Repurposing CO_2 from Human Respiration Inside Buildings to Enhance Growth in Rooftop Gardens

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Key Points:

- Biologically relevant higher levels of CO_2 were found in occupied classrooms and linked to high CO_2 from rooftop exhaust vents.
- Growth of crops was increased by 2-4 times with exposure to high CO_2 exhaust air from inside buildings.
- Wind speed negatively affected spinach growth and other characteristics of exhaust vent air likely also played a role in enhancing growth.

Abstract

Cities face many environmental challenges while providing opportunities for integrating human infrastructure with the surrounding environment. One effort to improve environmental conditions in cities is to increase the amount of green space in creative ways within city limits. Here we propose a unique system taking carbon dioxide (CO_2) from indoor spaces and applying it to rooftop gardens or farms through existing ventilation systems with the elevated CO_2 levels leading to a fertilization effect that increases plant growth. CO_2 measurements were taken inside multiple classrooms as well as at the exhaust vents on a rooftop and air from exhaust was applied to crops and biomass and leaf number were measured. High concentrations of CO_2 ([CO_2]) persisted inside university classrooms as well as at rooftop exhaust vents in correlation with expected human occupancy and stayed around 1070 ± 70 and 830 parts per million (ppm) CO_2 reaching a max of 4470 and 1300 ppm CO_2 respectively. Growth in *Spinacia oleraceae L.* (spinach) grown next to exhaust air increased 4-fold in comparison to plants grown next to a control fan applying atmospheric air. High wind speed decreased growth by approximately 2-fold. *Zea mays* (corn), a C4 plant, grown next to exhaust experienced a 2 to 3-fold increase, indicating alternative environmental factors additionally playing a part in growth enhancement. Enhancing growth in rooftop gardens using indoor air, could help rooftop plants grow larger and survive harsh conditions. This would make rooftop gardens more viable and better able to provide environmental services and connect urban areas to the surrounding environment.

1 Introduction

Cities concentrate people and therefore reduce overall development and destruction of natural ecosystems, at the same time, they change the local environment. Urban areas can be seen as distinct from their surrounding environments because of effects such as the urban heat island (UHI) (Memon et al., 2008; Mohajerani et al., 2017; Stathopoulou & Cartalis, 2007) and altered water cycling patterns (Bounoua et al., 2015; Oberndorfer et al., 2007). Climate change is expected to produce hotter, longer summers with more extreme heat waves (Centers, 2012), which would be exacerbated in hotter cities made of materials that absorb more heat (Elmes et al., 2017; Trlica et al., 2017; Ziter et al., 2019). The presence of More impervious surfaces decreases infiltration and increases run off, erosion, and flooding (Oberndorfer et al., 2007). This excess runoff can contain pollutants and overwhelm current storm water systems (Oberndorfer et al., 2007). Integrating urban areas with the surrounding environment and decreasing differences between urban and non-urban areas could decrease negative impacts of cities on both urban ecosystems and populations.

Expanding green spaces in cities can be one approach to reintegrating urban spaces (Batchelor et al., 2009; Ngan, 2004). Recent studies have found that vegetation in urban areas can have large and unexpected impacts (Briber et al., 2015; Reinmann, 2016; Templer, 2015). While there are fewer trees in cities and therefore a smaller carbon stock, evidence has been found that trees grow significantly faster in cities, though the rate of mortality is high (Briber et al., 2015). Studies of carbon budgets of cities found less, but still considerable amounts of vegetation as well as higher levels of soil carbon in urban versus non-urban areas (Raciti et al., 2012). In a study of Massachusetts and the city of Boston, cities are projected to contain 35% of the terrestrial carbon sink by 2050 (Reinmann et al., 2016). Changes such as the exportation of detritus from cities also contribute to the unique dynamics observed (Templer et al., 2015). Therefore increasing urban vegetation and ecosystems could influence carbon cycling and overall ecological dynamics within cities.

Rooftops are greatly underutilized areas occupying approximately 20 to 50% of urban aerial space (Shafique & Kim, 2017; US EPA, 2008; Vaughan & Lenton, 2011). If vegetated, these spaces could provide considerable environmental and social benefits. Rooftop gardens and farms can mitigate the UHI effect by decreasing local temperatures (ArrowStreet, 2016; Ismail et al., 2012; Ito et al., 2015; Kleerekoper et al., 2012; Santamouris, 2014), increasing storm water retention and precipitation release through evapotranspiration, which decreases flooding (Carter & Rasmussen, 2007; He et al., 2016; Nagase & Dunnett, 2012; Nitsch, 2016; Shafique et al., 2018; Whittinghill et al., 2015), providing air pollutant filtration (Rowe, 2011), and decreasing building energy use through increased insulation (Garrison et al., 2012; Toudeshki et al., 2013; Wong et al., 2003) and natural cooling (Batchelor et al., 2009; Garrison et al., 2012; Saadatian et al., 2013). Rooftops also offer economic and community building opportunities, aesthetic and mental health benefits (Guite, Clark, & Ackrill, 2006; Johnson, Malecki, Peppard, & Beyer, 2018), and food security when used for urban agriculture (Ahmed et al., 2017; Oberndorfer et al., 2007; Orsini et al., 2014). Urban food production would decrease dependency on external communities and increase the redundancy and resiliency of our agricultural system while addressing climate change by helping with climate enhanced negative urban environmental impacts and harvesting CO_2 (Davies et al., 2011; Ismail et al., 2012; Oberndorfer et al., 2007; Orsini et al., 2014; Rowe, 2011; Shafique et al., 2020; Whittinghill et al., 2014).

In this paper, we propose a concept for a system that could enhance growth in rooftop gardens and farms. A major challenge facing rooftop gardens is decreased plant growth due to extreme environmental conditions such as higher wind and temperatures, heightened solar radiation, and limited soil moisture content (Ahmed et al., 2017). To help ameliorate these challenges, our system uses air from inside buildings to create more favorable conditions and enhance plant growth with CO_2 generated from human breath inside buildings. Almost all population growth in the next few decades is expected to occur in cities (Medek et al., 2017; UN, 2017; UN, 2014), with urban populations increasing from 3.65 to 5 billion (Seto et al., 2012). People stay inside buildings for significant amounts of time and continuously respire large quantities of CO_2 which concentrates inside buildings (Apte et al., 2000; Jin et al., 2015; Lee & Chang, 1999).

This build up of CO_2 is most often seen through a public health lens since elevated [CO_2] can be associated with high levels of other indoor air pollutants (Apte et al., 2000; Lee & Chang, 1999; Seppanen et al., 1999). The primary direct impact of CO_2 on humans is decreased performance and cognitive function (Rice, 2004; Zhang et al., 2018). Concentrations as low as 1000 ppm have been found to significantly decrease performance on mental tasks (Allen et al., 2016; Persily & de Jonge, 2017; Satish et al., 2012) and concentrations of 2500 ppm have an even larger significant effect (Satish et al., 2012). Therefore legal indoor CO_2 limits have been set at 5000 ppm for workspaces with 1000 ppm as a suggested limit (ACGIH, 2011; Apte et al., 2000; EPA, 1991; OSHA, 2012). Some states, such as Massachusetts have even recommended limits of 800 ppm CO_2 (MA EOHHS, 2020). However, CO_2 regularly is found to exceed these limits inside buildings (Apte et al., 2000b; Lee & Chang, 1999; Myhrvold et al., 1996; Roulet & Foradini, 2002).

