UNIVERSITÀ DEGLI STUDI DI PADOVA
Department of Agronomy, Food, Natural Resources, Animals, and Environment

Second Cycle Degree (MSc) in Sustainable Agriculture

Green roofs as a climate change adaptation strategy in cities: Evaluation of greenhouse gas emissions, substrate temperatures, and water balance in northeastern Italy

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Abbreviations and acronyms

ARPAV	Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto
CG	Cold season grasses
GHG	Greenhouse gas
GR	Blue-green roofs
GWP	Global warming potential
Se	*Sedum* spp.
WF	Wildflower mix
WG	Warm season grasses

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Summary

Covering building rooftops with vegetation [green roofs (GR)] holds promise as a climate change adaptation strategy in cities through the provision of ecosystem services, such as, lowering building temperatures, reducing stormwater runoff, and reducing greenhouse gas (GHG) emissions. However, there is a need for more studies that quantify these potential ecosystem services and evaluate how they are impacted by design and management practices. This work aims to evaluate three selected ecosystem services (reduction of GHGs, cooling of the microclimate, and stormwater management) and how they are affected by abiotic and biotic components of their design and management—i.e., vegetation type, substrate depth, and irrigation regime. We sought to test this by comparing daytime GHG emissions (i.e., CO_2, CH_4, and N_2O), daily substrate temperatures, and the water balance of 48 GR microcosms in north-eastern Italy during two monitoring periods (a dry summer season and an entire year). Four vegetation types (Sedum spp., cold season grasses, warm season grasses, or wildflowers), two substrate depths (8 or 14 cm), and two irrigation levels during summer time (1 or 2 L m^{-2} day^{-1}) were evaluated, for a total of 16 treatments with 3 replicates. We found that the design and management considerations mattered for GR ecosystem services. In both monitoring periods, substrate depth was the most important control for substrate temperatures, where deeper depths provided greater thermal benefits. Irrigation and plant species were important for thermal benefits only during the hottest month in our dry summer season. For water balance, vegetation species (where *Sedum* spp. and WF retained the most water in all seasons) and substrate depth (where 14 cm treatments retained the most water

in all seasons) mattered the most. GHG emissions were mainly determined by plant species and substrate depth treatment. In both our dry summer monitoring periods and spring, GRs were a significant CO_2 flux due to plant death in the mesocosms as a consequence of particular dry meteorological conditions. They served as a CO_2 sink in the colder months and as a small sink for CH_4 and N_2O. Higher irrigation levels promoted greater N_2O sinks in our GR systems, especially in the hottest seasons.

1. Structure of the thesis

Firstly, a main overview with a brief theoretical background is given to frame the work of this thesis. The main findings of this work are divided into two chapters, corresponding to the two different monitoring periods which were observed. Both chapters read as a self-contained publishable paper. Chapter 1 gives an introduction, details the methodology, and goes over the main findings for our measurements of GHG emissions and substrate temperatures during a hot dry summer season (submitted to Scientia Horticulturae). Similarly, Chapter 2 gives an introduction, details the methodology, and goes over the main findings for our measurements of GHG emissions, substrate temperatures, and water balance for our year-long monitoring season (will be submitted to Italian Journal of Agronomy). To reiterate and highlight our most important findings, this thesis concludes with a general conclusion.

2. Introduction

In developed countries, urbanization is expected to reach 83% in the year 2030, further degrading the surrounding environment and intensifying the negative consequences of climate change (Shafique et al., 2018). A proposed strategy to alleviate some of the pressures of climate change in urban areas is the establishment of green infrastructure (Oberndorfer et al., 2007; Francis & Jensen, 2017; Shafique et al., 2018, Langemeyer et al., 2020; Manso et al., 2021). Given that roofs comprise approximately 25% of overall urban surfaces areas, green roofs represent a significant opportunity to mitigate climate change in cities without building extensive infrastructure (Nguyen Le Trung et al., 2018). Green roofs are broadly defined as roofs populated with vegetation and a growing substrate (Shafique et al., 2018). The components of green roofs may vary slightly according to national construction standards and availability of materials, but they typically follow the same general structure. According to the Italian design, management, and construction standards for green roofs and roof gardens defined in UNI 11235, green roofs are comprised of a vegetation layer, a growth substrate layer, a filter fabric, a drainage element, a protection layer, a root barrier, an insulation layer, and a water proofing membrane stacked on top of the roof deck (Nguyen Le Trung et al., 2018). Blue-green roofs have an additional layer for the temporary storage of drained water (Andenæs et al., 2018). The green infrastructure evaluated in this work are blue-green roofs. For brevity, they will be referred to as GRs throughout.

GRs can be further classified into types, based on the vegetation used, the management intensity, and the substrate depth used. They are mainly classified as extensive, semi-intensive, or intensive systems (Shafique et al., 2018).

Extensive GRs have the shallowest substrate depths (10 – 15 cm), the lowest management intensity, and are typically vegetated with succulents perennial herbs, or grasses (Langemeyer et al., 2020). On the other hand, intensive GRs have the deepest substrate depths (30 – 100 cm), the highest management intensity, and are vegetated with medium to large shrubs and small trees (Langemeyer et al., 2020). Semi-intensive GRs have intermediate characteristics and vegetated with grasses, aromatics, and small shrubs (Langemeyer et al., 2020). The focus of this work is on extensive GR systems.

Extensive GR systems provide a wide variety of economic, social, and ecosystem services that are conducive towards sustainable urban development, such as stormwater management, reduced Urban Heat Island (UHI) effect, decreasing energy consumption of buildings, provision of space for food production, increased biodiversity, decreased air pollution, and increased aesthetic value (Francis & Jensen, 2017; Shafique et al., 2018). Among the ecosystem services, the mitigation of the UHI effect and the potential for stormwater management are particularly emphasized in the literature (Oberndorfer et al., 2007; Alexandri & Jones, 2008; Van Mechelen et al., 2015; Starry et al., 2016; Sanchez & Reames, 2019; Liu et al., 2021).

The UHI refers to the warming effect that urban infrastructure has on the climate of a region, causing a significant rise in average temperatures (Alexandri & Jones, 2008). These higher temperatures, or the formation of these *urban heat islands*, are caused by the low albedo of urban infrastructure, which absorbs and re-emits most of the sunlight as heat with little to no reflectance and transfers an appreciable amount to the building, increasing cooling costs (Francis & Jensen, 2017; Sanchez & Reames, 2019). Green roofs can reduce the UHI effect, mainly via evapotranspiration — effectively cooling the surrounding microenvironment — and, to a slightly lesser degree, by using materials in their construction that have a higher albedo than typical roofs (Oberndorfer et al., 2007). Reduction of the UHI effect is well established for green roofs. A systemic review of temperature decreases after implementing green roofs found that in all nine cities distributed globally under consideration showed a decrease in asphalt surface temperature, roof surface temperature, and air temperature, with more marked effects in the hotter regions (Alexandri & Jones, 2008).

Better stormwater management that can decrease flooding potential and runoff in urban landscapes is another well-researched and proven benefit of green roof infrastructure. Urbanization increases flooding and runoff mainly because it shifts land area from previously pervious surfaces, such as vegetation and soil cover, to highly impervious and porous surfaces, such as pavements, rooftops, and sidewalks (Starry et al., 2016; Liu et al., 2021). This increase in flooding potential and runoff due to an abundance of impervious urban infrastructure is likely to become exacerbated by the increasing frequency of more intense climatic precipitation events promoted by the ongoing climate change (Liu et al., 2021). In developed cities, rooftops comprise anywhere from 40 – 50% of a city’s total impervious surfaces (Shafique et al., 2018). Therefore, rooftops represent an ideal space for the implementation of green infrastructure.

Recently, the potential of green roofs to reduce and mitigate greenhouse gas emissions from cities has garnered attention. It is important to note that green roofs can serve as either a source or sink of greenhouse gas emissions, depending primarily on the accumulation and decomposition of organic matter in the system, substrate depth, irrigation, and vegetation characteristics (Halim et al., 2021). They have been hypothesized to counterbalance CO_2 emissions, by acting as potential sink through plant photosynthesis (Ismail et al., 2019; Teemusk et al., 2019). Green roofs may also act as a potential source for CH_4, particularly in extensive systems populated with low evapotranspiration plants, such as *Sedum,* due to increased moisture conditions and, consequently, anoxic conditions (Halim et al., 2021). Conversely, they have been found to act as sink for CH_4 under strongly oxic conditions in very well drained substrates of both shallow and deep depth (Halim et al., 2021). Moreover, fertilization and management of urban green areas have been found to be sources of N_2O and CO_2 (Teemusk et al., 2019). Moreover, N_2O losses may also occur from denitrification, an anoxic process that is favored under the same high moisture conditions as CH_4 production detailed previously (Mitchell et al., 2018). Given that green roofs are typically fast draining with shallow substrates, losses of greenhouse gases from anaerobic pathways are expected to be minor (Mitchell et al., 2018).

However, the benefits and services green roofs can provide depend strongly on their design and management. This means that the potential ecosystem services from GRs can be both negatively and positively affected by abiotic and biotic factors. Important considerations are substrate depth, irrigation practices, and vegetation type (Li & Yeung, 2014; Van Mechelen et al., 2015; Dusza et al., 2017; Teemusk et al., 2019; Halim et al., 2021). There is a need to quantify how these considerations affect the performance of GR's and how it varies throughout the seasons. This project will focus on evaluating how three selected ecosystem services are affected by substrate depth, irrigation, and vegetation type in an experimental green roof mesocosm system in northeastern Italy during (i) a hot, dry summer season.

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3. Chapter 1: Diurnal greenhouse gas emissions and substrate temperatures from blue-green roofs in northeastern Italy during a dry-hot summer season

Abstract

Covering building rooftops with vegetation [Green roofs (GR)] 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_4, CO_2, and N_2O) 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^{-1}) 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_4, CO_2, and N_2O emissions. While all vegetation types had net CO_2 emissions (median values from 147 to 671 mg m^{-2} h^{-1}) and net N_2O uptake (median values from -0.06 to -0.28 mg m^{-2} h^{-1}), CH_4 flux had net negative values (capture) only in microcosms with wildflowers (-0.07 mg m^{-2} h^{-1}), whereas other treatments had a median CH_4 emissions of 0.09 mg m^{-2} h^{-1}. Substrate depth significantly affected CO_2 and N_2O fluxes with deeper substrate leading to higher CO_2 emission (+ 60.7%) and greater N_2O uptake (+ 30.8%). Irrigation level only significantly influenced N_2O fluxes with 2 mm irrigation resulting in higher fluxes

(-0.20 mg m^{-2} h^{-1}) than 1 mm irrigation (-0.09 mg m^{-2} h^{-1}). Our study suggests that under heat induced plant-stress conditions, GRs can improve N_2O and CH_4 capture but might increase the emissions of CO_2 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.

3.1 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_2; methane, CH_4; nitrous oxide, N_2O), habitat fragmentation, and water scarcity (Van Mechelen et al., 2015; Teemusk et al., 2019; Han & 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 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 (Nguyen Le Trung et al., 2014). 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 trough 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 & 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_2 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_4, 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_4 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_2O and CO_2 (Teemusk et al., 2019). Nitrogen losses from these systems may be primarily through conversion of readily retained NH_4^+ to readily leached NO_3^-, which might be prevalent in readily drained systems, such as GRs (Dusza et al., 2017; Mitchell et al., 2018). Losses of N_2O may also occur from denitrification, an anoxic process that is favored under the same high moisture conditions as CH_4 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 & 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.

3.2 Materials and Methods

3.2.1 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^{-2} day^{-1} or 2 L m^{-2} day^{-1}). Wildflower and Se treatments were a mix of wildflower and *Sedum* species, respectively; CG was 10% *Poa pratensis* ‘Nublue Plus’ and 90% *Festuca arundinacea* ‘Rhambler’ by weight and WG was *Cynodon dactylon* ‘Paul 1’*.* 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).

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^{-2} day^{-1})	**Total irrigation applied (L m^{-2})**	**Cumulative rainfall (L m^{-2})**	**Total water input (L m^{-2})**
1	72	250.6	322.6
2	144		394.6

3.2.2 Greenhouse gas (GHG) flux and temperature measurements

The GHG (CO_2, CH_4, and N_2O) fluxes for each microcosm were measured using a portable Fourier Transform Infrared Spectroscopy (FTIR) analyzer by Gasmet Technologies (The Gasmet™ 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 minutes 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_2 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.

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

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

$$\text{GWP (CO}_2\text{ eq. mg m}^{-2}\text{ h}^{-1}) = CO_2 + (CH_4 \times 34) + (N_2O \times 298) \tag{2}$$

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).

3.2.3 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.

3.3 Results

3.3.1 Meteorological data

The meteorological data from June to September 2022 (Figure 1A and Figure 1B) 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://wwwold.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 MJ m^{-2} and the average wind speed was 1.7 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 ºC in June, 19.8 ºC in July, 18.9 ºC in August, and 14.6 ºC in September. The maximum average temperatures were 30.1 ºC in June, 32.0 ºC in July, 30.4 ºC in August, and 24.6 ºC in September. The temperatures overall averaged 24.5 ºC in June, 26.2 ºC in July, 24.6 ºC in August, and 19.3 ºC in September.

Precipitation was afflicted by unusually dry weather. The cumulative rainfall during the sampling season was 250.6 L m^{-2} (Table 1), very close to the long-term value 263 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 (Figure 2).

