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Short communication

Measuring the effect of plant-community composition on carbon fixation on green roofs

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A B S T R A C T

Green roofs provide many ecosystem services such as regulation of building temperatures, reducing urban heat-island effects and draining rainwater. In addition, they are expected to reduce the high levels of CO_2 concentrations in big cities. Previous CO_2 fixation studies on green roofs were done by taking long-time-period samples using expensive equipment and with limited replication. To plan green roofs for optimal CO_2 reduction, a simple method to quantify CO_2 fixation rate in relation to plant species-composition is required. The method we tested is direct measurement of CO_2 concentrations with a portable air-quality meter, which allows a large number of samples. Here we focus on differences in the photosynthetic effect between plots containing the local Mediterranean succulent, *Sedum sediforme* and plots containing various annuals. In a factorial design (presence or absence of *Sedum* crossed with presence or absence of annuals), we tested the effect of *sedum* and annual treatments on CO_2 concentrations. To compare our results with a commonly used method, and to evaluate the role of the different species, we examined the photosynthetic activity at the single plant level under these treatments by using a portable gas-exchange measuring system. We found that our method can detect the effect of different green roof plots and can be used as a simple and reliable tool for green-roof planers. We found that annuals reduced CO_2 concentrations, but only in the absence of *Sedum*. *Sedum* alone had no effect on CO_2 concentrations. This emphasizes the importance of integrating plots with annual plants in *Sedum*-based green roofs.

1. Introduction

Urban ecosystems are expanding globally, and assessing the ecological consequences of urbanization is critical to understanding the biology of local and global changes related to land use changes (Lambin et al., 2001; Alberti et al., 2003). 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 substrate depths greater than 15 cm and have "intense" maintenance needs. In contrast, extensive green roofs consist of herbaceous perennials or annuals, use shallower media depths (less than 15 cm), and require minimal maintenance. Due to building weight restrictions and costs, extensive green roofs are more common than deeper intensive roofs and carbon fixation on extensive green roofs will be the focus of this study. Green roofs are shown to provide many ecosystem services (Sutton 2015). Most of the green roof research until now has been on their role in regulation of building temperatures, reducing urban heat-island effects and rainwater management. Green roofs may also sequester carbon in plants and soils. Photosynthesis removes carbon dioxide from the atmosphere and stores carbon in plant biomass, a process commonly referred to as terrestrial carbon sequestration. Carbon is transferred to the substrate via plant litter and exudates. The length of time that this carbon remains in the soil before decomposition has yet to be quantified for green roofs, but if net primary production exceeds decomposition, this man-made ecosystem will be a net carbon sink, at least in the short term (Getter et al., 2009). Most previous studies of photosynthesis on green roofs concentrated in measuring direct CO_2 uptake by the plants and producing models. The ones that measured CO_2 directly did so by either studying specific species or plant groups under lab conditions or on the actual green roofs by taking long-time-period samples using permanent sensors with limited repetitions.

Getter et al. (2009) examined carbon fixation on green roofs of different *Sedum* species and found that above-ground plant material storage varied among species. Li et al. (2010) examined

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the effect of green roofs on ambient CO_2 concentrations in Hong Kong and found that green roofs may lower CO_2 concentrations, that were about 750 ppm in the nearby region by as much as 2%. Chen (2015) measured the effects of different green roof plants on CO_2 concentration and carbon sequestration and found that the C_4 and CAM plants had longer CO_2 absorption periods than did the C_3 plants. 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. The model provided evidence of carbon sequestration by plants as a potential environmental benefit of vegetated structures installed in urban areas.

Considering the variety of plant species that is available to green-roof planners, a simple method that can quantify CO_2 fixation rates in relation to plant species composition is required. Interactions between plants can affect many aspects of plant functions, including photosynthesis. In addition, different plant compositions can cause differences in soil composition, in arthropod populations and possibly in other unknown factors that can affect the CO_2 balance in a green roof plot. Therefore, to determine differences between plots that were planted with different compositions of species or functional groups, it is essential to be able to measure at the whole plot scale, not just at the single species levels. Here we examined whether the effect of different plant assemblages in green roof plots on the immediate ambient CO_2 concentrations can be measured using short-time-period samples, taken in the open environment with a portable air-quality meter, which allows a large number of repetitions.

