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A Preliminary Study on Carbon Sequestration Potential of Different Green Roof Plants

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Abstract: *In this preliminary study, the carbon sequestration potential of five green roof plants, representative of three carbon fixation types, were tested. The influences of the ambient carbon dioxide concentration and the carbon changes in biomass were analyzed. Three common sedum plants, i.e., Sedum linearevariegatum, Sedum sarmentorsum bunge, and Sedum mexicanum were tested. The other plants we tested include one C_4 plant, Zoysia matrella, and one CAM (Crassulacean acid metabolism) plant, Sansevieria trifasciate. The results indicated differences in the CO_2 absorption trends of the three carbon-fixation type plants (C_3, C_4, and CAM) over the 24 hours of observation. The CAM plant had the longest carbon utilization period, implying better carbon sequestration potential in comparison with the others. The total carbon (TC) content of the above- and below-ground samples was analyzed in November 2013 and May 2014 to estimate the carbon sequestration potential. The aboveground samples contributed 55.0%–93.9% of the TC. The content of the Zoysia matrella system increased to 29.51 g TC/kg after six months, while that of the Sansevieria trifasciate system decreased to 37.73 g TC/kg. The Sedum mexicanum showed decreased TC contents in the above- and the belowground samples. The plant growth rate was not measured in this study. However, if the plant growth rate in the system is taken account of, the sedums and the Sansevieria trifasciate system could increase the carbon storage potential.*

Keywords: *Carbon sequestration, Green roofs, Carbon fixation, CO_2.*

1. INTRODUCTION

Green roofs can beautify the urban landscape and modify the developed urban hydrology, reduce the energy consumption of buildings, improve the air quality, and provide biological habitats [1-4]. Thus, green roofs have been used as a practical strategy for urban environmental management, climate change adaptation, and landscape reconstruction. In contrast with other strategies that need additional land space, green roofs utilize the unused tops of buildings and create a space to cultivate plants. The increase in the use of green roofs is a promising tendency [5-9]. In Taiwan, green roofs are used in integrated stormwater management in Taipei city, low-carbon city development in New Taipei city, the promotion of green buildings in Kaohsiung city, for sustainable campus establishment, as advocated in the Ministry of Education master plan, and in local and national low impact development.

Studies on the environmental benefits of green roofs have progressed gradually from focusing on the aesthetic aspects [7] to the energy saving effects [10]. After substantive research on energy saving and temperature adjustment, the focus shifted to the contribution of green roofs to urban stormwater management [7, 9, 11]. The contribution of green roofs to the management of the urban environment has been recognized, especially with regard to water runoff. Air quality has also come under discussion and research has indicated that green roofs could improve the quality of the urban air [12-14]. Air pollution is a significant problem in urban areas and is detrimental to human health [13, 15, 16]. Studies have been done on the use of urban trees to reduce air pollutants, especially particulate pollutants [17]. Hagler et al. (2012) [18] tested the isolation effects of street trees on air ultrafine particles and found that the trees were able to reduce up to 50% of ultrafine particles. Other than particulate pollutants, urban trees can also reduce gaseous pollutants, such as O_3, PM_{10}, NO_2, SO_2, and CO [15, 16, 19]. However, it should be noted that the absorption rate of gaseous air pollutants by plants changes seasonally. In addition, the absorption is affected by illuminance and temperature [20]. In addition to air quality improvement, the prospect of carbon storage and sequestration by the growing of plants has received much attention, as carbon offset by urban trees is an attractive prospect.

Zhao et al. (2010) [21] analyzed the carbon sequestration capacity of urban trees and found that they were able to offset 18.57% of the total carbon emitted by the industries in Hangzhou, China. Yang et al. (2005) [19] researched the carbon storage ability of urban trees in Beijing, China. Awal et al. (2010) [22] concluded that urban forests could be a greater sink for carbon in comparison with rural forests, because of the higher levels of CO_2 and the higher temperature in urban areas compared with rural areas.

