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Short Communication

Sedum-dominated green-roofs in a semi-arid region increase CO_2 concentrations during the dry season

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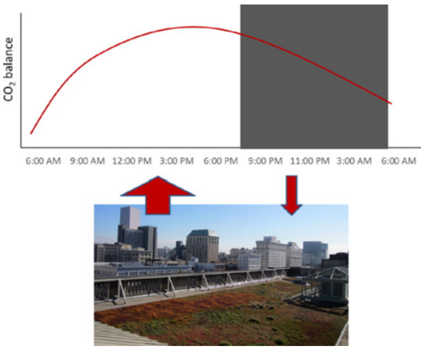
HIGHLIGHTS

- We evaluated CO_2 fixation/emission rates of *Sedum* green-roofs in semi-arid region in the beginning of the dry season.
- We measured CO_2 concentrations inside transparent polyethylene tents placed over 1 m^2 *Sedum* and control plots.
- We measured photosynthetic activity at the leaf level using a portable gas-exchange system.
- During the dry season *Sedum* green roofs emit a substantial amount of CO_2 in the daytime.
- We conclude that alternatives to the use of *Sedum* in green roofs in semi-arid climate areas should be considered.

GRAPHICAL ABSTRACT



During the dry season the common *Sedum* green roofs located in semi-arid regions emit a substantial amount of CO_2 in the daytime, which adds to the high CO_2 concentration in the city at these times. Our results show that the night-time CO_2 uptake do not fully compensate for the high daytime emission, which suggests that these green roofs add CO_2 to the city ambient throughout the dry season.

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ABSTRACT

Green roofs are expected to absorb and store carbon in plants and soils and thereby reduce the high CO_2 concentration levels in big cities. *Sedum* species, which are succulent perennials, are commonly used in extensive green roofs due to their shallow root system and ability to withstand long water deficiencies. Here we examined CO_2 fixation and emission rates for Mediterranean *Sedum sediforme* on green-roof experimental plots. During late winter to early spring, we monitored CO_2 concentrations inside transparent tents placed over 1 m^2 plots and followed gas exchange at the leaf level using a portable gas-exchange system. We found high rates of CO_2 emission at daytime, which is when CO_2 concentration in the city is the highest. Both plot- and leaf-scale measurements showed that these CO_2 emissions were not fully compensated by the nighttime uptake. We conclude that although carbon sequestration may only be a secondary benefit of green roofs, for improving this ecosystem service, other plant species than *Sedum* should also be considered for use in green roofs, especially in Mediterranean and other semi-arid climates.

1. Introduction

Urban ecosystems are expanding globally, and assessing the ecological consequences of urbanization is critical to understanding the

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biology of local and global changes related to land-use changes (Lambin et al., 2001; Alberti et al., 2003). Green roofs are shown to provide many ecosystem services (Sutton, 2015; Starry, 2016). Most of the green roof research until now has been on their role in regulation of building temperatures, reducing urban heating and rainwater management.

Green roofs are also expected to absorb and store carbon in plants and soils and thus reduce the high CO_2 concentration in big city centers (Getter et al., 2009). This effect had been quantitatively evaluated only partially until now but it is assumed to be more important as green roofs are becoming more popular and are seen as a solution for reducing CO_2 concentrations (Li and Babcock, 2014). The use of green roof landscapes may reduce the payback period of carbon embodied in the green roof materials from 15 years to <3 years (Whittinghill et al., 2014).

Li et al. (2010) examined the effect of green roofs on ambient CO_2 concentrations in Hong Kong. They found that green roofs may lower CO_2 concentrations, which were about 750 ppm in the nearby region, by as much as 2%. Marchi et al. (2015) used a dynamic model to estimate CO_2 removal from the atmosphere by perennial herbaceous plants installed in a vertical greenery system (green façade). The model provided evidence of carbon sequestration by plants as a potential environmental benefit of vegetated structures installed in urban areas.

1.1. Local effects of CO_2 emissions

Local CO_2 emissions can also affect the urban "heat-island" (Bornstein, 1968; Goward, 1981), i.e., the phenomenon of city area that is significantly warmer than its surrounding rural areas. The urban "heat-island" is spatially connected with the urban "CO_2 dome" phenomenon (Idso et al., 1998), which is a buildup of CO_2 over an urban area. The urban "heat-island" is assumed to be partially derived from heat trapping by elevated levels of locally produced CO_2 (Idso et al., 2001). Therefore, urban greening and green roofs in particular are expected to minimize both the urban "CO_2 dome" and "heat island" phenomena.