To test our method, we examined differences between green-roof types that are in common use in Mediterranean climates. *Sedum* species, which are succulent plants, are commonly used in extensive green roofs due to their shallow root system, efficient water use and ability to withstand long water deficiencies (Dvorak and Volder, 2010; Wolf and Lundholm, 2008). Conversely, the use of annuals is expected to reduce establishment and management costs, reduce use of fertilizers and is also suggested to enhance different arthropod genera (Nagase and Dunnett, 2013). Use of annuals would suit the typical Mediterranean bi-seasonal climate which supports various annual life cycles for many of the native plants and arthropods. This life form would bypass the extended dry period of the summer in the seed stage. The succulent plant *Sedum sediforme* is expected to fixate less CO_2 at day time than the annuals (Sajeva et al., 1995). Therefore, we hypothesize that its effect on CO_2 concentration will be smaller. The effect of the annuals on CO_2 concentration is expected to be significant and is not expected to interact with the effect of the *Sedum*.

2. Materials and methods

2.1. Experimental design

A green roof experiment was established in fall 2013. The experimental plots are located on the roof of Beit Ha-Student at the University of Haifa, Israel (32°45N, 35°01E), which is a pre-existing terraced green roof on the North-facing slope of the Carmel mountain range, and on the Northeastern edge of the roof it merges with the natural mountainside. Elevation is 460 m a.s.l. (see Appendix A in Supplementary information for detailed plan).

The design is factorial with two factors fully crossed: *Sedum* (present or absent) and annuals (present or absent). It consists of 20 plots randomly assigned to five replicate plots of each of the four treatments: 'Control' (no plants), 'Annuals', 'Sedum' and 'Annuals + *Sedum*'. Size of each plot (Length × width × depth) was 100 × 100 × 18 cm. In all Annuals and Annuals + *Sedum* plots, we seeded a mix composed of equal numbers of seeds of 20 local annual species (Appendix B in Supplementary information), 1000 seeds per m^2. In all *Sedum* and Annuals + *Sedum* plots, we planted 36 *Sedum sediforme* shoots of similar size (10 cm long) per m^2.

2.2. CO_2 concentration measures

During four different days in February 2016, we measured CO_2 concentrations in the air directly above the plots (50 cm from the ground). We used a portable air quality meter Lutron AQ-9901SD, with a NDIR (Non-Dispersive Infra-Red) based sensor (Neethirajan et al., 2009). Each day, we simultaneously measured CO_2 concentration, temperature (dry and wet) and relative humidity above each plot. We started at 9:00 to 10:00 AM and measured plot after plot. We monitored each plot for four minutes measuring in three seconds intervals.

To avoid the effect of the different times of the day we randomly divided the plots to five time-groups (each consisted of all four treatment combinations) and performed the measures group after group. The order of the treatments inside the time-groups was random.

2.3. Net carbon assimilation

Net carbon assimilation was measured on mature leaves using 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. Measurements were performed consequently on the eight most common species (*Trifolium stellatum, Trifolium purpureum, Stipa capensis, Silene aegyptiaca, Chrysanthemum coronarium, Lagurus ovatus, Erodium malacoides, Sedum sediforme*) growing in 13 of the plots, on 7 February 2016 between 9:00 and 13:00. Temperature at 9:00 was 13.4 °C and the ambient photosynthetically active radiation (PAR) due to heavy clouds was ~150 $\mu mol\, m^{-2}\, s^{-1}$. Soil moisture was saturated with rain water falling shortly before measurements. Chamber conditions were adjusted to CO_2 level of 400 ppm and PAR of 1000 $\mu mol\, m^{-2}\, s^{-1}$. Data were logged as soon as the photosynthetic rate remained constant, typically within 2–3 min.

2.4. Species-specific area coverage

Relative cover percentage for each of the species and total annual cover percentage was calculated with CPCe software (Kohler and Gill, 2006) for all Annuals and Annuals + *Sedum* plots using photos that were taken three days after the net carbon assimilation measurements.

2.5. Estimating carbon assimilation at the plot level

For each plot, we determined the estimated net carbon assimilation by multiplying the mean net carbon assimilation of each species with its relative cover percentage in the plot.

2.6. Analysis

To examine differences in CO_2 concentrations, we used the means of the samples of each four-minute measure as our independent sample. To examine the effect of the annuals and the *Sedum* considering the different measuring days, we used a nested model (SPSS; Mixed Models, Linear) with measuring-days nested within treatment combinations. We used the **heat-load**, defined as the average of the dry and wet bulb temperatures, as a covariate.

To determine differences in net carbon assimilation between species we used one-way ANOVA followed by Tukey's post-hoc test (JMP software, Cary, NC, USA).

