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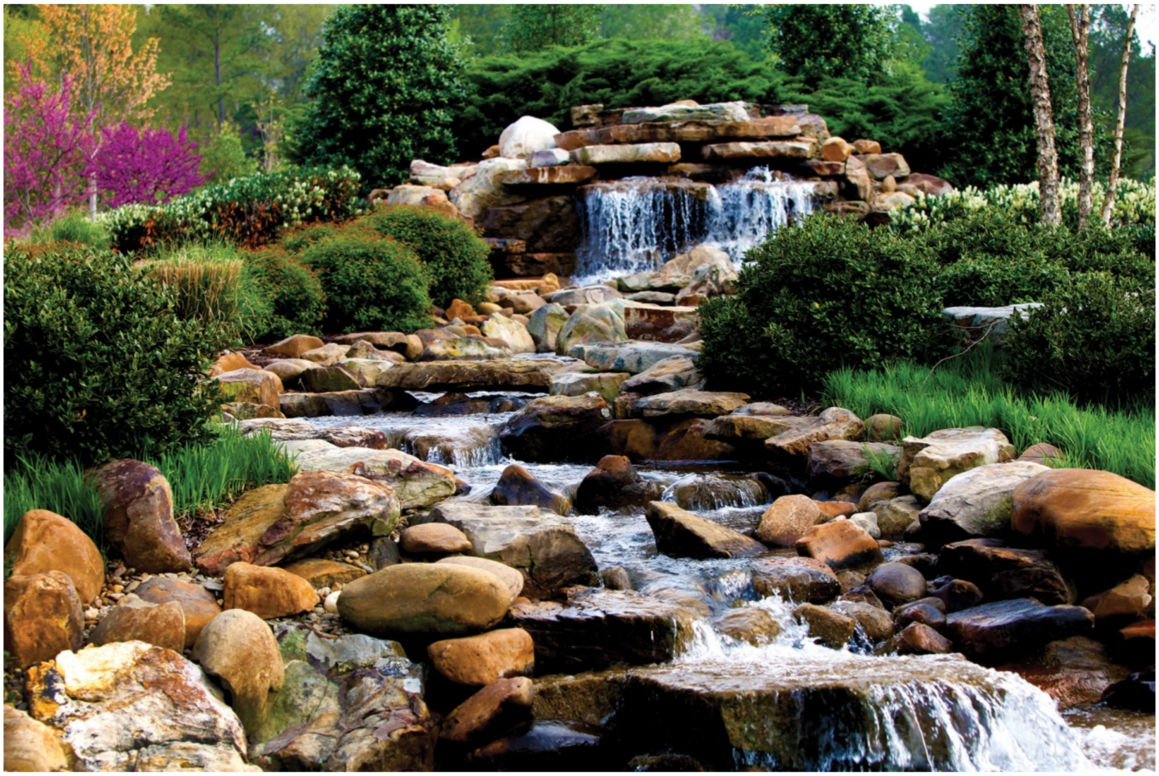
BTRIC Technical Support for Appalachia: FY 2023 Summary Report on Net Negative Carbon Building Demonstration with AgPod



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OAK RIDGE National Laboratory

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

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Buildings and Transportation Science Division

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ABBREVIATIONS

ADUS	automated DAC/utilization system
AgPod	agricultural pod
Ca	atmospheric CO_2 concentration
Ci	internal leaf CO_2 concentration
CEA	controlled-environment agriculture
CO_2	carbon dioxide
DAC	direct air capture
DOE	US Department of Energy
ECEA	enriched controlled-environment agriculture
EGH	enriched greenhouse horticulture
KCDC	Knoxville's Community Development Corporation
LED	light-emitting diode
ORNL	Oak Ridge National Laboratory
PAR	photosynthetically active radiation

EXECUTIVE SUMMARY

The overall goal of this 3-year project is to demonstrate how a small neighborhood could become net negative in carbon dioxide (CO_2) emissions. The project consists of six major tasks: (1) direct air capture (DAC) system development, (2) DAC integration with the agricultural pod (AgPod), (3) deployment of the combined system at Knoxville's Community Development Corporation, (4) data collection, (5) research on crop enhancement, and (6) final report. This document reports on the project's progress through the end of fiscal year 2023.