Local CO_2 emissions in isolation may also increase local ozone and particulate matter. Reducing this locally emitted CO_2 may reduce local air pollution mortality even if CO_2 in adjacent regions is not controlled (Jacobson, 2010).

1.2. Carbon fixation in different kinds of green roofs

Green roofs may be "intensive" or "extensive". Intensive green roofs may include shrubs and trees and appear similar to landscaping found at natural ground level. As such, they require greater substrate depths and have "intense" maintenance needs. In contrast, extensive green roofs consist of herbaceous perennials or annuals, use shallower media depths (generally <15 cm), and require minimal maintenance. Due to building weight restrictions and costs, and for benefiting ecosystem services, extensive green roofs are more common than deeper intensive roofs.

Different plant species fixate carbon at different rates (Marchi et al., 2015; Kuronuma and Watanabe, 2017). Therefore, to achieve maximum environmental benefit, it is important to consider plant selection. *Sedum* species, which are succulent plants (i.e., plants that have thickened and fleshy parts, and usually to retain water under arid conditions), are commonly used in extensive green roofs due to their shallow root system and ability to withstand long water deficiencies (Dvorak and Volder, 2010; Wolf and Lundholm, 2008). However, if taking into account considerations of carbon fixation and benefits for decreasing the CO_2 concentration levels in the cities, using only *Sedum* is not beneficial since it has low CO_2 fixation rates at day time compared with other herbaceous life forms (Sajeva et al., 1995; Marchi et al., 2015). In addition, *Sedum* species were shown to change their photosynthesis course to CAM (crassulacean acid metabolism) in response to drought. Under these conditions, the CO_2 uptake at day time was decreased and turned negative (Schuber and Kluge, 1981; Silvola, 1985).

In this paper, we tested the performance of *Sedum sediforme* green roofs located under Mediterranean climate conditions. Our hypotheses were: a) at day time, *Sedum* CO_2 balance will be positive in the rainy season and will turn negative in the dry season; b) the overall all-day CO_2 balance will remain positive throughout the whole year. These two hypotheses were tested in a field experiment by comparing CO_2 intake/emission of *S. sediforme* and control (empty) plots, and by measuring gas exchange in *Sedum* at the leaf level.

2. Materials and methods

We established the experiment in fall 2013. The experimental plots are located on the roof at Haifa University, Israel (32°75N, 35°02E), which is a pre-existing terraced green roof on the North-facing slope of the Carmel Mountain. Elevation is ~460 m asl. The climate is Mediterranean with mean annual rainfall of 685 mm falling mainly from November through March. Maximum average monthly temperatures for January and August are 18.5 °C and 30.4 °C respectively. Annual rainfall in the year of our experimental measurements (2015–2016) was lower than normal −426 mm (Israel Meteorological Service 2016).

The experiment consisted of two treatments: 10 *Sedum* and five control plots (no plants). In each *Sedum* plot, we planted 36 *Sedum sediforme* shoots of similar size (10 cm long) on an 18 cm depth substrate composed of 70% perlite, 10% tuff, 10% compost and 10% peat (in volume). Size of each experimental plot (length × width × depth) was 100 × 100 × 18 cm.