We used linear regression to test the connection between the calculated plot-scale estimated net carbon assimilation and total

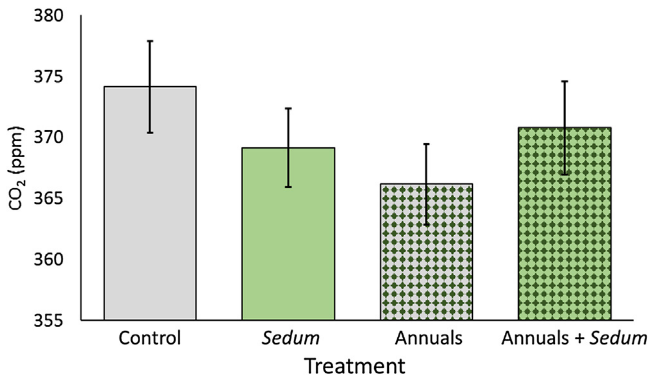

Fig. 1. CO_2 concentrations 50 cm above the ground (mean ± SE) in the different treatments: 'Control' (no plants), 'Annuals', '*Sedum*' and 'Annuals + *Sedum*'. Measures were taken in four different days during February 2016.

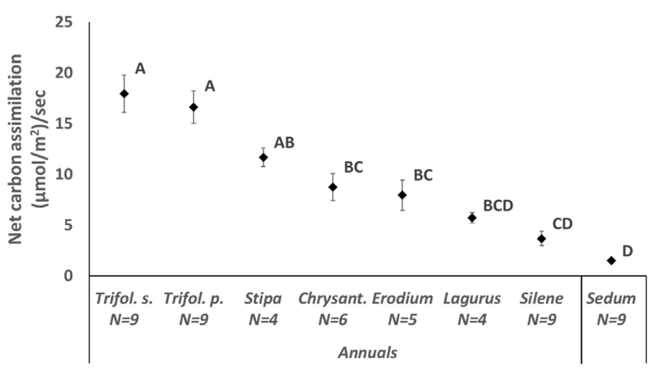

Fig. 2. CO_2 fixation rates (mean ±SE) of different plant species sampled in nine roof plots. ANOVA results: F = 7.40, $P < 0.001$. Means marked with the same capital letter are not significantly different (Tukey's post-hoc $P > 0.05$).

annual plant cover and CO_2 concentrations. We used CO_2 concentrations measures taken at the same dates with the photos we used to determine annual species cover.

3. Results

3.1. CO_2 concentrations

CO_2 concentrations were lower in Annuals than in the control plots that represented the ambient concentration in the surrounding area, and intermediate in *Sedum* and *Sedum* + Annuals plots (Fig. 1).

ANOVA results (see Appendix C in Supplementary information) showed significant effect of the annuals ($F_{1,62} = 4.25$, $P = 0.043$) but not of the *Sedum* ($F_{1,62} = 1.18$, $P = 0.281$) on CO_2 concentrations. The effect of the interaction between the annuals and the *Sedum* was significant ($F_{1,62} = 7.15$, $P = 0.010$).

3.2. Net carbon assimilation

We found significant differences between CO_2 fixation rates of different plant species. Of the eight most abundant species, the two *Trifolium* species showed the highest fixation rates, up to 5-fold the rate of the succulent *Sedum*, which showed the lowest fixation rate among the species (Fig. 2).

3.3. Correlating CO_2 concentrations with plants' relative cover and net carbon assimilation

We estimated the plot-scale net carbon assimilation by multiplying the mean net carbon assimilation of each species with its relative cover percentage in the plot. CO_2 concentrations were correlated with the plot-scale net carbon assimilation as well as with the total annual cover percentage (Fig. 3).

4. Discussion

The benefits of green roofs in decreasing ambient CO_2 concentrations in cities had not been quantitatively evaluated until now, but it is assumed to be more important as green roofs are getting more popular and are seen as a solution for reducing CO_2 concentrations (Li and Babcock, 2014). Planning green roofs for optimal carbon-fixation performances requires a measuring method that can relatively quantify CO_2 fixation rate in green roofs in relation to plant species composition. In this paper, we used a simple non-destructive method to examine carbon fixation in different green roof plots of different vegetation type and species composition. The method we examined here is direct ambient CO_2 concentration measurements *in situ* in a short time using a portable air-quality meter with a LDIR based sensor. The CO_2 concentration values (~375 ppm) were initially low at our study sites compared with typical roofs in the middle of crowded urban areas that are usually characterized by much higher CO_2 concentrations (>500 ppm) (Idso et al., 2002; Widory and Javoy 2003; Gratani and Varone 2005). This fact could have reduced the statistical power to finding significant effects. Another factor that could potentially increase the variability and prevent us from detecting treatment effects is the sensitivity of our method to atmospheric conditions. Due to the proximity (0.5–15 m between plots) CO_2 concentrations in the plots might be affected by wind velocity and direction. In addition, the plots we used (1 m^2) are small compared with actual green roof plots and therefore are expected to have much weaker effect. Nevertheless, we were able to show that the method can detect differences between annuals and *Sedum*-based plots. We showed that the CO_2 concentration results (Fig. 1.) are indeed correlated with the expected trends that we calculated using the species-specific relative cover percentage and leaf-scale gas-exchange measurements (Figs. 2, 3). Therefore, we assert that the method that we examined is reliable and can be an important tool for green-roofs planning.