This study investigates the effects of various concentrations of CO_2 on the photosynthesis and biomass accumulation of crops growing in an AgPod, using kale as the initial test crop. Increasing the CO_2 concentration in the AgPod was found to promote higher photosynthetic rates in kale plants up to 1,300 ppm (the highest CO_2 concentration measured). An interesting finding was that net photosynthetic rates of kale leaves remain unsaturated until reaching unusually high levels of photosynthetically active radiation (PAR, > 1,200 µmol m^{-1} s^{-1}) and CO_2 concentration (> 1,100 ppm). Such high levels of saturating PAR and CO_2 concentration values rarely occur under natural conditions, suggesting a promising potential for carbon capture via enriched greenhouse crop production. This task is one part of an overall plan to incorporate an AgPod to utilize carbon captured from the atmosphere to achieve net negative carbon emissions in a small neighborhood or community.

Net negative carbon emissions are defined in this study as offsetting operational carbon emissions for the energy used by a building (power plant emissions) by capturing carbon from the environment and converting it into a useful product. This approach uses the CO_2 onsite, thereby eliminating emissions from transportation of the captured carbon for utilization in an application such as cement. Later, as lower embodied carbon building products become available, the goal will be to reduce the embodied carbon in buildings. For this study, we are focusing on a single building with plans to scale up as the project progresses.

We have incorporated a holistic approach for the net negative carbon demonstration by first designing the building to reduce heat loss with an improved envelope design and advanced weatherization techniques. Next, high-efficiency electric building equipment, such as heat pumps and heat pump water heaters, is used to reduce energy consumption. The addition of renewable energy sources further reduces energy acquired from the power plant.

The last step in the overall process involves carbon captured from the atmosphere as one air stream passes through a rotating wheel embedded with a carbon-absorbing material. As the wheel slowly rotates, the material is regenerated at a lower temperature in another air stream that passes through the wheel. The carbon driven out of the material is then sent to the AgPod to enhance crop yield. This holistic approach enables the total carbon emissions to be net negative.

1. BACKGROUND

1.1 EMISSIONS

Global carbon dioxide (CO_2) emissions have been increasing over the last century. In the United States, emission levels have dropped since around 2007, mainly as the result of a decrease in the number of coal plants and an increase in renewables (Figure 1). Emission reductions can also be achieved with carbon capture technologies, although the carbon must be captured and sequestered in some manner. Natural forms of sequestration, such as forests, grasslands, soil, oceans, and other water bodies that can store carbon, are known as carbon sinks. Geological carbon sequestration happens when carbon is stored in places such as underground geological formations or rocks. This process is largely artificial or "direct," representing an effective way of neutralizing emissions from manufacturing or construction. The CO_2 emissions, especially flue gases, can be captured in various forms before they are emitted to the atmosphere (Wang and Song 2020).

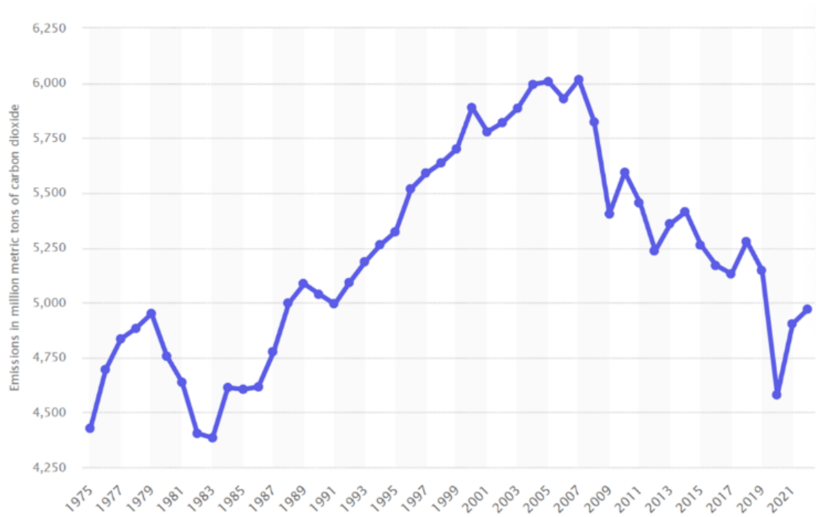

Figure 1. Carbon dioxide emissions in the United States, 1975–2022.

