

# Diurnal greenhouse gas emissions and substrate temperatures from blue-green roofs in north-eastern Italy during a dry-hot summer season

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## ABSTRACT

Covering building rooftops with vegetation [Green roofs (GRs)] holds promise for lowering building temperatures, reducing stormwater runoff, and providing other ecosystem services, but it is unclear how this will impact greenhouse gas (GHG) emissions. The latter may also be influenced by vegetation type, substrate depth, and irrigation regime and we sought to test this by comparing daytime GHG emissions (i.e., CH<sub>4</sub>, CO<sub>2</sub>, and N<sub>2</sub>O) and daily substrate temperatures in 48 GR microcosms in North-eastern Italy during a dry-hot summer season (June to September). Four vegetation types (*Sedum* mixture, cold season grasses, warm season grasses, or wildflowers), two substrate depths (8 cm or 14 cm), and two irrigation levels (1 or 2 mm d<sup>-1</sup>) were evaluated, for a total of 16 treatments with 3 replicates. We found that vegetation type had a significant effect on temperature [average temp. of 24.8 °C (*Sedum*) vs 25.5 °C (warm season grasses)] and CH<sub>4</sub>, CO<sub>2</sub>, and N<sub>2</sub>O emissions. While all vegetation types had net CO<sub>2</sub> emissions (median values from 147 to 671 mg m<sup>-2</sup> h<sup>-1</sup>) and net N<sub>2</sub>O uptake (median values from -0.06 to -0.28 mg m<sup>-2</sup> h<sup>-1</sup>), CH<sub>4</sub> flux had net negative values (capture) only in microcosms with wildflowers (-0.07 mg m<sup>-2</sup> h<sup>-1</sup>), whereas other treatments had a median CH<sub>4</sub> emissions of 0.09 mg m<sup>-2</sup> h<sup>-1</sup>. Substrate depth significantly affected CO<sub>2</sub> and N<sub>2</sub>O fluxes with deeper substrate leading to higher CO<sub>2</sub> emission (+ 60.7%) and greater N<sub>2</sub>O uptake (+ 30.8%). Irrigation level only significantly influenced N<sub>2</sub>O fluxes with 2 mm irrigation resulting in higher fluxes (-0.20 mg m<sup>-2</sup> h<sup>-1</sup>) than 1 mm irrigation (-0.09 mg m<sup>-2</sup> h<sup>-1</sup>). Our study suggests that under heat induced plant-stress conditions, GRs can improve N<sub>2</sub>O and CH<sub>4</sub> capture but might increase the emissions of CO<sub>2</sub> fixed by plants in the previous years in the substrate and that vegetation type and substrate depth can significantly alter emissions and are thus important design parameters.

## 1. Introduction

The effects of the ongoing climate change are becoming increasingly visible, with phenomena like land change and urbanization exacerbating challenges such as greenhouse gas (GHG) emissions (carbon dioxide, CO<sub>2</sub>; methane, CH<sub>4</sub>; nitrous oxide, N<sub>2</sub>O), habitat fragmentation, and water scarcity (Van Mechelen et al., 2015; Teemusk et al., 2019; Han and Zhu, 2020). Projections estimate that by 2030 the urban population may rise 60% overall and, in developed countries, reach up to 87%, which will further intensify these negative effects (Shafique et al., 2018; Manso et al., 2021). However, there is an opportunity to link sustainable urban development with climate change adaptation (Manso et al., 2021). Studies have signaled green roofs (GRs)—defined as roofs

with substrate and a vegetated surface—as a possible climate change adaptation strategy in cities, highlighting their environmental benefits—or ecosystem services—such as a reduction in GHG emissions, carbon sequestration, thermal regulation, and reduction of Urban Heat Island (UHI) effect, stormwater management, and increased biodiversity (Oberndorfer et al., 2007; Shafique et al., 2018; Manso et al., 2021; Halim et al., 2022). Blue-green roofs are GRs that enhance the stormwater management capacity, although they are often used interchangeably (Andanæs et al., 2018). The main difference is that blue-green roofs have an additional storage layer that can temporarily store drained water, while conventional GRs depend solely on the existing retention capacity of the substrate and canopy of the vegetation used (Andanæs et al., 2021). The GRs used in this study are blue-green

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roofs, but they will be referred throughout as GRs for brevity.

Given that roof tops comprise approximately 25% of overall urban surfaces areas, GRs represent a significant opportunity to mitigate climate change in cities without building extensive infrastructure (Le Trung et al., 2018). In other words, they represent an opportunity to both *implement* climate change mitigation as green infrastructures in new buildings and to *integrate* climate change mitigation through the retrofitting of existing buildings. However, there is a need to quantify this ecosystem service and assess how it is affected by the choice of design, components, and management. Important design elements are substrate depth, vegetation type and irrigation practices, which are inter-related (Li and Yeung, 2014; Van Mechelen et al., 2015; Dusza et al., 2017; Teemusk et al., 2019; Halim et al., 2022).

It is important to note that GRs can serve as either a source or sink of GHGs, depending primarily on the accumulation and decomposition of organic matter in the system, substrate depth, irrigation, and vegetation characteristics (Halim et al., 2022). GRs have been hypothesized to counterbalance CO<sub>2</sub> emissions by acting as potential sink through plant photosynthesis (Mitchell et al., 2018; Teemusk et al., 2019). They may also act as a potential source for CH<sub>4</sub>, particularly in extensive systems populated with plant species characterized by low evapotranspiration rate, such as *Sedum* spp., due to increased moisture conditions and, consequently, anoxic conditions (Halim et al., 2022). Conversely, they have been found to act as sink for CH<sub>4</sub> under strongly oxic conditions in very well drained substrates of both shallow and deep depth (Halim et al., 2022). These highly drained GRs are also conducive towards leaching dissolved organic carbon (Dusza et al., 2017). Moreover, fertilization and management of urban green areas can be sources of N<sub>2</sub>O and CO<sub>2</sub> (Teemusk et al., 2019). Nitrogen losses from these systems may be primarily through conversion of readily retained NH<sub>4</sub><sup>+</sup> to readily leached NO<sub>3</sub><sup>-</sup>, which might be prevalent in readily drained systems, such as GRs (Dusza et al., 2017; Mitchell et al., 2018). Losses of N<sub>2</sub>O may also occur from denitrification, an anoxic process that is favored under the same high moisture conditions as CH<sub>4</sub> production detailed previously (Mitchell et al., 2018). Given that GRs are typically fast draining with shallow substrates, losses of GHGs from anaerobic pathways are expected to be minor (Mitchell et al., 2018). The linkage between abiotic and biotic factors in the design and management of GRs (e.g., substrate depth, moisture conditions, and vegetation type) and GHG fluxes highlights the need to close the carbon and nitrogen cycle in GRs to maximize their ecosystem services and to maintain their long-term fertility (Mitchell et al., 2018).

As already stated, substrate depth, vegetation and irrigation are key elements in affecting the GHGs cycle of GRs. Substrate depth influences water retention which, in turn, affects GHG emissions, stormwater retention and runoff, and temperature by controlling evapotranspiration (Li and Yeung, 2014; Mitchell et al., 2018; Halim et al., 2022). Although extensive GRs are designed to function under minimal management and to be mainly dependent on rainfall, irrigation may be necessary during the hot summer months or in periods of drought (Van Mechelen et al., 2015). Irrigation can affect substrate water retention, as moist substrates retain less water during rain events, decreasing stormwater management, and affecting the remaining ecosystem services by controlling moisture (Van Mechelen et al., 2015). Moreover, irrigation is considered unsustainable in regions with water scarcity and when the water used is potable or saline (Van Mechelen et al., 2015).

The main objective of this study is to evaluate the effect of GR's substrate depth, vegetation type, and irrigation level applied on GHG emissions and substrate temperatures. For this, we evaluated 48 microcosms of an extensive GR during a dry summer season—specifically, the months of June to September—in Northeast Italy.