Green roof is a soil-plant system in urban areas that could have ecological functions similar to those of urban trees. However, the difference is in the plant species used. Herbaceous plants, succulent plants, and shrubs are commonly used for extensive green roof vegetation, and not trees. Therefore, the capacity of green roofs to filter and intercept air pollutants and sequester carbon might not be on par with that of urban trees. However, several studies have proven that green roofs do contribute comparable environmental benefits. Yang et al. (2008) [13] used a dry deposition model to estimate the effects of green roofs on air pollutant reductions. The results indicated that 85 kg of air pollutants could be removed annually per hectare of green roof. Getter et al. (2009) [14] measured the carbon storage potential of 12 green roofs and concluded that the above- and below-ground systems could store an average of 375 g/m^2 of carbon. Li et al. (2010) [23] found that the respiration and photosynthesis of plants affected the ambient CO_2 concentration and that the CO_2 absorption rate of green roofs is higher than is the emission rate. Therefore, green roofs could contribute to reducing CO_2. As indicated in the review paper of Li et al. (2014) [24], green roofs could sequester carbon in the plants and the soils by photosynthesis and by reducing the ambient CO_2 concentrations. Whittinghill et al. (2014) [25] also quantified the carbon sequestration ability of green roofs. Moreover, the tests of Luo et al. (2015) [26] on sewage sludge as green roof substrates indicated significant carbon storage and sequestration capacities as compared to most other ecosystems.

Although the potential of green roofs to improve air quality and aid in carbon sequestration has been confirmed, the experimental data are still insufficient. Additionally, detail information on the effects of factors such as the plant canopy and the plant growth speed on the carbon sequestration rate is not available. Aspects such as different climatic conditions and different plants and substrates would also affect the potential for carbon storage and sequestration. Moreover, the intensive management of urban forests or green roofs could result in carbon emissions larger than the amount of carbon sequestrated. Careful consideration should therefore be given to this aspect [27]. Other factors, such as the elevation of a cultivation plot above sea level and the sampling depth could serve as explanatory variables for carbon sequestration in soils [28]. Carbon offset is an important concern in climate change mitigation; however, in urban areas it is more difficult to find enough space to plant trees for carbon offset. Therefore, green roofs, which do not need additional land, could help to sequester ambient CO_2 as an alternative carbon offset measure, contributing significantly to low carbon city development. In the study on the carbon sequestration potential, the likely influence of carbon fixation on the results has to be considered. Therefore, in the attempt to understand their carbon sequestration potential, five green roof plants, representing three carbon transformation types (C_3, C_4, and CAM [Crassulacean acid metabolism]), were assessed in this study. The purpose of one experiment was to measure the ambient CO_2 concentration over 24 hours, while the other experiment measured the carbon content in the above- and the belowground biomass. The focus of this study was on the change in carbon content and, therefore, other air pollutants were not assessed.

2. MATERIALS AND METHOD

2.1. Plant Species

As different plant species have different pollution reduction capacities, the plant species chosen for green roofs is an important aspect in the endeavor to improve the quality of the environment [9, 29, 30]. Forbs and grasses, for example, show different water retention abilities [29], while sedums and herbaceous perennials present different effects on the reduction of nitrate in water [31]. As this study is aimed at understanding the carbon sequestration potential of green roofs, the ability of plants to use carbon could influence the results. Consequently, various carbon-fixation plant species among the local green roof plants used in Taiwan were selected. The study focuses on extensive green roofs, thus sedums, herbs, and shrubs were considered.

There are three carbon fixation pathways in plants, i.e., C_3, C_4, and CAM, of which the most common is the C_3 pathway. Some plants use the C_4 and the CAM pathways to utilize CO_2 more efficiently in arid environments. The particulars of the C_3, C_4, and CAM pathways are not described further in this manuscript. Some C_4 and CAM plants that tolerate drought and need less exposure to direct sunlight are used as green roof plants. However, sedums (C_3 type) are the most commonly used plants for extensive green roofs. We chose three sedums, *Sedum linearevariegatum*, *Sedum sarmentorsum bunge*, and *Sedum mexicanum*, for our tests. The other plants we chose were the *Zoysia matrella,* a C_4 type, and, as a CAM plant, the *Sansevieria trifasciate*, a succulent with larger leaves than the sedums. All three of these carbon-fixation type plants are used for green roofs in Taiwan, but their appearance differs completely. Table 1 presents a summary of the tested plant species.