1.2 DIRECT AIR CAPTURE

Direct air capture (DAC) is a method of carbon capture used to selectively extract CO_2 from atmospheric air so that it can be moved and/or used in a concentrated form (Brilman 2020). However, the cost of DAC is significantly higher than the cost of extracting CO_2 from a point source, such as a fossil-fueled power plant (National Academies of Sciences, Engineering, and Medicine 2018). Therefore, ideas for lowering the cost of DAC, such as piggybacking the DAC function on existing infrastructure, could be appropriate. HVAC and other air moving equipment can be leveraged for their dual use—as a space conditioning machine and as a mechanism to capture carbon from air passing through or by the machine. These ideas could also help reach the US Department of Energy's (DOE's) Energy Earthshots Initiative goal of reducing the cost of DAC to below \$100/t of CO_2 (DOE 2021).

1.3 NET NEGATIVE CARBON DEMONSTRATION

The demonstration in this study, shown in Figure 2, in a low-income neighborhood uses captured CO_2 from a building to saturate the CO_2 of a greenhouse to maximally accelerate plant growth. Decarbonization of low-income neighborhoods can be accomplished through the engineered removal of ambient CO_2 through community-scale DAC and plant-based carbon absorption/storage in facilities such as community gardens or greenhouses. In combination, these have the potential to offer significant benefits to both community members and broader decarbonization goals. The approach in this study is to integrate DAC with an agricultural pod (AgPod) to provide supplemental CO_2 to optimize growing conditions in the AgPod.

Figure 2. Net negative carbon demonstration including electric vehicles, agricultural pod, photovoltaic cells, and building envelope with improved insulation.

1.4 DIRECT AIR CAPTURE SYSTEM DEVELOPMENT/INTEGRATION WITH AGPOD

A DAC system can provide economic value by utilizing the captured CO_2 in a greenhouse carbon enrichment exercise. The captured CO_2 can be directly released from capture devices and used for processing without purification or post-processing to reach a high purity of CO_2. This simplifies the overall integration process. As an added benefit, the present practice of burning hydrocarbon to produce supplemental CO_2 for greenhouse crop production can be eliminated.

The research team at DOE's Oak Ridge National Laboratory (ORNL) has successfully demonstrated that a building air handling system can be used for direct CO_2 removal from ambient air (Figure 3).[1] The study included the regeneration process of the adsorbents for reutilization in experimentation. However, this regeneration process was performed off-site in a lab environment. As such, further investigation is required to develop a system for automatically transporting enriched CO_2 streams to the AgPod. One such concept is shown in Figure 4. The idea is to capture carbon on a process side, regenerate on the other side, and then send CO_2 to the AgPod through ducting.[2]

[1] US Patent App. 17/974,227, "Multi-functional equipment for direct decarbonization with improved indoor air quality."
[2] ID no. 202305285 DAC integrated to AgPod or GreenHouse for CO_2 enrichment.

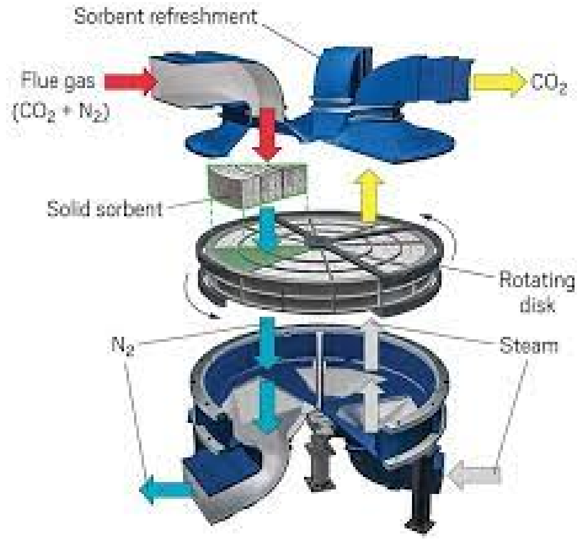

Figure 3. A direct CO_2 removal demonstration.