## 2. Materials and methods

### 2.1. Experimental design

The study site is located at the University of Padova Experimental Farm “L. Toniolo” located in Legnaro, Padova, Italy (45° 21' 5.82" N, 11° 57' 2.44" E). Forty-eight microcosms were studied in a split plot experiment, with irrigation in the whole plot and the vegetation type and substrate treatments used as subplots arranged in a completely randomized 4 × 2 × 2 factorial design and three replicates. The experimental variables are: 4 types of vegetation (*Sedum* mixture (Se), cold season grasses (CG), warm season grasses (WG), or wildflowers (WF)), 2 substrate depths (8 cm or 14 cm), and irrigation regime (1 L m<sup>-2</sup> day<sup>-1</sup> or 2 L m<sup>-2</sup> day<sup>-1</sup>). *Sedum* treatment was a mix of 9 species/varieties among which the most represented, during the experiment, were *S. album*, *S. kamtschaticum* and *S. reflexum*; CG was 10% *Poa pratensis* ‘Nubblue Plus’ and 90% *Festuca arundinacea* ‘Rambler’ by weight and WG was *Cynodon dactylon* ‘Paul 1’; Wildflower treatment was a mix grass and forb species. The year of establishment, four grass species (*Lolium perenne*, *Poa pratensis*, *Festuca rubra* subsp. *rubra* and *Festuca ovina*) and 36 forb species were identified. However, at the time of the experiment, the grasses were the most represented while forbs were strongly reduced (species number reduced to about 12, with *Calendula officinalis*, *Coreopsis grandiflora*, *Coreopsis tinctoria*, *Cota tinctoria*, *Erysimum* sp. and *Leucanthemum vulgare* being the most represented). The microcosms were established in June 2020 and the monitored period ranged between June and September 2022. Irrigation was manually applied using calibrated watering cans, with of one - two times per week depending on rain events (Table 1).

### 2.2. Greenhouse gas (GHG) fluxes and temperature measurements

The GHG (CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O) fluxes for each microcosm were measured using a portable Fourier Transform Infrared Spectroscopy (FTIR) analyzer by Gaset Technologies (The Gaset™ DX4040) using a static non-stationary chamber technique once a week. A PVC collar (200 mm in diameter) was fitted into the center of each microcosm one month before monitoring was initiated. A custom-made cylindrical flux chamber was used to measure the GHG fluxes. It was designed with a lining of wind machines on the inside of the cylinder (which served to homogenize the air) and contained a rubber sheathed aperture on towards the middle where the portable FTIR analyzer sensor probe was introduced.

The cylindrical flux chamber was fitted over the PVC collar in each sampling area. The GHG concentration within the chamber was monitored for 5 min per unit after GHG values stabilization, yielding an average of 10–15 measurements per microcosm. The portable FTIR analyzer was calibrated before and purged after each use with N<sub>2</sub> according to the manufacturer's manual.

The data collected was then used to calculate the fluxes, according to the following formula given by Maucieri et al. (2016), where *V* is the volume and *A* is the area of the flux chamber, *c* is the concentration measured, and *t* is the time step.

$$\text{GHGs (mg m}^{-2} \text{ h}^{-1}) = \frac{V}{A} \times \frac{dc}{dt} \quad (1)$$

**Table 1**

Distribution of water inputs (irrigation and rainfall) received per green roof microcosm and cumulative rainfall for the sampling season (June to September 2022).

Irrigation level (L m <sup>-2</sup> day <sup>-1</sup> )	Total irrigation applied (L m <sup>-2</sup> )	Cumulative rainfall (L m <sup>-2</sup> )	Total water input (L m <sup>-2</sup> )
1	72	250.6	322.6
2	144		394.6

The global warming potential (GWP) of each treatment was calculated with the following formula, using the coefficients established in IPCC report (2013):

$$GWP(\text{CO}_2\text{eq. mg m}^{-2} \text{ h}^{-1}) = \text{CO}_2 + (\text{CH}_4 \times 34) + (\text{N}_2\text{O} \times 298) \quad (2)$$

Temperature measurements were taken using a handheld soil thermometer at a depth of approximately 3 cm from the bottom of the substrate. Measurements were taken and recorded at a frequency of 3 times per day once a week. The measurements were made in the morning (8:00–9:00), at midday (12:00–13:00) and in the evening (17:00–18:00).

### 2.3. Statistical analysis

All statistical analysis was conducted in R 4.2.2 software.

Greenhouse gas data were not normally distributed; therefore, the Kruskal-Wallis test was used to evaluate the median responses of the effect of vegetation species on each GHG flux and GWP and the Mann-Whitney test was used to evaluate the effect of substrate depth and irrigation on GHG fluxes and GWP. Given significance, Dunn’s test with Bonferroni adjustment post-hoc comparisons were done. All data were visualized with boxplots. The temperature data were normally distributed, and they were analyzed by conducting 3-way ANOVA in each month. Correlations between emissions and GWP with temperatures were assessed using Spearman’s Correlation test.