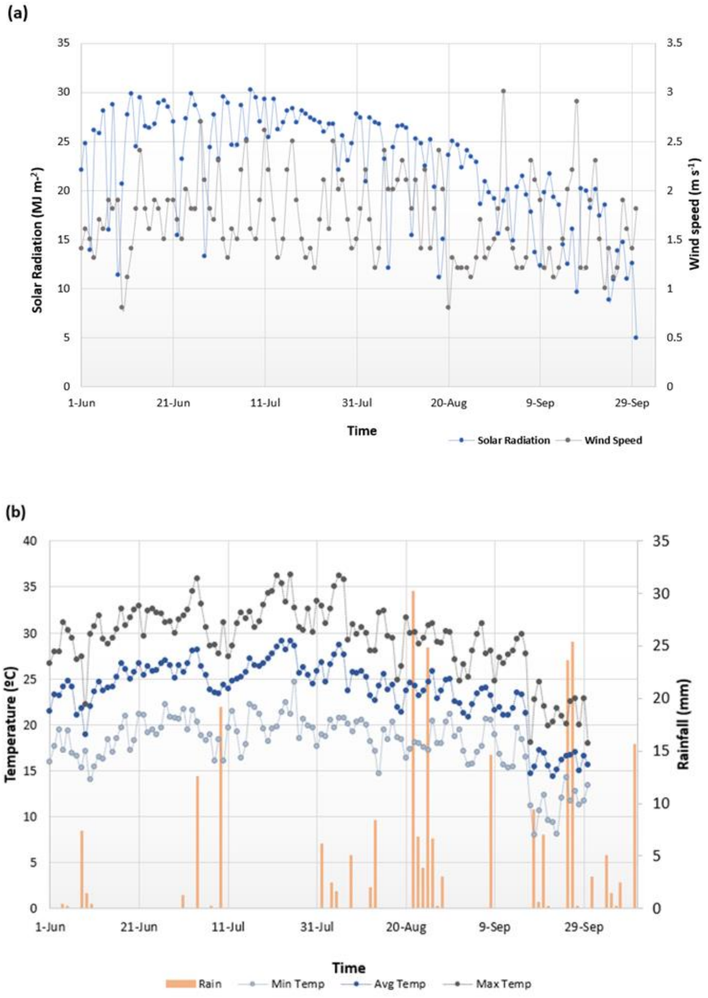

Figure 1. (a) Daily average solar radiation (MJ m^{-2}) and wind speed (m s^{-1}) and (B) daily minimum, average, and maximum temperatures (ºC) and daily rainfall (mm) for the summer season (June to September 2022).

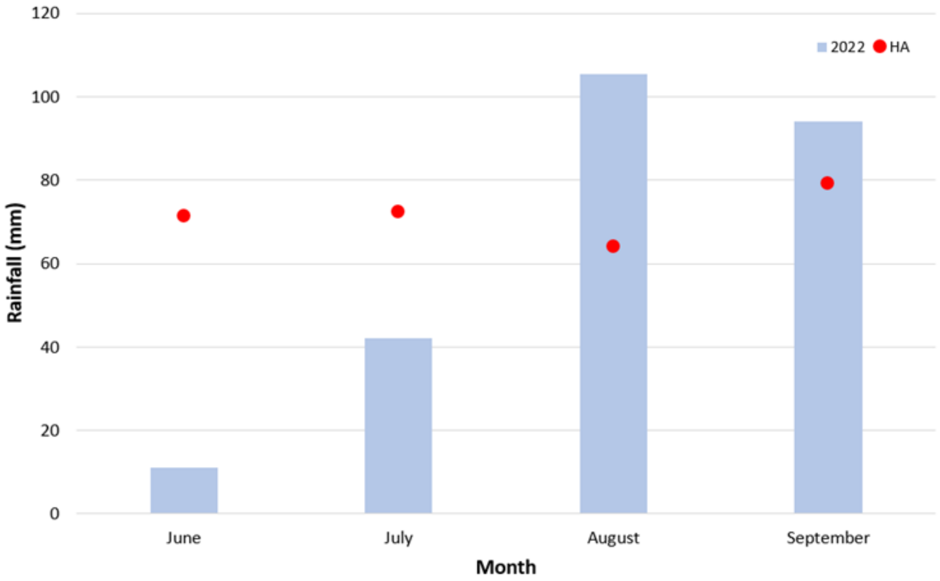

Figure 2. Monthly distribution of the rainfall (mm) received in 2022 compared to the historic average (HA) during the summer months.

3.3.2 Greenhouse gas (GHG) flux and global warming potential (GWP)

The Kruskal-Wallis test for the effect of vegetation types on GHG fluxes and GWP was significant for all gases—namely CO_2 ($p < 0.001$), CH_4 ($p < 0.01$), and N_2O ($p < 0.05$) as well as the GWP ($p < 0.001$) (Figure 3). All vegetation treatments were net emitters of CO_2, with median values of 147 mg m^{-2} h^{-1} (WG), 268 mg m^{-2} h^{-1} (Se), 384 mg m^{-2} h^{-1} (CG) and 671 mg m^{-2} h^{-1} (WF). Fluxes of CH_4 were low and close to 0, with a positive median value with WG (0.068 mg m^{-2} h^{-1}), Se (0.097 mg m^{-2} h^{-1}), and CG (0.11 mg m^{-2} h^{-1}); and a negative median value (net sink) with WF (-0.66 mg m^{-2} h^{-1}). Only WF differed significantly from Se and CG with no other significant differences between treatment means. All treatments were net sinks of N_2O, with median values of -0.15 mg m^{-2} h^{-1} (WG), -0.16 mg m^{-2} h^{-1} (CG), -0.28 mg m^{-2} h^{-1} (WF), and -6.34 x 10^{-2} mg m^{-2} 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 CO_2 eq. mg m^{-2} h^{-1} (WG), 314 CO_2 eq. mg m^{-2} h^{-1} (CG), 564 CO_2 eq. mg m^{-2} h^{-1} (WF), and 241 CO_2 eq. mg m^{-2} 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.

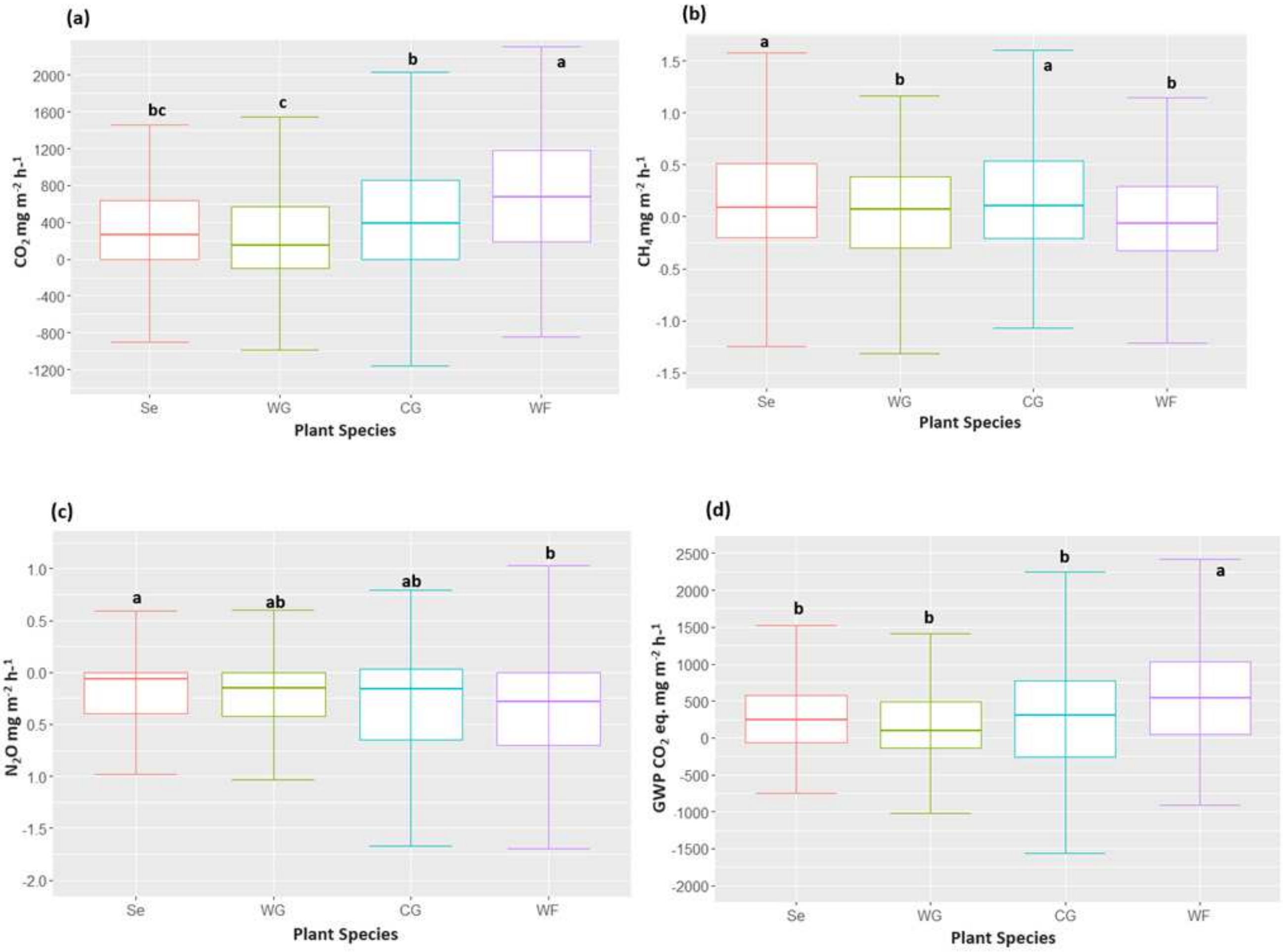

Figure 3. Effect of vegetation type (*Sedum* spp., Se; warm season grasses, WG; cold season grasses, CG; and wildflowers, WF) in green roof microcosms on (a) CO_2, (b) CH_4, (c) N_2O, and (d) global warming potential (GWP) fluxes. Significant differences between treatments are denoted by lowercase letters. Error bars represent the standard deviations of each treatment.

The Mann-Whitney test for the effect of substrate depth on GHG fluxes and GWP was significant for CO_2 ($p < 0.01$) and N_2O ($p < 0.05$) but was not significant for CH_4 or GWP (Figure 4). Both substrate depths yielded net emission of CO_2, with median values of 266 mg m^{-2} h^{-1} (8 cm) and 428 mg m^{-2} h^{-1} (14 cm). Notably, both were net sinks for N_2O, with median values of -0.13 mg m^{-2} h^{-1} (8 cm) and -0.17 (14 cm). On average of the substrate depth, a median CH_4 flux of 0.07 mg m^{-2} h^{-1} and GWP of 273 CO_2 eq. mg m^{-2} h^{-1}. The Mann-Whitney test for the effect of irrigation on GHG fluxes and GWP yielded significant results only for N_2O ($p < 0.01$) (Figure 5). Both irrigation treatments were also net sinks for N_2O, with median values -0.09 L m^{-2} day^{-1} (1 L m^{-2} day^{-1}) and -0.20 (2 L m^{-2} day^{-1}). On average for irrigation level, median values were 340 mg m^{-2} h^{-1} (CO_2), 0.07 mg m^{-2} h^{-1} (CH_4), and 284 CO_2 eq. mg m^{-2} h^{-1} (GWP).

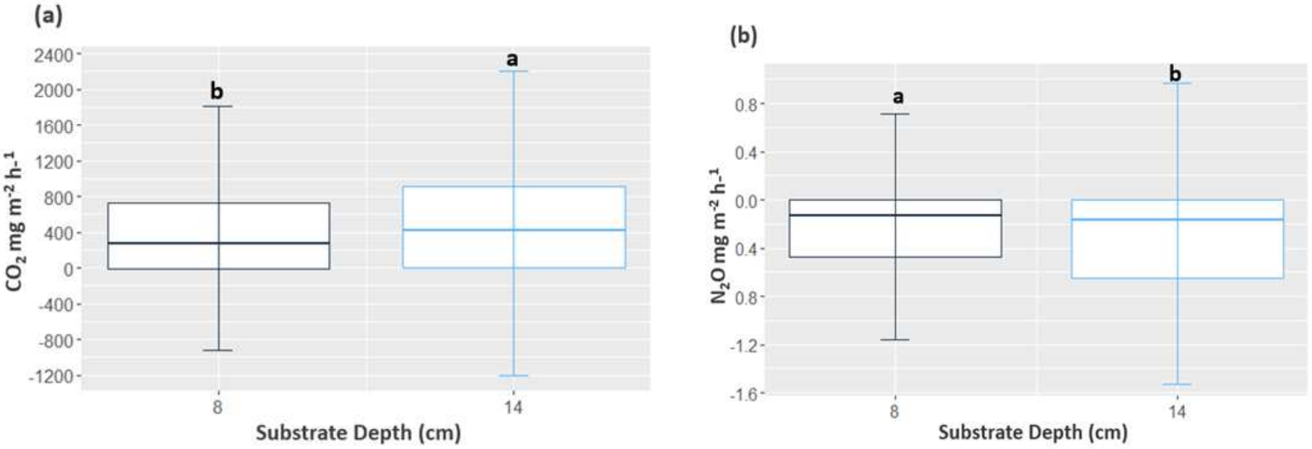

Figure 4. Effect of substrate depth (8 or 14 cm) in green roof microcosms on (a) CO_2 and (b) N_2O fluxes. Significant differences between the treatments are denoted by lowercase letters. Errors bars represent the standard deviation of each treatment.