The CO_2 produced in buildings can be harnessed to induce a CO_2 fertilization effect on rooftop vegetation. CO_2 is typically exhausted from buildings through HVAC systems and exhaust vents on rooftops. It is possible to apply CO_2 in building exhaust to rooftop gardens to increase growth of crops for consumption, yet to our knowledge no study has examined this potential. At elevated concentrations, the CO_2 fertilization effect increases photosynthetic efficiency (Ainsworth & Long, 2005) by decreasing photorespiration. Photorespiration is a wasteful side process in plants that occurs in the presence of relatively low [CO_2] and high concentrations of O_2 when the primary enzyme of photosynthesis, Ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO), reacts with O_2 instead of CO_2. Decreasing photorespiration can increase the amount of carbon taken in by photosynthesis by up to 25% (Sharkey, 1988).

The effect of the CO_2 fertilization effect has been primarily confirmed through Free Air Carbon Dioxide Enrichment (FACE) experiments, which administered higher [CO_2] to plants within open systems. This allows for the soil-plant-atmosphere continuum to remain intact to garner more realistic assessments (Ainsworth et al., 2008; Kimball et al., 1997; Leakey et al., 2009; Long et al., 2006; McLeod & Long, 1999; Norby & Zak, 2011). FACE studies illuminated the potential magnitude of CO_2 fertilization on plant growth with limitation from nutrients, photosynthetic strategy, and many other factors (Ainsworth & Long, 2005; Long et al., 2004; Norby & Zak, 2011; Nowak et al., 2004). The design of our rooftop garden system is modeled after these experiments, though it differs in that it uses only waste CO_2 from human respiration. This provides concentrated CO_2 in a more sustainable way and could make this system more feasible and cost effective compared to the CO_2 importation of the FACE experiments (Calfapietra et al., 2010; Chakrabarti et al., 2012; Hendrey et al., 1993; Reece et al., 1995). Multiple of the twelve initial FACE experiments are no longer running, potentially in part due to the high cost of purchasing and transporting condensed CO_2 (Ainsworth & Long, 2005; Calfapietra et al., 2010; Chakrabarti et al., 2012; Hendrey et al., 1993; Miglietta et al., 1997; Reece et al., 1995). The proposed system does not apply constant CO_2, but is opportunistic and takes advantage of the fact that [CO_2] is higher during the day in non-residential buildings, which coincides with when plants require CO_2 for photosynthesis. Enhancing plant growth would make rooftop farms more productive and potentially capable of surviving harsher conditions, expanding their viability as an urban greening strategy.

One study by Sanyé-Mengual et al. (2014) installed an Integrated-Rooftop Greenhouse (i-RTG), rather than a garden, on a building in Barcelona, Spain. Indoor air brought to the greenhouse created more hospitable temperatures for growing plants (Nadal et al. 2017), but there was too little CO_2 to test for a CO_2 induced growth effect. They also did not measure growth in individual plants (Sanjuan-Delmás et al. 2018ab). Greenhouses are expensive both financially and in terms of carbon footprint (van Beveren et al. 2015; Pons et al. 2015; Sanjuan-Delmás et al. 2018ab; Sanyé-Mengual et al. 2015a; Vadiee and Martin 2013). Shading from the i-RTG decreased output and their hydroponic system did not store extra carbon. Fertilizers used in this system were a considerable amount of the environmental impact. While i-RTGs are a very interesting option, they were not considered in this study for these reasons and because the goal of this study was to develop a system that could be easily implemented on existing rooftops and test for a growth enhancement effect.

We hypothesized that when there is a large build-up of CO_2 indoors, enough CO_2 is released from exhaust vents to affect plant growth in rooftop gardens, and that plants exposed to exhaust vent air grow larger than plants not exposed to building exhaust. To test this hypothesis, the sources, sinks, and fluxes of CO_2 within and out of buildings and atop rooftops were monitored to determine what could be considered the “building metabolism”. This [CO_2] was tracked through the ventilation system and a rooftop garden was built attached to building exhaust vents to test for a CO_2 fertilization effect. Applying exhaust air from buildings enhanced plant growth in this rooftop garden. These systems could help make rooftop gardens and farms more robust and therefore a more viable option for building owners and city managers, helping to use untapped urban resources and make buildings more actively engage with the surrounding environment.

3 Results

3.1 Indoor Classroom [CO_2] Measurements

[CO_2] in classrooms varied highly between day and night with spikes in [CO_2] occurring during scheduled class times. In general, classes ran between 8:00 am and 4:00 pm. During this time [CO_2] increased dramatically and maintained high concentrations (Figure 2) relative to background [CO_2]. Throughout all classrooms, 37% of the weekday-time was spent above 1000 ppm with an average daytime concentration of 1060 ppm and maximum of 4470 ppm. Levels dropped closer to atmospheric concentration around 410 ppm (Dlugokencky & Trans, 2018; Ng et al., 2019) by the end of the day. Weekend [CO_2] were more variable. Based on the subset of classes that were compared with their schedules, increases and decreases in [CO_2] coincided directly with class times (Figure 2a). As soon as class time started, levels increased though the range of [CO_2] appeared to vary based on the classroom. This was most likely dependent on both classroom size and the number of students, which were both provided by the 25Live scheduling data. Increased [CO_2] was almost entirely contained within the times when events or classes were scheduled though there were a few extra peaks as seen in room 213 (Figure 2b).