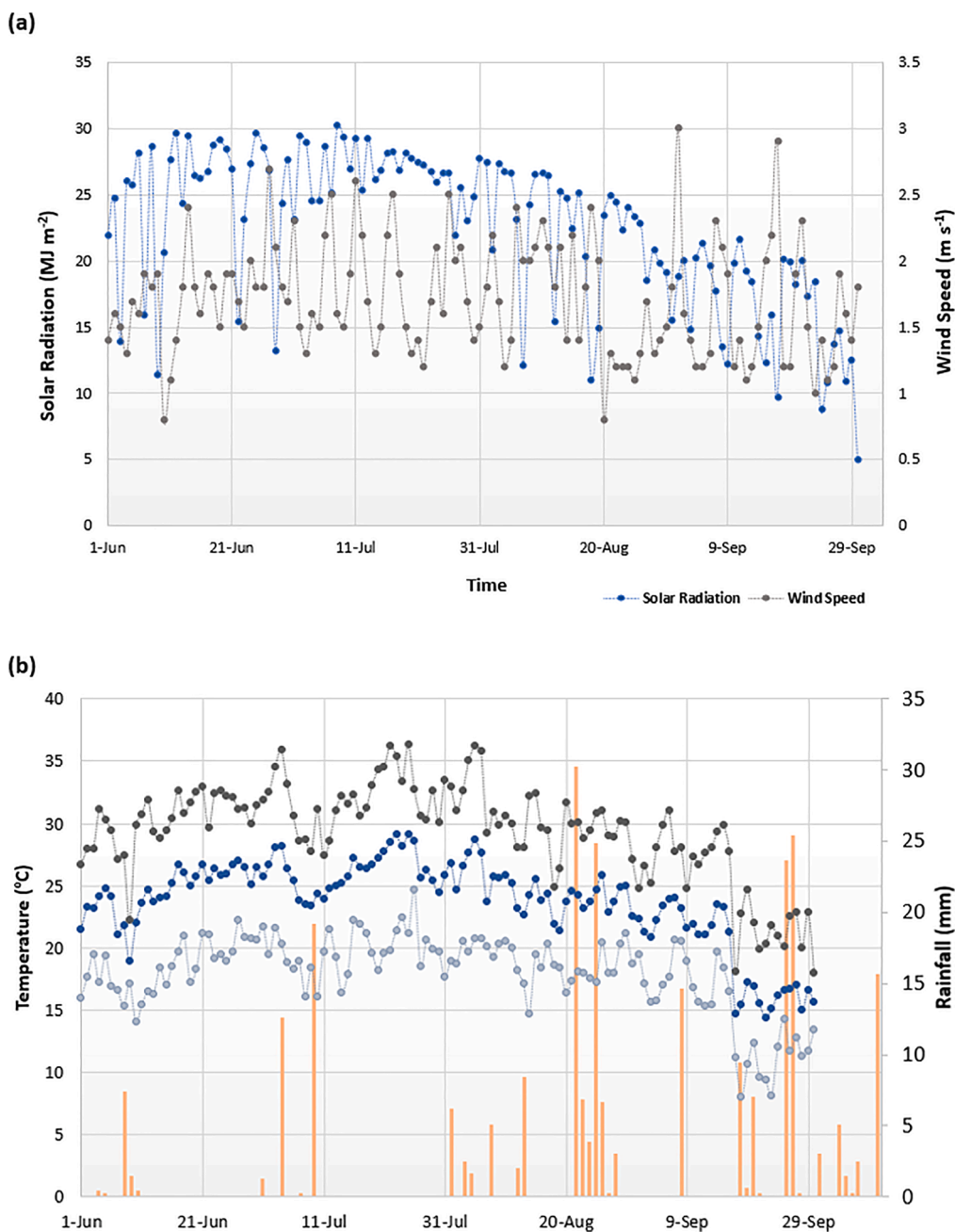


Fig. 1. (a) Daily average solar radiation ( $\text{MJ m}^{-2}$ ) and wind speed ( $\text{m s}^{-1}$ ) and (b) daily minimum, average, and maximum temperatures ( $^{\circ}\text{C}$ ) and daily rainfall (mm) for the summer season (June to September 2022).

### 3. Results

#### 3.1. Meteorological data

The meteorological data from June to September 2022 (Fig. 1A and B) were obtained from a weather station managed by the Regional Agency for the Prevention and Environmental Protection of Veneto (ARPA Veneto, by its Italian acronym) (<https://www.wold.arpa.veneto.it/>) and located at a distance of 500 m from the experimental site. The average solar radiation for the season was  $22.4 \text{ MJ m}^{-2}$  and the average wind speed was  $1.7 \text{ m s}^{-1}$ . The temperature during the season steadily increased, reaching its peak in July, and then started decreasing in September. The minimum average temperatures were  $18.4 \text{ }^\circ\text{C}$  in June,  $19.8 \text{ }^\circ\text{C}$  in July,  $18.9 \text{ }^\circ\text{C}$  in August, and  $14.6 \text{ }^\circ\text{C}$  in September. The maximum average temperatures were  $30.1 \text{ }^\circ\text{C}$  in June,  $32.0 \text{ }^\circ\text{C}$  in July,  $30.4 \text{ }^\circ\text{C}$  in August, and  $24.6 \text{ }^\circ\text{C}$  in September. The temperatures overall averaged  $24.5 \text{ }^\circ\text{C}$  in June,  $26.2 \text{ }^\circ\text{C}$  in July,  $24.6 \text{ }^\circ\text{C}$  in August, and  $19.3 \text{ }^\circ\text{C}$  in September.

Precipitation was afflicted by unusually dry weather. The cumulative rainfall during the sampling season was  $250.6 \text{ L m}^{-2}$  (Table 1), very close to the long-term value  $263 \text{ L m}^{-2}$  (1994–2022). Although the cumulative rainfall averages are similar, the monitoring season was characterized by intensive dryness occurred in June and July (Fig. 2).

#### 3.2. Greenhouse gas (GHG) fluxes and global warming potential (GWP)

The Kruskal-Wallis test for the effect of vegetation types on GHG fluxes and GWP was significant for all gasses—namely  $\text{CO}_2$  ( $p < 0.001$ ),  $\text{CH}_4$  ( $p < 0.01$ ), and  $\text{N}_2\text{O}$  ( $p < 0.05$ ) as well as the GWP ( $p < 0.001$ ) (Fig. 3). All vegetation treatments were net emitters of  $\text{CO}_2$ , with median values of  $147 \text{ mg m}^{-2} \text{ h}^{-1}$  (WG),  $268 \text{ mg m}^{-2} \text{ h}^{-1}$  (Se),  $384 \text{ mg m}^{-2} \text{ h}^{-1}$  (CG) and  $671 \text{ mg m}^{-2} \text{ h}^{-1}$  (WF). Fluxes of  $\text{CH}_4$  were low and close to 0, with a positive median value with WG ( $0.068 \text{ mg m}^{-2} \text{ h}^{-1}$ ), Se ( $0.097 \text{ mg m}^{-2} \text{ h}^{-1}$ ), and CG ( $0.11 \text{ mg m}^{-2} \text{ h}^{-1}$ ); and a negative median value (net sink) with WF ( $-0.66 \text{ mg m}^{-2} \text{ h}^{-1}$ ). Only WF differed significantly from Se and CG with no other significant differences between treatment means. All treatments were net sinks of  $\text{N}_2\text{O}$ , with median values of  $-0.15 \text{ mg m}^{-2} \text{ h}^{-1}$  (WG),  $-0.16 \text{ mg m}^{-2} \text{ h}^{-1}$  (CG),  $-0.28 \text{ mg m}^{-2} \text{ h}^{-1}$  (WF), and  $-6.34 \times 10^{-2} \text{ mg m}^{-2} \text{ h}^{-1}$  (Se). The only significant difference between treatments was between Se and WF, with no other pairwise comparisons differing significantly. All treatments had a positive GWP,

with median values of  $102 \text{ CO}_2\text{eq. mg m}^{-2} \text{ h}^{-1}$  (WG),  $314 \text{ CO}_2\text{eq. mg m}^{-2} \text{ h}^{-1}$  (CG),  $564 \text{ CO}_2\text{eq. mg m}^{-2} \text{ h}^{-1}$  (WF), and  $241 \text{ CO}_2\text{eq. mg m}^{-2} \text{ h}^{-1}$  (Se). Wildflower (WF) treatment mean was significantly different from all other treatments, while all other vegetation types were not significantly different from one another.

The Mann-Whitney test for the effect of substrate depth on GHG fluxes and GWP was significant for  $\text{CO}_2$  ( $p < 0.01$ ) and  $\text{N}_2\text{O}$  ( $p < 0.05$ ) but was not significant for  $\text{CH}_4$  or GWP (Fig. 4). Both substrate depths yielded net emission of  $\text{CO}_2$ , with median values of  $266 \text{ mg m}^{-2} \text{ h}^{-1}$  (8 cm) and  $428 \text{ mg m}^{-2} \text{ h}^{-1}$  (14 cm). Notably, both were net sinks for  $\text{N}_2\text{O}$ , with median values of  $-0.13 \text{ mg m}^{-2} \text{ h}^{-1}$  (8 cm) and  $-0.17 \text{ mg m}^{-2} \text{ h}^{-1}$  (14 cm). On average of the substrate depth, a median  $\text{CH}_4$  flux of  $0.07 \text{ mg m}^{-2} \text{ h}^{-1}$  and GWP of  $273 \text{ CO}_2\text{eq. mg m}^{-2} \text{ h}^{-1}$ . The Mann-Whitney test for the effect of irrigation on GHG fluxes and GWP yielded significant results only for  $\text{N}_2\text{O}$  ( $p < 0.01$ ) (Fig. 5). Both irrigation treatments were also net sinks for  $\text{N}_2\text{O}$ , with median values  $-0.09 \text{ mg m}^{-2} \text{ h}^{-1}$  (1 L  $\text{m}^{-2} \text{ day}^{-1}$ ) and  $-0.20 \text{ mg m}^{-2} \text{ h}^{-1}$  (2 L  $\text{m}^{-2} \text{ day}^{-1}$ ). On average for irrigation level, median values were  $340 \text{ mg m}^{-2} \text{ h}^{-1}$  ( $\text{CO}_2$ ),  $0.07 \text{ mg m}^{-2} \text{ h}^{-1}$  ( $\text{CH}_4$ ), and  $284 \text{ CO}_2\text{eq. mg m}^{-2} \text{ h}^{-1}$  (GWP).

