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Ecological CO2 Flux of a Green Roof Ecosystem and a Typical Grassland Ecosystem

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Abstract

The Hillside Auditorium Green Roof is a low impact development feature on the University of Arkansas campus. It retains storm water and allows plants living on the roof to take up and transpire the water. Green roofs work to mimic natural ecosystems in urban environments. A key property is ecosystem respiration, which plays a large role in the global carbon cycle and is an important biologic activity indicator. The ecosystem respiration of Hillside Auditorium Green Roof was compared to a typical grassland ecosystem at the University of Arkansas farm to determine how closely the green roof is able to mimic this ecosystem. The CO_2 flux was compared to multiple parameters, such as soil temperature, soil moisture content, soil organic matter content, and amount of vegetation in testing area. The CO_2 flux was found to have a positive relation with soil temperature on the green roof. There was little correlation between CO_2 flux and soil moisture content on the green roof. There was a significant relationship between the CO_2 flux and soil moisture content at the BENG Lab. In theory, increased amounts of organic matter will increase the flux of CO_2 from the soil; however, the two study locations were found to have similar organic matter contents, and a conclusion could not be drawn if amount of organic matter caused a higher flux rate or not. The amount of vegetation in the study area will increase the amount of respiration and therefore increase the CO_2 flux. Overall, the green roof had statistically higher rates of CO_2 flux during the spring season.

Introduction

Green roofs are low impact development (LID) features built on roofs of flat or slightly-sloped roofs. LID features in an urban watershed work to retain and infiltrate stormwater close to its source (Bhaskar et al., 2016). Green roofs specifically retain water and allow evapotranspiration of the water back into the atmosphere. Improved water cycling helps alleviate the stress on city storm water ways and the local stream and rivers. Green roofs also contribute other ecosystem services, defined as the benefits humankind derive from the ecosystem (Jax et al., 2013), including the insulation of buildings, release of oxygen, aiding in reducing the urban heat island effect, and some can grow food.

Through these ecosystem services, green roofs are able to mimic natural ecosystems. Green roofs can also conduct other ecosystem benefits, such as provide habitat to plants, insects, and other wildlife. One key process of ecosystems is respiration, as it is related to ecosystem productivity, soil fertility, and regional and global carbon cycles (Luo and Zhou, 2006). Ecosystem respiration is the combination of plant and soil respiration (Bitzer, 2006).

The research goals are to determine the similarity between a green roof and a typical grassland ecosystem through studying ecosystem respiration, using a LiCOR LI-8100 Infrared Gas Analyzer. The research determines the ecosystem respiration of the Hillside Auditorium green roof on the University of Arkansas campus, as well as a typical grassy lawn behind the Biological Engineering Design Laboratory (BENG lab) at the University of Arkansas farm on Highway 112 in Fayetteville, Ark. Soil temperature, moisture, and bulk density were measured to aid in the determination of site similarity.

Literature Review

Green roofs

Green roofs are built with many benefits in mind. Some of these include stormwater mitigation, passive cooling of buildings, increased biodiversity, ecological benefits, sociological benefits, and economic benefits (Magill, 2011). There are two main types of green roofs: intensive and extensive. Magill (2011) describes the intensive system as a green roof with a substrate layer greater than 150 mm and the extensive system as one with a substrate layer of less than 150 mm. An intensive system can sustain more diverse plants and crops, such as rooftop gardens for food production or small trees. However, extensive systems can be installed on more roofs due to their lighter weight.

When constructing a green roof, Brady and Weil (2017) state that soil bulk density is a crucial part of the design of the roof. The mass of soil must be minimized so that a cost-effective structure can be designed with sufficient strength to carry the soil load. There are several different options for green roof planting media, according to Brady and Weil (2017). These authors state that a natural soil, such as a well-aggregated loam or peat soil, could be used if the bulk density is low enough. However, artificial planting media is often used, and Magill (2011) recommends an engineered planting media for green roofs. These medias offer a compromise between water retention and drainage. If the roof retains too much water, the load may become too heavy for the building structure. If the roof drains too much water, the plant will not be able to survive. Many green roofs use a kiln-expanded substrate, either expanded shale, clay, or slate (Magill, 2011). The original mineral soil is heated in a kiln to about 1150°C. This heating causes the formation of vesicles, which create a large surface area for the bonding of water while increasing air-filled pore space. Increasing the pore space will reduce the weight of the planting media; however, Brady and Weil (2017) warn not to make the media too light or it may require a surface netting system to prevent wind erosion.

Green roof vegetation is often designed as a monoculture. This planting helps simplify the design and prioritizes efficiency over ecological complexity. Grasses in the *Sedum* genus are often used (Lundholm, 2015; Magill, 2011) due to their ability to survive in many ecologic conditions. However, having a mixture of plant species on a green roof will help the roof better perform the duties it was built to carry out. Lundholm (2015) shows evidence for positive relationships between species richness and ecosystem functioning through their research on a green roof on the Saint Mary's University campus in Halifax, Nova Scotia. Some species were able to control substrate temperature, even raising the minimum temperature of the substrate nearly 30% during the winter. Other plant species were able to help the roof retain a larger amount of stormwater, as compared to the control. With a more diverse ecosystem, a green roof is better able to mimic natural ecosystems, which are very rarely monocultures.

Ecosystem respiration

Ecosystem respiration is the second largest terrestrial carbon flux (Mukhopadhyay et al., 2014). Luo and Zhou (2006) divide ecosystem respiration into two parts: above-ground plant respiration and soil respiration. Soil respiration is the respiration of underground plant materials and well as microorganism respiration. Soil respiration has been shown to make up 55-85% of the overall ecosystem respiration (Knohl et al., 2007). Mukhopadhyay et al. (2014) state that soil CO_2 flux has the potential to be used as an indicator of ecosystem processes. These processes can include metabolic activity in the soil, persistence and decomposition of plant residue in soil, and conversion of soil organic carbon to atmospheric CO_2. Luo and Zhou (2006) also relate soil CO_2 flux to gross primary production, net primary production, and net ecosystem production.