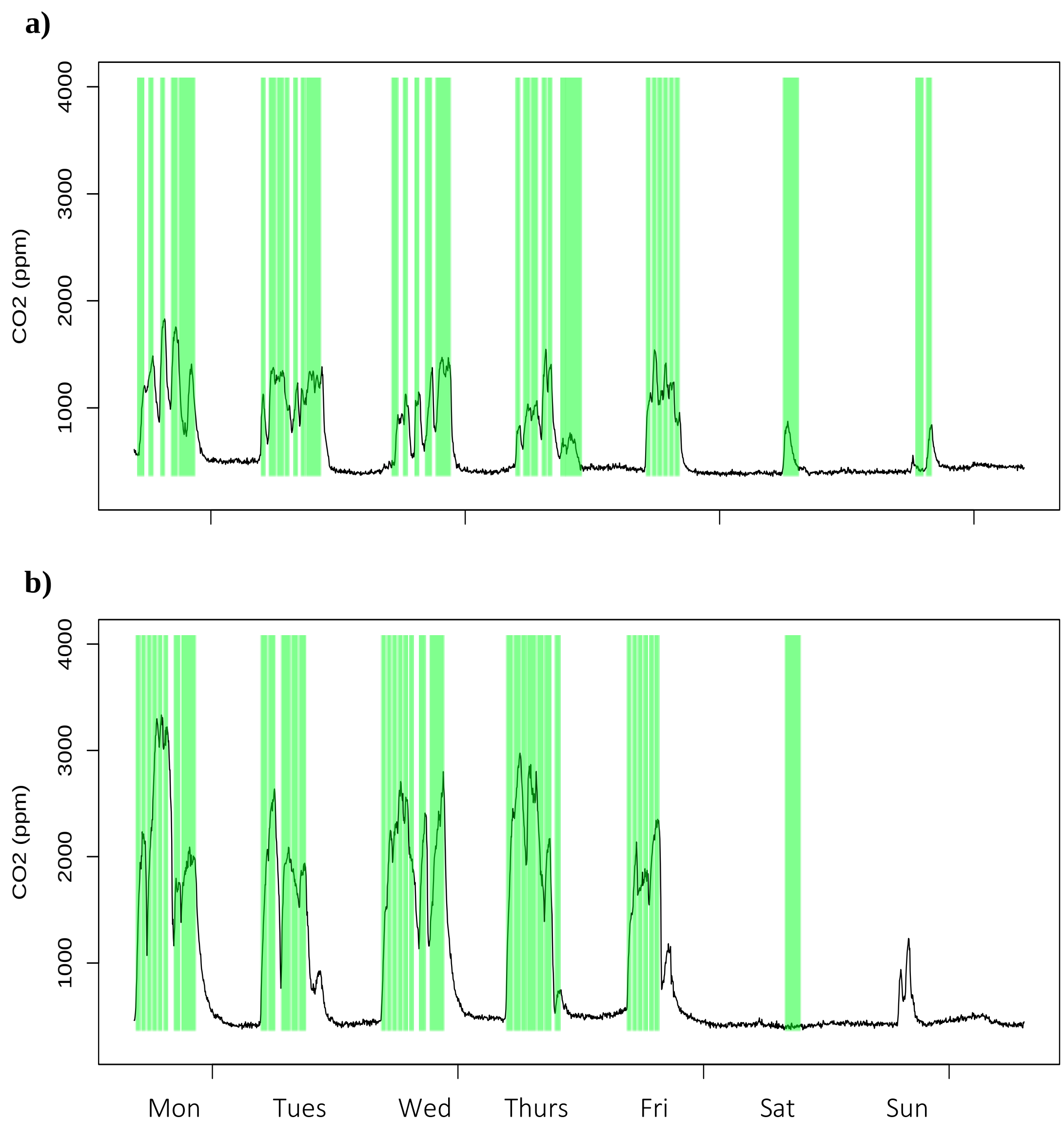

Figure 2. Classroom CO_2 measurements and class times. CO_2 sensors (Onset HOBO Bluetooth Low Energy Carbon Dioxide – Temp – RH Data Logger, #MX1102) were installed in classrooms for one week. Occupation data was collected for these classrooms from the 25Live scheduling system used by BU. Class times (green boxes) were plotted against CO_2 concentrations (black lines) over time to compare CO_2 spikes with classroom usage. Spikes occurred primarily during class time in classrooms a) CAS 201 and b) CAS 213.

3.2 Rooftop [CO_2] Measurements

Rooftop Exhaust Vent [CO_2] differed depending on whether summer camp classes were occurring inside the buildings. The measurements taken from the Exhaust Vents over the summer during the first two weeks when very few people were in the building were consistently low and no clear temporal pattern was identified (Figure 3a). Once a camp began during the second two weeks of measurements and the number of people in the building increased to approximately 175 people, a clear pattern became visible. [CO_2] approached similar levels as seen within the classrooms (Figure 3b) though they were overall lower most likely due to diffusion and leakage in the system. During the weekday-time over the second two weeks of these measurements, Exhaust Vent [CO_2] stayed above 1000 ppm 10% of the time with an average daytime concentration of 830 ppm and maximum of 1300 ppm. Similar to indoors, [CO_2] dropped to atmospheric levels around 410 ppm at the end of the day and stayed lower over the weekend. During the rooftop garden experiments, these patterns remained true with daytime [CO_2] from the Exhaust Vents during the week being increased to around the same levels as described above (Figure S1). These correlated well with the indoor [CO_2] measurements taken in the second floor bathroom (Inside) (Figure S4a).

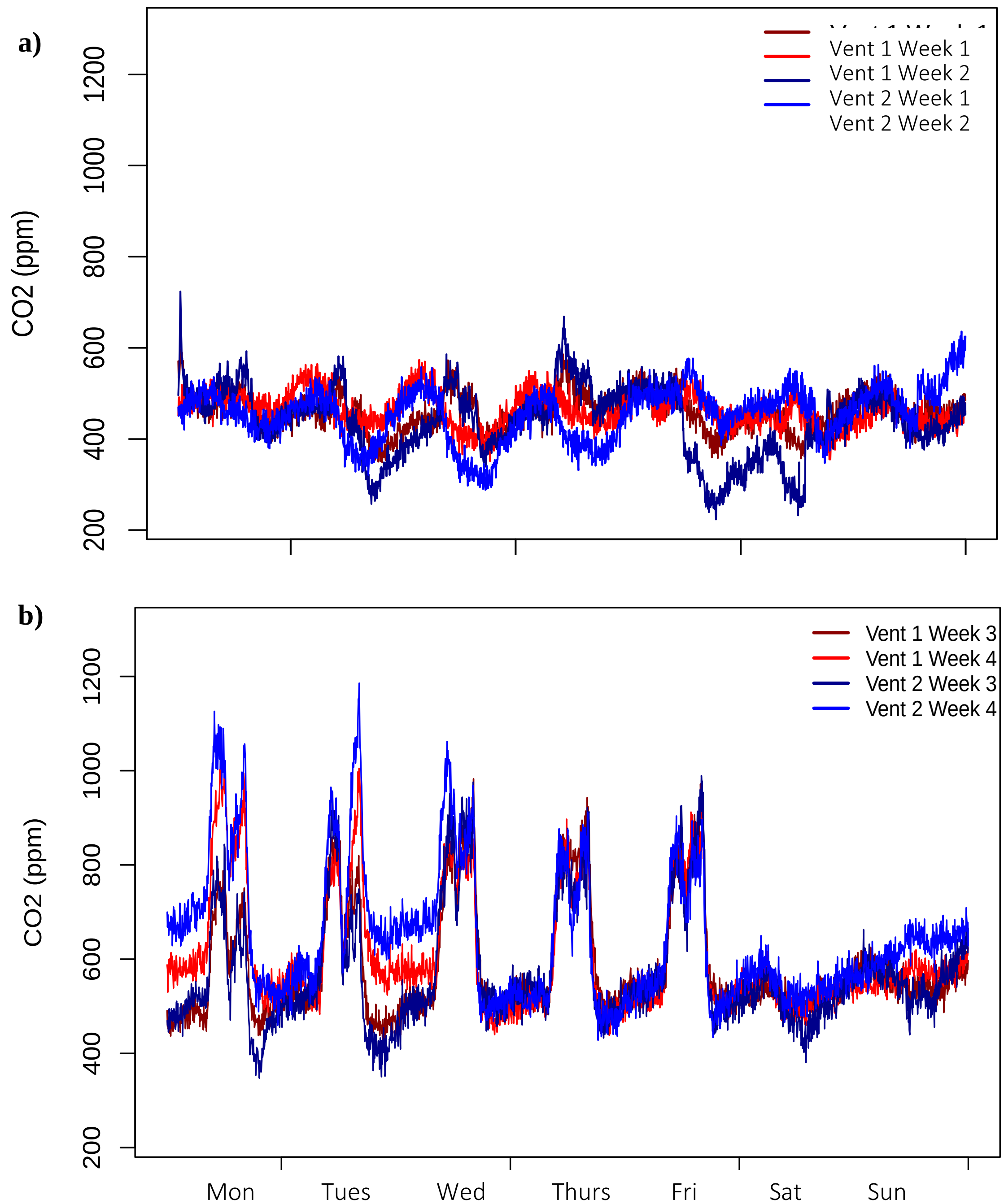

Figure 3. CO_2 released from rooftop vents on a building while unoccupied and occupied. Sensors were attached to two vents on The BUA roof for four weeks. During the a) first two weeks, only baseline staff were present and the second two weeks a camp was being run. There

were no CO_2 peaks in the first two weeks and peaks up to 1300 ppm during the second two weeks indicating the connection between Exhaust Vent CO_2 and building occupancy.