The gas exchange measures found low carbon fixation rate of the *Sedum* relative to the annual species (Fig. 2), which agrees with our prediction based on the existing knowledge on photosynthesis in succulent plants (Borland et al., 2000). *Trifolium* species showed the highest fixation rates (Fig. 2), and if we consider also the potential leaf-cover percentage for individual it seems that *Trifolium* species are good candidates for green roofs when aiming for maximum carbon fixation.

As expected following the gas-exchange results, the two-way ANOVA found that the annuals reduced the ambient CO_2 concentration in the plots and the *Sedum* had no significant effect (Fig. 1). In addition, we found a significant interaction between the annuals and the *Sedum* effects; CO_2 levels were slightly lower In *Sedum* compared with control, and slightly higher in Annuals + *Sedum* than in Annuals plots (Fig. 1). This suggests that the presence of *Sedum* negatively affect the efficiency of CO_2 fixation by the annual plants.

Annuals in general and *Trifolium* species in particular are strong carbon fixers. Nevertheless, they finish their life cycle at the end of the rainy season; therefore, using them in green roofs is problematic for aesthetic reasons. *Sedum* stays alive above ground all year round without the need for watering and other maintenance,

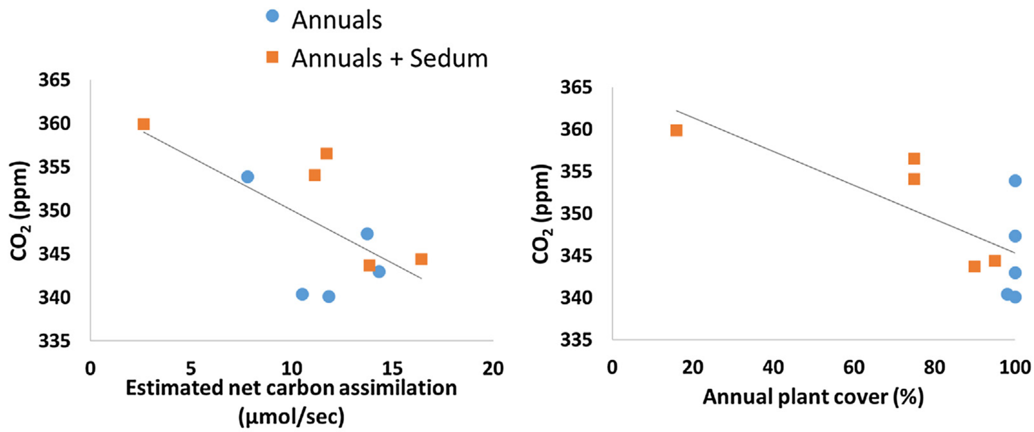

Fig. 3. Linear regression between CO_2 concentrations and: (A) calculated CO_2 assimilation rate (R^2 = 43.7%, P = 0.037); (B) annual plant cover (R^2 = 54.4%, P = 0.016), in 'Annuals' and 'Annuals + *Sedum*' treatment plots.

which makes it ideal for use on extensive green roofs for aesthetic and practical reasons (Oberndorfer et al., 2007). On the other hand, if considering carbon fixation, *Sedum* species are far from ideal. Our measures showed that in the winter season, the carbon fixation rate of the *Sedum* is very low, lower than any annual species. In addition, *Sedum* species were shown to change their photosynthetic metabolism 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). Therefore, we expect that the carbon fixation rate of *Sedum* will be even lower in the summer. In conclusion, we assert that when taking into account carbon fixation and benefits for decreasing the CO_2 concentration levels in the cities, using only *Sedum* is not beneficial. To insure a higher carbon fixation rate throughout the year, especially at day times when CO_2 levels are the highest, we need to integrate strong carbon fixers such as *Trifolium* species and other annual plants in *Sedum*-based green roofs. The annuals should be placed in separate plots to insure maximum cover, avoiding competition with the *Sedum*.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ufug.2017.03.003

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