The CO_2 efflux measured at the soil surface can be considered equal to soil respiration when CO_2 production and transport are at a steady state (Luo and Zhou, 2006). One situation in which CO_2 production may not be at a steady state with CO_2 transport is during rain or irrigation events. The water drives CO_2 in the soil air space into the atmosphere. After the watering, CO_2 produced by soil organisms

is partially stored in the soil to rebuild the CO_2 concentration gradient. In the absence of major disturbances, the rate of CO_2 production in the soil is indistinguishable from the rate of CO_2 efflux at the soil surface on a daily or longer time scale. However, CO_2 efflux rates measured at a shorter time scale may not be equivalent to the rate of soil respiration.

Luo and Zhou (2006) emphasize the importance of tracking soil respiration, because the carbon pool in the soil is approximately four times the atmospheric carbon pool. Thus, a small change in soil respiration could seriously alter the balance of the atmospheric CO_2 levels. Due to the difference in CO_2 concentrations between the soil and the atmosphere, any measurement that disturbs the soil could result in major errors. The most popular method for respiration studies is the Closed Dynamic Chamber (CDC) with an infrared gas analyzer (IRGA). To determine respiration rate, IRGA measures the increase of CO_2 in a chamber over time. The rate of increase is proportional to the soil CO_2 efflux, using the following equation:

$$F = \frac{(c_f - c_i) * V}{\Delta t * A}$$

Where: c_f = final CO_2 concentration

c_i = initial CO_2 concentration

V = system volume

Δt = time between two measurement points

A = soil surface area covered by the chamber

Luo and Zhou (2006) recommend installing the soil collars once at the beginning of the study and leave them in place for the duration of the study. These collars help the machine by sealing the area to be studied. When conducting soil CO_2 flux experiments, Luo and Zhou (2006) remind researchers that a soil collar exactly the diameter of the chamber must be used, and it should be buried a few centimeters into the soil to avoid CO_2 leakage. During the experiment, air is pumped from the chamber to the IRGA to analyze. Luo and Zhou (2006) also mention that the vegetation in the collar should be trimmed 1 to 2 days before measurements if soil flux readings are the end goal. On the contrary, Knohl

et al. (2007) conducted a study to determine the ecosystem respiration of a beech forest, so they did not require the clipping of vegetation during the test. Yu et al. (2017) conducted a laboratory experiment on switchgrass soil respiration. They placed collars where there was no visible vegetation, but the root system was still intact. They also placed a collar to block all roots and used the collar to measure only microbial respiration.

Many studies have focused on CO_2 flux from forests, grasslands, farmlands, and other ecosystems (Knohl et al., 2007; Mukhopadhyay et al., 2014; Flowers, 2016). One study measured the CO_2 flux from three green roofs in Brisbane, Queensland (Muller et al., 2014). The age of the green roofs varied from 1-4 years old, and all had a planting media made with loam and sand with mulch. Muller et al. (2014) found a significant positive relationship between soil temperature and soil CO_2 respiration. The green roofs had a minimum CO_2 flux of 4 µmol m^{-2} s^{-1} and a maximum value of 36 µmol m^{-2} s^{-1}, with an average around 8 µmol m^{-2} s^{-1}. However, there have been no studies conducted comparing a green roof ecosystem to a natural or typical ecosystem in terms of the ecosystem respiration.

Methods

Study Site

The study sites of this experiment were at the mowed lawn behind the BENG lab and on the green roof of Hillside Auditorium on the University of Arkansas campus. The Hillside Auditorium green roof was chosen to better understand how the green roof functions. The BENG lab site was chosen because the field behind the building contains a similar ecosystem to the green roof. The sites contain similar vegetation, have similar weather patterns, and were easy to access. The NRCS Web Soil Survey (2017) states that the field behind the BENG Lab contains silt loam and gravely silt loam. The green roof contains an artificial planting media, made up of 80% expanded clay and 20% mushroom compost (Rogers, 2011).

Soil Study

To determine the bulk density and other physical properties of the planting media (PM) and soil, both sites were sampled on April 3rd, 2019. To begin, 10 soil tins and their lids were weighed to determine the empty weight. Then the soil at the BENG Lab and the PM at the green roof were sampled. Five soil samples were taken at each site.

During the sampling process, 2 cm of soil was cleared from the surface to remove plant matter and some root matter. The PM of the green roof is 15 cm deep, so access to a deeper soil sample was not available. The depth was kept constant for the sampling at the BENG Lab site. Once the plant matter was cleared, a 6 cm diameter x 5 cm tall soil ring was placed on the soil surface and hammered into the ground. When the ring was flush with the soil surface, the trowel was used to carefully extract the ring. A soil knife was used to remove any excess soil from the bottom of the ring, and the sides were cleaned. The sample was moved into a labeled soil tin, using a screwdriver to scrape the inside of the ring to ensure all sampled soil was moved into the tin. A lid was placed on the tin to reduce evaporative water losses between the time the sample was collected and when the sample was weighed.