Figure 4. An automated direct air capture/ utilization system.

Deployments leveraging existing infrastructure can revolutionize DAC technology with minimal operational and capital costs associated with retrofit approaches. In one promising case, existing modular and scalable building equipment represents an excellent platform for an application in which the DAC modules can be included with marginal increments in required fan power to operate the system. Using the waste heat for regeneration of DAC modules to offset a dedicated energy source for process (directly or after upgrades) provides an additional value. The captured CO_2 would provide CO_2 enrichment for the greenhouse, resulting in an environment that can be controlled to optimize photosynthesis, rather than opportunistically capturing CO_2 from building exhaust. This would eliminate the potential for introducing less-desired components of indoor air to the growing space.

Dong et al. (2018) reviewed the influence of elevated CO_2 concentration on the yields of vegetables and found that elevated CO_2 (827 ppm) increased the yield of vegetables by 34%. The benefits of CO_2 enrichment (higher CO_2 concentration) are well documented for commercial greenhouse crops, including fruits, flowers, and vegetables (such as tomato, cucumber, pepper, lettuce, and rose crops). On average, greenhouse crops benefit from concentrations between 700 and 1,000 ppm, which produce yield increases from 21% to 61% in dry mass. Currently, CO_2 enrichment is conducted with pure CO_2 or from the combustion of hydrocarbon fuel, such as natural gas or propane.

1.5 DATA COLLECTION

The building to be used in the scaled-up study is a 32-unit apartment complex (Figure 5). A groundbreaking ceremony was conducted in August 2023, and the building is expected to be completed by May 2024 (KCDC 2023). Electricity consumption of the whole building is equal to the combined electricity usage of various sources including HVAC systems, domestic water heaters, indoor lighting, and appliances such as TVs, clothes dryers, refrigerators, dishwashers, and ceiling fans. The collected data will serve the purpose of assessing the building's total energy usage and operational carbon emissions. Additionally, the data can be further analyzed to differentiate between HVAC and other electric loads. Furthermore, the data will also be used to evaluate the estimated energy and carbon savings compared with typical multifamily buildings in the same climate zones.

Figure 5. Rendering of the 32-unit apartment complex being used in this study.

To determine the electricity consumption of the whole building, watt transducers will be utilized to measure electricity usage. Depending on the specific measurement point, the number of required sensors may vary. If a measurement can be obtained through a single data point, then only one watt transducer is necessary for measuring electrical consumption. However, if that is not possible, multiple sensors may be required for each residential unit and commercial area. In addition, unit-level electricity consumption will be monitored in selected sample residential units.

For the main energy-use equipment (space conditioning and water heating), ORNL worked with Knoxville's Community Development Corporation (KCDC) to specify higher efficiency heat pumps (SEER = 16.5) and heat pump water heaters (UEF = 3.8), rather than the originally planned equipment (standard efficiency heat pump [SEER = 14.5] and electric resistance water heater). The building will have a solar photovoltaic (PV) system with a capacity of 76.3 kW estimated to generate approximately 95,912 kWh of electricity per year. A monitoring system will track the solar PV system's energy generation data. Analyzing the electricity output makes it possible to determine the amount of energy and carbon emissions that potentially could be reduced. Energy generated by the solar array will be subtracted from the total building energy consumption to determine the net energy consumed by the building. The CO_2 emissions will be determined by multiplying energy consumption by a carbon emission factor for the region available from the US Environmental Protection Agency's eGrid.