Table1. *Summary of the tested plant species in this study.*

Carbon fixation pathway	Name	Family	Appearance
C_3	*Sedum sarmentorsum bunge*	Crassulaceae	Succulent herbaceous
C_3	*Sedum linearevariegatum*	Crassulaceae	Succulent herbaceous
C_3	*Sedum mexicanum*	Crassulaceae	Succulent herbaceous
C_4	*Zoysia matrella*	Gramineae	Grass
CAM	*Sansevieria trifasciate*	Agavaceae	Succulent

2.2. Ambient CO_2 Concentration Measurement

The CO_2 concentration monitoring experiment was modified by Li et al. (2010) [23]. The plants were placed in a closed transparent box to ensure that they would still be exposed to sunlight. The CO_2 concentration meter was placed inside the box and the CO_2 concentration was recorded once every hour for a period of 24 hours to monitor the daytime and nighttime difference. Every plant was tested three times during the 24-hour monitoring period. A photograph of the experiment is presented as Fig. 1. All the plants were bought from the local market and all were mature. Before the experiment commenced, the plants were placed outside to grow naturally, with little irrigation and no additional fertilizer.

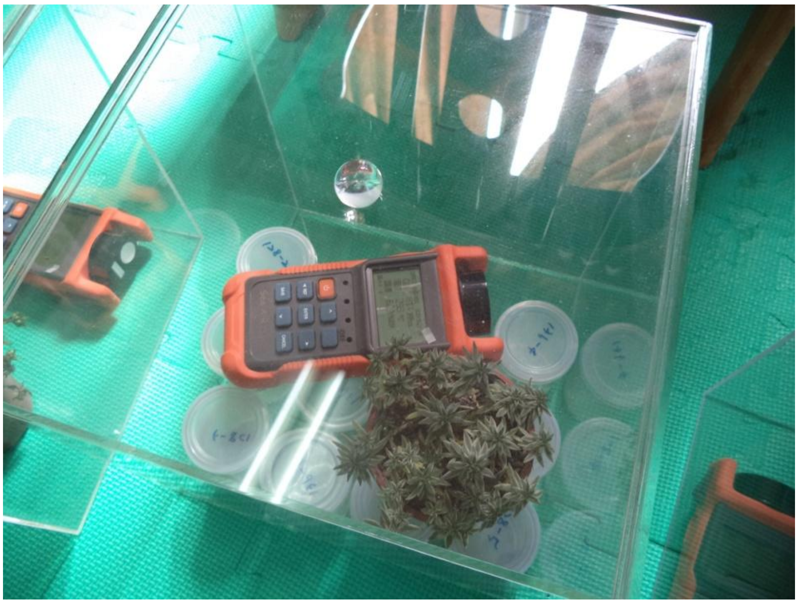

Fig1. *Photograph of the CO_2 measurement experiment.*

2.3. Carbon Sequestration Potential Measurement

The measurement of the carbon sequestration potential includes both the plants (above the ground) and the substrates (below the ground). Getter et al. (2009) [14] collected data for their experiments on green roofs on the aboveground biomass, root biomass, and the substrate carbon. Although plants and soils are able to absorb and store carbon, the use of soil high in organic carbon as substrate for plant growth and additional fertilization could be viewed as contributing to carbon emissions [32]. Conversely, the energy saving contribution of the green roofs could also be a contribution to the carbon sink. In this study, we did not consider other carbon emissions or absorption pathways, but concentrated on plants and soils.

At the start of the experiment (November 2013), the plant leaves and stems, and the substrates were collected. The samples were dried in an oven at 105 °C and were subsequently pulverized. The carbon content of the powdery samples was then analyzed. The element analyzer used is the elemental vario EL cube (Germany). After six months (May 2014), the above- and the belowground biomass were resampled and reanalyzed.

3. Results and Discussion

3.1. CO_2 Concentration Changes

While testing the ambient CO_2 concentration effects, the selected plants were placed individually in a closed box and monitored continually for 24 hours. Every plant was tested three times to obtain reduplications. The experiment was done on a sunny day and the testing dates were in February, June, and July 2013, to allow for seasonal variability. In addition, the ambient temperature and the humidity were recorded. Because the background CO_2 concentrations differed, all the CO_2 concentrations were standardized. The trend for the 24 hours is presented in Fig. 2.