After collecting the wet weight of the soil samples, the lids were removed, and the samples were dried for 72 hours at 65°C. Traditionally, soil is dried at 105°C for 24 hours or until the weight of the sample no longer changes. Since the green roof planting media is 20% mushroom compost, a lower temperature and longer time period were used to ensure that none of the organic matter was lost to ignition. The oven was allowed to come to temperature and equilibrate for 24 hours before the samples were introduced. When the samples were dry, the lids were replaced during transport to the scale to avoid any humidity in the air being absorbed by the soil sample. The soil tins were weighed, and the dry weight was calculated. The bulk density of the samples was calculated using the following equation (Brady and Weil, 2017):

$$Bulk\ Density = \frac{Weight\ of\ oven\ dry\ soil}{Volume\ of\ soil\ (solid\ \ + pores)}$$

To find the volumetric water content of the soil, the following equation is used (Brady and Weil, 2017):

$$Volumetric\ water\ content = \frac{mass\ of\ water}{mass\ of\ oven\ dry\ soil} * bulk\ density$$

To determine the amount of organic matter in the soil, a loss-on-ignition test (LOI) was conducted. Each of the oven dried soil samples (10 g) was measured into a crucible. The crucibles and soil were placed in a furnace at 450°C for 4.5 hours. After the furnace cycle had finished, the samples were reweighed to determine the amount lost, and the percent organic matter was calculated using the following equation (Brady & Weil, 2017):

$$\%\ organic\ matter = \frac{mass\ oven\ dry\ soil - mass\ ash}{mass\ oven\ dry\ soil} * 100\%$$

Ecosystem Respiration

Ecosystem respiration data were collected during the spring of 2019. The data were collected at six points at the BENG lab and at six points on the green roof using a LI-8100 Infrared Gas Analyzer (LiCOR, Inc.). Three trials were conducted at each of the two sites. The first trial was conducted in March of 2019. The BENG lab and green roof were sampled March 25th and 27th, respectively. The second and third trials were conducted on April 3rd and April 8th. At each of the 12 sampling points, a 20.3 cm PVC soil collar was inserted 2-4 cm into the soil. The collars were left to equilibrate for one week before the sampling began. Figures 1 and 2 show the placement of the collars at the BENG lab and the green roof, respectively.

Figure 1. Placement of soil collars on the Hillside Auditorium green roof. Photo adapted from Google Earth (accessed April 15, 2019).

Figure 2. Placement of soil collars at the BENG lab. Photo adapted from Google Earth (accessed April 15, 2019).

Using the LI-8100, three observations were taken at each of the soil collars during each trial. Each observation started with a pre-purge of 1 minute, observed the respiration for 3 minutes, and ended with a post-purge of 45 seconds. During the observations, a temperature probe and a soil moisture probe were connected to the LI-8100 and placed in the soil next to the collar.

Results

Soil Study

The calculated bulk density of soil samples analyzed from the field behind the BENG lab ranged from 1.48 to 1.71 g/cm^3 (table 1). The average value was found to be 1.63 g/cm^3 with a standard deviation of 0.11 g/cm^3. Next, samples were analyzed from the green roof. The calculated bulk density ranged from 1.02 to 1.20 g/cm^3. The average value was found to be 1.12 g/cm^3 with a standard deviation of 0.09 g/cm^3 (table 2).

Organic matter determined by the loss-on-ignition test revealed that soil from the field behind the BENG lab had an average soil organic matter (SOM) content of 4.40% with a standard deviation of 0.70% (table 1). The samples ranged from 3.79% to 5.30%. The samples from the green roof had an average percent of soil organic matter (SOM) of 4.57% with a standard deviation of 1.06% (table 2). The samples ranged from 3.20% to 5.50%.

When examining the data collected by the LI-8100, the soil moisture readings appeared to be abnormally high. The soil moisture sensor readings were compared to the volumetric water content (VWC) calculated from the soil samples taken on the same day (tables 1 and 2). The two VWC measurements were compared with a linear regression, and a calibration equation was calculated. The calibration equation was found to be: VWC = 0.1723*(sensor reading) + 0.2883 (figure 3).

Table 1. Soil properties of the BENG Lab soil as of April 8th, 2019.

Parameter	n	Minimum	Maximum	Mean	Std. Deviation
Bulk density (g/cm^3)	5	1.48	1.71	1.63	0.11
SOM (%)	4	3.79	5.30	4.40	0.70
VWC (probe) (m^3/m^3)	5	0.58	0.78	0.72	0.09
VWC (calculated) (m^3/m^3)	5	0.39	0.46	0.42	0.03

Table 2. Soil properties of the Green Roof planting media as of April 8th, 2019.

Parameter	n	Minimum	Maximum	Mean	Std. Deviation
Bulk density (g/cm^3)	5	1.02	1.20	1.12	0.09
SOM (%)	4	3.20	5.50	4.57	1.06
VWC (probe) (m^3/m^3)	4	0.30	0.59	0.46	0.12
VWC (calculated) (m^3/m^3)	4	0.34	0.36	0.35	0.01

Table 3. Soil properties of the BENG Lab and the Green Roof planting media, statistically compared.

Sample Location	Bulk Density (SD) (g/cm^3)	% SOM (SD)	VWC (SD) (m^3/m^3)
BENG Lab	1.63 (0.11)	4.40 (0.70)	0.42 (0.03)
Green Roof	1.12 (0.09)	4.57 (1.06)	0.35 (0.01)
p-value (α = 0.05)	3.9E-5	0.79	2.4E-3