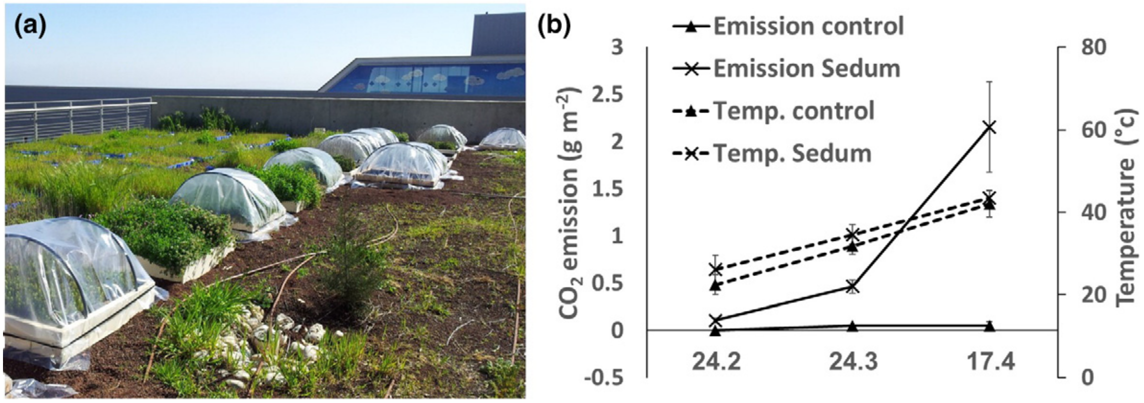

Fig. 1. (a) *Sedum* and control empty plots covered with polyethylene tents for measuring CO_2 concentrations (uncovered plots are part of a different experiment). (b) CO_2 emission between 9 AM and 2 PM (complete lines) and temperatures inside the tents at 2 PM (dashed lines) in *Sedum* and control plots on three days during the end of the winter/beginning of the dry season . Data points are means ± SE ($n = 5$).

2.1. CO_2 concentration measures

Five of the 10 *Sedum* plots were used for the CO_2 concentration measures. We measured inside 0.35 m^3 temporary tents made of transparent polyethylene (Fig. 1a) that we built at the beginning of each measuring session and removed immediately afterwards. We used a portable air quality meter (Lutron AQ-9901SD), with a NDIR (Non-Dispersive Infra-Red) sensor (Neethirajan et al., 2009). We simultaneously measured CO_2 concentration, temperature (dry and wet) and relative humidity. To insert the sensors, we cut a 15 cm notch on the roof of the tent. After each measurement, we sealed the notch with transparent tape until the next measure. We started the measurements at 9 AM, monitoring each plot for 4 min, and measuring in 3 s intervals.

We conducted the measurements on three different dates throughout 2016. On February 24th and on March 24th, we conducted two measures: immediately (~9 AM) and 5 h after covering the plots (~2 PM). On April 17th, after the second measure (at ~2 PM), we left the tents intact overnight and performed a third measure in the following morning (~9 AM).

2.2. Gas exchange measurements

The five remaining *Sedum* plots were used for the gas exchange measurements. We measured three parameters to quantify photosynthesis rate in single *Sedum* leaves: a) net carbon assimilation, b) stomatal conductance and c) transpiration. To measure these, we used a portable gas exchange system (Li-6400XT, Li-Cor, Lincoln, NE, USA) equipped with light source and a CO_2 mixer to control the CO_2 level in the chamber. We performed the measurements on May 31st approximately each hour between 11 AM and 11 PM on six mature *Sedum sediforme* leaves each hour. We adjusted CO_2 level in the chamber to of 400 ppm. We set PAR (photosynthetically active radiation) level in the chamber to be similar to the level outside. We logged the data as soon as the photosynthetic rate remained constant, typically within 2–3 min.

2.3. Upscaling of leaf-scale to plot-scale gas exchange

We further used leaf-scale gas exchange data for a simulation of CO_2 changes at the plot-scale. First, we transformed net carbon assimilation (either positive or negative) from μmol m^{-2} s^{-1} to g $plot^{-1}$ h^{-1}. We used estimated plot leaf area of 3 m^2, confirmed by image analysis. To compare with measurements performed in the sealed, transparent tent, we further used plot-scale gas exchange rates to simulate the tent CO_2 content. We used known tent volume of 0.35 m^3 and assumed linear behavior between the hourly measurement points. We recognize that such an upscaling procedure is simplistic, assuming that the plot CO_2 balance is the sole factor affecting the plot gas exchange. However, this assumption is most likely safe in soil as dry as in our experimental plots. Soil-atmosphere gas exchange is almost negligible under very dry conditions (Grünzweig et al., 2009).

2.4. Statistical analysis

We used mixed ANOVA (SPSS: linear mixed models) to examine the effects of the treatment, the time and their interactions on a) CO_2 emission between 9 AM and 2 PM along the season and b) CO_2 concentration inside the tents (on April 17th at 9 AM and 2 PM and April 18th at 9 AM). We used the temperature inside the tent as covariate in the analysis.

3. Results

3.1. CO_2 emission along the season

CO_2 emission between 9 AM and 2 PM was significantly higher in *Sedum* than control plots at each of the measuring days. In *Sedum* plots, it showed a remarkable positive trend along the season, up almost five-fold by March 24th and more than 20-fold by April 17th compared with the first measure performed on February 24th. CO_2 emission between 9 AM and 2 PM in control plots remained between 0.00 and 0.05 g m^{-2} along the three measurement days (Fig. 1b).