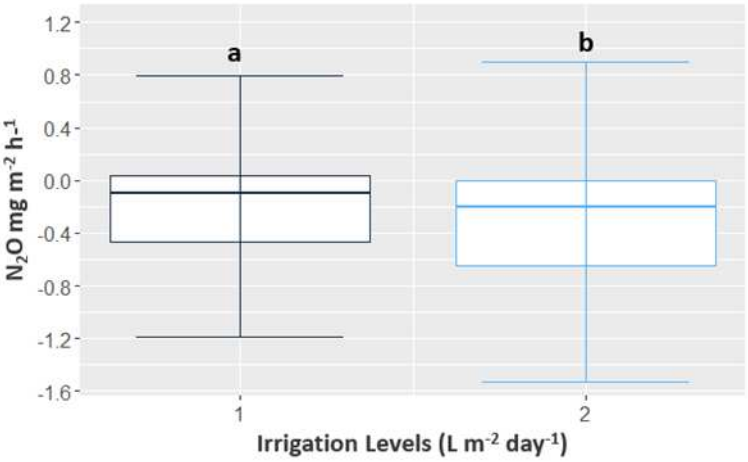

Figure 5. Effect of irrigation level (1 or 2 L m^{-2} day^{-1}) in green roof microcosms on N_2O fluxes. Significant differences between the treatments are denoted by lowercase letters. Errors bars represent the standard deviation of each treatment.

3.3.3 Substrate temperatures

For June data, results showed a significant effect of substrate depth for both morning ($p < 0.001$) and evening temperatures ($p < 0.05$) (Figure 6). The average temperatures were 21.8 ºC (8 cm) and 23.1 ºC (14 cm) in the morning and 29.9 ºC (8 cm) and 28.8 ºC (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 ($p < 0.001$) (Figure 6). The average temperatures for each depth were 22.9 ºC (8 cm) and 24.9 ºC (14 cm) in the morning, 26.4 ºC (8 cm) and 27.2 ºC (14 cm) at midday, and 33.0 ºC (8 cm) and 31.4 ºC (14 cm) in the evening. There was also significance of irrigation for the morning ($p < 0.05$) and midday ($p < 0.01$) temperatures (Figure 7). The temperatures for each irrigation level averaged 23.7 ºC (1 L m^{-2} day^{-1}) and 24.1 ºC (2 L m^{-2} day^{-1}) at midday. For evening temperatures, the vegetation species type was also significant ($p < 0.001$), with average temperatures of 33.5 ºC (WG), 32.0 ºC (CG), 31.0 ºC (WF), and 32.5 ºC (Se) (Figure 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 ($p < 0.01$). For the month of August, there was a significant relationship with substrate depth for midday ($p < 0.05$) and evening ($p < 0.001$) temperatures (Figure 6). Higher irrigation level yielded higher average temperature in all cases. The average temperatures for each depth were 25.4 ºC (8 cm) and 26.1 ºC (14 cm) at midday and 32.7 ºC (8 cm) and 31.3 ºC (14 cm) in the evening. Moreover, irrigation was significant for midday temperatures ($p < 0.05$), with temperatures averaging 25.4 ºC (1 L m^{-2} day^{-1}) and 26.1 ºC (2 L m^{-2} day^{-1}) (Figure 7). In September, the only significant factor was substrate depth for the morning temperatures ($p < 0.001$), with average temperatures of 15.4 ºC (8 cm) and 17.1 ºC (14 cm) (Figure 6). The difference between the maximum and minimum temperatures observed for each substrate depth was 8.1 ºC (8 cm) and 5.7 ºC (14 cm) in June, 10.2 ºC (8 cm) and 6.5 ºC (14 cm) in July, 8.1 ºC (8 cm) and 7.2 ºC (14 cm) in August, and 6.1 ºC (8 cm) and 3.5 ºC (14 cm) in September.

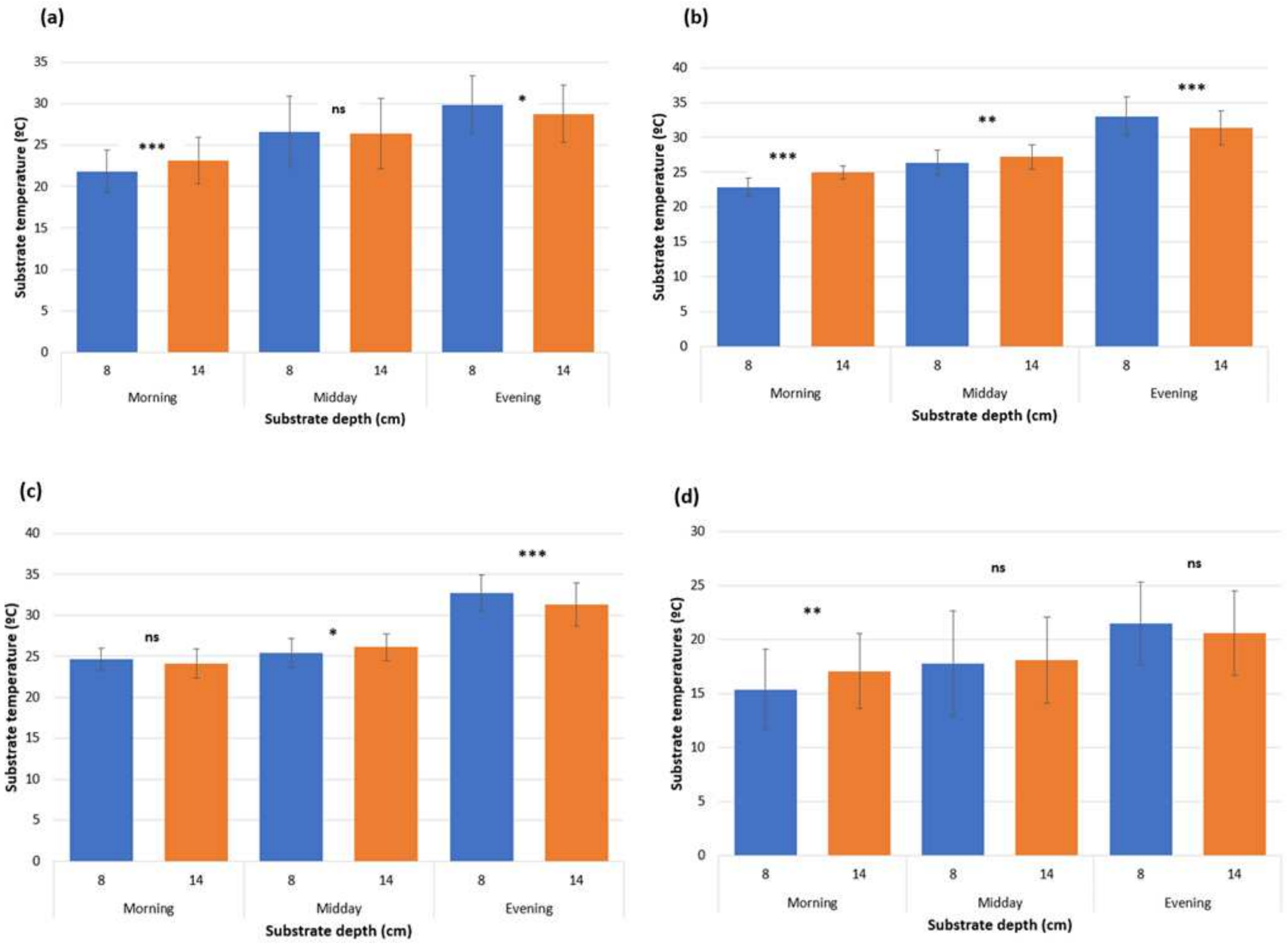

Figure 6. Average morning, midday, and evening substrate temperatures by depth (8 or 14 cm) in green roof microcosms in (a) June, (b) July, (c) August, and (d) September. Significant differences between the two substrate depths are denoted with asterisks (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$,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

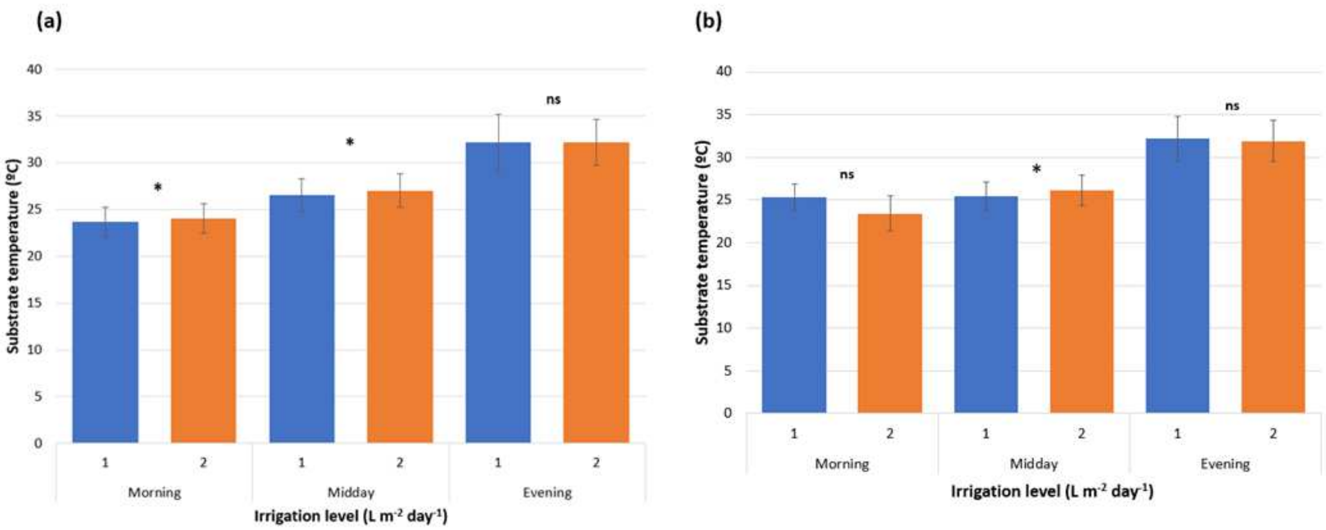

Figure 7. Average morning, midday, and evening substrate temperatures by irrigation level (1 or 2 L m^{-2} day^{-1}) in green roof microcosms in (a) July and (b) August. Significant differences between the two substrate depths are denoted with asterisks (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$,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

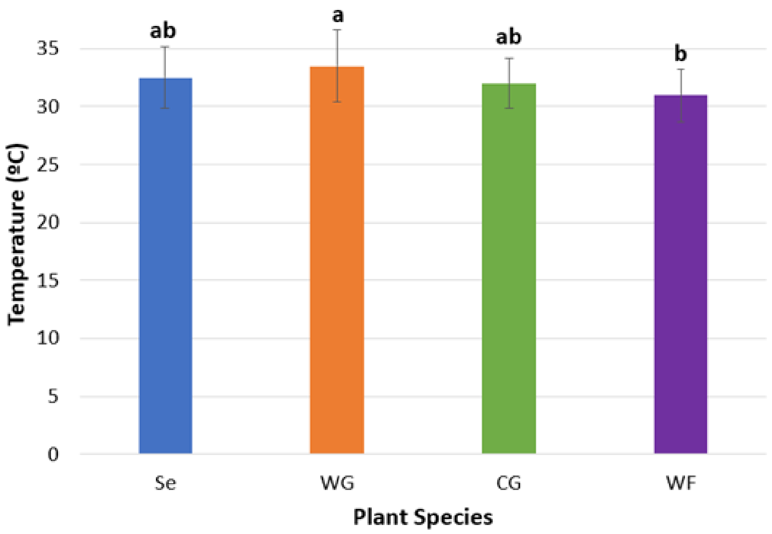

Figure 8. Effect of vegetation type (*Sedum* spp., Se; warm season grasses, WG; cold season grasses, CG; and wildflowers, WF) in green roof microcosms on evening substrate temperatures. Significant differences between treatments are denoted by lowercase letters. Error bars represent the standard deviations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

3.3.4 Correlation between GHG fluxes and GWP with substrate temperatures

Fluxes of CO_2 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_2 fluxes and evening temperatures. Likewise, CH_4 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_2O 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 = 0.13, $p = 0.001$) temperatures.

3.4 Discussion

During our summer sampling season, hotter than average temperatures and irregular rainfall distribution diminished the role of vegetation for CO_2 uptake through photosynthesis. Due to substantial drought stress, a significant portion of plant cover in the mesocosms was dying or dead. This means that respiration was a much greater contributor to CO_2 fluxes across treatments than photosynthesis and, consequently, resulted in higher than expected CO_2 efflux from our GR systems.

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

Overall, we measured net CO_2 emission during the daytime, meaning that both autotrophic and heterotrophic respiration were higher than the photosynthesis rate. The high respiration and CO_2 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 and greenness early on in the summer, which lead to some plant death. 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_2. Studies suggest *Sedum* spp. is among the least effective in reducing CO_2 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_2 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_2 than WF, in contrast to some studies. Since the positive values of CO_2 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_2 sequestration potential (Charoenkit & Yiemwattana, 2016; Vijayaraghavan, 2016). A review of studies looking at CO_2 sequestration have found that GRs emit less CO_2 than their natural controls (Charoenkit & 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_2 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_2 emissions across treatments. Teemusk et al. (2019) found a negative correlation between CO_2 fluxes and substrate moisture—i.e., less moisture content leads to higher CO_2 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_2 emissions and, in conjunction with overall decreasing plant biomass caused by drought stress, increased CO_2 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_4 fluxes, we measured that all treatments served as a net, albeit small, source of CH_4, except for WF which was a net sink. The main control for CH_4 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_2 fluxes, but also produce CH_4 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_2O. 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_2O emissions because it regulates oxygen availability to soil microbes (Bateman & Baggs 2005; Butterbach-Bahal et al., 2013). The difference between N_2O 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_2O (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_4 fluxes, considering the main driver for both fluxes is assumed to be moisture content. Previous studies of CH_4 and N_2O 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_2 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.

3.4.2 Effect of substrate depth on GHG fluxes and GWP

Our study found that deeper depths resulted in higher CO_2 fluxes, with no significant effect on CH_4. 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 & 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_2 fluxes in GRs but not for CH_4 fluxes, where increasing depth resulted in higher CO_2 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^{-2} for a 10 cm substrate layer (Buffam & Mitchell, 2015). Halim et al. (2022) highlighted that deeper substrate, and higher organic matter, would have a considerably higher CO_2 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_2O sink. There is a general lack of studies looking at the effect of substrate depth on N_2O 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 & 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_3-N $^-$ (Mitchell et al., 2018). In general, previous studies have found that GRs were net emitters of N_2O, 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_2O emissions. Our dry sampling season could have led to a limitation of water content in the substrate, favoring N_2O uptake over emission. Although Mitchell et al. (2018) found that their treatments were net emitters, there were some negative values for N_2O fluxes, supporting our finding that GRs can potentially serve as N_2O sinks under certain conditions.