3.3 Rooftop Garden Experiment

3.3.1 Crop Performance, Wind Speed Effect

In Fall 2018, there was a highly significant difference between growth at the high and low speed fans for both dry ($F(1,1) = 14.96$, $p < .001$) and wet ($F(1,1) = 25.98$, $p < .001$) biomass. The plants grown next to the fans running at the higher speed (17 mph) for the Exhaust Vent were significantly smaller than those grown next to the lower speed fan (10 mph) for the Exhaust Vent (Figure 4a; $p < .001$, $p < .001$). The growth next to both Control Fans was too low for a difference to be detected ($p = .96$, $p = .99$), but even at the higher wind speed, the growth enhancement effect of the Exhaust Vent significantly increased dry and wet biomass compared to growth next to both the Control Fans at high ($p = .0058$, $p = .011$) and low speeds ($p = .0028$, $p = .043$).

Even with wind effects, leaf number was higher for plants surrounding the exhaust fan than for plants surrounding the Control Fan (Figure S2b; $F(1,1) = 23.64$, $p < .001$). The number of leaves grown next to the Exhaust Vent at the higher speed was less than at the Exhaust Vent at the lower speed ($p < .001$), but the difference between leaf number at the high and low speed Control Fans was not significant ($p = .25$). The Exhaust Vent effect did still lead to more leaves being produced at the high speed Exhaust Vent in comparison to the high speed Control Fan ($p = .0017$). However leaf number at the high speed Exhaust Vent was not significantly different than the leaf number next to the low speed Control Fan ($p = .23$). To isolate only the exhaust fan effect, going forward, only the data from the plants surrounding the lower speed fans were used.

3.3.2 Crop Performance, Biomass and Leaf Number

In the Fall 2018, spinach grew larger and had more leaves next to Exhaust Vents. The dry weight (Figure 4b; $F(1,1) = 56.87$, $p < .001$), wet weight (Figure S7b; $F(1,1) = 57.69$, $p < .001$), and leaf number (Figure S2b; $F(1,1) = 41.11$, $p < .001$) of the spinach next to Exhaust Vents were significantly greater than those of the spinach grown next to the Control Fan. The average dry weight of plants next to the Exhaust Vent was 0.45 g ± 0.013 (± SE) compared to 0.12 ± 0.041 at the Control Fan. The average leaf number of plants next to the Exhaust Vent was 7 ± 0.08 compared to 5 ± 0.15 at the Control Fan. Dry biomass around the Exhaust Fan was almost four times larger than dry biomass around the Control Fan with means of 0.45 ±0.04 g and 0.12 ±0.13 g.

During Spring 2019, there was a significant difference in the corn dry and wet biomass ($F(1,2) = 10.13$, $p < .001$, $p < .001$) with the growth next to the Exhaust Vent being significantly higher than at both the Control Fan and the Control for both dry ($p < .001$, $p = .0045$) and wet (Figure S7; $p < .001$, $p = .012$) biomass. There was also a difference in color between the treatments (Figure S3) with corn next to exhaust vents appearing greener than corn next to the control fans which appeared more yellow. The corn was between 2 and 3 times larger at the Exhaust Fan versus the Control Fan with means of 0.17 ±0.005 g and 0.065 ±0.008 g.

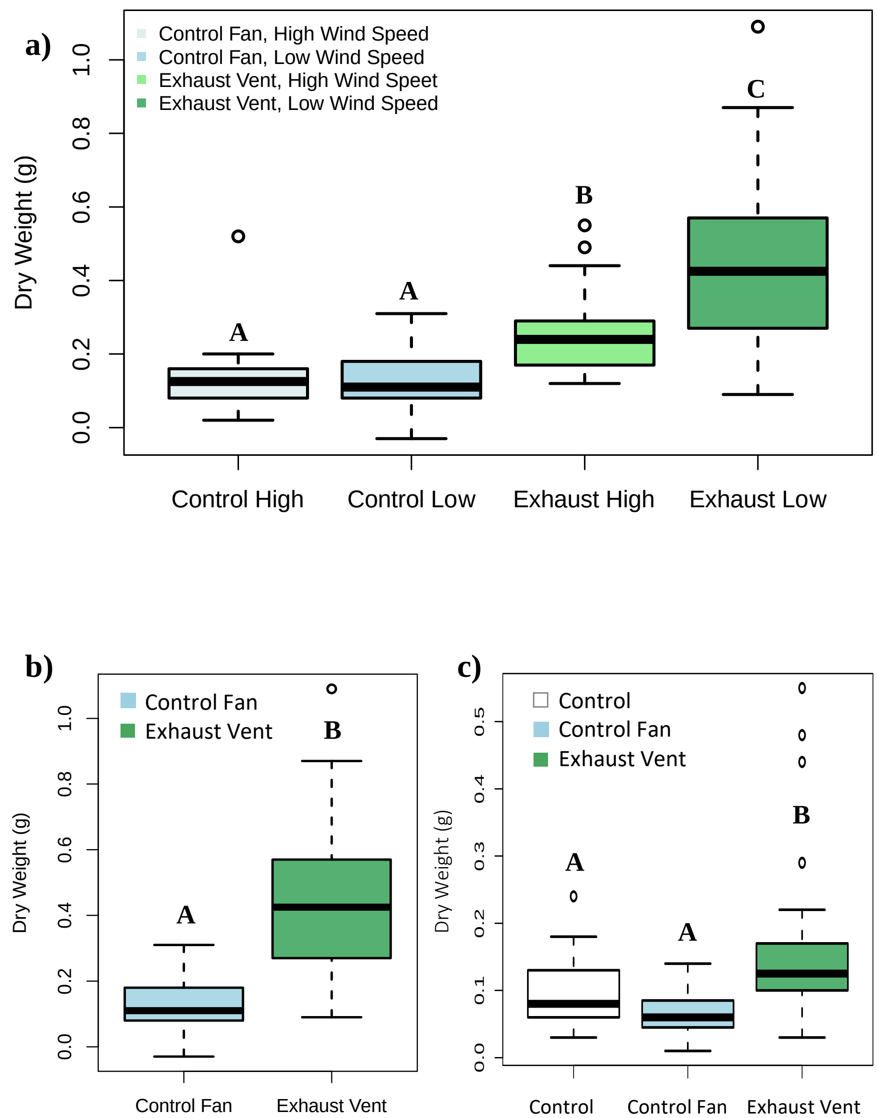

Figure 4. Average dry weight of spinach and corn plants in response to Exhaust Vent air. a) Spinach was grown in Fall 2018 next to two fans at a higher wind speed (17 mph) and two at a lower speed (10 mph) and one of each of these was a Control Fan and Exhaust Vent. Between the Exhaust Vents, the spinach plants exposed to high wind speeds were smaller ($p < .001$). Even with this, the Exhaust Vent was able to recover growth compared to both the low ($p = .0058$) and high-speed ($p = .0028$) Control Fans. At only low wind speeds there was a significant increase in b) dry biomass ($p < .001$) with exposure to exhaust air. These data were from harvest 3. c) Corn

was grown in Spring 2019 to look at the response of a crop that should not respond strongly to CO_2. Another control was added to further assess the effect of wind speed. Corn grown next to the Exhaust Vent was larger than at both the Control Fan ($p < .001$) and control garden ($p = 0.0045$). Different capital letters indicate statistically significant differences among treatments.