We found significant effects of the date ($F_{1,8.4} = 29.0$, $P = 0.001$), the treatment ($F_{2,8.8} = 17.4$, $P = 0.001$), the date ∗ treatment interaction ($F_{2,9.7} = 15.2$, $P = 0.001$) and of the temperature as covariate ($F_{1,7.9} = 7.6$, $P = 0.025$) on CO_2 emission between 9 AM and 2 PM (Fig. 1b).

3.2. Gas exchange in sedum plants

CO_2 uptake (net carbon assimilation) was synchronized with the decrease in vapor pressure deficit (VPD) below 2.5 kPa at 4:00 PM (Fig. 2a, b). But the increase in CO_2 uptake was consistent only after stomatal

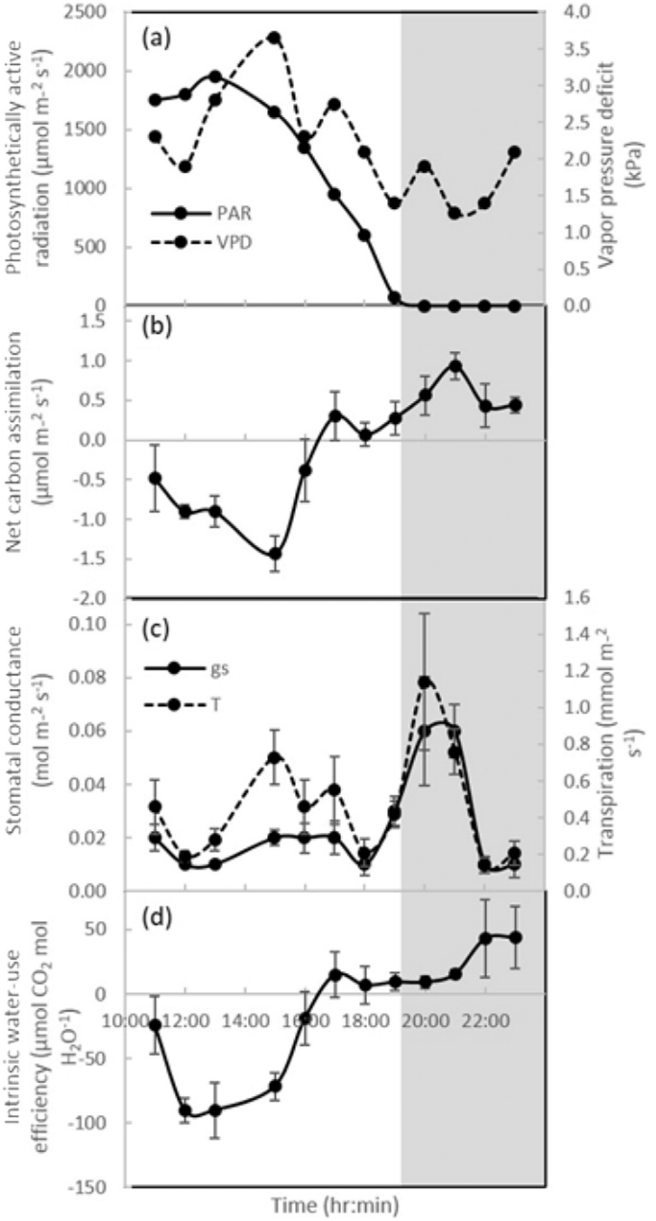

Fig. 2. Contrasting carbon balance of *Sedum sediforme* leaves in day time and night time of a dry season day. Atmospheric conditions (a), leaf gas exchange (b, c), and intrinsic water-use efficiency (d) in the green roof plots on 31 May 2016. Gray background indicates night time hours. Data points are means ± SE ($n = 6$). PAR, photosynthetically active radiation; VPD, vapor pressure deficit; gs, stomatal conductance; T, transpiration.

aperture (opening of the stomata) at 7 PM, just before sunset, and remained >0.5 μmol m^{-2} s^{-1} for 3 h, until stomata closed again (Fig. 2c). Net carbon assimilation was negative between 11 AM and 3 PM and positive between 4 and 11 PM. Values were relatively low, between −1.5 to 1.0 μmol m^{-2} s^{-1} (Fig. 2b). In accordance with these trends, the intrinsic water-use efficiency (WUE_i) – ie the ratio between net carbon assimilation and stomatal conductance – was negative before 5 PM (Fig. 2d). We calculated the highest WUE_i (44 ± 24 μmol CO_2 mmol H_2O^{-1}) after 9 PM, due to continued CO_2 uptake after stomatal closure.