The C_3 plants, *Sedum linearevariegatum, Sedum sarmentorsum bunge,* and *Sedum mexicanum*, were only tested twice because of an equipment error. However, the six reduplications (the three C_3 plants and the two reduplications of each plant) indicated a similar trend. The CO_2 concentration started to decrease at 8 am, implying that photosynthesis was active. The photosynthesis stopped at 3 pm and the CO_2 concentration started to increase. It appears that the tested C_3 plants absorbed CO_2 from 8 am to 3 pm, i.e., for only seven hours, and released CO_2 for another 17 hours. However, the rate of the CO_2 decrease was larger than the rate of increase. Consequently, from the preliminary study, it is unclear whether C_3 plants should be considered as a carbon sink or a carbon source. The monitoring periods of the *Zoysia matrella*, the C_4 plant tested, indicated that the CO_2 concentration started to decrease at 6 pm and this trend continued until 8 am. The CO_2 started to increase between 8 am and 6 pm, a trend that is quite different from that of the C_3 plants. The CO_2 concentration decreased from 6 pm to 8 am, i.e. for 14 hours, and there was no discernible difference between the rate of decrease and the rate of increase. The longer absorption time implies that the C_4 plant, *Zoysia matrella*, could contribute to sequestering carbon. In addition, the CO_2 concentration of this plant showed more dramatic changes compared with those of the tested sedums. The experiment on the CAM plant (*Sansevieria trifasciate)* showed that the CO_2 concentration only increased from 6 pm to 10 pm and decreased for the rest of the time. This decreased level was maintained for almost 20 hours, implying a long CO_2 absorption period. In comparison with the other tested plants, the difference between the highest and the lowest levels of CO_2 concentration was most noticeable for this plant.

The three measurements were taken in different months and the effects of the ambient temperature and the humidity on the CO_2 concentration were assessed. Correlation analysis was performed for the hourly CO_2 measurements and the temperature, as well as the humidity. The results of the correlation coefficients are summarized in Table 2, which indicate no significant relations between the temperature and the humidity, and the CO_2 concentrations. There was low correlation coefficient and the associations were not consistently positive or negative. It seems that higher humidity induced lower levels of CO_2 (opposite effects), but this correlation is not obvious. Only two pairs presented a larger correlation coefficient (>0.5), which are the positive relations of temperature and CO_2 in the *Sedum sarmentorsum bunge*, and the negative relations of humidity and CO_2 in *Zoysia matrella*. Therefore, the effects of the ambient temperature and humidity on the CO_2 concentration are considered insignificant and can be disregarded.

Table2. *Correlation coefficient of hourly CO_2 concentration and temperature, and humidity.*

Plant species (carbon fixation) Environmental factors	*Sedum linearevariegatum* (C_3)	*Sedum sarmentorsum bunge* (C_3)	*Sedum mexicanum* (C_3)	*Zoysia matrella* (C_4)	*Sansevieria trifasciate* (CAM)
Temperature	0.06	0.54	0.15	-0.20	-0.03
Humidity	-0.15	-0.10	0.10	-0.65	-0.26