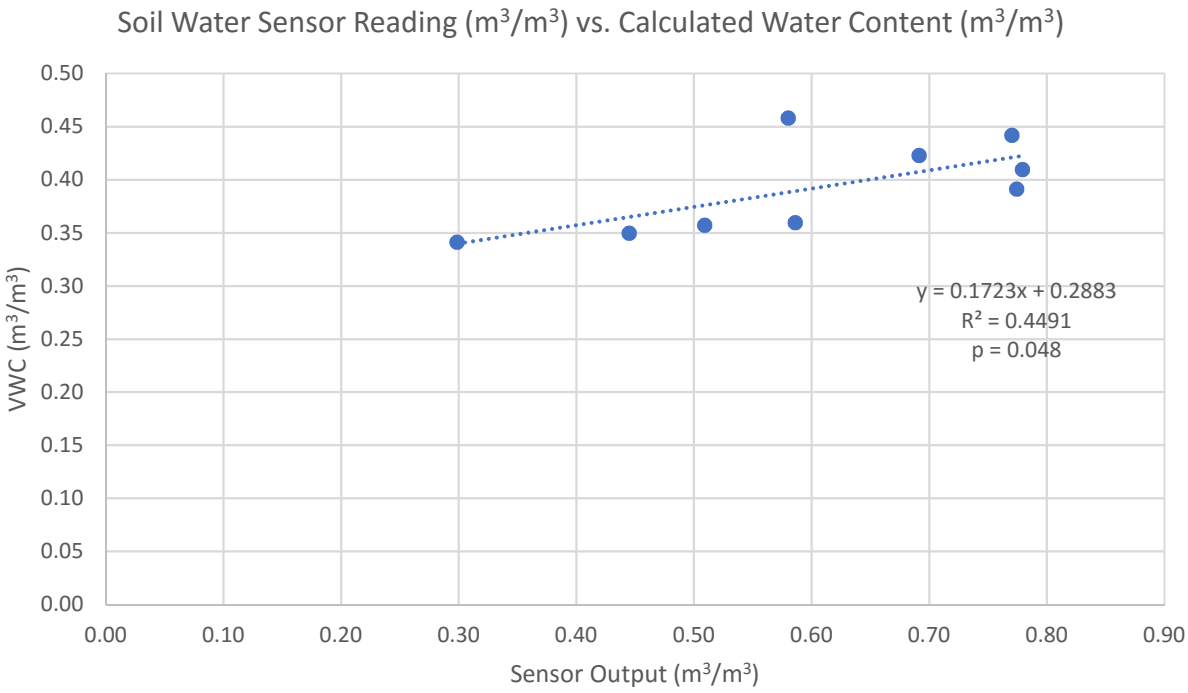


Figure 3. Calibration curve for the soil moisture sensor.

A box and whisker plot (figure 4) was created to show the median and quartiles of the data collected during each of the six trials. At the BENG lab, the median CO_2 efflux was found to be 2.33 µmol m^{-2} s^{-1} on March 25th, 3.72 µmol m^{-2} s^{-1} on April 3rd, and 6.29 µmol m^{-2} s^{-1} on April 8th. On the Green Roof, the median CO_2 efflux was found to be 6.04 µmol m^{-2} s^{-1} on March 27th, 6.17 µmol m^{-2} s^{-1} on April 3rd, and 11.61 µmol m^{-2} s^{-1} on April 8th.