1.6 IMPACT

Global demand for food and biofuel is projected to increase substantially in the coming decades because of population growth and economic development. This increased demand is not expected to be met via traditional means of agricultural production such as expanding arable land area and improving crop productivity, both of which have plateaued worldwide. However, this project could aid in meeting that demand. Meanwhile, climate change has led to more frequent occurrences of extreme events such as drought, heat waves, and floods, which increasingly disrupt agricultural production worldwide. Although genetic modification of crops can increase photosynthetic efficiency and crop yields, such efforts are still at the conceptual stage (Gu 2023). A new green revolution could be realized by a marriage between energy industries and controlled-environment agriculture (CEA). A major strategy will be to feed flue gas and waste heat to greenhouse horticulture (i.e., enriched greenhouse horticulture, or EGH), to enable year-round growth of vegetables, fruits, and staple crops. Flue gas contains a high CO_2 concentration but a low

O_2 concentration. High CO_2 concentration increases the carboxylation efficiency of Rubisco (the main photosynthetic enzyme), and low O_2 concentration suppresses photorespiration; both processes increase the rate of photosynthesis. Therefore, fumigating greenhouse horticulture with flue gas can significantly increase horticultural productivity. Currently, agricultural production is largely a summertime activity in subtropical and temperate regions where most populations reside, primarily because of temperature limitation in winter. Using waste heat to warm greenhouses makes winter horticulture possible. Enriched controlled-environment agriculture (ECEA), under which EGH is a major approach, can be a significant negative carbon emission activity because it reduces greenhouse gas emissions from power plants and refineries and from traditional agricultural production that ECEA displaces. ECEA can also reduce greenhouse gas emissions associated with food transportation because it can be developed close to population centers.

2. CROP EVALUATION PROCEDURE

After receiving the AgPod (Figure 6), the research team performed shakedown tests to ensure all systems were operating properly. Next, a baseline crop was planted. For the first crop, CO_2 concentration was equal to the ambient conditions, approximately 415 ppm, with the addition of ambient air for mixing. Figure 7 shows the crop growing in the AgPod approximately 9 weeks after seeding. The AgPod is equipped with light-emitting diodes (LEDs; Figure 8) that are controlled at different wavelengths to produce light optimized for each type of crop grown in the AgPod.

In future tests, the CO_2 concentration will be enriched to higher levels. Other environmental conditions such as temperature, relative humidity, irrigation, and nutrient supply will be controlled during those future CO_2 enriched experiments.

Figure 6. The agricultural pod facility at Oak Ridge National Laboratory.

Figure 7. The first crop in the agricultural pod.

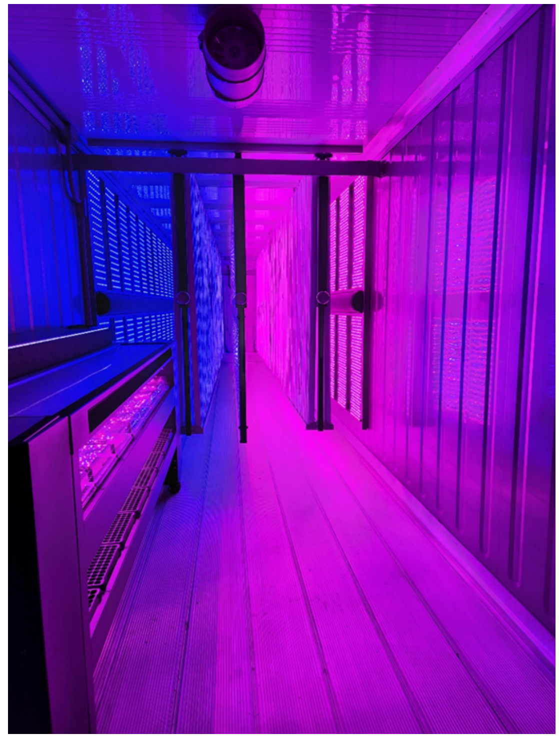

Figure 8. Agricultural pod LED grow lights.