3.3. Daily changes in CO_2 concentration inside covered plots

On April 17th, CO_2 concentration in *Sedum* 5 h after covering all plots (2 PM) was about 10-fold greater than the ones in the control and went down to about third of this value by 9 AM the next morning (Fig. 3a). We found significant effect of the time ∗ treatment interaction ($F_{2,8.3} = 36.6$, $P < 0.001$) on CO_2 concentrations; the effect of the treatment ($F_{2,8.3} = 28.9$, $P = 0.001$) existed only at April 17th 2 PM and at April 18th 9 AM, and the effect of the time ($F_{1,8.3} = 42.6$, $P < 0.001$), existed only in the *Sedum* plots. The temperature as covariate had no effect ($F_{1,7.3} = 7.6$, $P = 0.129$) (Fig. 3a).

We used the leaf-scale gas exchange data to simulate changes in CO_2 concentration in a sealed transparent tent of the same dimensions as the one we used. This simple upscaling exercise showed a major increase, from 450 to 5100 ppm CO_2 during daytime up until 4 PM, followed by gradual decrease during night time, down to 2650 ppm in 11 PM (Fig. 3b).

4. Discussion

Sedum species are widely used in extensive green roofs for a variety of reasons — mainly their low maintenance and their ability to survive above ground throughout the year. Here we tested CO_2 balance of *Sedum sediforme* in a Mediterranean green-roof system, from the end of the winter to the beginning of the dry season. *Sedum* species were shown to shift their photosynthesis pathway from C_3 to CAM and consequently reduce water loss in response to drought (Schuber and Kluge, 1981; Silvola, 1985). This change is expected to occur in *S. sediforme* in the dry Mediterranean summer. According to our results (in opposition to our hypothesis), *Sedum* CO_2 balance at day time was negative from the first measure that was taken in February 24th. *Sedum* CO_2 emission rate at daytime went up markedly as the season advanced; in April it was about 20 times higher than in February (Fig. 1). On April 17, we found a negative whole-day CO_2 balance of approximately 0.47 g m^{-2} in *Sedum* plots. Substrate depth, particle size distribution and percentage of organic matter would influence water holding capacity and potentially influence the results. Ondoño et al. (2016) found that carbon fixation was higher in substrate depth of 10 compared with 5 cm, and was higher when the substrate contained soil in addition to crushed bricks and compost. Nevertheless, if extrapolating this result assuming a similar balance throughout 200 days of dry season, we predict total CO_2 emission of approximately 100 g m^{-2}. If we located the Ford factory with its famous 40,000 m^2 *Sedum* green roof (see Getter and Rowe, 2006) in a semi-arid area with similar conditions, it would emit over 4 tons CO_2 during one summer. This is likely to be an underestimation, since we took our measurements at the early stages of the dry season.

Marchi et al. (2015) estimated that a *Sedum spurium* vertical plot on building facade in Siena, Italy would capture an average CO_2 flow of 137 g m^{-2} yr^{-1}. However, they did not consider seasonal changes. At the end of two years of study on extensive green-roof system in Michigan, USA, Getter et al. (2009) found that aboveground plant material and root biomass stored an average of 168 g C m^{-2} and 107 g C m^{-2}, respectively. Carbon content in the substrate was 913 g C m^{-2} and in total, this green roof system held 1188 g C m^{-2}. After subtracting the 810 g C m^{-2} initially existing in the substrate, the calculated net carbon sequestration was 378 g C m^{-2}. Kuronuma and Watanabe (2017) found that during the first year after the construction of the green roofs in Japan, carbon sequestration of *Sedum mexicanum* was 336 g C m^{-2} in wet irrigated treatment, 364 g C m^{-2} in dry irrigated treatment and 276 g C m^{-2} in non-irrigated treatment. Both studies were done in relatively high-rainfall regions. An important emphasis is that extensive green roofs will only store new net carbon during the first few years of its life. Once the plants are mature, net carbon sequestration will reach an equilibrium where decomposition of organic matter will equal sequestration (Rowe, 2011; Whittinghill et al., 2014).