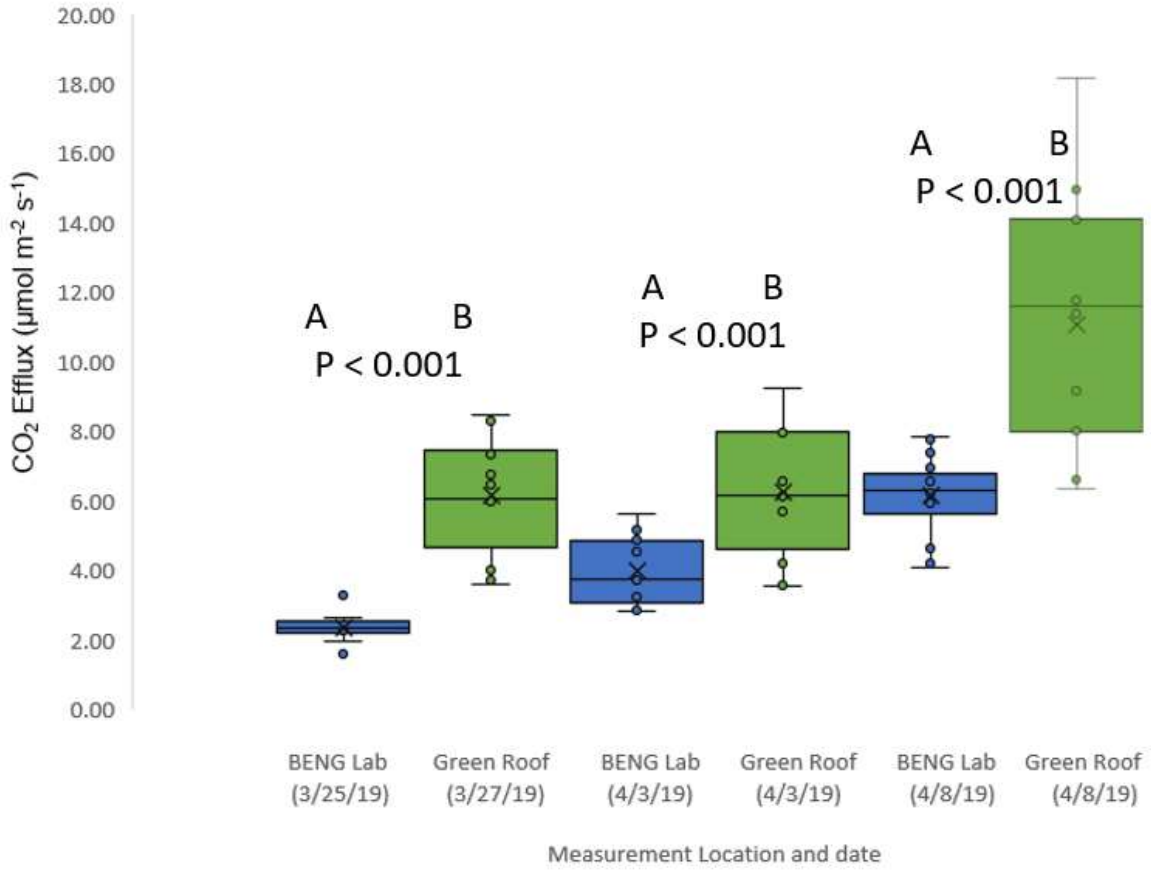
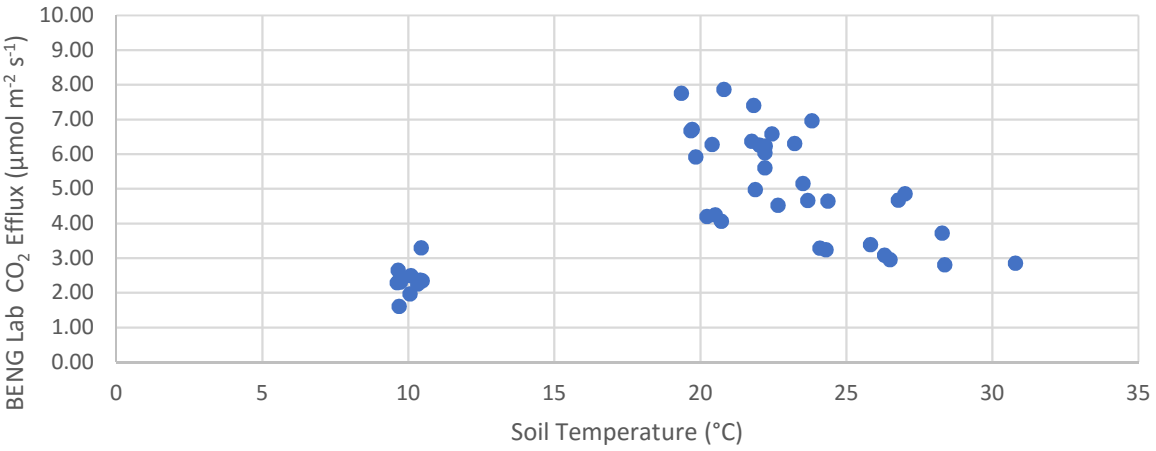
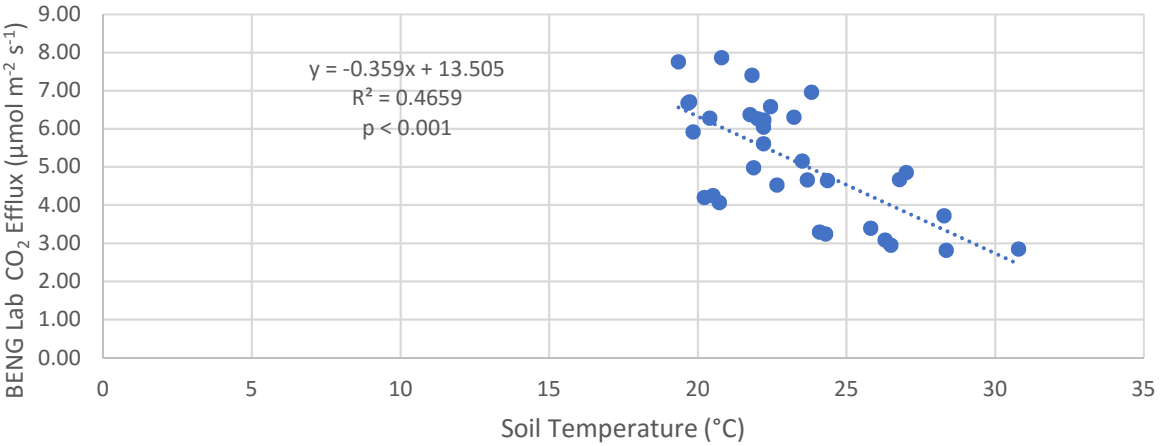


Figure 4. Box and whisker plot showing the quartiles of CO_2 efflux from each sample site. The circles represent the collected data points, and the x's represent the average value of the data set.

Both of the locations' collected data was graphed and compared using a linear regression. An exponential relationship was also considered. However, it returned a lower R^2 value than the linear regression. The data from the BENG Lab contained a gap of 10°C (figure 5.A), therefore a linear regression was not appropriate. A linear regression was run on the clustered data, independent of the outlier set (figure 5.B). The CO_2 flux at the BENG Lab showed an inverse relationship with soil temperature, with an R^2 of 0.47. The CO_2 efflux on the Green Roof had a direct relationship with soil temperature, with an R^2 value of 0.34 (figure 5.C).



A.