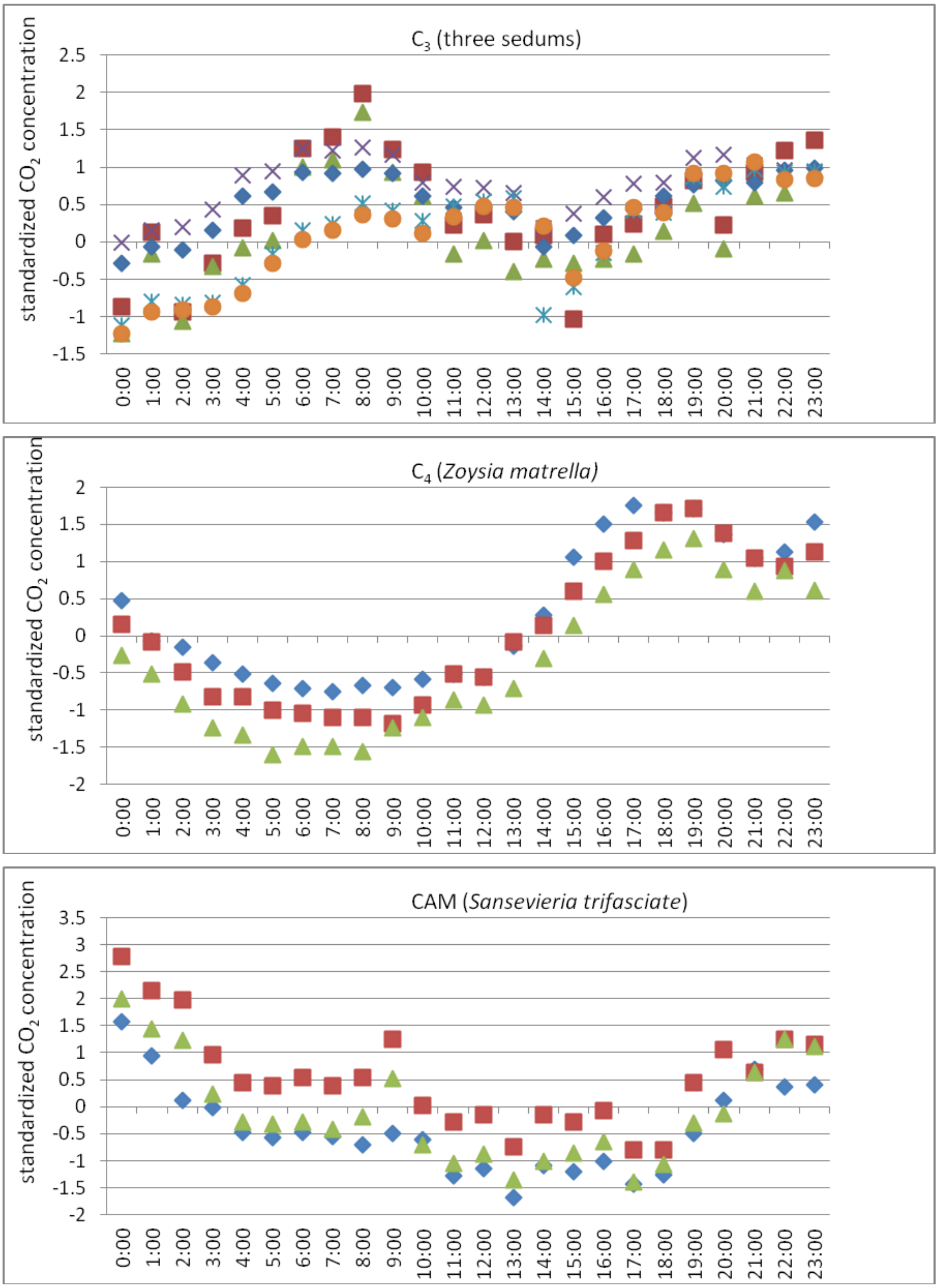

Fig2. *Ambient CO_2 concentration trends over 24 hours of different carbon fixation plants (C_3: Sedum linearevariegatum, Sedum sarmentorsum bunge, and Sedum mexicanum, C_4: Zoysia matrella, CAM: Sansevieria trifasciate).*

3.2. Carbon Sequestration Analysis

The carbon contents in the above- and belowground biomass were sampled and analyzed in November 2013 and May 2014 to assess the carbon sequestration potential of the green roof plants. The results of the carbon contents of the different plants are summarized in Table 3. The aboveground carbon contents indicated more than 300 g carbon per kilogram in the dry samples, except for the *Zoysia matrella* plants that contained only 229 g C/ kg. However, after six months, the carbon content in the leaves and stems was reduced, except for the *Zoysia matrella* plants. The aboveground carbon contents of this plant had increased by 11%. The *Sansevieria trifasciate* had the most carbon content (414 g C/kg) in the leaves and stems; however, this content decreased to 367 g C/kg, which is the largest decrease. The three sedum plants had similar carbon contents and the decrease was less than 5% after six months.

At the start of the experiment, the substrates were different to accommodate the various needs of the different plants. The substrates had been bought along with the plants and the carbon contents below the ground differed significantly. The carbon in the *Zoysia matrella* substrate was only 14 g C/kg, but, in the *Sansevieria trifasciate* substrate, it was as high as 314 g C/kg. It was assumed that the carbon in the substrates would be used for plant growth and would therefore be reduced after six months. Surprisingly, it was found that the carbon contents of all the substrates had increased, except for the substrate of the *Sedum mexicanum*. This means that the substrates could be carbon sinks, comparable with the plants. The *Zoysia matrella* substrate showed the highest rate of increase, and the *Sansevieria trifasciate* contributed the largest sequestered amount of carbon, namely 10 g C/kg. This finding confirmed that with time it was possible to store carbon in the substrates. Deeper levels of the same substrate, i.e., greater volumes of the substance, could be expected to sequestrate more carbons than could shallower levels, i.e., smaller volumes of the substance.

