,m^{-1}}$ in solutions prepared from mixtures of sea and tap water. The salinity used in the experiment was much higher than levels (EC up to $3.7\,\mathrm{dS\,m^{-1}}$) that would be found in actual applications of high-salinity irrigation water (Gerhart et al., 2006; Al-Hamaiedeh and Bino, 2010; Klay et al., 2010). Therefore the treatments in this study were viewed as a worst-case scenario. Two irrigation schedules were adopted: (1) frequent irrigation with a 1–3-d interval, and (2) intermittent irrigation with a 5–17-d interval. The intermittent irrigation interval was determined based on observations of the frequency of watering required to avoid extensive leaf mortality. We observed the condition of plants under intermittent irrigation with tap water, in which leaf wilting was due primarily to drought, and the irrigation interval was changed according to weather conditions. For instance, the shortest irrigation interval was 5 d, between the second and third irrigation events during which the average maximum daily temperature was 47.2 °C, comparatively severe conditions in the experimental period. The daily ET ratio ($\mathrm{ET_r}$) was calculated by dividing ET by the pan-evaporation rate. The amount of irrigation water (V_i) applied to each pot was 1.2× the observed ET during each irrigation interval, so that the excess of water V_d (equal to $0.2 \times \mathrm{ET}$) could be used to leach salts from the soil by drainage. The EC of the drainage water (EC_d) was measured using a portable EC meter (HORIBA Compact Conductivity Meter/B-173). At the end of the experiment, the dry matter yield (DM) of each plant was measured by weighing the shoots after drying them at 80 °C for 3 d. Water-use efficiency (WUE) was defined as the ratio of plant DM to total irrigation water. The irrigation experiment was replicated 3 times in each treatment; treatments included the 2 irrigation methods (frequent and intermittent), and 4 levels of irrigation EC (tap water, and 6, 12, and $18\,\mathrm{dS\,m^{-1}}$), for a total of 24 pots. The pots receiving frequent irrigation with tap water were labeled as the controls. The triplicate data were subjected to mean separation analysis using 1-way ANOVA (Ekuseru-Toukei 2012). When there were significant differences, means were separated by Tukey–Kramer test at the probability level $P < 0.05$.

Calculation of soil water potential

Nondestructive measurements of soil water content and soil EC can be conducted with commonly used methods such as time-dominant reflectometry (TDR), frequency domain reflectometry (FDR), and amplitude-domain reflectometry (ADR). Measurements of EC under conditions of high soil salinity were challenging, because the measurement of water content is strongly affected by soil EC (Inoue et al., 2008; Topp et al., 2000). Therefore, soil water content and soil EC were calculated from the water and salt balance in pot soil, as described below.

ET (m) was calculated from pot mass, W_{po} (Mg) as follows:

$$\mathrm{ET} = \left[(W_{po})_t - (W_{po})_{t-1}\right] / \rho_w / A \tag{1}$$

where t is the t-th irrigation interval, W is mass (Mg), ρ_w is the density of water ($\simeq 1.0\,\mathrm{Mg\,m^{-3}}$), and A is surface area of the pot ($0.02\,\mathrm{m^2}$).

The volume of soil water, V_{sw} was calculated from Eq. (2):

$$V_{sw} = (\mathrm{ISWC} - \mathrm{ET}) \times A \tag{2}$$

where ISWC is the initial soil water content (depth) when irrigation water is gravimetrically drained, calculated from Eq. (3):

$$\mathrm{ISWC} = (W_{fcpo} - W_{dspo} - W_{nspo}) / \rho_w / A \tag{3}$$

where the subscripts *fcpo*, *dspo*, and *nspo* represent pots with wet soil under field capacity, packed dry soil, and no soil, respectively. Measured values of W_{dspo} and W_{nspo} were approximately 1.8 kg and 0.45 kg, respectively. W_{fcpo} was measured after irrigation water was applied and then drained for approximately 1–2 h, which resulted in values of approximately 60 mm.

The accumulated soil salt under each irrigation method, $\Delta(C_s V_{sw})$, and total salt accumulation in soil, $C_s V_{sw}$, were calculated from Meiri and Plaut's equation (1985) as follows:

$$\Delta(C_s \cdot V_{sw}) = C_i \cdot V_i - C_d \cdot V_d \tag{4}$$