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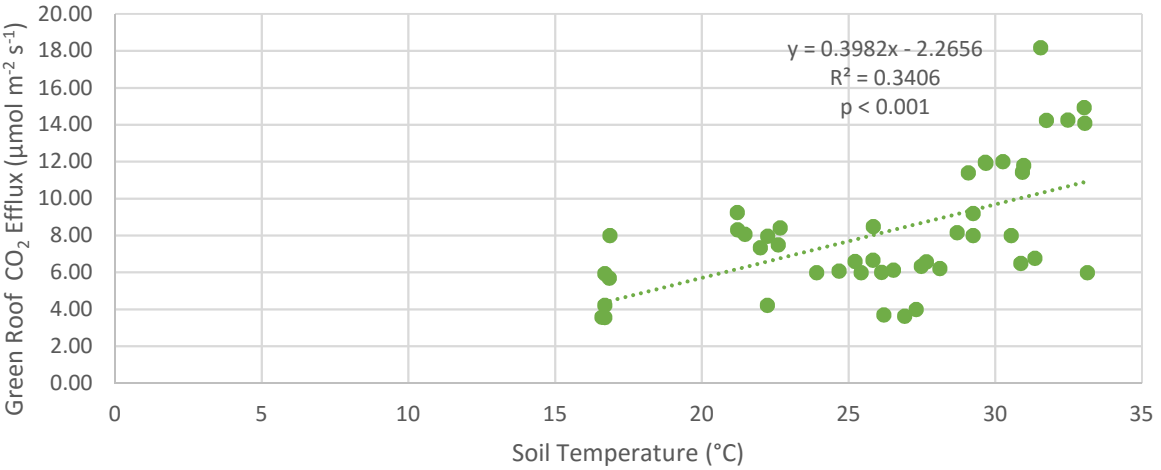
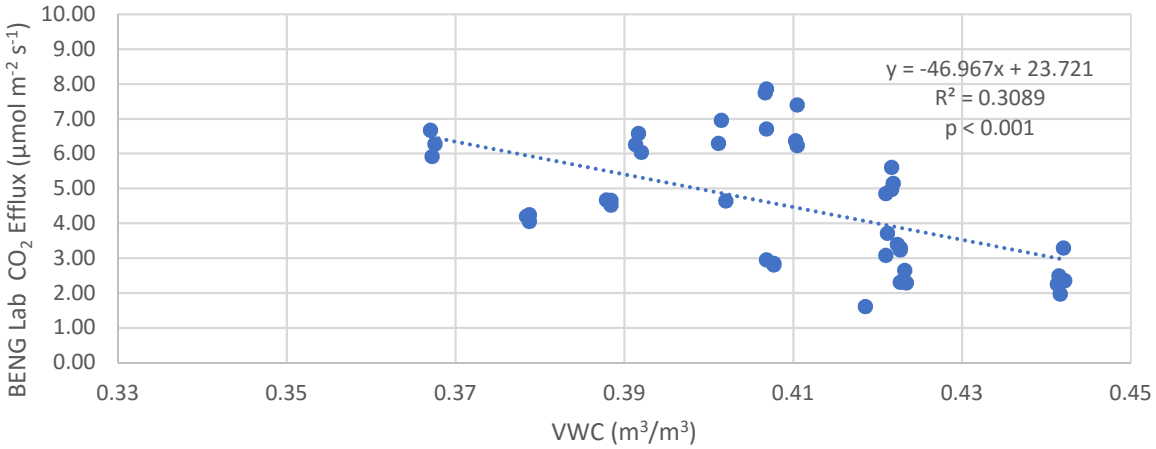


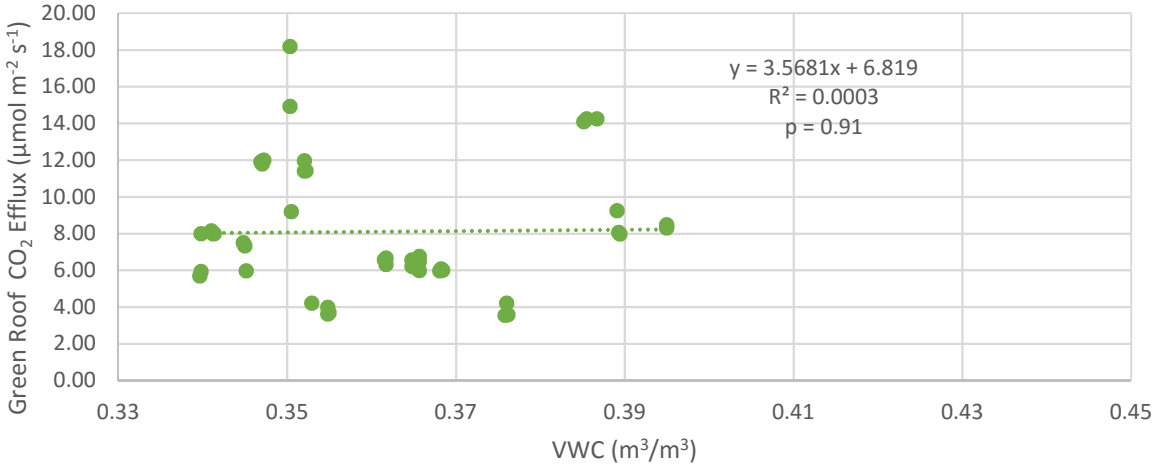
C.

Figure 5. A. CO_2 flux compared to soil temperature at the BENG Lab. Regression not included due to the gap in the data. B. CO_2 flux compared to soil temperature at the BENG Lab without outliers. C. CO_2 flux compared to soil temperature on the Green roof.

The CO_2 efflux at the BENG Lab site showed an inverse relationship to soil moisture content, with an R^2 of 0.31. The CO_2 efflux on the Green roof showed little correlation to the soil moisture content, having an R^2 value of 0.0003 and a p-value of <0.91 (figure 6).



A.



B.

Figure 6. A. CO_2 flux compared to soil moisture at the BENG Lab. B. CO_2 flux compared to soil moisture on the Green roof.

The soil collars were also compared by the amount of vegetation growing in each one. Photos of each collar were taken on April 14th (figure 7).

Figure 7. i. BENG Lab 1

Figure 7. ii. BENG Lab 2

Figure 7. iii. BENG Lab 3

Figure 7. iv. BENG Lab 4

Figure 7. v. BENG Lab 5

Figure 7. vi. BENG Lab 6

Figure 7. vii. Green Roof 1

Figure 7. viii. Green Roof 2

Figure 7. ix. Green Roof 3

Figure 7. x. Green Roof 4

Figure 7. xi. Green Roof 5

Figure 7. xii. Green Roof 6

Figure 7. Vegetation within the 12 soil collars, taken on April 14, 2019.