#### 3.3. Substrate temperature

For June data, results showed a significant effect of substrate depth for both morning ( $p < 0.001$ ) and evening temperatures ( $p < 0.05$ ) (Fig. 6). The average temperatures were  $21.8 \text{ }^\circ\text{C}$  (8 cm) and  $23.1 \text{ }^\circ\text{C}$  (14 cm) in the morning and  $29.9 \text{ }^\circ\text{C}$  (8 cm) and  $28.8 \text{ }^\circ\text{C}$  (14 cm) in the evening. There were no other significant interactions. The data for July yielded significant results for substrate depth for the morning ( $p < 0.001$ ), midday ( $p < 0.01$ ), and evening ( $p < 0.001$ ) (Fig. 6). The average temperatures for each depth were  $22.9 \text{ }^\circ\text{C}$  (8 cm) and  $24.9 \text{ }^\circ\text{C}$  (14 cm) in the morning,  $26.4 \text{ }^\circ\text{C}$  (8 cm) and  $27.2 \text{ }^\circ\text{C}$  (14 cm) at midday, and  $33.0 \text{ }^\circ\text{C}$  (8 cm) and  $31.4 \text{ }^\circ\text{C}$  (14 cm) in the evening. There was also significance of irrigation for the morning ( $p < 0.05$ ) and midday ( $p < 0.01$ ) temperatures (Fig. 7). The temperatures for each irrigation level averaged  $23.7 \text{ }^\circ\text{C}$  (1 L  $\text{m}^{-2} \text{ day}^{-1}$ ) and  $24.1 \text{ }^\circ\text{C}$  (2 L  $\text{m}^{-2} \text{ day}^{-1}$ ) at midday. For evening temperatures, the vegetation species type was also significant ( $p < 0.001$ ), with average temperatures of  $33.5 \text{ }^\circ\text{C}$  (WG),  $32.0 \text{ }^\circ\text{C}$  (CG),  $31.0 \text{ }^\circ\text{C}$  (WF), and  $32.5 \text{ }^\circ\text{C}$  (Se) (Fig. 8). Tukey's HSD yielded that only WF differed significantly from WG, with no other significant differences between treatments. There was a significant interaction term of substrate depth and vegetation species for midday temperatures ( $p < 0.01$ ).

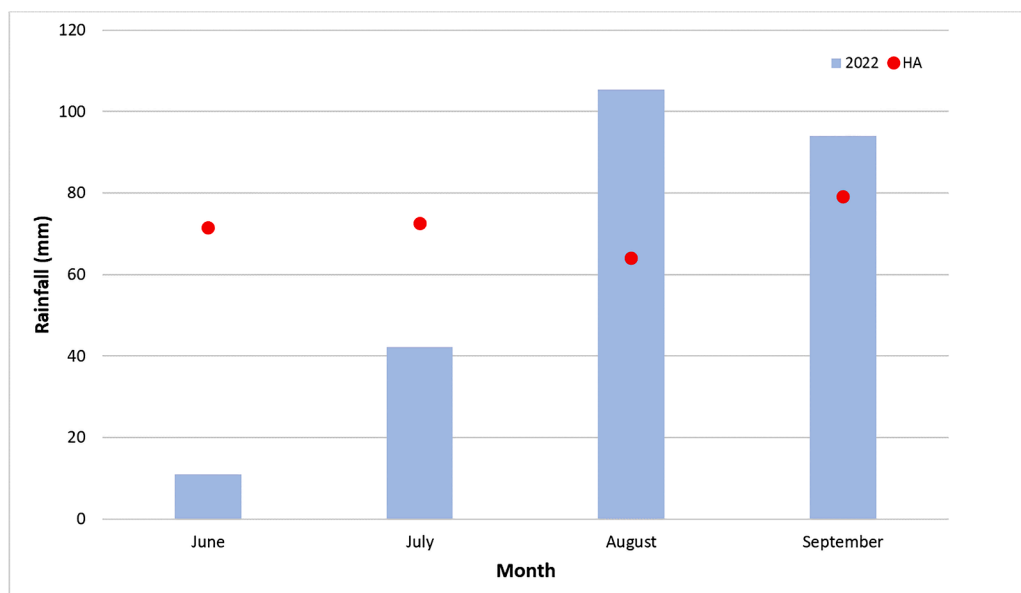


Fig. 2. Monthly distribution of the rainfall (mm) received in 2022 compared to the historic average (HA) during the summer months.

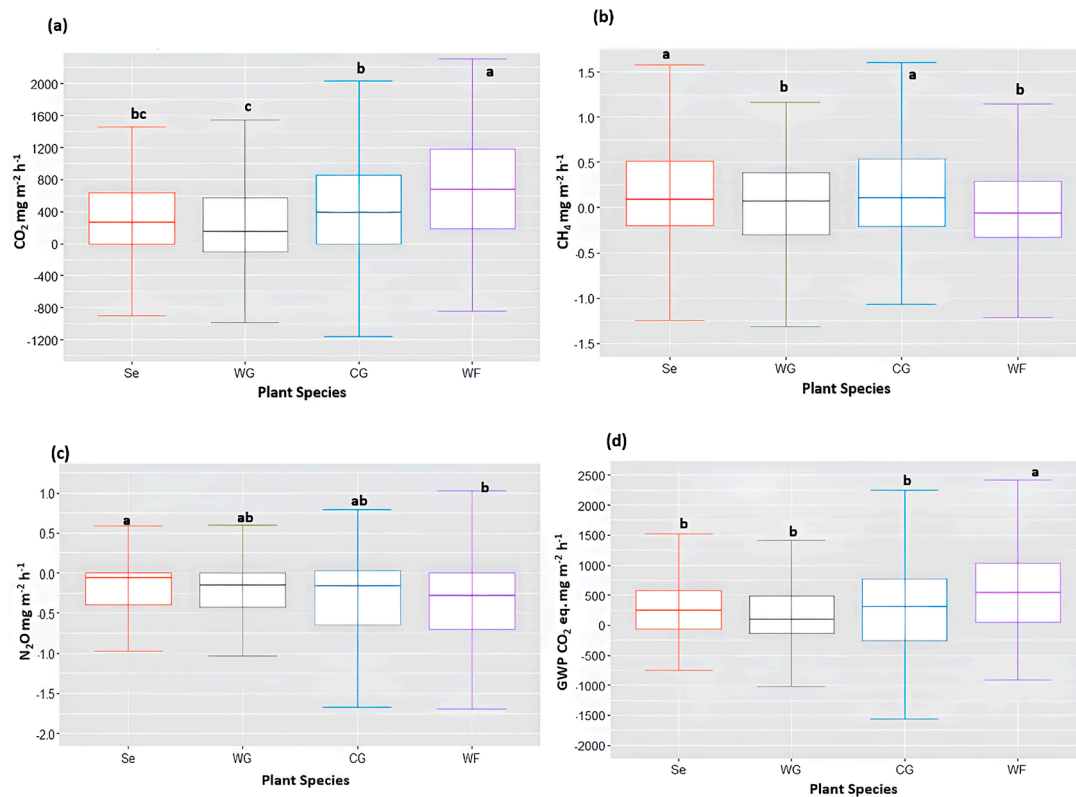


Fig. 3. Effect of vegetation type (*Sedum* spp., Se; warm season grasses, WG; cold season grasses, CG; and wildflowers, WF) in green roof microcosms on (a) CO<sub>2</sub>, (b) CH<sub>4</sub>, (c) N<sub>2</sub>O, and (d) global warming potential (GWP) fluxes. Significant differences between treatments are denoted by lowercase letters.