3.4.3 Effect of irrigation on GHG fluxes and GWP

Our study found that irrigation only significantly affected N_2O fluxes, where all treatments were net sinks. There is a lack of studies that focus on the effect of irrigation on N_2O 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_2O emissions (Livesley et al., 2010). Our dry season highlighted this condition and resulted in N_2O sinks across all treatments. We found that higher irrigation levels led to greater N_2O sinks, which could indicate that a higher level of irrigation in dry conditions could positively affect this GR ecosystem service.

3.4.4 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 cm and 20 cm can have a dampening effect over air temperature in the summer, further supporting our results.

3.4.5 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 & 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 ºC air temperature (Reyes et al., 2016).

3.4.6 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).

3.4.7 Correlation between GHG fluxes and substrate temperatures

CO_2, CH_4, and GWP were positively correlated with substrate temperatures, while N_2O was negatively correlated. Halim et al. (2022) found an exponential relationship between substrate temperatures and CO_2 fluxes and an increase of CH_4 fluxes with increasing temperatures. This suggests that substrate temperatures can serve as a predictor of CH_4 and CO_2 fluxes, where higher temperatures will correspond to higher fluxes in both cases. Teemusk et al. (2019) also found a positive correlation of CO_2 with temperature, but a negative relationship between CH_4 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_2 and CH_4 are, in general, of a higher magnitude than N_2O fluxes in GR systems, we can assume that GWP's correlation with substrate temperatures is mostly determined by the correlation of CO_2 and CH_4 with substrate temperature. Teemusk et al. (2019) found no significant correlation between N_2O 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_2O fluxes. Potentially, higher temperatures can further decrease the moisture content of the substrate, which is the largest determinant in N_2O uptake or emissions.

3.4.8 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.

3.5 Conclusion

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_2 source and, albeit smaller, sinks of CH_4 and N_2O. This behavior was mainly due to the atypical summer meteorological conditions that determined a dramatic plants stress till the dead. *Sedum* spp. was the driest resistant species among the tested once and determined the lowest CO_2 fluxes and GWP. Although wildflower (WF) treatments outperformed *Sedum* spp. in N_2O and CH_4 capture, it had more than double the CO_2 emissions. Higher irrigation levels, during the monitored atypical summer season increased the GR's ability to function as a N_2O sink. With regards to substrate depth, deeper substrate depths, during an atypical summer season emitted more CO_2 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. GRs 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.

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4. Chapter 2: Diurnal greenhouse gas emissions, substrate temperatures, and water balance from green roofs in northeastern Italy

Abstract

Covering building rooftops with vegetation [green roofs (GR)] holds promise as a climate change adaptation strategy in cities through the provision of ecosystem services, such as, lowering building temperatures, reducing stormwater runoff, and reducing greenhouse gas (GHG) emissions. However, there is a need for more studies that quantify these potential ecosystem services and evaluate how they are impacted by design and management practices. This work aims to evaluate three selected ecosystem services (reduction of GHGs, cooling of the microclimate, and stormwater management) and how they are affected by abiotic and biotic components of their design and management—i.e., vegetation type, substrate depth, and irrigation regime. We sought to test this by comparing daytime GHG emissions (i.e., CO_2, CH_4, and N_2O), daily substrate temperatures, and the water balance of 48 GR mesocosms in north-eastern Italy during an entire year. Four plant species (*Sedum* spp., cold season grasses, warm season grasses, or wildflowers), two substrate depths (8 or 14 cm), and two irrigation levels during summer season (1 or 2 L m^{-2} day^{-1}) were evaluated, for a total of 16 treatments with 3 replicates. We found that plant species was a significant control for CO_2 emissions in all seasons, and treatments were small sources in the spring season, large sources in a dry summer season, and modest sinks in the fall and winter. Deeper substrate depth leads to about 30 times higher CO_2 emissions in the spring compared to the shallower substrate depth. Substrate depth mattered for

N_2O fluxes only in the summer, where deeper depths were almost two times greater a sink than shallower substrate depths. Irrigation level during summer season most notably affected CO_2 emissions only in the following winter season, although there was a small effect on CH_4 fluxes in fall and on N_2O fluxes in summer. For the water balance, we found that both plant species and substrate depth mattered for seasonal effects. The fall season had the greatest water outputs, and, in all seasons, *Sedum* spp. had the least stormwater retention capacity, with values various orders of magnitude higher than the other plant species treatments. Deeper substrate depth leads to higher water retention in all seasons. Substrate temperatures were significantly affected by substrate depth in all seasons. Deeper substrate depths had 2 – 3 ºC less temperature oscillation than the shallower substrate depths. The combined effect of irrigation level and substrate depth was significant only during the summer season. Ultimately, our results suggest that GRs can aid in capturing CO_2 in the colder months (due to the particular meteorological conditions during the experimental year), providing thermal insulation benefits, and in stormwater management year round.

4.1 Introduction

Blue-green roofs, defined as vegetated rooftops with an additional layer for the temporary storage of rainwater, are a potential strategy for coupling urban climate change adaptation with sustainable development (Andanæs et al., 2018; Manso et al., 2021). Increasing rates of urbanization and the current climate change crisis are accelerating greenhouse gas (GHG) emissions—namely, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)—

increasing temperatures, and water scarcity (Van Mechelen et al., 2015; Teemusk et al., 2019; Han & Zhu, 2020). Blue-green roofs (abbreviated as GRs throughout this work) provide an abundance of ecosystem services, including carbon sequestration and capture of GHGs, thermal benefits, and increased stormwater management that aid in mitigating these issues in urban environments (Oberndorfer et al., 2007; Shafique et al., 2018; Manso et al., 2021; Halim et al., 2022). In particular, the aforementioned ecosystem services can aid in closing nutrient, energy, and water cycles in cities while providing ancillary benefits such as improving landscape connectivity, increasing biodiversity, improving water quality, and increasing the longevity of conventional roof membranes (Oberndorfer et al., 2007).

The thermal benefits of GRs are well-researched. GRs can provide both increased comfort and reduced energy costs by cooling the microclimate. The cooling effect of GRs is attributed to the combined effect of plant evapotranspiration, shading by the plant canopy, thermal insulation of the substrate-drainage layers, and an increased albedo when compared to conventional rooftops that leads to an overall reduction in absorbed solar radiation (Jim & Peng, 2012; Shafique et al., 2018). When GRs are upscaled, these thermal benefits can translate into a reduction of the Urban Heat Island (UHI) effect in cities (Sanchez & Reames, 2019). Although these thermal benefits have been documented in both cold and hot regions, studies have found that the effects are more marked in hotter regions and those with high seasonal variability (Shafique et al., 2018). Factors that affect GR’s thermal benefits, particularly in terms of energy savings include the GRs’ substrate characteristics, meteorological parameters, plant type, and design insulation (Shafique et al., 2018).

On the other hand, less quantified ecosystem services of GRs include carbon sequestration and capture of GHGs. GRs can influence CO_2 emissions both indirectly and directly. Directly, vegetated rooftops capture carbon through photosynthesis and store carbon and other nutrients in the substrate layer as organic matter (Shafique et al., 2020). Indirectly, vegetated rooftops reduce the building temperature and associated energy costs which, consequently, reduces the burning of fossil fuels (Shafique et al., 2020). However, GRs can function as either a sink or source of GHGs besides CO_2. Whether GRs are a source or sink of GHGs depends on the accumulation and decomposition of organic matter in the system, substrate depth, irrigation, vegetation characteristics (Halim et al., 2022) and meteorological conditions (Lugo-Arroyo et al., 2023). For both CH_4 and N_2O, the predominant loss pathways occur during anaerobic metabolism (Dusza et al., 2017; Mitchell et al., 2018). Studies have signaled potential losses of CH_4 from extensive GR systems populated with low evapotranspiration plants, such as *Sedum* spp., that lead to higher substrate moisture (Halim et al.,2022). Similarly, these higher substrate moisture conditions can also cause higher N_2O losses through denitrification. However, since most GRs are designed to promote oxic conditions and readily drained, losses from anaerobic pathways are expected to be minor (Mitchell et al., 2018). Aerobic metabolism can also drive N_2O losses during nitrification, where N_2O and CO_2 often increase following fertilization and certain management activities (Dusza et al., 2017; Mitchell et al., 2018; Teemusk et al., 2019).

Stormwater management is another well-known, but less quantified ecosystem service of GR systems. At a building-scale, GRs can reduce the runoff volume at an annual scale and delay the peak runoff flow for an individual rain event (Versini et al., 2020). This is important because delaying peak runoff ultimately results in a reduction of the rainwater that reaches conventional stormwater management infrastructure (Versini et al., 2020). Blue-green roofs specifically serve to both *retain*—or reduce the water flow—and to *detain*—or temporarily store the water (Versini et al., 2020). Together, the vegetation, substrate, and additional water storage layer can capture water from rain events and, thus reduce the incidence of flash flooding in urban areas with impermeable soils (Ouldboukhitine et al., 2012; Shafique et al., 2018). The stormwater management potential of GRs can be measured using a simplified water balance model, which considers water inputs (such as precipitation and irrigation) and the drainage water as outputs (Versini et al., 2020). The factors that can influence water retention capacity of GRs are plant species, substrate characteristics (depth and porosity), antecedent moisture conditions, and rainfall volume (Shafique et al., 2018; Versini et al., 2020).

These potential ecosystem services of GRs are affected by both biotic and abiotic design and management practices, such as substrate depth, plant species choice, and irrigation regime. To quantify the impact design and management practices have on potential ecosystem services, we measured GHG emissions, substrate temperatures, and the water balance of 48 extensive GR mesocosms in northeastern Italy during an entire year. Moreover, given a lack of information of GHG fluxes and water balance from GR systems, this work aims to provide data towards bridging this literature gap, solidifying our understanding of GRs as a potential climate change mitigation strategy, and better guiding the decisions of policymakers.

4.2 Materials and Methods

This study was conducted in the University of Padova Experimental Farm “L. Toniolo” located in Legnaro, Padova, Italy (45° 21' 5.82" N, 11° 57' 2.44" E). Data was collected for an entire year, starting April 2022 and until April 2023. The experiment consisted of 48 GR mesocosms in a split-plot design experiment, where each treatment had 3 replicates each. Summer irrigation levels were used as the whole plot treatments, plant species and substrate depths as the sublot treatments. The subplots were arranged in a completely randomized 4x2 factorial design. The plant species treatments were either *Sedum* mixture (Se), cold season grasses (CG; 10% *Poa pratensis* ‘Nublue Plus’ and 90% *Festuca arundinacea* ‘Rhambler’ by weight), warm season grasses (WG; *Cynodon dactylon* ‘Paul 1’), and wildflower mix (WF). Summer irrigation level applied was 1 L m^{-2} day^{-1} or 2 L m^{-2} day^{-1}. Irrigation frequency varied depending on rain events (Table 1). Meteorological data were obtained from the local weather station (500 m from experimental site) managed by the Regional Agency for the Prevention and Environmental Protection of Veneto (ARPA Veneto, by its Italian abbreviation) (https://wwwold.arpa.veneto.it/).

Table 1. Distribution of water inputs (irrigation and rainfall) received per green roof microcosm and cumulative rainfall for each sampling season.

Irrigation level (L m^{-2} day^{-1})	Season	Total irrigation applied (L m^{-2})	Cumulative Rainfall (L m^{-2})	Total water input (L m^{-2})
1	Spring	0	115.2	115.2
	Summer	48	225.0	273.0
	Fall	0	200.2	200.2
	Winter	0	68.4	68.4
2	Spring	0	115.2	115.2
	Summer	96	225.0	321.0
	Fall	0	200.2	200.2
	Winter	0	68.4	68.4

4.2.1 Greenhouse gas (GHG) concentration measurements and flux calculations

Greenhouse gas (CO_2, CH_4, and N_2O) fluxes were measured using a portable Fourier Transform Infrared Spectroscopy (FTIR) analyzer by Gasmet Technologies (The Gasmet™ DX4040) with a static non-stationary chamber technique. The portable FTIR was calibrated before and cleaned after each use with N_2 according to the manufacturer's manual. GHG measurements were taken once a week during the entire monitoring period. A custom-made cylindrical flux chamber was fitted over a PVC collar (200 mm in diameter) to measure the GHG concentrations. The flux chamber had a rubber sheathed aperture for the insertion of the sensor probe and was lined with wind machines to homogenize the air. The concentration data collected was then used to calculate the fluxes following Maucieri et. al. (2016):

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

Here, V is the volume of the chamber, A is the area of the chamber, c is the concentration measured, and t is the time step.

Using the coefficients given in IPCC (2013), the global warming potential of each treatment was calculated as:

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

4.2.2 Substrate temperature measurements

Substrate temperatures were recorded using a handheld soil thermometer three times per day (morning, midday, and evening) once a week. Morning measurements were made at 8:00 – 9:00, midday measurements at 12:00 – 13:00, and evening measurements at 17:00 – 18:00. The handheld soil thermometer was inserted at a depth of about 3 cm from the bottom of the substrate.