The vegetation was compared to the average CO_2 flux of each soil collar on April 8th, which is the closest flux measurement to the date the photos were taken (figure 8). Of the collars placed at the BENG Lab, collar 6 had a smaller amount of vegetation than the other collars. It also has the least amount of CO_2 flux. On the green roof, collar 3 had the least vegetation and the smallest CO_2 flux. For most collars, the CO_2 flux had a small variance. At the BENG Lab, the readings between collars did not appear to vary as much as the readings across the green roof. This could be partially due to the uniformity of plant cover and species at the BENG Lab. While this analysis is qualitative, it suggests a possible positive relationship between vegetation cover and flux that could be explored in a further study.

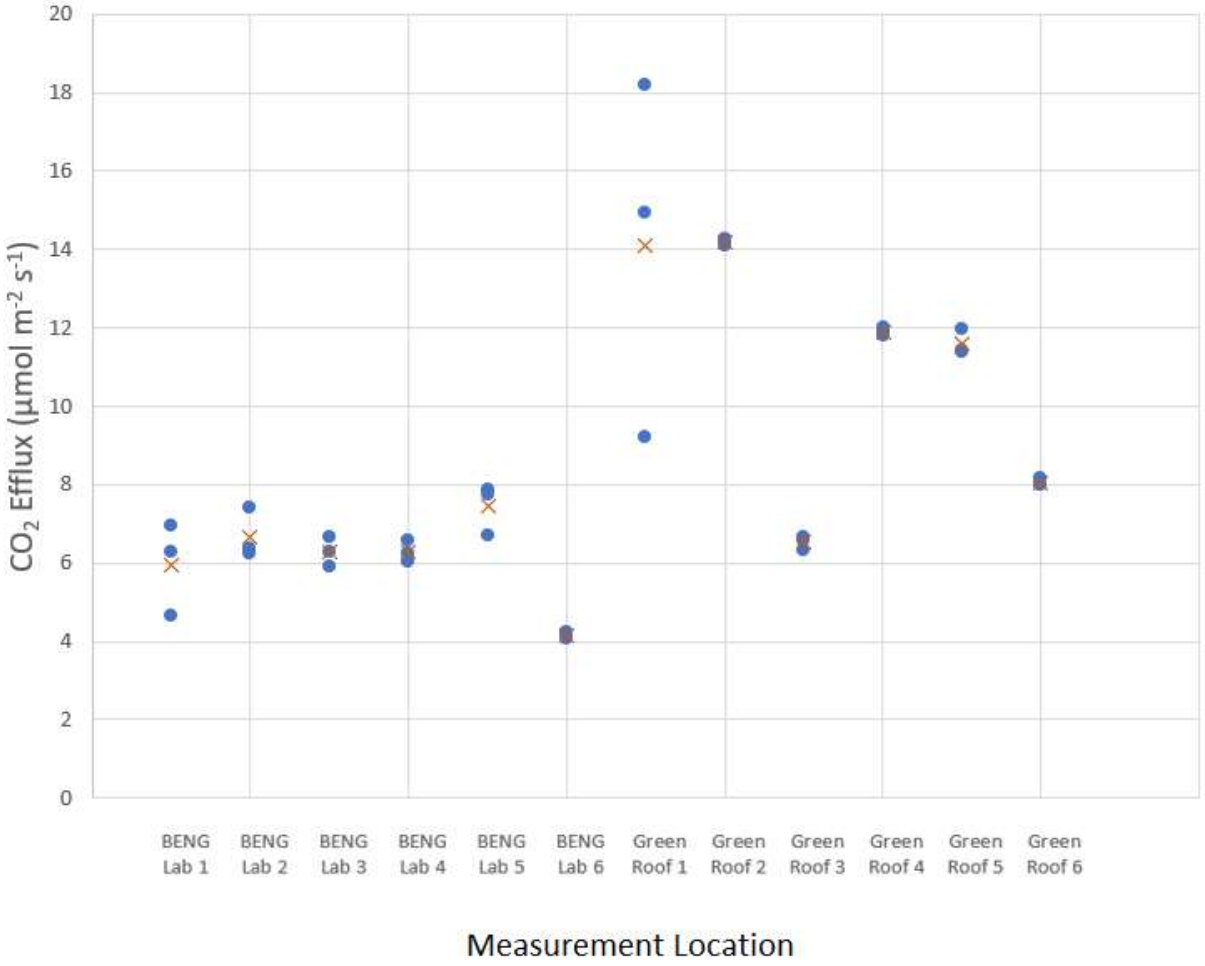


Figure 8. CO_2 flux at each collar at the BENG Lab and on the Green Roof on April 8, 2019. Circles represent collected data points, and x's represent the average of the data set.

Discussion and Future Opportunities

The bulk density of the soil at the BENG lab was greater than expected (1.63 g/cm^3). An average bulk density for a cultivated silt loam normally ranges between 0.9-1.5 g/cm^3 (Brady and Weil, 2017). The reason behind the higher bulk density could be due to the artificial compaction of the soil from farm machinery driving in the area and the high amount of management.

The bulk density of the PM of the green roof was found to be 1.12 g/cm^3 and was close to the expected value. Typically, green roof planting medias have a bulk density around 1.05 g/cm^3 (Perelli, 2014). The PM was made up of 80% expanded clay particles and 20% mushroom compost when it was placed on the green roof at its construction (Rogers, 2011). Expanded clay is a kiln fired mineral soil with a low density as compared to its volume due to the heat expansion. The large amount of compost in the PM will help decrease the bulk density, as compost has an average bulk density of 0.4 g/cm^3 (Brady and Weil, 2017).