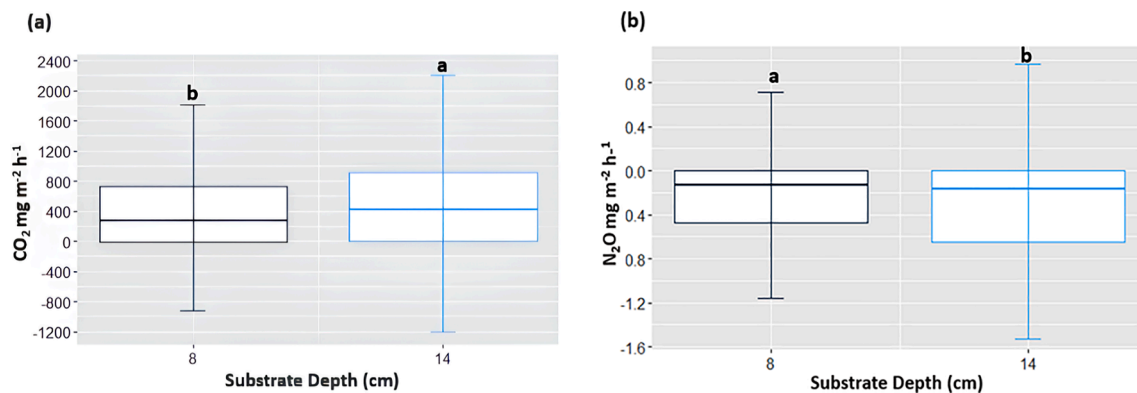


Fig. 4. Effect of substrate depth (8 or 14 cm) in green roof microcosms on (a) CO<sub>2</sub> and (b) N<sub>2</sub>O fluxes. Significant differences between the treatments are denoted by lowercase letters.

For the month of August, there was a significant relationship with substrate depth for midday ( $p < 0.05$ ) and evening ( $p < 0.001$ ) temperatures (Fig. 6). Higher irrigation level yielded higher average temperature in all cases. The average temperatures for each depth were 25.4 °C (8 cm) and 26.1 °C (14 cm) at midday and 32.7 °C (8 cm) and 31.3 °C (14 cm) in the evening. Moreover, irrigation was significant for midday temperatures ( $p < 0.05$ ), with temperatures averaging 25.4 °C (1 L m<sup>-2</sup> day<sup>-1</sup>) and 26.1 °C (2 L m<sup>-2</sup> day<sup>-1</sup>) (Fig. 7). In September, the only significant factor was substrate depth for the morning temperatures ( $p < 0.001$ ), with average temperatures of 15.4 °C (8 cm) and 17.1 °C (14 cm) (Fig. 6). The difference between the maximum and minimum temperatures observed for each substrate depth was 8.1 °C (8 cm) and 5.7 °C (14 cm) in June, 10.2 °C (8 cm) and 6.5 °C (14 cm) in July, 8.1 °C (8 cm) and 7.2 °C (14 cm) in August, and 6.1 °C (8 cm) and 3.5 °C (14 cm) in September.

#### 3.4. Correlation between GHG fluxes and GWP with substrate temperatures

Fluxes of CO<sub>2</sub> showed a positive correlation ( $p < 0.001$ ) with both morning (Spearman  $R = 0.20$ ) and midday (Spearman  $R = 0.18$ ) substrate temperatures. There was no significant correlation between CO<sub>2</sub> fluxes and evening temperatures. Likewise, CH<sub>4</sub> fluxes showed a positive correlation with all temperatures taken—morning (Spearman  $R = 0.15$ ,  $p < 0.01$ ), midday (Spearman  $R = 0.16$ ,  $p < 0.001$ ), and evening (Spearman  $R = 0.16$ ,  $p < 0.001$ ). Also, N<sub>2</sub>O fluxes had a strongly significant negative correlation with all temperatures ( $p < 0.001$ )—morning (Spearman  $R = -0.28$ ), midday (Spearman  $R = -0.19$ ), and evening (Spearman  $R = -0.23$ ). Global warming potential yielded no correlation with evening temperatures but had a positive correlation with morning (Spearman  $R = 0.12$ ,  $p < 0.05$ ) and midday (Spearman  $R$

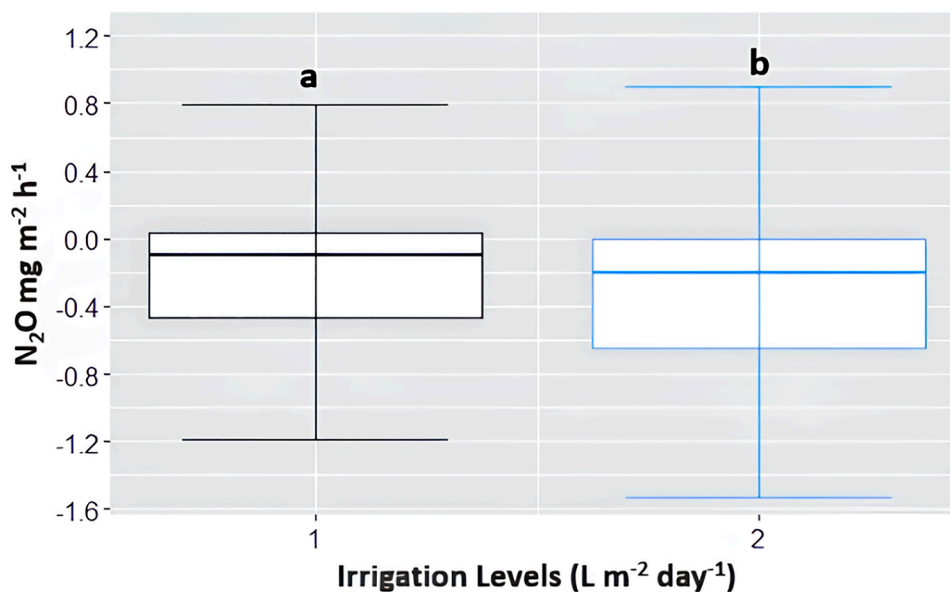


Fig. 5. Effect of irrigation level (1 or 2 L m<sup>-2</sup> day<sup>-1</sup>) in green roof microcosms on N<sub>2</sub>O fluxes. Significant differences between the treatments are denoted by lowercase letters.