3.4 Environmental Measurements

For soil moisture, no significant differences were found (Figure S2a). Data from the last day of data collection was used for consistency with harvest and leaf number measurements. Frost covering the rooftop in November showed an approximately 2 m outline around the exhaust vents where the warmer indoor air melted the frost (Figure S11a) in contrast to around the control vents (Figure S11b) where no outline was seen giving a preliminary indication of the spatial extent of the effect.

4 Discussion

4.1 Building Metabolism

"Building Metabolism" could be considered to be all of the sources, sinks, and fluxes of CO_2 in a building (Sanyé-Mengual et al. 2014; Pons et al. 2015). Ventilation brings in fresh air based on indoor temperatures and energy efficiency while used indoor air is either recycled back into the room or exhausted from vents, releasing CO_2 into the atmosphere. CO_2 could be diluted by diffusion or lost through windows, doors, and leaks and introduce differences between concentrations in indoor spaces and the exhaust stream.

Humans were the most important source of CO_2 in this study leading to high levels both indoors and in exhaust vent air. Normally indoor [CO_2] measurements are used in the context of health and energy efficiency. This study also considers [CO_2] in classrooms from the perspective of using CO_2 as a resource for plant growth. As expected, considerable build-up of CO_2 was found during the daytime from human respiration connected with scheduling patterns (Figure 2). A more surprising result is how high [CO_2] persists and for how long it remains high. Daytime [CO_2] from Monday to Friday remained above suggested limits of 1000 ppm over a third of the time people were in the classrooms (Figure 2). This could be problematic for students and other BU community members whose performance could be affected by the [CO_2] since even concentrations of 1000 ppm have been found to be detrimental to mental performance (Allen et al., 2016; MA EOHHS, 2020; Persily & de Jonge 2017; Satish et al. 2012). It would be beneficial to reassess the current system and make necessary changes to decrease [CO_2]. In exhaust vents, [CO_2] was slightly lower than, but still fairly similar to, indoor air levels (Figure S4, Figure S6). The clear change in pattern in the [CO_2] exhaust vent data when there were and were not people in the building (Figure 3) supports the hypothesis that human respiration also drives CO_2 fluxes from exhaust vents, which are therefore still representative of and influenced by overall building metabolism.

4.2 Plant Growth Enhancement

The overall [CO_2] patterns found for exhaust air (Figure 3) indicate that it could be used to induce CO_2 fertilization and act as a resource for plant growth enhancement. Exhaust air [CO_2] was between 500 and 1000 ppm. As [CO_2] increases above 400 ppm, photosynthesis increases until approaching around 1000 ppm (Rogers et al. 1994) when you begin to see diminishing returns. Plant physiology can also be altered by higher [CO_2]. A study by Fleisher et al. 2008 looked at interactive effects of drought and higher [CO_2] and found that characteristics such as stem and apical stem length, plant length, leaf appearance duration and rate, leaf area, and leaf number can be altered by higher [CO_2] though primarily through interactive effects. The fact that these characteristics could vary based on [CO_2] could help explain the increase in leaf number found in this study (Figure S2b) and be part of the mechanism for increased biomass in plants exposed to exhaust vent air (Figure 2b).

Intermittent application of increased [CO_2] could alter the effectiveness of the CO_2 fertilization effect. This system involves inherent variability in CO_2 application since CO_2 is not constantly produced or applied. Some studies found that when CO_2 is applied intermittently, as in for some number of hours or days on and off, this can decrease the CO_2 fertilization response though significant increases were always found (Clough and Peet, 1981; Mortensen, 1986; Both et al., 1998 Both 2002). While the weekends would most often be days without CO_2 application, this system would still apply CO_2 constantly throughout most days. A study by Calvert and Slack (1976) showed that as long as you apply CO_2 through most of the day, you still get a similar increase and it's more important to apply CO_2 in the morning than later at night, which would be the case in this system. Some FACE studies purposely created a system where CO_2 was applied intermittently, only during the day either to match the timing of photosynthesis or because [CO_2] was already higher at night. Growth enhancement effects were still found in all studies (Miglietta et al., 1997; Moore et al., 1999; Edwards et al., 2001; Leakey et al., 2009).

This application system is also opportunistic since it redirects air already being expelled through exhaust vents towards plants. It avoids complicated and energy intensive processes such as condensing the CO_2 or controlling application to produce a constant CO_2 source, which would alter the overall carbon footprint of this system. This makes this system easier to construct, which would aid in wider implementation.

It is both plausible and probable that factors aside from [CO_2] affect plant growth. Potential examples include temperature, relatively humidity, and wind speed. This study hypothesized that [CO_2] would impact growth while attempting to get a preliminary understanding of whether other factors contribute as well by growing both a C3 and a C4 plant, spinach and corn (Figure 4). C3 plants should have a stronger response than C4 plants to increased [CO_2] (Ainsworth & Rogers, 2007; Hatfield et al., 2011; Kimball et al., 2002; Long et al., 2006; Nowak et al., 2004; Sharkey, 1988). This is because C4 metabolism is a photosynthetic process specifically designed to increase CO_2 uptake efficiency, so even at low concentrations it already experiences higher concentrations and rates of photosynthesis, which therefore would not be changed by higher external levels (Ainsworth & Rogers, 2007). However, in this study, there was a multiple-fold increase in growth for both spinach in the fall and corn in the spring (Figure 4), implying other environmental factors such as temperature could be enhancing plant growth. Both spinach and corn are sensitive to temperature and have approximate optimal temperatures of 20 °C for spinach and 30 °C for corn (Warrington & Kanemasu, 1983; Boese & Huner, 1990; Yamori et al., 2006), so the buffering effect of applying heated internal air would theoretically assist in avoiding extreme temperatures.

Studies have looked at the different and combined effects of [CO_2] and temperature on plant growth in multiple species (Nijs et al., 1997; Zvereva & Kozlov, 2006; Cai et al., 2016) including corn (Hatfield et al., 2011; Tongson et al., 2017). [CO_2] and temperature are two of the most critical factors relating to plant growth and are highly likely to be altered by climate change (Dentener et al., 2013). This initial observational study indicates that future studies able to fully control for [CO_2], temperature, and other environmental factors should be considered.

4.3 Environmental Impact and Scaling Up: Preliminary Calculation of Potential Impact

This exhaust air application system could improve an overall carbon footprint in multiple ways. In relation to carbon harvesting systems, it would be more sustainable for using concentrated waste CO_2 from human respiration instead of from fossil fuel exhaust as do almost all current large-scale carbon removal attempts. The system's associated rooftop garden or farm's more direct carbon footprint would include the carbon stored in the garden, the embodied carbon or carbon emitted in building the garden, and avoided carbon emissions from environmental benefits. Whittinghill et al. 2014 found that stored carbon varied based on species with herbaceous plants and grasses holding an average of 68.2 kg C m^{-2} compared to 0.38 kg C m^{-2} in sedum gardens (Getter et al., 2009). Getter et al. 2009 estimated embodied carbon to be 6.5 kg C m^2. Avoided CO_2 emissions could be expected from either decreased energy use of the building below (Batchelor et al., 2009; Garrison et al., 2012; Oberndorfer et al., 2007; Toudeshki et al., 2013) primarily from 10 to 43% decreases in air conditioning use (Meier, 1990; Garrison et al., 2012), or avoided transport of food from rooftop farms (Pirog et al., 2001; Halwell, 2002; Weber and Matthews 2009; Lower & Dining, 2014). Pirog et al. 2001 found produce brought to Chicago travels an average of 1,518 miles and that using local food from the surrounding area reduced the associated carbon emissions by 5 to 17 times. Studies from the i-RTG project, which contains more carbon costs associated with infrastructure, found the environmental impact of their produce would be lower from decreased packaging and transportation (Sanye-Mengual 2015ab).