The organic matter content of the BENG Lab soil and the green roof PM were as expected and were not significantly different between sites. The BENG Lab soil did not have much dark, organic matter within the sampled area. Based on the construction plans, the PM was designed to be 20% mushroom compost (Rogers, 2011). Compost is 50% organic matter and overtime will decompose. The lower organic matter amount is expected due to decomposition over the years since it was installed.

Overall, the CO_2 flux from the green roof is significantly greater than the flux from the BENG Lab. This was expected originally because the organic matter content was thought to be higher on the green roof than in the soil at the BENG Lab. Bacterial decomposition rates increase as the amount of organic matter increases, therefore also increasing the CO_2 flux. However, the LOI test did not show a statistically different amount of organic matter between the two locations. On the green roof, the CO_2 flux was found to be primarily driven by soil temperature, rather than VWC. At the BENG Lab, both the soil temperature and the VWC played a significant role in influencing the CO_2 flux.

The collars on the green roof did appear to have a more diverse plant community within the collar. An increased amount of aboveground plant mass would also increase the CO_2 flux due to plant respiration. The two sites likely had differentiated sources of soil respiration. The soil microorganisms are subjected to a harsher environment on the green roof, where the south-facing roof is always exposed to the sunlight. The field at the BENG lab receives less sun, due to the lab building to the south of the field and a row of large trees to the east. There may also be unaccounted variables that are affecting the CO_2 flux.

There were a few inconsistencies in the LiCOR CO_2 flux measurements. During the first set of trials, the battery of the laptop died while at the BENG Lab, and the LiCOR battery died while on the green roof. The first set of measurements was also taken two days apart, with a 12°C temperature change between the two days. During the green roof trial on April 3rd, the machine had to be left for 5 hours between readings. The air temperature dropped approximately 5.5°C, and the sun set during that time. Lastly, there was variance in the number of readings taken each day, due to machine malfunction and human error.

There are many opportunities to continue this research in the future. The soil flux could be studied solely by clipping the vegetation in the collar 24 hours prior to taking the flux measurement. The soil and planting media could be incubated outside of the field to study the microbial respiration. The soil organic matter could be tested for quality in addition to quantity. While the total organic matter shows no difference between the two sites, analyzing the labile, or easily decomposed, pool of organic matter could yield a different result.

An increased number of data points would benefit this study greatly. The machine could be left running for longer periods of time to gain a better understanding of the daily CO_2 flux. Measurements should be taken at multiple times of year to better understand how the flux responds to changes in soil

temperature. Measurements should also be taken before and after rain events, to study the effects of precipitation on the respiration rate.

During this study, the green roof was found to release a larger amount of CO_2 as compared to a typical grassland ecosystem. From this study, the green roof does not appear to be properly mimicking the typical ecosystem. However, this research was confined to only one month of study. If more data points could be collected, researchers may find that during the dry season, the green roof produces less CO_2 than a typical ecosystem, evening out its effect over time. Green roofs may still be a viable option to contribute ecosystem services to an urban area while trying to mimic a natural ecosystem, however, more research should be done to verify the effects.

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Appendix

Figure

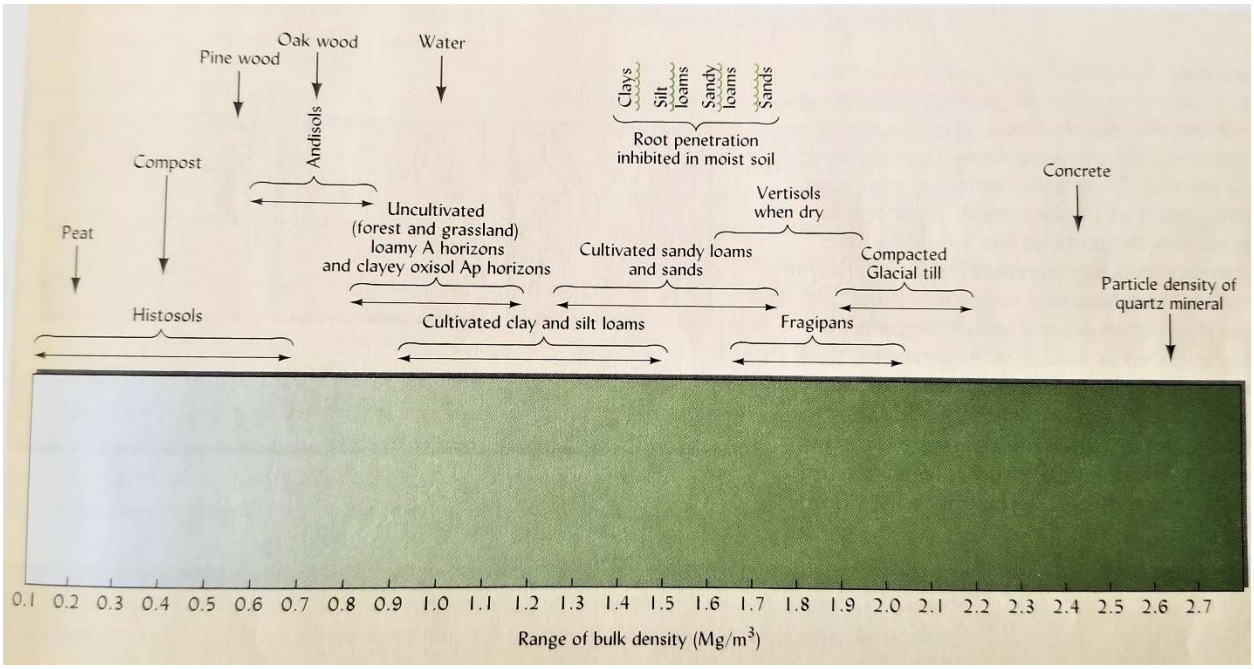

Figure A1. Bulk densities typical of a variety of soils and soil materials (Brady and Weil, 2017).