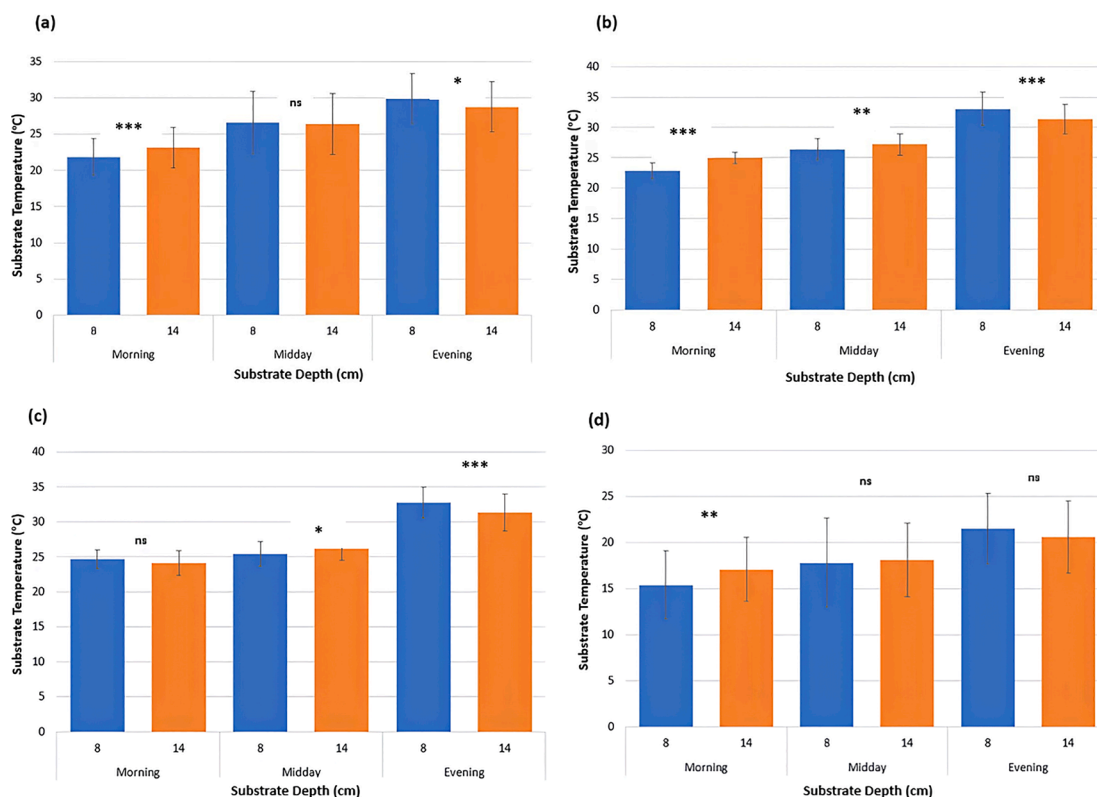


Fig. 6. Average morning, midday, and evening substrate temperatures by depth (8 or 14 cm) in green roof microcosms in (a) June, (b) July, (c) August, and (d) September. Significant differences between the two substrate depths are denoted with asterisks (\* =  $p < 0.05$ , \*\* =  $p < 0.01$ , \*\*\* =  $p < 0.001$ , ns = no significance). Error bars represent the standard deviation of each treatment.

= 0.13,  $p = 0.001$ ) temperatures.

#### 4. Discussion

During our summer sampling season, hotter than average temperatures and irregular rainfall distribution diminished the role of vegetation for CO<sub>2</sub> uptake through photosynthesis. Due to substantial drought

stress, a significant portion of plant cover in the microcosms was dying or dead. This means that respiration was a much greater contributor to CO<sub>2</sub> fluxes across treatments than photosynthesis and, consequently, resulted in higher than expected CO<sub>2</sub> efflux from our GR systems.

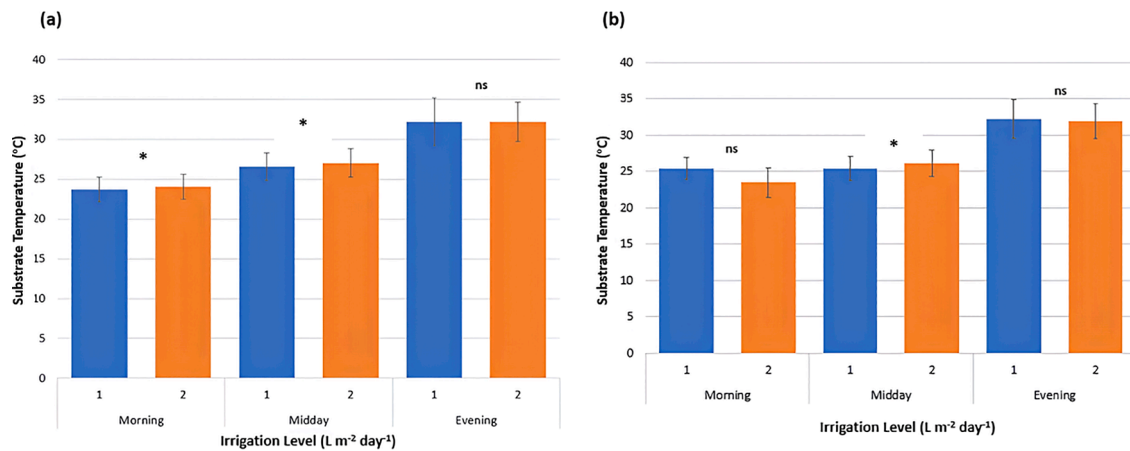


Fig. 7. Average morning, midday, and evening substrate temperatures by irrigation level (1 or 2 L m<sup>-2</sup> day<sup>-1</sup>) in green roof microcosms in (a) July and (b) August. Significant differences between the two substrate depths are denoted with asterisks (\* =  $p < 0.05$ , \*\* =  $p < 0.01$ , \*\*\* =  $p < 0.001$ , ns = no significance). Error bars represent the standard deviation of each treatment.

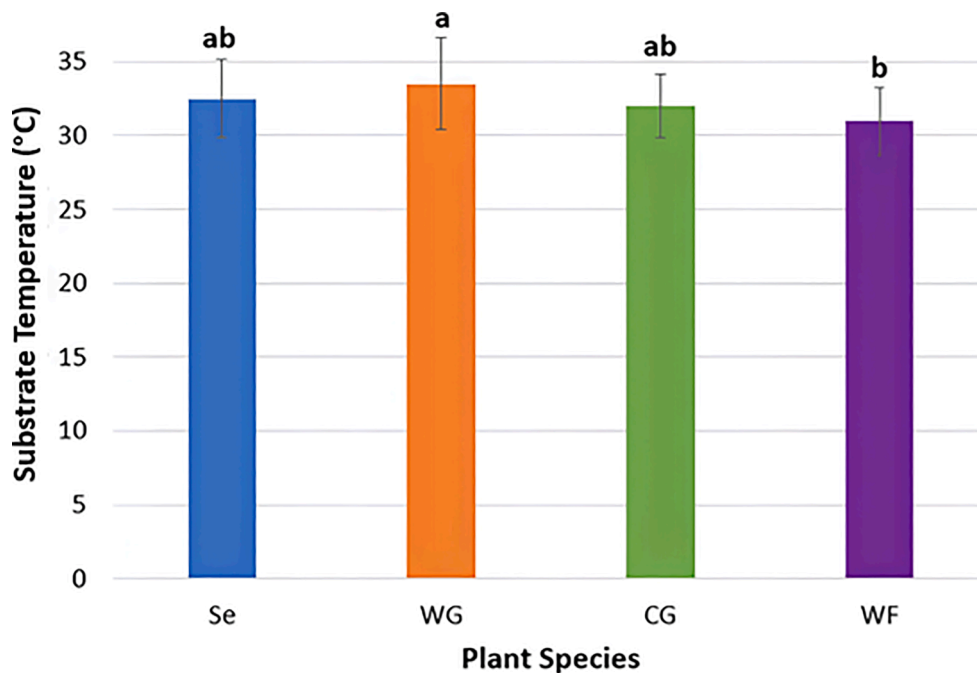


Fig. 8. Effect of vegetation type (*Sedum* spp., Se; warm season grasses, WG; cold season grasses, CG; and wildflowers, WF) in green roof microcosms on evening substrate temperatures. Significant differences between treatments are denoted by lowercase letters. Error bars represent the standard deviations of each treatment.

#### 4.1. Effect of vegetation species on greenhouse gas (GHG) fluxes and global warming potential (GWP)

Overall, we measured net CO<sub>2</sub> emission during the daytime, meaning that both autotrophic and heterotrophic respiration were higher than the photosynthesis rate. The high respiration and CO<sub>2</sub> efflux was probably caused by increased degradation of the organic matter that was accumulated during previous seasons. Notably, water stress due to dryness of our monitoring season was not compensated for by the irrigation, which was a limiting factor for plant growth. In particular, we observed a decrease in biomass early on in the summer, and the death of some plants (particularly affected were CG and WF, where 70%, green canopy cover dropped down to 35% and 40%, respectively). This highly influenced the GHG emissions given that the plants were probably releasing the carbon accumulated previously in their biomass instead of sequestering carbon to grow. In spite of this, there were some negative values present in all vegetation types suggesting that, under some