For our preliminary calculations of impact, since vegetables would be one of the primary commodities and benefits rooftop farms could provide to urban communities, we attempted to quantify potential increases in yield from this system. Orsini et al., 2014, looked at vegetable production in rooftop farms in a field study conducted to optimize the amount of crops that could be produced. They used their estimate to scale up across the city of Bologna, Italy by identifying all of the flat rooftops and determining that 77% of produce used by the city could be grown in rooftop farms within city limits. We extended this to estimate how many more vegetables they could produce using a system such as the one described here. Given the limitations of this study, we assumed similar increases in yield could be found for different crops across the growing season in different environmental conditions, which would increase the productivity of an individual rooftop area. We found that 86% to 144% of required vegetables could be produced depending on the spatial extent of the effect and number of vents on buildings (Table S1). This was also expanded to Boston where, using only growth rates from Orsini et al., an estimated 190% of required vegetables could be produced. By adding exhaust vent application systems, 207% to 290% of Boston's vegetable requirement could be produced (Text S1, Table S1). This indicated that covering rooftops within a city with rooftop farms could contribute a substantial amount of produce to the overall needs of the city.

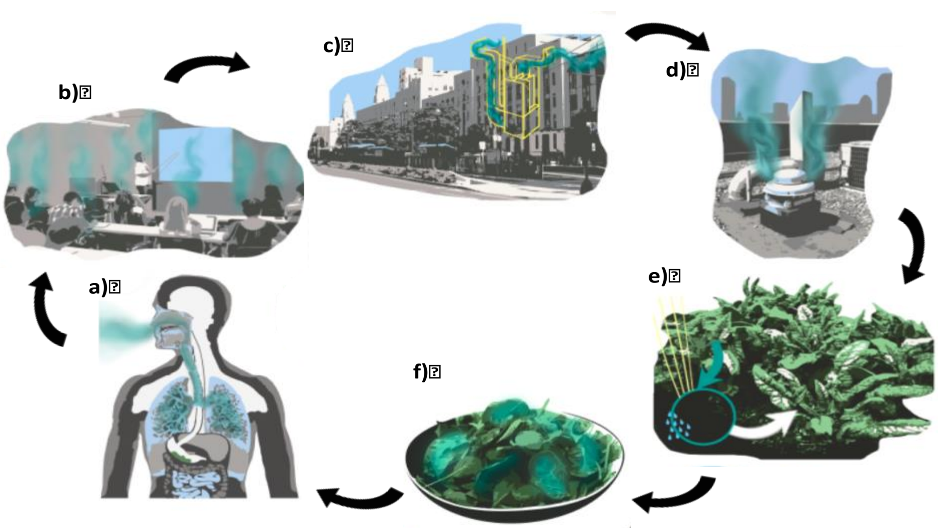

Figure 5. Conceptual diagram showing the carbon cycle within experimental rooftop gardens. CO_2 travels a) from the human body b) out into the classroom within a building. This CO_2 then is brought c) through the ventilation system to the rooftop and d) released through an exhaust vent. Our system will apply this CO_2 to e) plants in a rooftop garden after which f) humans can consume the crops and the carbon can return to the human body.

4.4 CO_2 Application System Design and Implementation Considerations

The system described in this study creates a more circular carbon process with high [CO_2] from human respiration (Barrett et al., 2012) traveling through the building, into the garden system where some is used (Hanson et al., 2000) to produce food that can be eaten by humans and respired anew (Figure 5). While a fascinating concept, there are many opportunities for optimizations. Ideal wind speed must be identified since higher wind speeds negatively impacted plant growth (Figure 4a). Air from the fans could either dry out the soil or physically impact the plant (Onoda & Anten, 2011). Rooftop gardens can be relatively dry given the hotter temperatures experienced on rooftops, impacting soil moisture (Ahmed et al. 2017). Weight restrictions on buildings also limit soil depth and therefore how much water can be stored. Throughout the year, temperature, relative humidity, etc. can be higher or lower in exhaust vent air compared to outdoor air depending on how we are modifying our internal environment. During the Fall, internal and therefore exhaust vent air had a lower relative humidity than outdoor air. However, there were no differences found in soil moisture between treatments or by wind speed (Figure S2). Therefore this was most likely not the mechanism of growth inhibition. The mechanical impact of the air and/or its desiccating tendency on leaves could have caused the decrease in growth. Some wind is necessary for plants to develop their overall structure (Onoda & Anten, 2011), but they are limited by higher wind speeds (Bang et al., 2010). A unique vent or vent attachment could be designed that decreases wind speed at the plant, while maintaining conditions that increase growth. The air could be funneled into a series of tubes that run along the soil and release exhaust vent air upward or sideways towards the plants. This could be addressed with mechanical engineering approaches and further knowledge of gas and fluid transport.

New designs should also increase the spatial extent of the exhaust effect. Opportunistic frost observations gave a preliminary indication of the current extent (Figure S11ab), but sensors could be placed at different distances from the vent to measure where conditions return to background. Plants could be grown in lines extending away from the vent to determine the extent of the growth effect, which is the desired impact. Designs could also be developed that entirely replaces normal ventilation fans but should at least account for different types and numbers of exhaust vents, which could be identified by a survey of many buildings. As previously mentioned, a full factorial experiment that controls for the different variables, especially CO_2 and temperature, should be carried out since this was an observational study mostly limited to looking at overall effects of ventilation air on plants as a proof of concept experiment. Isotopes could be used to determine how much of the CO_2 in these plants was from human breath versus atmospheric air to confirm or disprove the influence of a CO_2 fertilization effect.

Further development of this system could be used as an inexpensive method for conducting more FACE studies that use a waste source of CO_2 and therefore would not be inhibited by high CO_2 costs. This could provide options for studies on gradually increasing [CO_2] (Miglietta et al., 1997), different kinds of plants, how to optimize production (Ainsworth et al., 2008; Ainsworth & Long, 2005), how responses might change with different combinations of factors (Cai et al., 2016; Nijs et al., 1997), and whether or not the CO_2 fertilization effect decreases the nutritional content of crops (Idso & Idso, 2001; Loladze, 2002; Myers et al., 2014; Medek et al., 2017). The response of plant nutrients and secondary chemicals grown in this system might be different than in other FACE studies since there are differences in nutrient cycling in cities when compared to rural, natural and other agricultural sites (Rao et al., 2014; Templer et al., 2015; Decina et al., 2016) with higher [CO_2], temperature, ozone, nitrogen, and other environmental factors (Briber et al., 2015; Patterson & Eatough, 2000; Weschler, 2006; Xue et al., 2014) which could change plant responses (Kangasjärvi et al., 2005; Prajapati, 2012; Rao et al., 2014). The effects of increased [CO_2] in urban systems in general as well as different biomes could be examined. While this study focuses on urban environments, it is important to note that this concept could also be applied to buildings in rural areas if a large enough number of people are present in a building.