4.2.3 Water balance measurements and calculations

The water balance for the GR mesocosms considered only irrigation and rainfall as inputs, and drained water as outputs. Rainfall data was obtained from the ARPAV weather station. Irrigation was applied only during the summer season about 1 – 2 times per week depending on rain events (Table 1). The drainage water collected was weighted after every few rain events, depending on rainfall intensity and duration. With these data, the water balance for each treatment per season was calculated as:

$$H_2O \text{ Balance} = \frac{(irrigation\ applied + rainfall)}{water\ drained} \qquad (3)$$

4.2.4 Statistical Analysis

Data analysis was divided into seasons, where spring was designated as March 21 – June 20, summer was June 21 – September 22, fall was September 23 – December 21, and winter was December 22 – March 20. Statistical analysis was done in R 4.2.2 software. Since GHGs data were not normally distributed, non-parametric tests of Kruskal-Wallis was used to evaluate effect of plant species and Mann-Whitney to evaluate effect of substrate depth and irrigation level on GHG fluxes and global warming potential (GWP). For post-hoc comparisons in the case of significance with Kruskal-Wallis test, Dunn's test with Bonferroni adjustment was used. Data were visualized with boxplots. Kruskal-Wallis and Mann-Whitney were also used to analyze the main effects for the water balance of each season. For the normally distributed temperature data, 3-way ANOVA was done. Given significance of only substrate depth as a main effect with no other interactions, a coefficient of variability was calculated for each treatment. For the coefficient of variability obtained, a 3-way ANOVA was also done. Spearman's correlation was used to evaluate correlations between GHG emissions and temperatures in each season.

4.3 Results

4.3.1 Meteorological data

Meteorological data monitored from April 2022 to April 2023 are represented in Figure 1. In spring, average solar radiation was 21.1 MJ m^{-2}, average wind speed was 1.8 m s^{-1}, average minimum temperature was 11.5 ºC, average maximum temperature was 22.6 ºC. In summer, average solar radiation was 22.8 MJ m^{-2}, average wind speed was 1.8 m s^{-1}, average minimum temperature was 18.5 ºC, average maximum temperature was 30.0 ºC. In fall, average solar radiation was 7.5 MJ m^{-2}, average wind speed was 1.3 m s^{-1}, average minimum temperature was 8.1 ºC, average maximum temperature was 16.6 ºC. In winter, average solar radiation was 7.7 MJ m^{-2}, average wind speed was 1.5 m s^{-1}, average minimum temperature was 2.9 ºC, average maximum temperature was 11.2 ºC. The temperature followed expected trends, peaking in summer and at its minimum in the winter. Wind speed stayed relatively constant throughout the entire year. Solar radiation was substantially reduced in fall and winter by over half compared to spring and summer. The rainfall received by the GRs (Figure 1 and Table 1) was mainly in the late summer and early autumn, with very few rainfalls received in spring and early summer. This created a very dry growing season, particularly evident during the summer months in 2022 and the spring months in 2023. The long term historical averages (1992 – 2022) for minimum temperatures were 10.8 ºC in spring, 16.7 ºC in summer, 6.7 ºC in fall, and 1.2 ºC in winter. Average historical mean temperatures were 15.9 ºC in spring, 22.4 ºC in summer, 10.7 ºC in fall, and 4.9 ºC in winter. For maximum temperatures, the historical average was calculated with data from the years 2010 – 2022 due to a lack of daily values from 1992 – 2009 for this parameter. Historical maximum temperatures were 21.8 ºC in spring, 29.0 ºC in summer, 15.1 ºC in fall, and 9.7 ºC in winter. Historically, cumulative rainfall was 4.4 mm in spring, 4.4 mm in summer, 4.2 mm in fall, and 3.5 mm in winter.

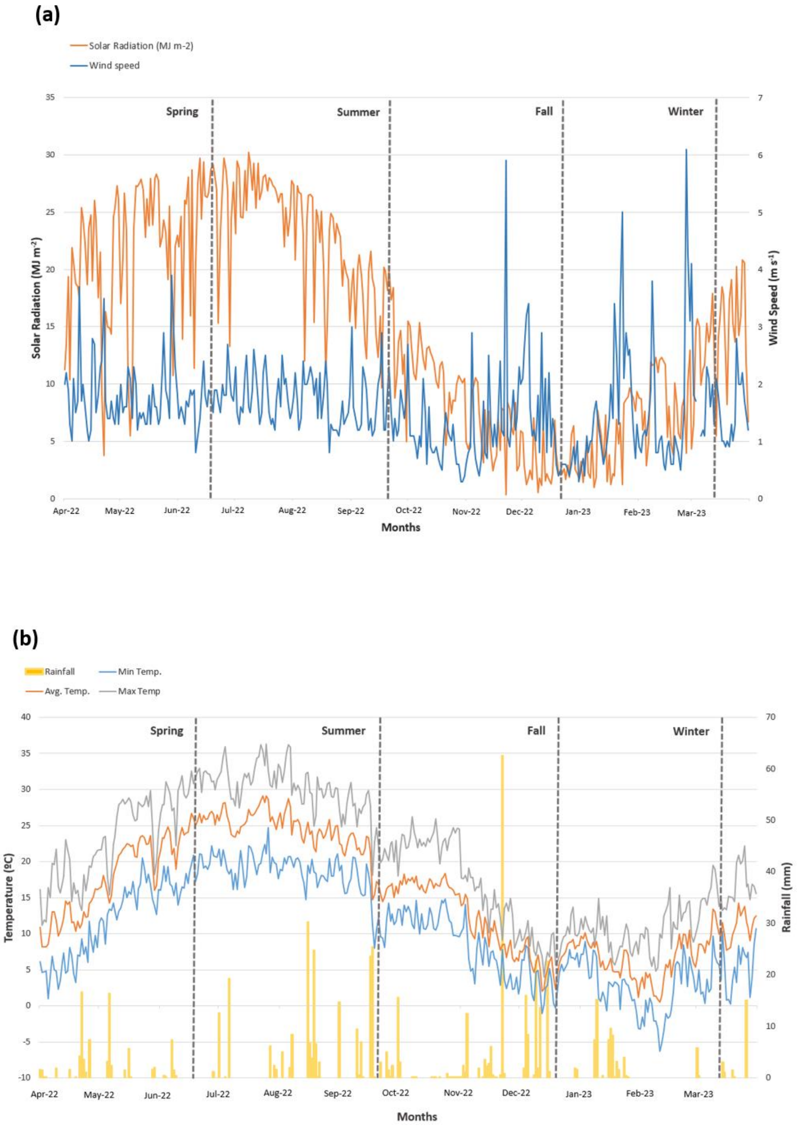


Figure 1. (a) Daily solar radiation (MJ m^{-2}) and wind speed (m s^{-1}) from April 2022 to April 2023 and (b) Daily minimum, average, and maximum temperatures (ºC) and rainfall (mm) from April 2022 to April 2023. Gray lines serve as dividers for each season (spring, summer, fall, and winter).

Greenhouse gas (fluxes) by season

4.3.2 GHG fluxes in spring

The Kruskal-Wallis test yielded significant results for the effect of plant species on CO_2 ($p = 0.001$) (Figure 2) fluxes. In spring, all treatments were net emitters of CO_2, with median values 3.65 mg m^{-2} h^{-1} (CG), 95.32 mg m^{-2} h^{-1} (Se), 116.10 mg m^{-2} h^{-1} (WG), and 275.34 mg m^{-2} h^{-1} (WF). Here, only WF differed significantly from CG, with no other significant differences among treatments. There was no significance of plant species for N_2O (0.00 mg m^{-2} h^{-1}) or CH_4 (0.02 mg m^{-2} h^{-1}). The Mann-Whitney test yielded significant results for the effect of substrate depth for CO_2 ($p < 0.001$) (Figure 3). Both substrate depths showed positive values, where the median CO_2 values were 10.23 mg m^{-2} h^{-1} (8 cm depth) and 308.41 mg m^{-2} h^{-1} (14 cm depth). Spearman's correlation between GHG fluxes and substrate temperature yielded significant results for CO_2 and N_2O but not for CH_4. CO_2 fluxes were positively correlated ($p < 0.0001$) with morning (Spearman R = 0.290), midday (Spearman R = 0.354), and evening (Spearman R = 0.186) temperatures. N_2O showed a negative correlation ($p < 0.05$) with evening (Spearman R = -0.0912) temperatures.

4.3.3 GHG fluxes in summer

The Kruskal-Wallis tested showed significance of plant species for CO_2 ($p < 0.0001$) (Figure 2). All treatments, in summer, were net emitters of CO_2, with median values of 86.31 mg m^{-2} h^{-1} (WG), 268.01 mg m^{-2} h^{-1} (Se), 404.96 mg m^{-2} h^{-1} (CG), and 765.22 mg m^{-2} h^{-1} (WF). There was no significant effect of plant species for CH_4 (mg m^{-2} h^{-1}) or N_2O (-0.23 mg m^{-2} h^{-1}). The Mann-Whitney test yielded significance for substrate depth only for N_2O fluxes ($p < 0.01$) (Figure 4). Both substrate depths were a net sink of N_2O with median values of -0.199 mg m^{-2} h^{-1} (8 cm) and -0.304 mg m^{-2} h^{-1} (14 cm). The Mann-Whitney test also yielded significant results for irrigation level as a control for N_2O fluxes ($p < 0.01$) (Figure 5). Both irrigation levels were also a net sink, with median values of -0.178 mg m^{-2} h^{-1} (1 L m^{-2} day^{-1}) and -0.306 mg m^{-2} h^{-1} (2 L m^{-2} day^{-1}). Spearman's correlation yielded significant results for all GHG fluxes in summer. CO_2 fluxes showed a positive correlation ($p < 0.0001$) with morning (Spearman R = 0.187) and midday temperatures (Spearman R = 0.168). CH_4 showed a positive correlation with morning ($p < 0.05$, Spearman R = 0.110), midday ($p = 0.01$, Spearman R = 0.123), and evening ($p < 0.001$, Spearman R = 0.141). N_2O fluxes showed negative correlation for morning ($p < 0.0001$, Spearman R = -0.222), midday ($p < 0.001$, Spearman R = -0.141), and evening ($p < 0.05$, Spearman R = -0.105) temperatures.

4.3.4 GHG fluxes in fall

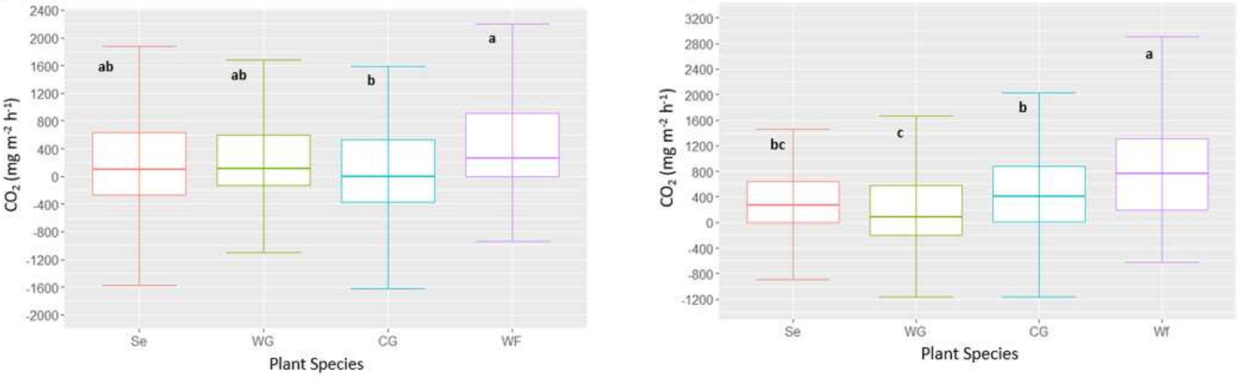
Statistical analysis showed that plant species significantly influenced the CO_2 fluxes ($p < 0.0001$) (Figure 2). Treatments CG (-65.15 mg m^{-2} h^{-1}), WG (-35.94 mg m^{-2} h^{-1}), and WF (-2.21 mg m^{-2} h^{-1}) were net sinks of CO_2, while Se (122.98 mg m^{-2} h^{-1}) was a net source. There was no significance of plant species for CH_4 (-0.07 mg m^{-2} h^{-1}) or N_2O (-0.03 mg m^{-2} h^{-1}). There was no significant effect of substrate depth. However, the Mann-Whitney test yielded significance of irrigation level for CH_4 fluxes ($p = 0.05$), with median values of -0.05 mg m^{-2} h^{-1} (1 L m^{-2} day^{-1}) and -0.09 mg m^{-2} h^{-1} (2 L m^{-2} day^{-1}) (Figure 6). Spearman's correlation yielded significant results for CO_2 and N_2O but not CH_4.

There was positive correlation between CO_2 fluxes with morning ($p < 0.0001$, Spearman R = 0.233), midday ($p < 0.0001$, Spearman R = 0.197), and evening ($p < 0.05$, Spearman R = 0.111) temperatures. N_2O fluxes yielded negative correlation with midday ($p < 0.01$, Spearman R = -0.135) and evening ($p < 0.0001$, Spearman R = -0.186) temperatures.

4.3.5 GHG fluxes in winter

The Kruskal-Wallis test yielded significance ($p < 0.001$) of plant species effect on CO_2 fluxes in winter (Figure 2). All treatments were net sinks of CO_2, with median values of -109.94 mg m^{-2} h^{-1} (CG), -93.91 mg m^{-2} h^{-1} (WF), -29.28 mg m^{-2} h^{-1} (WG), and -9.72 mg m^{-2} h^{-1} (Se). There was no significant effect of plant species for CH_4 (-0.05 mg m^{-2} h^{-1}) or N_2O (0.00 mg m^{-2} h^{-1}). There was no significant effect of substrate depth. However, Mann-Whitney test yielded significance of irrigation level on CO_2 ($p < 0.01$) fluxes (Figure 7). Both irrigation levels had negative values, with median CO_2 fluxes of -83.49 mg m^{-2} h^{-1} (1 L m^{-2} day^{-1}) and -38.19 mg m^{-2} h^{-1} (2 L m^{-2} day^{-1}). Spearman's correlation yielded significant results only for CH_4 fluxes, with a positive correlation with only evening temperatures ($p = 0.01$, Spearman R = 0.105).