conditions and even with stress-induced senescence, GRs can sink CO<sub>2</sub>. Studies suggest *Sedum* spp. is among the least effective in reducing CO<sub>2</sub> emissions and suggest grass species as the more effective choice (Shafique et al., 2018). In contrast, our results show that *Sedum* spp. did not differ significantly from the other grass species treatments (CG and WG). Actually, WF had a significantly higher CO<sub>2</sub> emission rate than *Sedum* spp. Wildflower (WF) treatments had an efflux that was approximately 2.5 times higher than *Sedum* spp. Thus, our results imply that *Sedum* spp. was a significantly smaller net source of CO<sub>2</sub> than WF, in contrast to some studies. Since the positive values of CO<sub>2</sub> could also be due to oxidation of organic carbon stored in the substrate with the growth of plants in previous years, and the higher release values observed in the WF microcosms could be the results of the higher biomass that was produced in the previous two years of growth (data not shown). Conversely, the lower emission of *Sedum* spp. could be due to the lower plant growth in the past years but also to their better adaptation to extreme conditions. The research on the effect of vegetation on GHG

fluxes in GRs has been mostly centered around *Sedum* spp. and a limited range of herbaceous and flowering plants and their CO<sub>2</sub> sequestration potential (Charoenkit and Yiemwattana, 2016; Vijayaraghavan, 2016). A review of studies looking at CO<sub>2</sub> sequestration have found that GRs emit less CO<sub>2</sub> than their natural controls (Charoenkit and Yiemwattana, 2016), but another found that—specifically for *Sedum* spp.—carbon sequestration was found to be only a secondary benefit and recommended the use of other species (Agra et al., 2017). This inconsistency with the literature could be due to variations in meteorological variables and substrate characteristics driven by local differences, given that a considerable amount of studies are done in temperate climates typical of North America, whereas our study site has a humid subtropical climate. The main controls for CO<sub>2</sub> emissions are signaled to be temperature and moisture (Teemusk et al., 2019). Since vegetation type was not statistically significant across temperatures in our study, we can assume that moisture played a greater role in regulating CO<sub>2</sub> emissions across treatments. Teemusk et al. (2019) found a negative correlation between CO<sub>2</sub> fluxes and substrate moisture—i.e., less moisture content leads to higher CO<sub>2</sub> fluxes—due to the role of substrate moisture in regulating the organic matter cycle and promoting microbial activity but only when moisture is the limiting factor to plant growth. Our dry monitoring season could have also intensified the effect of moisture as a control for CO<sub>2</sub> emissions and, in conjunction with overall decreasing plant biomass caused by drought stress, increased CO<sub>2</sub> emissions. Notably, the water supplied during the experimental period was aimed to reduce and not to avoid the drought stress, in order to maximize the rainwater retention capacity of GRs.

For CH<sub>4</sub> fluxes, we measured that all treatments served as a net, albeit small, source of CH<sub>4</sub>, except for WF which was a net sink. The main control for CH<sub>4</sub> emission or consumption in GRs has been signaled to be moisture—where high moisture and anoxic conditions lead to emissions while low moisture and aerobic conditions are conducive to consumption (Halim et al., 2022). Drought resistant plant species with low evapotranspiration rates, such as *Sedum* spp. and some cold season grasses can have low CO<sub>2</sub> fluxes, but also produce CH<sub>4</sub> due to a retention of high soil moisture (Braun et al., 2022; Halim et al., 2022). This directly supports our results as we found that WF (sink) differed significantly only from *Sedum* spp. and CG (sources). These results could have been intensified by the context of the dry monitoring season, where, potentially, drought resistant plant species—such as *Sedum* spp. treatments—could have had markedly low evapotranspiration rates.

Interestingly, our study found that for all vegetation types, the microcosms were a net sink of N<sub>2</sub>O. Given the dryness of our summer season, this can be attributed to reduced water inputs, leading to a possible limitation of water content in the substrate, which has been highlighted as a main driver for N<sub>2</sub>O emissions because it regulates oxygen availability to soil microbes (Bateman and Baggs 2005; Butterbach-Bahal et al., 2013). The difference between N<sub>2</sub>O emission or capture in GRs due to biotic factors—such as plant species—is mainly attributed to plant-microbe-substrate interactions and evapotranspiration rates depending on type of photosynthetic cycling, which fall outside of the scope of this study (Dusza et al., 2017; Mitchell et al., 2018; Halim et al., 2022). However, in general, previous studies have signaled that GRs do not have significant fluxes of N<sub>2</sub>O (Mitchell et al., 2018; Teemusk et al., 2019). Again, only WF and *Sedum* spp. differed significantly, which follows the same reasoning as with differences between *Sedum* spp. and WF treatment means on CH<sub>4</sub> fluxes, considering the main driver for both fluxes is assumed to be moisture content. Previous studies of CH<sub>4</sub> and N<sub>2</sub>O fluxes from GRs have primarily evaluated the effect of substrate characteristics and meteorological parameters on these fluxes, and not vegetation type (Teemusk et al., 2019; Halim et al., 2022).

Our results show that WF had the highest GWP, which can be attributed to the fact that WF microcosms also showed the highest CO<sub>2</sub> flux, which is the largest magnitude that contributes when calculating GWP. Moreover, GWP differing across plant species is due to the fact the

vegetation type fluxes differed significantly for each individual flux.

#### 4.2. Effect of substrate depth on GHG fluxes and GWP

Our study found that deeper depths resulted in higher CO<sub>2</sub> fluxes, with no significant effect on CH<sub>4</sub>. Previous studies have highlighted substrate depth as a major driver for modulating the ecosystem services GRs provide, particularly in reducing GHG emissions through its control on water retention (Li and Yeung, 2014; Dusza et al., 2017; Halim et al., 2022). Halim et al. (2022) found that the main effects of substrate depth were significant for CO<sub>2</sub> fluxes in GRs but not for CH<sub>4</sub> fluxes, where increasing depth resulted in higher CO<sub>2</sub> efflux rates. These studies strengthen our findings. The relationship between carbon cycling and substrate depth has been attributed to the capacity for accumulation of organic matter in the substrate, particularly notable in extensive GR systems over time, where theoretically each 1% substrate organic matter content increase would lead to a net storage of 500 g C m<sup>-2</sup> for a 10 cm substrate layer (Buffam and Mitchell, 2015). Halim et al. (2022) highlighted that deeper substrate, and higher organic matter, would have a considerably higher CO<sub>2</sub> efflux. Unfortunately, we have no data on organic matter content for these treatments, but our 14 cm-depth microcosms are likely to have higher values because of both higher initial input and higher plant biomass accumulation for their greater support to plant growth.

Remarkably, our study also found that deeper substrate depths corresponded to a larger N<sub>2</sub>O sink. There is a general lack of studies looking at the effect of substrate depth on N<sub>2</sub>O fluxes. However, the literature highlights that substrate depth can influence the N cycling dynamics of GRs by altering hydrology, substrate moisture and temperature, microbial habitat, and the amount of leachable material (Buffam and Mitchell, 2015). Most N losses from GR systems are thought to be in the form of dissolved N, given that they are typically well drained systems prone to leaching losses—especially in the form of NO<sub>3</sub>-N (Mitchell et al., 2018). In general, previous studies have found that GRs were net emitters of N<sub>2</sub>O, with low fluxes that were highly variable in time (Mitchell, 2017; Mitchell et al., 2018; Teemusk et al., 2019). As cited previously, moisture is a main driver of N<sub>2</sub>O emissions. Our dry sampling season could have led to a limitation of water content in the substrate, favoring N<sub>2</sub>O uptake over emission. Although Mitchell et al. (2018) found that their treatments were net emitters, there were some negative values for N<sub>2</sub>O fluxes, supporting our finding that GRs can potentially serve as N<sub>2</sub>O sinks under certain conditions.

#### 4.3. Effect of irrigation on GHG fluxes and GWP

Our study found that irrigation only significantly affected N<sub>2</sub>O fluxes, where all treatments were net sinks. There is a lack of studies that focus on the effect of irrigation on N<sub>2</sub>O fluxes. However, a study on an urban lawn system—which can be compared to an extensive GR system—found that decreasing moisture resulted in smaller N<sub>2</sub>O emissions (Livesley et al., 2010). Our dry season highlighted this condition and resulted in N<sub>2</sub>O sinks across all treatments. We found that higher irrigation levels led to greater N<sub>2</sub>O sinks, which could indicate that a higher level of irrigation in dry conditions could positively affect this GR ecosystem service.