The measures in the single *Sedum* leaves confirmed the expected pattern of a negative CO_2 balance in daytime (Fig. 2). Our measurements highlight the benefit of the CAM pathway for the *S. sediforme* plants. The nocturnal gas exchange was accompanied by water loss, but at levels much lower than could have been lost if photosynthesis was occurring in daytime: For example, at 3 PM, transpiration was >0.7 mmol m^{-2} s^{-1} when stomata were almost entirely closed. After sunset, when stomatal conductance finally peaked, transpiration was 1.1 mmol m^{-2} s^{-1}. Although high, transpiration would soar to 2.2 mmol m^{-2} s^{-1} if such stomatal conductance occurred during the day.

Simulating the plot-scale CO_2 changes based on the leaf-scale measurements yielded large CO_2 fluctuations at the same order of magnitude measured in the tents (Fig. 3a,b). This result supports the validity of the simple CO_2 measurements.

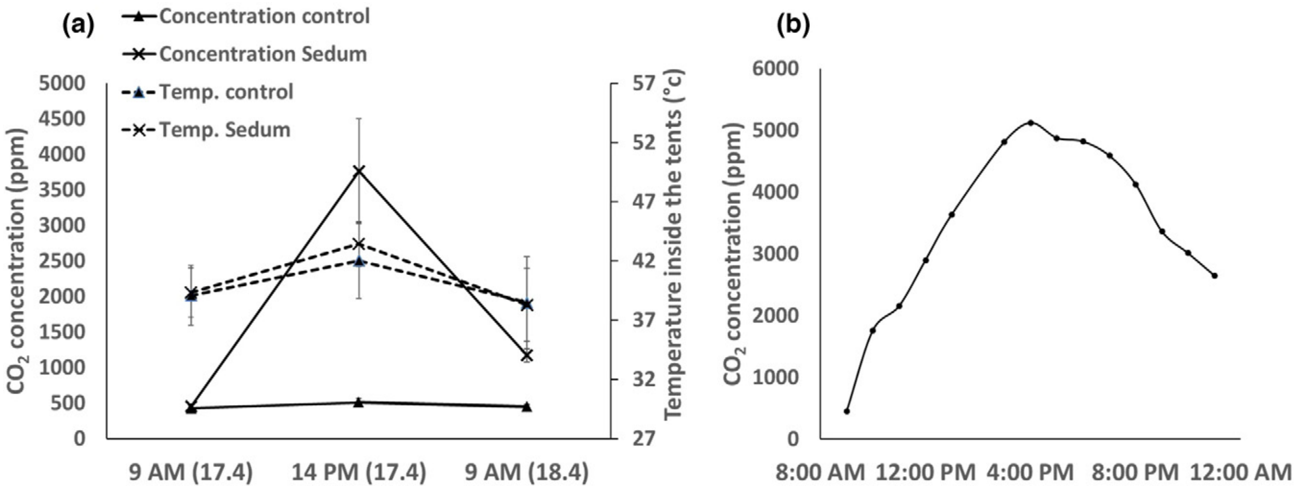

Fig. 3. (a) CO_2 concentration in *Sedum* and control (no plants) plots immediately (9 AM, 17.4), 5 h (2 PM, 17.4) and 24 h (9 AM 18.4) after being covered with sealed transparent tents. Data points are means ± SE ($n = 5$). (b) Simulated CO_2 concentration in *Sedum* plots covered with sealed transparent tents based on upscaling of leaf-scale measurements.

5. Conclusions

Both plot- and leaf-scale measurements in *Sedum sediforme* showed that the night-time CO_2 uptake did not fully compensate for the high daytime emission. This suggests that the whole-day CO_2 balance of *S. sediforme* is negative throughout the dry season. Then, in the middle of the day, which is the critical time when CO_2 concentration in the cities is the highest, *Sedum* green roofs emit CO_2 and add to the high ambient CO_2 concentration. In conclusion, although carbon sequestration may only be a secondary benefit of green roofs, more studies assessing how different plants contribute to carbon sequestration on green roofs should be done for improving this ecosystem service. Mainly in Mediterranean and other semi-arid climate regions.

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References

Alberti, M., Marzluff, J.M., Shulenberger, E., et al., 2003. Integrating humans into ecology: opportunities and challenges for studying urban ecosystems. Bioscience 53, 1169–1179.