(a) Spring (b) Summer



(c) Fall (d) Winter

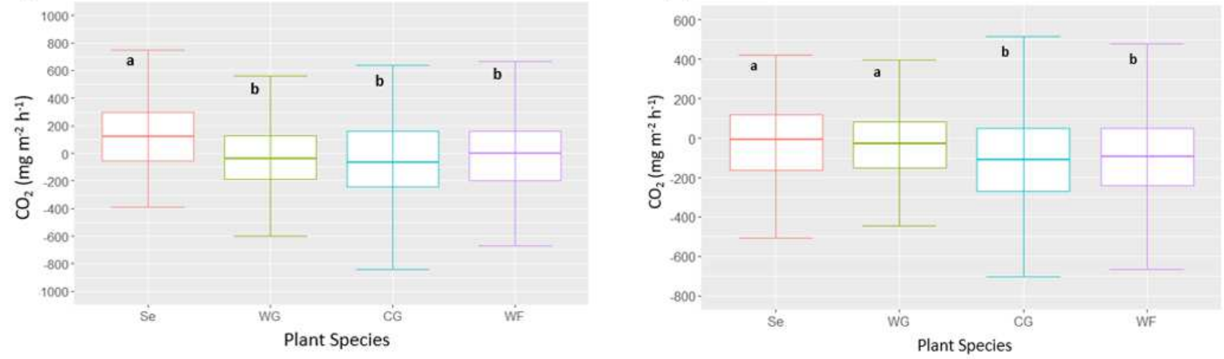


Figure 2. Effect of vegetation type (Sedum spp., Se; warm season grasses, WG; cold season grasses, CG; and wildflowers, WF) in green roof mesocosms on CO$_2$ fluxes during (a) spring, (b) summer, (c) fall, and (d) winter season. Significant differences between treatments are denoted by lowercase letters.

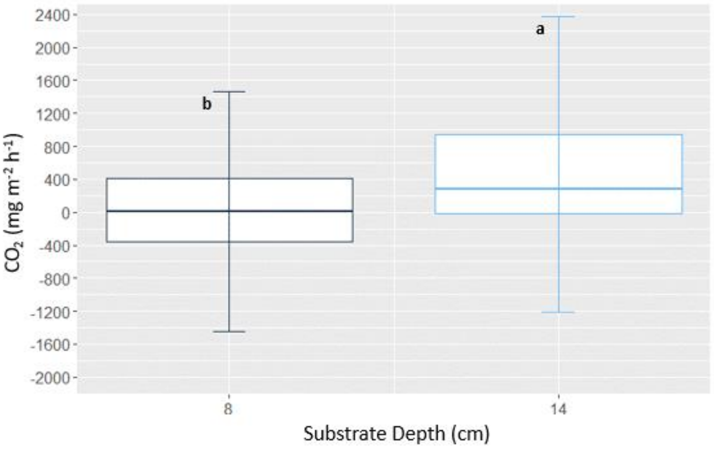


Figure 3. Effect of substrate depth (8 or 14 cm) in green roof mesocosms on CO_2 fluxes during the <u>spring season</u>. Significant differences between the treatments are denoted by lowercase letters.

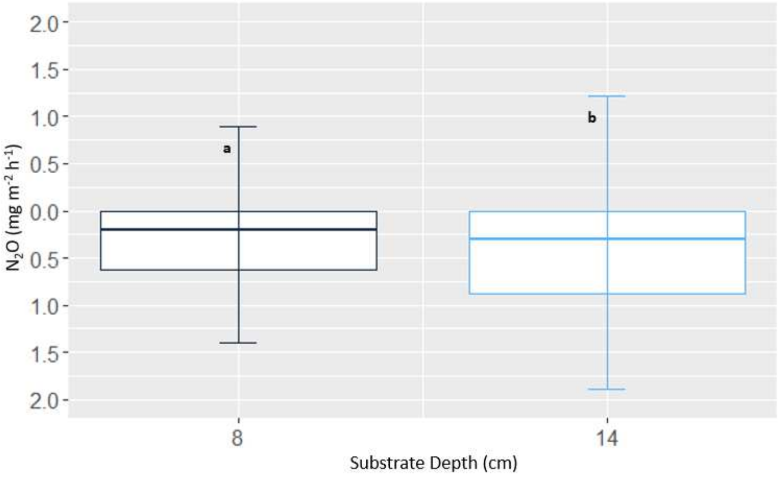


Figure 4. Effect of substrate depth (8 or 14 cm) in green roof mesocosms on N_2O fluxes during the <u>summer season</u>. Significant differences between the treatments are denoted by lowercase letters.

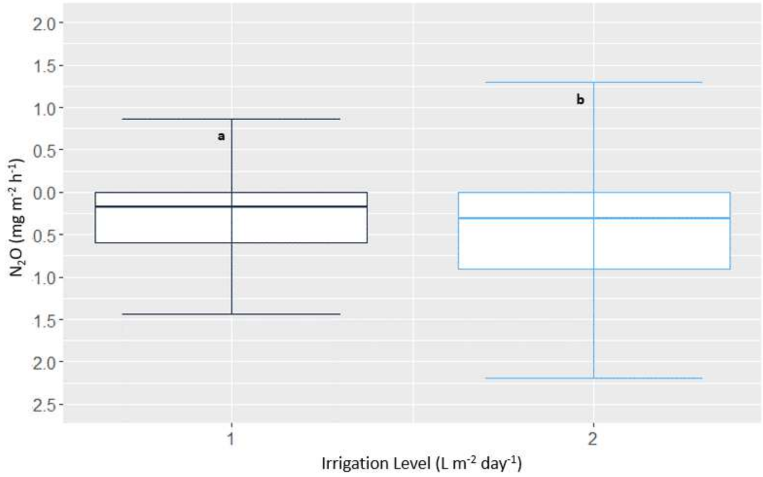


Figure 5. Effect of irrigation level (1 or 2 L m^{-2} day^{-1}) in green roof mesocosms on N_2O fluxes during the summer season. Significant differences between the treatments are denoted by lowercase letters.

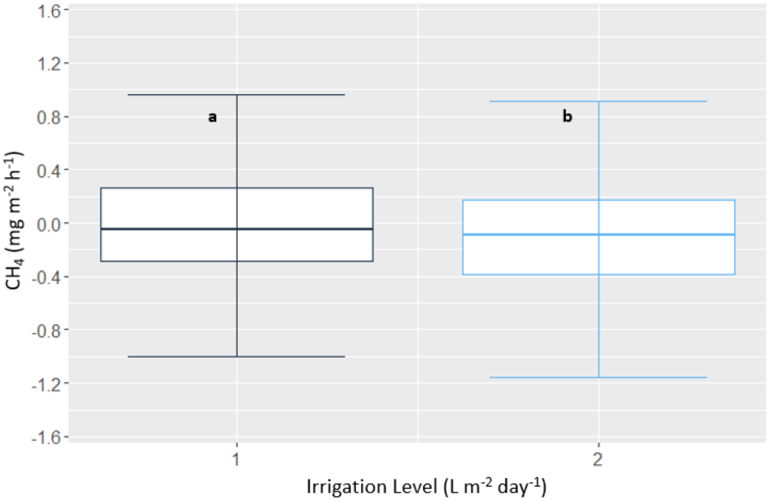


Figure 6. Effect of irrigation level (1 or 2 L m^{-2} day^{-1}) in green roof mesocosms on CH_4 fluxes during the fall season. Significant differences between the treatments are denoted by lowercase letters.

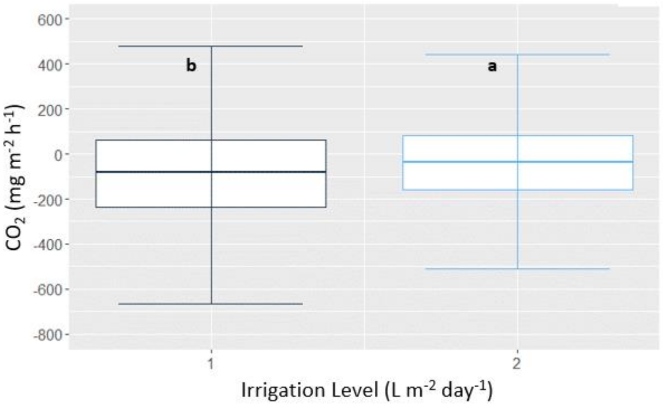


Figure 7. Effect of irrigation level (1 or 2 L m^{-2} day^{-1}) in green roof mesocosms on CO_2 during the winter season. Significant differences between the treatments are denoted by lowercase letters.

4.3.6 Yearly GHG fluxes

On a yearly basis, plant species treatments had median CO_2 fluxes of 74.42 mg m^{-2} h^{-1} (Se), 53.45 mg m^{-2} h^{-1} (WF), 9.15 mg m^{-2} h^{-1} (WG), and -1.99 mg m^{-2} h^{-1} (CG). For substrate depth treatments, the median CO_2 fluxes were 61.04 mg m^{-2} h^{-1} (14 cm) and 6.03 mg m^{-2} h^{-1} (8 cm). Cumulative N_2O and CH_4 median fluxes were 0.00 mg m^{-2} h^{-1} and -0.01 mg m^{-2} h^{-1}, respectively.

Global warming potential (GWP) by season

4.3.7 GWP in spring

Plant species had a significant effect on GWP ($p < 0.0001$) (Figure 8). GWP was positive for all treatments with median values 6.64 mg m^{-2} h^{-1} (CG), 91.97 mg m^{-2} h^{-1} (Se), 155.95 mg m^{-2} h^{-1} (WG), and 269.43 mg m^{-2} h^{-1} (WF). Moreover, depth was also significant for GWP ($p < 0.0001$) (Figure 9) with median values 11.38 mg m^{-2} h^{-1} (8 cm) and 343.10 mg m^{-2} h^{-1} (14 cm).

Spearman’s correlation yielded a significant positive correlation ($p < 0.0001$) for GWP with morning (Spearman R = 0.260), midday (Spearman R = 0.357), and evening (Spearman R = 0.177) temperatures.

4.3.8 GWP in summer

Plant species was a significant affecting factor for GWP ($p < 0.0001$) (Figure 8), with positive median values of 42.50 mg m^{-2} h^{-1} (WG), 185.17 mg m^{-2} h^{-1} (Se), 332.74 mg m^{-2} h^{-1} (CG), and 586.77 mg m^{-2} h^{-1} (WF). Spearman’s correlation showed a positive correlation between GWP and with morning ($p < 0.001$, Spearman R = 0.125) and midday ($p = 0.0001$, Spearman R = 0.162) temperatures.

4.3.9 GWP in fall

Plant species also significantly influence GWP ($p < 0.0001$) in the fall. GWP median values were negative for treatments CG (-55.13 mg m^{-2} h^{-1}), WG (-29.27 mg m^{-2} h^{-1}), and WF (-1.95 mg m^{-2} h^{-1}) and positive for Se (112.39 mg m^{-2} h^{-1}) (Figure 8). GWP showed a significant positive correlation ($p < 0.0001$) with morning (Spearman R = 0.219) and midday (Spearman R =0.177) temperatures.

4.3.10 GWP in winter

Plant species mattered for GWP ($p = 0.0001$), yielding negative GWP median values for all treatments— -124.77 mg m^{-2} h^{-1} (WF), -115.75 mg m^{-2} h^{-1} (CG), -30.49 mg m^{-2} h^{-1} (WG), and -21.53 mg m^{-2} h^{-1} (Se) (Figure 8). Irrigation also mattered for GWP ($p = 0.05$) (Figure 10), with negative median values of -

104.83 mg m^{-2} h^{-1} (1 L m^{-2} day^{-1}) and -41.70 mg m^{-2} h^{-1} (2 L m^{-2} day^{-1}). There was no significant correlation between GWP and substrate temperatures.

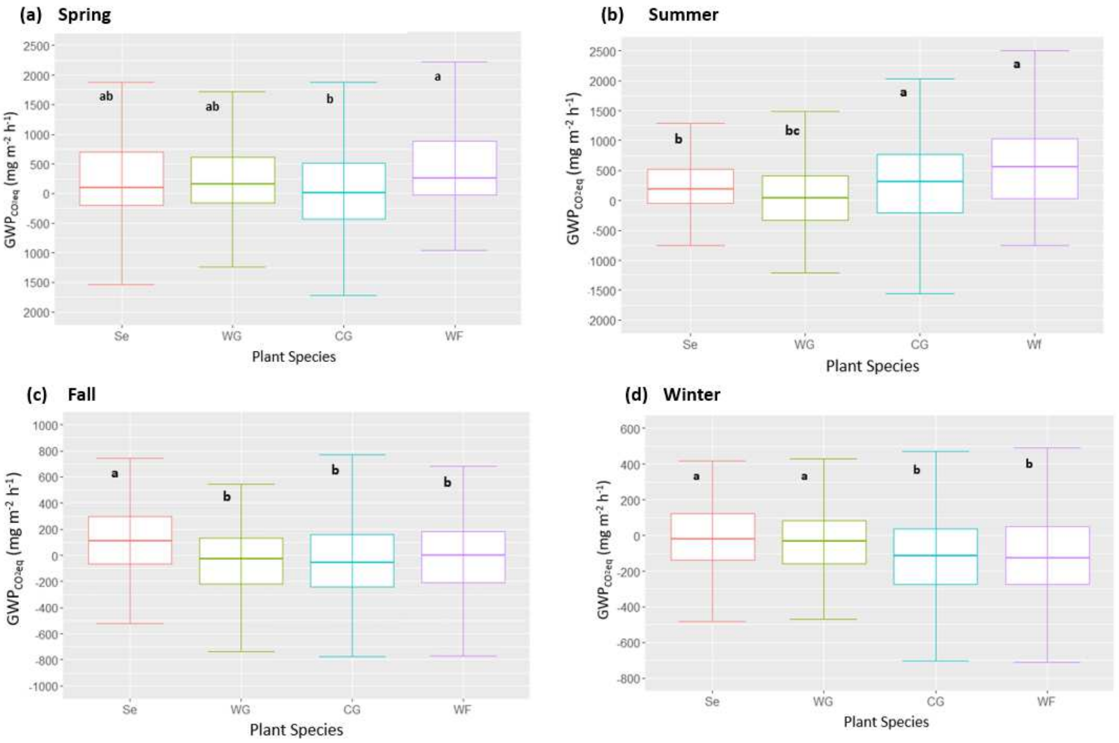


Figure 8. Effect of vegetation type (Sedum spp., Se; warm season grasses, WG; cold season grasses, CG; and wildflowers, WF) in green roof mesocosms on GWP during (a) spring, (b) summer, (c) fall, and (d) winter season. Significant differences between treatments are denoted by lowercase letters.