#### 4.4. Controls on substrate temperature

##### 4.4.1. Effect of substrate depth on substrate temperature

We found that depth was a significant factor for substrate temperatures in all months, although whether the shallow or deeper substrate corresponded to the higher temperature varied. Reyes et al. (2016) and Eksi et al. (2017) both found that increasing depth affected substrate temperature oscillations, where shallower substrate depths observed more extreme minimum and maximum temperatures than deeper substrates. This was especially prevalent during the summer sampling



season, where shallower substrate depths dried faster and produced higher temperature fluctuations (Eski et al., 2017). This phenomenon could have been intensified during our particularly dry summer sampling season. Moreover, Nardini et al. (2012) has signaled GR substrate depths between 12 and 20 cm can have a dampening effect over air temperature in the summer, further supporting our results.

#### 4.4.2. Effect of vegetation type and irrigation level on substrate temperature

Vegetation type significantly affected evening temperatures in July but did not cause significant differences for any other time periods. Warm season grasses (WG), the treatment with the highest evening temperature, differed significantly from wildflowers (WF), the treatment with the lowest temperature. A study evaluating evapotranspiration rates on grasses found that, when water is limited, transpiration rates for cool season grasses are higher than for warm season grasses (Romero and Dukes, 2016). However, since a significant effect was only observed in the hottest month during the time of day with the highest temperatures, it could suggest that vegetation type becomes an important driver for substrate temperature beyond a considerably high temperature and water deficit threshold. Literature emphasizes that the magnitude of evapotranspiration influence depends on daily meteorological conditions, such as solar radiation, ambient temperature, and substrate moisture (Eksi et al., 2017).

Similarly, a significant effect of irrigation was exerted only during the two hottest months of the season, namely July and August. A review on sustainable irrigation practices for extensive GR systems signaled that in Mediterranean regions with dry, hot summers irrigation is necessary for their success as well as the achievement of thermal regulation benefits (Van Mechelen et al., 2015). This supports our finding that irrigation only significantly affected temperatures during the driest and hottest months, indicating its effect could be triggered only after a certain threshold value. August, although with high levels of precipitation, still had consistent and considerably high temperatures, which could have maintained a dry microclimate in the microcosms. In contrast, September had a similar amount of precipitation to August but with markedly lower temperatures, with no significant effect of irrigation, sustaining our reasoning. Previous studies have demonstrated that, after irrigation, both vegetation and substrate temperature decreased compared to ambient temperature because irrigation increased daily evapotranspiration rates of extensive GRs (Chagolla-Aranda et al., 2017; Kaiser et al., 2019). However, a different study showed that increasing the irrigation supply did not decrease the substrate temperature on days that had over 50 °C air temperature (Reyes et al., 2016).

#### 4.4.3. Interaction effects between substrate depth and vegetation type

Interestingly, there was a significant interaction between substrate depth and species in July, for the midday temperatures. A previous study has shown that water retention in GR systems (which can influence evapotranspiration and, consequently, substrate temperatures) was significantly affected by the interaction between vegetation type, substrate depth, and substrate type; however, results were highly variable and yielded complex interactions that could result in trade-off between ecosystem services (Dusza et al., 2017).

#### 4.5. Correlation between GHG fluxes and substrate temperatures

CO<sub>2</sub>, CH<sub>4</sub>, and GWP were positively correlated with substrate temperatures, while N<sub>2</sub>O was negatively correlated. Halim et al. (2022) found an exponential relationship between substrate temperatures and CO<sub>2</sub> fluxes and an increase of CH<sub>4</sub> fluxes with increasing temperatures. This suggests that substrate temperatures can serve as a predictor of CH<sub>4</sub> and CO<sub>2</sub> fluxes, where higher temperatures will correspond to higher fluxes in both cases. Teemusk et al. (2019) also found a positive correlation of CO<sub>2</sub> with temperature, but a negative relationship between CH<sub>4</sub> fluxes and temperature. There is also a lack of studies looking at GWP in the context of its relationship to substrate temperatures. However, since

CO<sub>2</sub> and CH<sub>4</sub> are, in general, of a higher magnitude than N<sub>2</sub>O fluxes in GR systems, we can assume that GWP's correlation with substrate temperatures is mostly determined by the correlation of CO<sub>2</sub> and CH<sub>4</sub> with substrate temperature. Teemusk et al. (2019) found no significant correlation between N<sub>2</sub>O fluxes and any meteorological parameters, including temperature. However, the dryness of our monitoring season could have intensified the effect of temperature as a predictor for N<sub>2</sub>O fluxes. Potentially, higher temperatures can further decrease the moisture content of the substrate, which is the largest determinant in N<sub>2</sub>O uptake or emissions.

#### 4.6. Limitations and future research

Our results stem from a very atypical and particular dry summer season relative to normal expected rainfall—specifically, in the first two months of the sampling season—and temperatures of the study area. This means that the replicability of these results is ascribed to these conditions. Further research measuring evapotranspiration rates across vegetation species, substrate moisture content, and organic matter content can serve to better elucidate interactions between the biotic and abiotic components of GRs and their effect on ecosystem services.

### 5. Conclusions

Although our results are circumscribed to one atypical summer season, they suggest that GRs' ecosystem services are significantly affected by meteorological conditions, vegetation type, substrate depth, and irrigation regime. Surprisingly we found that GRs had a positive GWP due to GRs acting as a significant CO<sub>2</sub> source and, albeit smaller, sinks of CH<sub>4</sub> and N<sub>2</sub>O. This behavior was mainly due to the atypical summer conditions that caused dramatic stress, resulting in the death of some of the plants used in this study. *Sedum* species, the genus most resistant to both thermal and water stress among those tested, resulted in the lowest CO<sub>2</sub> fluxes and GWP. Although wildflower (WF) treatments outperformed *Sedum* spp. in N<sub>2</sub>O and CH<sub>4</sub> capture, it had more than double the CO<sub>2</sub> emissions. Higher irrigation levels, during the monitored atypical summer season increased the GR's ability to function as a N<sub>2</sub>O sink. With regards to substrate depth, deeper substrate depths, during an atypical summer season emitted more CO<sub>2</sub> due to the major stock accumulated in the previous years. Similarly, substrate depth was the main control for substrate temperatures, where deeper depths can provide more thermal insulation. However, irrigation level and vegetation type were significant controls only in the hottest and driest months of the monitoring season. This means that these parameters can be useful considerations in dry, hot climates in order to maximize the thermal benefits from GRs.

Overall, these factors can lead to complex interactions that can result in trade-offs between ecosystem services. To deepen our knowledge on GRs as a nature-based solution for climate change adaptation in cities, the effect of seasonality should be assessed to evaluate how GRs perform and how design and management parameters affect this performance throughout an entire year. The design, component choice, and management practices of GRs for optimization of their potential ecosystem services needs to be counterbalanced with practical considerations, such as building weight limits, relative costs, management intensity, and—in the case of irrigation regime—ethical concerns in water-scarce regions. Green roofs can serve as a potential strategy for climate change mitigation in cities, however, their application needs to be guided by the scientific considerations that govern the ecosystem services—and their interactions with biotic and abiotic factors of GRs—that they are designed to provide.

#### CRedit authorship contribution statement

**Alexandra Lugo-Arroyo:** Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing.

**Giampaolo Zanin:** Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing, Supervision. **Aaron Thompson:** Writing – review & editing, Supervision. **Maurizio Borin:** Conceptualization, Writing – review & editing. **Carmelo Maucieri:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Data availability

Data will be made available on request.

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