The influence of this system could be understood for different plants and for buildings with different building metabolisms as well as for what plants would be best suited for each building type. For example, there could be building types where people are more likely to inhabit the building at night, which would decouple the largest source of CO_2 from the time when the plants are growing most. This type of building might benefit from a storage and concentration option or growing plants using a CAM photosynthetic strategy. In a school building, the largest number of people will be inside from September until May or June, so cold weather crops like spinach and kale could be easier to produce. An office building would most likely be occupied throughout the year and a wider variety of crops could be grown for a longer period of time. Therefore different design considerations would most likely have to be made for different types of buildings.

5 Conclusions

Cities are facing a variety of environmental challenges and it would be beneficial to find ways to grow plants on underutilized rooftops. To our knowledge, this is the first study to take indoor air with higher [CO_2] and apply it to plants grown in a rooftop garden or farm. The enhanced growth found is consistent with a CO_2 fertilization effect as characterized by FACE experiments though it also indicates the influence of other environmental characteristics of the exhaust vent air, such as temperature, in increasing growth. There is a lot of potential for further optimization of the system design, but this system takes advantage of an underutilized resource that particularly exists in large quantities in cities and opens the door for considering other potential unique resources such as nutrients, microclimates, etc. Depending on further assessments of scaling up this system, implementing this approach on rooftops across cities and increasing overall urban vegetation could help address some environmental challenges facing cities including producing hyper local food more efficiently and sustainably, harvesting carbon, and helping integrate into the surrounding environment.

2 Materials and Methods

Experiments were carried out in the fall of 2018 and the spring of 2019 in the northeastern United States in Boston, Massachusetts. [CO_2] and other environmental measurements were taken inside of classrooms and at the rooftop exhaust vents. The vent air was directed at the plants, spinach and corn, and the effect on growth was measured.

2.1 Site Selection

Buildings and rooftops at Boston University (BU) were used for this research. The local facilities staff was consulted in order to determine the safest location for the experiment, with considerations including condition of the roof, accessibility, and presence of parapets around the edge of the roof. Eight buildings were identified and an initial survey of exhaust [CO_2] was conducted. Short-term measurements of [CO_2] were taken during the middle of the day when buildings were occupied. Initial results indicated that [CO_2] was elevated at most buildings, ranging from 500 ppm to 1000 ppm in comparison to atmospheric CO_2 at 410 ppm. A high school on the BU campus, the BU Academy (BUA), located at 785 Commonwealth Avenue had

CO_2 levels of approximately 700 ppm and was chosen as the site for the rooftop garden/farm experiments. A large academic building, The College of Arts and Sciences (CAS), 725 Commonwealth Avenue, was also chosen for further indoor [CO_2] measurements due to its central location on campus and the use of an online scheduling system within the building that provided more information about building occupation.

2.2 CO_2 and Classroom Measurements

2.2.1 Classroom Occupancy Data

25Live (CollegeNET, Portland OR) is a scheduling software used at multiple universities, including BU. It assists with classroom management in buildings like CAS. This system allows for approved community members to reserve spaces for various events including classes. Event room, date, time, and anticipated occupancy data along with room size were collected from this system for 20 classrooms for the weeks during which the [CO_2] sensors were installed.

2.2.2 Indoor Classroom [CO_2] Measurements

From January 2018 through March 2019, three [CO_2] monitors (Onset HOBO Bluetooth Low Energy Carbon Dioxide – Temp – RH Data Logger, #MX1102) were installed in 20 classrooms throughout CAS. There was an initial factory calibration process where the monitors were placed outside and calibrated for 5 minutes using this internal system when first acquired and before use. Additionally, monitors were cross-checked with each other across a range of [CO_2] by placing them together in a closed chamber with a series of [CO_2] produced by human breath. Overall measurements as well as trends matched across all three monitors. Factory calibrations were also compared with and found to be within ±50 ppm of a 400 ppm standard compressed air source (AirGas, Rendon, PA), which is close to the current atmospheric background [CO_2] of 410 ppm at the time of the study (Dlugokencky & Trans, 2018; Ng et al., 2019).

Sensors were placed within classrooms at approximately the same height (1.5 m above the ground) and location as permanently installed [CO_2] sensors and air monitors found within the classrooms. Installment of these sensors allowed us to make measurements reflective of those taken by the university. The approximate height was between 1.25 and 1.5 m, which is also similar to other studies (Lee & Chang, 1999). Logging was started at least 2 minutes after installation to prevent CO_2 contamination from the breath of the investigators. No installation effect was ever identified. A week was used as the time frame for each classroom to capture the dynamics throughout a normal workweek and over the weekend when different usage patterns were expected. Classrooms were primarily used because they represent a primary function of the school building. It is a relatively confined space occupied by multiple people for a designated period of time and therefore easier to track.

2.2.3 Rooftop CO_2 Measurements

The [CO_2] sensors were also installed on vents on top of the BUA roof. Two sensors were placed on Direct Drive Centrifugal Roof Exhausters Model PRN (ACME Engineering and Manufacturing Corporation, Muskogee, OK) and two were placed on control fans of the same type installed at separate locations on the BUA rooftop. We chose these vents, commonly referred to as mushroom vents, because of their prevalence on rooftops and the higher than normal [CO_2] found in their exhaust air in comparison with other vents. Through discussions with facilities and inspection of building plans, they were also identified as general exhaust from internal human-occupied spaces. The sensors measured the [CO_2], temperature and relative humidity of emitted exhaust vent air to determine whether [CO_2] is higher than the atmospheric concentration and if measurements are correlated to internal dynamics connected to human usage of the building.

Sensors were first installed at the exhaust vents for four weeks from June 25th to July 22nd of 2018 to understand dynamics during periods of time when there were varying amounts of people in the building. Information regarding the schedule of the building was obtained. During the first two weeks, only instructional staff (no students) were present during the day, which consisted of 10-15 people. During the second two weeks, a camp program was run with around 175 students attending classes regularly throughout the day.

The rooftop sensors were also run throughout the rooftop garden experiments. During this time, a sensor was installed within a bathroom on the second floor of the BUA. Blueprints for the design of the building indicated that this location was most likely the closest point within the building to where the exhaust vents were connected. This could be because the vents associated with restrooms fall under specific guidelines and are always operational and constantly remove air from inside the building. These could be less directly connected to classroom [CO_2], but given general circulation and diffusion, could be representative of overall [CO_2] within a building.

2.3 Rooftop Garden Experiment

2.3.1 Plant Growth: Study Species

Spinach (*Spinacia oleraceae L.)*, used for the majority of rooftop garden experiments, is an economically and nutritionally important crop (Min, 2014; Reddy et al., 2014). It has a high nutritional value (Kuti & Konuru, 2004) and notable quantities of secondary chemicals (Nuutila, 2002; Bunea et al., 2008; Shohag et al., 2011), which protect against chronic diseases (Howard et al., 2005). It is a cold-season crop from southwestern Asia (Candlish et al., 1987), important because all experiments were run in the fall and spring seasons. This timing was used because this is when the largest number of people are present in university and high school buildings and the study was testing the impact of exhaust vent air with potentially higher [CO_2] from those people on plant growth. Spinach also utilizes the C3 photosynthetic metabolic pathway, which is more responsive to elevated [CO_2] over the expected range studied here than plant species with other metabolic pathways (Kimball et al., 2002; Nowak et al., 2004).