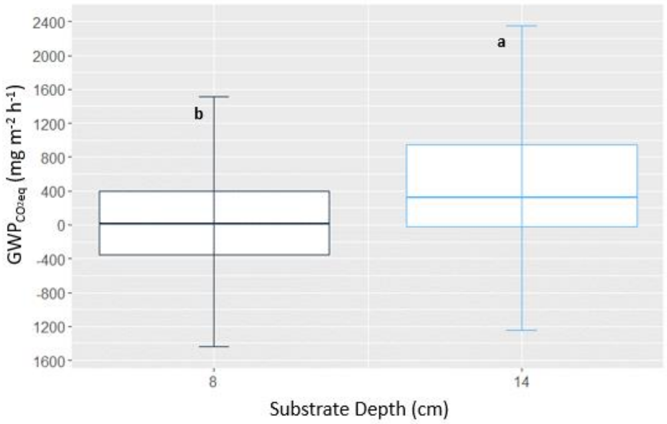


Figure 9. Effect of substrate depth (8 or 14 cm) in green roof mesocosms on GWP fluxes during the spring season. Significant differences between the treatments are denoted by lowercase letters.

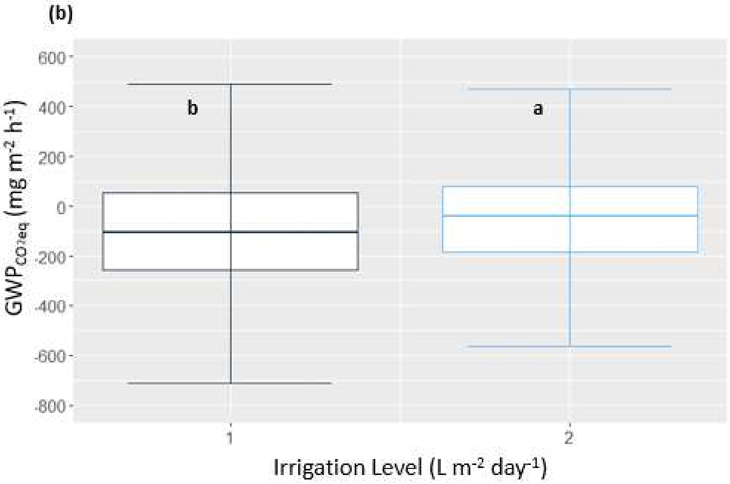


Figure 10. Effect of irrigation level (1 or 2 L m^{-2} day^{-1}) in green roof mesocosms on GWP during the winter season. Significant differences between the treatments are denoted by lowercase letters.

4.3.11 Yearly GWP

The yearly GWP median values for plant species treatments were 50.56 mg m^{-2} h^{-1} (Se), 44.14 mg m^{-2} h^{-1} (WF), 8.77 mg m^{-2} h^{-1} (WG), and -31.06 mg m-

^{2} h^{-1} (CG). For substrate depth, median values were 47.22 mg m^{-2} h^{-1} (14 cm) and -3.85 mg m^{-2} h^{-1} (8 cm).

4.3.12 Substrate temperatures

For all seasons, the only significant control on substrate temperatures was substrate depth with no significant interactions. During the spring, a significant effect of substrate depth was seen for morning ($p = 0.0001$) and evening temperatures ($p = 0.01$). Spring morning temperatures averaged 15.7 ºC (8 cm) and 17.0 (14 cm), while spring evening temperatures averaged 22.5 ºC (8 cm) and 21.4ºC (14 cm). During the summer, substrate depth was only significant for evening temperatures ($p = 0.0001$). Summer evening temperatures averaged 31.2 ºC (8 cm) and 29.9 ºC (14 cm). In the fall, substrate depth was significant only for morning ($p < 0.01$) temperatures. Fall morning temperatures averaged 10.3 ºC (8 cm) and 11.3 ºC (14 cm). In winter, substrate depth mattered for morning ($p < 0.001$) and evening ($p < 0.05$) temperatures. Winter morning temperatures averaged 4.6 ºC (8 cm) and 5.5 ºC (14 cm), while winter evening temperatures averaged 9.7 ºC (8 cm) and 9.0 ºC (14 cm).

The 3-way ANOVA on the temperatures coefficients of variability of each treatment yielded only significant effects in the summer season for the interaction between substrate depth and irrigation level ($p < 0.05$) (Figure 11). Average coefficients of variability were 0.19 (8 cm depth and 1 L m^{-2} day^{-1}), 0.18 (8 cm depth and 2 L m^{-2} day^{-1}), 0.13 (14 cm depth and 1 L m^{-2} day^{-1}), and 0.12 (14 cm depth and 2 L m^{-2} day^{-1}).

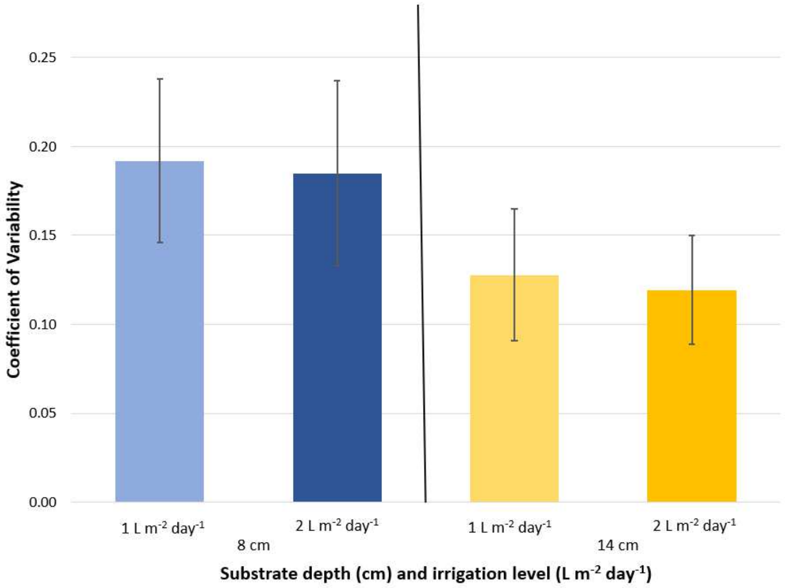


Figure 11. Average values of coefficient of variability showing interaction of irrigation level (1 or 2 L m^{-2} day^{-1}) and substrate depth (cm) in green roof mesocosms on GWP during the summer season. Errors bars represent the standard deviation of each treatment.

4.3.13 Water balance

The yearly water balance is reported in Table 2. For seasonal water balance, plant species was a significant control for spring ($p = 0.01$), summer ($p < 0.001$), fall ($p < 0.001$), and winter ($p < 0.0001$). In spring, summer, and fall, only WF and WG treatments differed significantly. In winter, WF treatments differed significantly from WG and Se treatments, with no other significant differences. In spring, the cumulative water input was 115.2 L m^{-2} whereas the water output median values were 2.87 L m^{-2} (Se), 3.38 L m^{-2} (WF), 3.51 L m^{-2} (CG), and 10.56 L m^{-2} (WG). In summer, with a cumulative water input of 273 L m^{-2} (1 L m^{-2} day^{-1} treatments) and 321 L m^{-2} (2 L m^{-2} day^{-1} treatments). The output median values in summer were 32.25 L m^{-2} (Se), 57.10 L m^{-2} (WF), 73.65 L m^{-2} (WG), and 75.25 L m^{-2} (CG). In fall, the output median values were 136.28 L m^{-2} (WF), 142.88 L m^{-2} (Se), 150.32 L m^{-2} (CG), and 153.69 L m^{-2} (WG) – the input 200.2 L m^{-2}. In winter, a cumulative water input of 68.4 L m^{-2}, determined an output median values of 48.86 L m^{-2} (WF), 51.95 L m^{-2} (CG), 54.32 L m^{-2} (Se), and 55.85 L m^{-2} (WG). Substrate depth was a significant control for spring ($p < 0.0001$), summer ($p < 0.0001$), and fall ($p < 0.0001$). Median values were 1.31 L m^{-2} (14 cm) and 8.61 L m^{-2} (8 cm) in spring, 43.81 L m^{-2} (14 cm) and 77.41 L m^{-2} (8 cm) in summer, and 138.60 L m^{-2} (14 cm) and 152.69 L m^{-2} (8 cm) in fall. There was no significant effect of irrigation level for any season.

Table 2. Cumulative yearly water balance for the 16 different treatment combinations between plant species (Se, *Sedum* spp.; WG, warm season grasses; CG, cold season grasses; and WF, wildflower mix), substrate depth (8 or 14 cm), and irrigation level (1 or 2 L m^{-2} day^{-1}).

Species	**Substrate Depth (cm)**	**Irrigation Level (L m^{-2} day^{-1})**	**Rain (mm)**	**Irrigation (L m^{-2})**	**Water Output (L m^{-2})**	**Water Drained (%)**
Se	8	1	606	128	259	31.9%
		2		206	295	36.4%
	14	1		128	264	32.6%
		2		206	238	29.3%
WG	8	1	606	128	252	34.4%
		2		206	253	34.5%
	14	1		128	268	36.5%
		2		206	274	37.3%
CG	8	1	606	128	252	34.3%
		2		206	235	32.0%
	14	1		128	263	35.9%
		2		206	270	36.8%
WF	8	1	606	128	247	30.4%
		2		206	285	35.1%
	14	1		128	279	34.4%
		2		206	266	32.8%

4.4 Discussion

4.4.1 Effect of plant species on GHG and GWP

We found that plant species was a significant control for CO_2 fluxes during all seasons. In the spring and summer, all treatments were net sources of CO_2, meaning that both autotrophic and heterotrophic respiration were higher than photosynthesis. In terms of the magnitude of CO_2 emissions, the summer emissions were various orders of magnitude higher than spring emissions for all treatments except WG (warm season grasses). Treatments *Sedum* spp., CG (cold season grasses), and WF (wildflowers) showed an increase in emissions from spring to summer of 181%, over 1000%, and 178% respectively. In contrast, WG showed a decrease of 25% from spring to summer. This decrease of WG emissions can be attributed to the fact that the summer is WG's preferred growing conditions, and thus, allowed the plant to photosynthesize and grow better than in the spring. Moreover, the dramatic increase in CO_2 emissions of the other treatments can be explained by a lack of rainfall and higher than average temperatures, which lead to plant death instead of plant growth. A long-term study looking at GHG fluxes from GRs found that drier conditions decreased the ability of extensive GRs to sequester carbon, while increased rainfall heightened it (Konopka et al., 2021). Konopka et al. (2021) attributed this phenomenon to the reduced availability of substrate water, which directly hinders photosynthesis and carbon assimilation. In the fall and winter, almost all treatments were net sinks of CO_2 (with the exception of Se in the fall), meaning that photosynthesis was higher than autotrophic and heterotrophic respiration. Notably, our fall and winter sampling season received the highest amount of rainfall. In our mesocosms, since the summer season was atypically dry, there was colonization of wild species that established during the stress period in summer and took advantage of the higher water availability at the end of summer and beginning of fall to grow. This occurrence could have also helped to increase CO_2 uptake in the treatments.

Overall, wildflower (WF) treatments showed the highest emissions in both spring and summer and were a relatively small carbon sink in fall and winter. Cold season grasses (CG) performed better in the colder seasons of spring, fall, and winter but very poorly in the summer having the second highest emission median values. The opposite was true for warm season grasses (WG), where these treatments had the lowest emissions in the summer.

Sedum spp. (Se) treatments are particularly noteworthy, given that they are one of the most widely used and studied plants in extensive GR systems. In the case of the Se treatments, CO_2 emission values followed a decreasing trend, where *Sedum* spp. had 56% less emissions in fall than in summer, and a 108% reduction from fall to winter, where it was a net sink. Agra et al. (2017) observed this same trend, where *Sedum* spp. had markedly lower emissions in the winter and cold months and increasingly higher emissions as the seasons progressed into the warmer months. Although some studies cite the drought resistance mechanism and capacity for crassulacean acid metabolism (CAM) of *Sedum* spp. as potentially allowing the plant to uptake enough carbon in the colder months to offset the higher emissions in the hotter months (Konopka et al., 2021), other studies cite the opposite and suggest the use of other grass species as a more effective choice for carbon sequestration (Agra et. al., 2017; Shafique et al., 2018). Our results suggest that *Sedum* spp. and WF are the least effective choices, while WG and CG could potentially be an effective strategy for carbon sequestration depending on the climatic conditions. In agreement with our findings, a literature review on studies examining the carbon sequestration potential of *Sedum* spp. as well as other herbaceous and flowering plants in green infrastructure systems found that GRs populated with these plants typically emit less CO_2 than their natural controls, but *Sedum* spp. consistently had the lowest sequestration rates (Charoenkit & Yiemwattana, 2016).

Additionally, plant species mattered for our calculation of the global warming potential (GWP) in all seasons. GWP fluxes for each season followed the same trend as CO_2 emissions. GWP was dominated by CO_2 trends because CO_2 fluxes were of the greatest magnitude, while CH_4 and N_2O, even when significant, had zero or very near zero mg m^{-2} day^{-1} magnitudes.