In total, the *Zoysia matrella* system showed an increase of carbon in both the above- and the belowground samples, indicating that this system could have the highest potential to sequester carbon. Although the carbon contents in the leaves and stems and the substrates of the *Zoysia matrella* system were lower than they were for the other four plants, the total carbon increment was 30 g C/kg, which is larger than is the increment for the other systems. Conversely, the *Sansevieria trifasciate* and *Sedum mexicanum* systems contained the largest amounts of carbon, but, after six months, these amounts had decreased to 38 g C/kg and 35 g C/kg, respectively. It should be noted that the carbon difference is presented as a mass unit, and not as a surface area unit. If the plant growth rate were taken into account, the evaluation of the aboveground carbon sequestration could show a different result. As plants grow, the size and number of leaves and stems increase and the carbon is absorbed. However, in this study, the plant growth was not measured and the carbon sequestration potential was expressed as a mass unit. The aboveground carbon contributes more than half of the total carbon (Table 4). Therefore, if the area unit were used, there could be more change in the aboveground carbon and the entire system could show positive carbon sequestration results. For example, the aboveground carbon content amounted to more than 60% of the carbon in the entire system.

Table3. *Carbon contents of different green roof plants.*

TC (g/kg-dry weight)	11/1/13	5/1/14	Difference
Aboveground			
Sedum linearevariegatum (C_3)	339.43	333.90	-5.53 (-1.6%)
Sedum sarmentorsum bunge (C_3)	369.70	352.80	-16.90 (-4.6%)
Sedum mexicanum (C_3)	377.43	368.00	-9.43 (-2.5%)
Zoysia matrella (C_4)	229.02	254.60	25.58 (11.2%)
Sansevieria trifasciate (CAM)	414.42	366.79	-47.63 (-11.5%)
Belowground			
Sedum linearevariegatum (C_3)	178.60	184.49	5.90 (3.3%)
Sedum sarmentorsum bunge (C_3)	174.09	177.40	3.31 (1.9%)
Sedum mexicanum (C_3)	247.10	222.00	-25.10 (-10.2%)
Zoysia matrella (C_4)	13.92	17.84	3.93 (28.2%)
Sansevieria trifasciate (CAM)	314.34	324.24	9.90 (3.1%)
Entire system			
Sedum linearevariegatum (C_3)	518.03	518.39	0.36 (0.1%)
Sedum sarmentorsum bunge (C_3)	543.79	530.20	-13.58 (-2.5%)
Sedum mexicanum (C_3)	624.53	590.00	-34.53 (-5.5%)
Zoysia matrella (C_4)	242.94	272.44	29.51 (12.1%)
Sansevieria trifasciate (CAM)	728.76	691.03	-37.73 (-5.2%)

Table 4. *Distribution of carbon content of the entire green roof system.*

Plant species	Aboveground	Belowground
Sedum linearevariegatum (C_3)	65.0%	35.0%
Sedum sarmentorsum bunge (C_3)	67.3%	32.7%
Sedum mexicanum (C_3)	61.4%	38.6%
Zoysia matrella (C_4)	93.9%	6.1%
Sansevieria trifasciate (CAM)	55.0%	45.0%

4. CONCLUSION

This study measured the effects of different green roof plants on CO_2 concentration and carbon sequestration to assess whether green roofs could serve as an alternative carbon offset method. The preliminary experiments were limited to the carbon changes of the above- and belowground samples, expressed in carbon mass per sample mass. The growth aspects of the plants, such as the cover expansion rate and the biomass growth rate, were not recorded. Therefore, an important factor in carbon sequestration was excluded, i.e., the biomass growth per green roof area. In the CO_2 concentration experiment, the sunlight illumination could influence the plants utilizing CO_2; however, as this study used natural sunlight, the intensity of light could not be controlled. The limitations in the experiments mean that the results of this study are based on incomplete information; therefore, further confirmation of all the inferences is needed. When drawing the conclusions for this study, the associated hypotheses should be mentioned with the data.

The plants considered for green roofs should preferably be drought-resistant species. Some of these plants have a special carbon fixation process to allow them to utilize carbon and water more efficiently. The results of the study show that plants with different carbon fixation processes do influence the absorption and emission of CO_2. The C_4 and CAM plants, especially the CAM plant, *Sansevieria trifasciate*, had longer CO_2 absorption periods than did the C_3 plants. The carbon content analysis indicated that the C_4 plant, *Zoysia matrella*, had increased carbon in both the above- and the belowground samples, implying a good potential for carbon sequestration. Although there was no quantification data of the plant growth rate, the high growth rate of the three C_3 plants was observed, meaning that the biomass per area increased, which could contribute to carbon sequestration.

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