Bornstein, R.D., 1968. Observations of the urban heat island effect in New York City. J. Appl. Meteorol. 7, 575–582.

Dvorak, B., Volder, A., 2010. Green roof vegetation for North American ecoregions: a literature review. Landsc. Urban Plan. 96, 197–213.

Getter, K.L., Rowe, D.B., 2006. The role of extensive green roofs in sustainable development. Hortscience 41, 1276–1285.

Getter, K.L., Rowe, D.B., Robertson, G.P., et al., 2009. Carbon sequestration potential of extensive green roofs. Environ. Sci. Technol. 43, 7564–7570.

Goward, S.N., 1981. Thermal behavior of urban landscapes and the urban heat island. Phys. Geogr. 2, 19–33.

Grünzweig, J.M., Hemming, D., Maseyk, K., et al., 2009. Water limitation to soil CO_2 efflux in a pine forest at the semiarid “timberline”. J. Geophys. Res. Biogeo. 114, G3.

Idso, C.D., Idso, S.B., Balling Jr., R.C., 1998. The urban CO_2 dome of Phoenix, Arizona. Phys. Geogr. 19, 95–108.

Idso, C.D., Idso, S.B., Balling Jr., R.C., 2001. An intensive two-week study of an urban CO_2 dome in Phoenix, Arizona, USA. Atmos. Environ. 35, 995–1000.

Jacobson, M.Z., 2010. Enhancement of local air pollution by urban CO_2 domes. Environ. Sci. Technol. 44, 2497–2502.

Kuronuma, T., Watanabe, H., 2017. Relevance of carbon sequestration to the physiological and morphological traits of several green roof plants during the first year after construction. Am. J. Plant Sci. 8, 14–27.

Lambin, E.F., Turner, B.L., Geist, H.J., et al., 2001. The causes of land-use and land-cover change: moving beyond the myths. Glob. Environ. Chang. 11, 261–269.

Li, Y., Babcock Jr., R.W., 2014. Green roofs against pollution and climate change. A review. Agron. Sustain. Dev. 34, 695–705.

Li, J.F., Wai, O.W., Li, Y.S., et al., 2010. Effect of green roof on ambient CO_2 concentration. Build. Environ. 45, 2644–2651.

Marchi, M., Pulselli, R.M., Marchettini, N., et al., 2015. Carbon dioxide sequestration model of a vertical greenery system. Ecol. Model. 306, 46–56.

Neethirajan, S., Jayas, D.S., Sadistap, S., 2009. Carbon dioxide (CO_2) sensors for the agri-food industry—a review. Food Bioprocess Technol. 2, 115–121.

Ondoño, S., Martínez-Sánchez, J.J., Moreno, J.L., 2016. The composition and depth of green roof substrates affect the growth of *Silene vulgaris* and *Lagurus ovatus* species and the C and N sequestration under two irrigation conditions. J. Environ. Manag. 166, 330–340.

Rowe, D.B., 2011. Green roofs as a means of pollution abatement. Environ. Pollut. 159, 2100–2110.

Sajeva, M., Oddo, E., Troìa, A., et al., 1995. Nocturnal malic acid accumulation in some Sicilian *Sedum* species (Crassulaceae). Qua Bot Ambientale Appl. 6, 23–28.

Schuber, M., Kluge, M., 1981. In situ studies on crassulacean acid metabolism in *Sedum acre* L. and *Sedum mite* Gil. Oecologia 50, 82–87.

Silvola, J., 1985. Photosynthesis measurements on a CAM plant, *Sedum telephium* (Crassulaceae). Ann. Bot. Fenn. 22, 195–200.

Starry, O.S., 2016. Ecosystem ecology as a framework for organizing and advancing greenroof research. Isr. J. Ecol. Evol. 62, 97–102.

Sutton, R.K., 2015. Introduction to green roof ecosystems. Green Roof Ecosystems. Springer International Publishing.

Whittinghill, L.J., Rowe, D.B., Schutzki, R., et al., 2014. Quantifying carbon sequestration of various green roof and ornamental landscape systems. Landsc. Urban Plan. 123, 41–48.

Wolf, D., Lundholm, J.T., 2008. Water uptake in green roof microcosms: effects of plant species and water availability. Ecol. Eng. 33, 179–186.