Corn (*Zea mays*) was grown in the spring to explore the effect of other characteristics of the exhaust vent air such as temperature. Corn is originally from Central America and the most widely planted crop in the United States with 31.9 million ha planted in 2002 (Kadam & McMillan, 2003). It has less tolerance for cold than spinach (Warrington & Kanemasu, 1982), but is known to use a C4 carbon fixation strategy, which makes it less sensitive to increased [CO_2] than C3 species (Ainsworth & Rogers, 2007; Hatfield et al., 2011). Therefore, corn would instead respond more strongly to other environmental characteristics of the exhaust vent air such as temperature (Ainsworth & Rogers, 2007; Leakey et al., 2004; Long et al., 2006).

2.3.2 Experimental Treatment and Garden Set Up

Test gardens were built around the two Direct Drive Centrifugal Roof Exhausters that were actively and continuously exhausting air on the rooftop and the two control fans. The control fans tested the effect of the fans alone without exhaust vent air from inside of the building. Hereafter these treatments are called Exhaust Vents and Control Fans. During the test period, daytime conditions from the exhaust vent were similar to indoor air and different from daytime conditions at the control fan as shown by [CO_2], temperature, and relative humidity measurements (Figure S1) taken with the Onset HOBO sensors described above. For [CO_2] the daytime measurements averaged 758 ±3.7 ppm at the Exhaust Vents, 512 ±2.8 ppm Inside, and 454 ±2.5 ppm at the Control Fan. None of the 95% confidence intervals for the Exhaust Vent (765.1-751.0), Indoor measurements (517.6-506.8), and Control Fan (459.4-450.0) overlapped though the Exhaust Vent was most different being 67% higher than the Control Fan compared to Indoor measurements being 13% higher than the Control Fan. For temperature, the daytime measurements averaged 72 ± 0.035 °F at the Exhaust Vent, 70 ±0.032 °F Inside, and 58 ±0.24 °F at the Control Fan. Since these measurements were taken in the fall, indoor temperatures were higher at the Exhaust Vent and Inside to compensate for cold outdoor temperatures. Confidence intervals for the Exhaust Vent (72.29-72.16), Inside (69.98-69.86), and Control Fans (58.32-57.37) showed a greater difference than with CO_2 with Exhaust Vent and Indoor measurements being 25% and 21% larger than Control Fan air. For relative humidity, the daytime measurements averaged 45% ±0.38 at the Exhaust Vent, 45% ±0.40 Inside, and 68% ±0.45 at the Control Fan. This was also reflected in the confidence intervals for Exhaust Vent (45.8-44.3), Indoor measurements (45.7-44.1), and Control Fan (68.9-67.1), which overlapped for Exhaust Vent and Indoor measurements and were 33.7% and 33.9% over the Control Fan measurements. These differences created the Exhaust Vent treatment experienced by plants grown in the test garden.

In the test gardens, plants were grown in milk cartons, which are large, mobile, and relatively accessible. Milk crates are also the primary container used by current installers of rooftop farms in Boston and across the region, such as Recover Green Roofs (www.recovergreenroofs.com). Recover Green Roofs has developed a RAMM (Recover Aerated Media Module) design with a non-woven Polypropylene Liner with organic compost-based potting mix (Recover, 2018). The milk crate and felt portion of Recover Green Roof's RAMMs were graciously lent by Recover Green Roofs to maintain a system similar to other rooftop farms in Boston. Eight of these milk crates were placed in pairs around each of the four sides of each fan for a total of 32 milk crates.

We used an open system to apply the vent air to avoid backpressure. Curved aluminum structures (Figure 1) were attached around the base of the vent to direct the vent air towards the plants. This avoided drying out the planting media, a common issue in rooftop gardens (Ahmed et al., 2017), by aiming the vent air above the media. Soil moisture was measured in each milk crate twice a week using a hand held Soil Moisture Meter (Vegetronix, Digital VG-Meter-200). An anemometer (HOLDPEAK 866B Digital Anemometer Handheld) was used to determine the wind speed of the exhaust vents. The wind speeds of the two exhaust vents were approximately 10 and 17 mph. It was not possible to change the speed of either of these fans. Therefore, the speed of the two control fans were adjusted to reflect these wind speeds.

Figure 1. Experimental garden set up around rooftop exhaust vents and control fans. Spinach and corn were planted in milk crates provided by Recover Green Roofs positioned next to various vents for four and a half weeks until harvest after which growth was measured.

2.3.3 Plant Growth

In the fall of 2018, spinach seeds (Bloomsdale, Long standing, USDA organic) were purchased from Mountain Valley Seed Co. and planted in starter trays for four weeks in a classroom in BUA with a large south facing window. They were watered from above approximately every other day until ready to be transplanted on the roof. Plants were hardened for a week before being transplanted by being moved onto the rooftop for increasing amounts of time. The sprouts were then moved permanently up to the rooftop and 12 spinach plants, three rows of four, were planted in each of the 32 boxes. The experiment produced a total of 384 plants with 96 in each of four treatments, with each treatment distributed among 8 boxes. In spring 2019, the same experiment was done except with corn seeds (Trinity Organic F1) purchased from Johnny's Selected Seeds (Winslow, ME). Nine corn sprouts, three rows of three, were planted in 12 boxes for a total of 81 plants, 27 in each treatment. This represents pseudo replication with multiple plants and boxes surrounding only two exhaust vents and two control fans, each with a different wind speed (Ellsworth et al., 1996). In the spring only the low wind speed exhaust vent and control fan was used along with a second control group where the fan was not turned on to further test the effect of the wind speed on the plants. Spring measurements were done to gain a preliminary understanding of whether environmental factors besides [CO_2] such as temperature contributed to the growth effect on plants.

Nature's Care potting soil, and organic, compost-based soil similar to the potting mix in the Recover Green Roof RAMM system was used. After one full day outside, the boxes were moved a foot away from the edge of the vents and fans at the end of the metal sheets directing the air. Plants were watered approximately every other day once it had not rained for three consecutive days.

2.3.4 Crop Performance

Every 10 days one row of three plants was harvested. Plants were cut at the base just below the soil surface and immediately weighed to measure the wet weight of biomass. All plants were then frozen and kept at -80 °C until they were placed within a lyophilizer and dried for three days. At the end of this, plants were again weighed to find the dry weight of biomass. In the fall, three harvests were carried out a week and a half apart and in the spring all plants were harvested at the end of the four and a half weeks. Each week the number of leaves was counted on each plant. A leaf was counted once it had unfolded and the petiole could be seen extending from the center of the spinach plant.

2.4 Statistical Analysis

All statistical analyses and data visualization were performed in R (Version 3.4.4). For a subset of the classrooms in CAS (Rooms B08A, 114B, 201, 213, and 315) where [CO_2] was measured, the scheduling data were merged with the [CO_2] data. The class times were then highlighted on the [CO_2] graphs in order to determine overlap of [CO_2] spikes and class times. Since people are mostly present in school buildings and plants primarily undergo photosynthesis during the day, the CO_2 and environmental conditions between 8:00 am and 4:00 pm were isolated and further analyses were conducted on this subset of data.

Overall effects of the different treatments of air from exhaust vents and control fans on the wet and dry biomass and leaf number of the crops were analyzed with an ANOVA with each plant as the experimental unit. The treatment was the independent variable and the biomass or leaf number the dependent variable. The multiple comparisons using least squares means Tukey's HSD method was used to identify significant differences between treatments. This same analysis was done to determine differences between the effect of different speeds at the four fans. An ANOVA was used for analysis of the environmental characteristics though averaging environmental data over time ignores non-linear impacts on trends. To further characterize these data, 95% confidence intervals and effect size were also calculated.

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