4.4.2 Effect of substrate depth on GHG and GWP

Substrate depth was a significant control for CO_2 fluxes and GWP in the spring and for N_2O in the summer. In spring, substrate depth treatments were both net sources of CO_2, where the deeper substrate depth (14 cm) had a median value about 30 times higher than the shallower substrate depth (8 cm). GWP followed the same trend. Halim et al. (2022) showed a positive relationship between substrate depth and CO_2 efflux because deeper substrate depths would accumulate a higher amount of organic matter for aerobic decomposition. However, they also highlight that this could potentially be mitigated by promoting greater vegetation growth (Halim et al., 2022). This is particularly relevant to our results given that plant biomass was less than expected due to a lack of rainfall in spring 2023 and heat stress in summer 2022. Potentially, this could have increased the CO_2 efflux from deeper substrate depths treatments. Future measurements of plant biomass and soil organic matter content can better quantify this relationship between carbon cycling, plant growth, and substrate depth.

Our study found that in the summer season, both substrate depths were a net sink of N_2O, with 14 cm treatments that were 1.5 times greater a sink than the 8 cm treatments, still with values close to 0. The effect of substrate depth as a control for N_2O emissions is poorly studied. Moreover, previous literature conflicts on whether GRs are a significant sink or source of N_2O. Mitchell et. al. (2018) found that their GR treatments were net emitters, while Teemusk et al. (2019) found that their GRs had highly variable N_2O fluxes in time with no statistical significance. Both of these studies yielded individual negative values of N_2O fluxes, supporting our findings that under some conditions GRs can potentially serve as N_2O sinks. It is widely accepted that substrate depth influences the nitrogen cycling dynamics of GRs, mainly by exerting control on the hydrology of the system (Buffam & Mitchell, 2015). Our summer sampling season was the hottest and driest of the seasons, meaning that the role of substrate moisture control as a regulator for N_2O fluxes could have been more important compared to other seasons. Unfortunately, we have no data on substrate moisture content.

4.4.3 Effect of summer irrigation level on GHG and GWP

Our results show that summer irrigation level was significant for CO_2 and GWP in the winter, CH_4 in the fall, and N_2O in the summer. For CO_2 fluxes and

GWP in the winter, the lower irrigation treatment (1 L m^{-2} day^{-1}) was two times a greater sink than the higher irrigation treatment (2 L m^{-2} day^{-1}). Since irrigation was applied only in the summer season, this suggests a delayed effect of irrigation. Similarly, Halim et al. (2022) found that irrigated GRs had higher CO_2 efflux than non-irrigated GRs and, notably, their irrigation treatments were phased out before measurements were taken, showing a similar delayed effect of irrigation on CO_2 fluxes. In the case of N_2O fluxes in the summer, the effect of irrigation was not delayed. A higher irrigation level (2 L m^{-2} day^{-1}) yielded a sink about 1.7 times greater than the lower irrigation level (1 L m^{-2} day^{-1}). Since moisture is assumed to be the main control for N_2O emissions and, given that the effect was only seen in the driest season (i.e., summer), this suggests that a higher irrigation level can favorably impact this ecosystem service and reduce N_2O emissions. In support of this result, Livesly et al. (2010) conducted a study on urban lawn systems, which can be considered similar to extensive GRs, and found that higher irrigation levels lead to smaller N_2O emissions.

4.4.4 Effect of substrate depth on substrate temperatures

We found that only substrate depth was a significant control for substrate temperatures in all seasons. The range between evening and morning substrate temperatures was always less in the 14 cm depth treatments than in the 8 cm depth treatments. In spring, fall, and winter the 14 cm depth treatments lessened the temperature oscillation by 2 ºC and, in the summer, by 3 ºC. These results are well supported by literature. Some studies have shown that increasing substrate depth reduces the heat flux entering and exiting the building (Eksi et al., 2017). Moreover, Getter et al. (2011) found that shallower green roofs experience higher temperature fluctuations and, similarly, Nardini et al. (2012) found that deeper substrate depths in extensive GRs decrease the amplitude of daily temperature changes. In the colder months, this thermal insulation can translate to increased heating savings while, in the hotter months, it can translate to increased cooling savings (Eksi et al., 2017). Our results showed that the greatest thermal benefits (i.e., the greatest reduction in thermal oscillation) were obtained during the dry summer season. In support of this, a literature review on GRs found that the hotter and drier a climate is, the more important the effect on urban temperature mitigation (Alexandri & Jones, 2008).

We found that the coefficients of variability were only significantly affected by the interaction between substrate depth and irrigation level treatments in the summer season. The lower level irrigation level and shallower substrate depth treatments yielded the highest variability, while the highest irrigation level and deeper substrate depth yielded the lowest variability. This means that there was higher within treatment variability in the shallower and less irrigated treatments. The importance of substrate depth as a control for variability in substrate temperatures is expected, but the importance of irrigation could have been highlighted during our dry summer season. A review of sustainable irrigation practices for extensive GRs found that in hot, dry summers irrigation was necessary to obtain thermal benefits (Van Mechelen et al., 2015). This could indicate that irrigation becomes important as a control for substrate temperatures beyond a certain threshold. In other words, deeper substrate depth and higher irrigation level highlighted the thermal benefits of our GRs mesocosms and reduced variability among replicates during the hottest season.

4.4.6 Water balance

On a yearly cumulative basis, the percentage of water drained relative to the water inputs received was similar for all treatment combinations, ranging from 29 – 36%. Based on this, our results suggest that all treatments are effective solutions for stormwater management in cities. However, statistical analysis showed some seasonal differences, particularly for the main effects of plant species and substrate depth.

We found that the water balance of GR mesocosms was affected by plant species in all seasons and substrate depth in all seasons except winter. For the effect of plant species, all treatments had the lowest water output in the spring season, increasing in the summer and peaking in the fall, and ultimately lowering again in the winter. Spring water output values were 1 or 2 orders of magnitude less than output values in summer, fall, and winter. This can be explained mainly by the water inputs received. Spring received little rain and no irrigation, while summer also received little rain but was supplemented with irrigation. On the other hand, fall and winter received higher amounts of rainfall. A literature review found that GRs retained all small rain events that were less than 10 mm (Li & Yeung, 2014). This, in conjunction with our results, implies that GRs retain less water with more frequent and intense rain events. Warm season grasses (WG) treatments performed the worst and yielded the highest amount of drained water in all seasons. This suggests that WG was the least effective solution for stormwater management. The best solutions were wildflower (WF) and *Sedum* spp. (Se), given that the drained water from these treatments was less than half the amount from WG treatments. Cold season grasses (CG) treatments performed very similarly to WG treatments, except in spring where CG treatments were more similar to WF and Se. Nagase & Dunnett (2012) studied the performance of various plant species in terms of runoff quantity from GRs and found that grasses performed the best and *Sedum* spp. the worst. The reason for the underperformance of *Sedum* spp. relative to other grass species has been shown to be plant height, where mat-forming plants such as *Sedum* spp. have less water storage capacity per unit surface (Nagase & Dunnet, 2012; Shafique et al., 2018). Moreover, Shafique et al. (2018) conducted a literature review that found that grasses held the most amount of water in GRs and stressed that the differences between plant species were attributed to the different water holding and transpiration capacities. Although these measurements were outside the scope of this study, future research incorporating these measurements can provide a better understanding of between treatment variability.

For the effect of substrate depth on the water balance of spring, summer, and fall, the shallower substrate depths (8 cm) had about double the amount of drained water that the deeper substrate depth (14 cm) had in all seasons. Thus, our results show that a deeper substrate depth is a more efficient solution for stormwater management. A literature review highlighted the role a thicker growing medium—i.e., deeper substrate depth—plays in increasing the moisture holding capacity of GRs and, consequently, their stormwater management ability (Shafique et al., 2018). Few studies have looked at the effect of substrate depth on the stormwater management ability of extensive GRs, but it is widely accepted that substrate depth is a pivotal control for the ecosystem services of GRs through its control on water retention and, consequently, the runoff quantity and runoff peaks (Li & Yeung, 2014).

4.5 Conclusions

Green roof ecosystem services were significantly affected by plant species, substrate depth, and summer irrigation level year-round. Regarding controls on GHG fluxes and GWP, plant species were especially important for CO_2 and GWP. We found that mesocosms populated with cold season grasses (CG) and warm season grasses (WG) could be a potential solution for carbon sequestration during the cold months, while mesocosms with *Sedum* spp. and wildflowers (WF) were much less effective. Substrate depth was only important for CO_2 and GWP fluxes in the spring season, substantially increasing efflux. We hypothesize this dramatic increase could be due to a lack of vegetation cover in our mesocosms caused by heat stress during the summer and spring season. For irrigation level, there was a delayed effect on CO_2 and CH_4 in the winter and fall, respectively, but an immediate effect for N_2O in the summer. Notably, a higher irrigation level yielded a higher N_2O sink which suggests that increasing irrigation level can be a management strategy to increase this ecosystem service from GRs. Regarding controls on substrate temperatures, only substrate depth was a significant control. Deeper substrate depth treatments lessened the fluctuations in substrate temperature which, when taken at a building-scale, can result in increased energy savings in both the summer and winter months. In the summer season, the effect of irrigation level as a control was highlighted, especially in its interaction with substrate depth. Higher irrigation level and deeper substrate depth during the hottest and driest season emphasized the thermal benefits of GRs. This is a valuable insight for the implementation of GRs for mitigation of urban temperatures in the context of climate change and increasing temperature extremes worldwide. For the stormwater management potential of the treatments, plant species and substrate depth were the most relevant controls. On a yearly cumulative basis, the water balance of the treatments showed that they were all effective at retaining water, ranging from 29 – 36%. However, seasonal differences showed that wildflower (WF) and *Sedum* spp. treatments retained the most amount of water in all seasons, while the performance of warm season grasses (WG) and cold season grasses (CG) had greater variability between seasons. Deeper substrate depth treatments were able to retain more water in all seasons.

Ultimately, we did not find a single solution or treatment combination that performed the best for all three ecosystem services. Different treatment combinations were more effective for one given ecosystem service over another. Moreover, these ecosystem services are further affected by local meteorological parameters. This means that when designing and implementing GRs for climate change adaptation in cities, clear and targeted objectives should be defined. In other words, GRs are not a “one-size fits all” solution and careful scientific consideration should guide policymakers in the implementation of them. This implies that there can be trade-offs between ecosystem services that should be evaluated depending on the context and the goal desired. As a case in point, our results found that, in northeastern Italy, *Sedum* spp. was one of the least effective solutions for carbon sequestration but one of the most effective for stormwater retention. All three ecosystem services were significantly affected by both abiotic and biotic design and management parameters year-round, which highlights the need for further research and continuous monitoring on the functioning of these green infrastructures even after implementation.

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5. Conclusion

Our studies found that ecosystem services from blue-green roofs (GR) are affected by plant species choice, substrate depth, and summer irrigation regime. In all monitored seasons, all plant species and substrate depth treatments were a significant control for CO_2 fluxes, where GRs mesocosms were a significant CO_2 source during a particular dry-hot summer season. The summer season had hotter than average temperatures and an irregular distribution of rainfall—i.e., June and July received substantially less rainfall than August and September—which resulted in plant stress and death. This dampened the role of photosynthesis while heightening the role of respiration, leading to higher than expected emissions. On a yearly basis, grass treatments (cold and warm season grasses, CG and WG) had lower CO_2 emissions but, considering data only from the hot summer season, drought tolerant *Sedum* spp. had the lowest CO_2 emissions. GRs were a significant carbon sink in fall and winter, which had more frequent rainfall, and were a source once again in spring, which had scant rainfall. Although these atypical meteorological conditions constrain the replicability of our results, in the broader context of climate change and increasing temperatures, it has important implications when implementing GRs for climate change mitigation in cities. Plant species adapted to drought conditions can be a more efficient solution for carbon sequestration in GRs and higher irrigation levels may be needed to allow for adequate plant growth and carbon uptake via photosynthesis to occur. Moreover, our study also showed that, potentially, GRs can also serve as N_2O sinks with higher irrigation levels especially during drought-induced stress conditions, which highlights a potential novel ecosystem service. Overall, our findings suggest that the most important considerations for implementing GRs with the purpose of GHG reduction are plant choice, foremost, and substrate depth.

The thermal benefits of our GRs were consistent during all monitoring seasons, where the deeper substrate depth treatments reduced the jump from minimum to maximum substrate temperatures compared to the shallower substrate depth treatments. Given that the effect of irrigation and plant species was important only during the hottest month in our dry summer season, this can imply that they are important considerations only above a certain threshold temperature or below a threshold substrate moisture content. Given this, the most significant design and management consideration for GRs designed to provide thermal insulation is substrate depth.

The water balance of our GRs indicated that, on a yearly basis, all vegetation treatments were efficient solutions to reduce water outflow. Moreover, deeper substrate depths led to a higher retention of water in all cases. However, there were seasonal differences among the retention of water of the different plant species treatments—where *Sedum* spp. and wildflower (WF) were more consistent across the seasons than warm and cold season grasses (WG and CG). The most important considerations for designing GRs for stormwater management is vegetation—where, plant species with a wider range of growing conditions or stress tolerance mechanisms are more successful than those circumscribed to either hot or cold seasons—and substrate depth.

Ultimately, GRs can be a beneficial solution towards coupling sustainable urban development and climate change adaptation in cities. There is no one singular solution for all three ecosystem services, meaning that there are trade-offs between them. All design and management parameters evaluated significantly affected the selected ecosystem services, meaning that careful consideration of these parameters should be taken when planning and managing a GR system. Moreover, performance of ecosystem services is linked to the meteorological conditions of the site, especially temperature and rainfall, and can be expected to become even more important with the effects of the ongoing climate change crisis.