During the growing period, the growth rate (head dimensions/height, outer leaf length/width) was monitored weekly (Table 1). Two leaves on each plant were monitored for length and width, and the total number of leaves on each plant was recorded. The first leaf selected on each plant for monitoring was the longest leaf 1 week after the seedlings had been placed in the growth curtains. The second leaf on each plant was selected for monitoring when each plant had 10 leaves on its stem. Any leaf could be selected midway from the center of the plant and the end of the leaf.

The same leaves were monitored through each plant's lifetime. Plant photosynthetic performance was measured with specialized leaf gas exchange and fluorometry equipment; these measurements will be compared with the performance of plants in subsequent trials (Figure 9).

Table 1. Initial plant growth measurements

ID of the plant monitored	**1-3D**			**ID of the plant monitored**	**1-3D**	
Date 9/15/23				**Date 9/22/23**		
First Leaf	**Length (inches)**	**3.75**		**First Leaf**	**Length (inches)**	**4.00**
	Width (inches)	**1.50**			**Width (inches)**	**1.75**
Second Leaf	**Length (inches)**			**Second Leaf**	**Length (inches)**	
	Width (inches)				**Width (inches)**	
Total number of leaves		**7.00**		**Total number of leaves**		**9.00**
Observer	**Jobe**			**Observer**	**Jobe**	

At weekly intervals during the growth period, random samples were harvested for analysis and data collection. Biomass of the harvested plants is being assessed to track the vegetative growth rate over time. Harvested plants are being dried to constant weight at 70°C in ovens at ORNL's Environmental Sciences Division facilities, then total biomass is recorded. Dried plant material will be ground, then percent carbon and percent nitrogen content will be measured. With knowledge of the number of plants per unit area in the AgPod, results will be scaled to quantify the total carbon that could be sequestered into the plant biomass on an annual basis, depending on the number of crop cycles and maximum CO_2 concentration as described later.

Figure 9. Photosynthesis measurements.

To assess the impact of carbon dioxide treatments on plant photosynthetic performance, photosynthetic parameters were assessed under each treatment condition. Response curves for photosynthetic light and CO_2 were measured on three randomly selected plants using portable gas exchange systems (model LI-6800, Licor BioSciences). Photosynthetic response is normalized by leaf area and also will be normalized by nitrogen content. Light response curves are completed by measuring the photosynthetic rate at progressively increasing light levels, from 0 to 1,800 µmol m^{-1} s^{-1} of photosynthetically active radiation. The CO_2 response curves are created by measuring the photosynthetic rate at progressively increasing atmospheric CO_2 levels, from 0 to 2,000 µmol m^{-1} s^{-1} of CO_2.

One of the major goals of the research is to understand how much CO_2 can potentially be captured and sequestered with the AgPod. In 2023, the baseline crop without CO_2 was planted and analyzed. Additional crops will be planted by introducing higher concentrations of CO_2. Future crops will be analyzed in a manner similar to the baseline crop. This will provide information to determine the optimum level a DAC system could saturate the atmosphere of the AgPod.

After the CO_2 study with kale is finished, other crops will be planted; a variety of vegetables, flowers, and herbs can be grown in an AgPod. The CO2 consumption of these alternate plants will be studied in the same manner as how the kale plants were studied.

3. RESULTS AND DISCUSSION

Figure 10 shows the photosynthetic light response curves at standard temperature (25°C) for two Lacinato kale plants grown under ambient atmospheric CO2 concentrations (400 ppm) where XX/YY days indicates the number of days in the nursery/number of days in the vertical growth racks when measurements were conducted. For example, Lacinato 1 was in the nursery for 34 days and in the vertical grow racks for 35 days. The horizontal dashed red lines indicate that light saturation of photosynthesis occurred at light levels greater than 1200 µmol m^{-1} s^{-1} of photosynthetically active radiation (PAR).

The light response curves indicate that photosynthesis increases with increasing light levels and approaches a point of saturation above 1,200 µmol m-1 s-1 of light. The saturation light level varied by plant; maximum light-saturated photosynthesis under ambient conditions (ambient CO2 at 400 ppm) ranged from 20 to 30 µmol m-1 s-1 of net carbon dioxide removal.

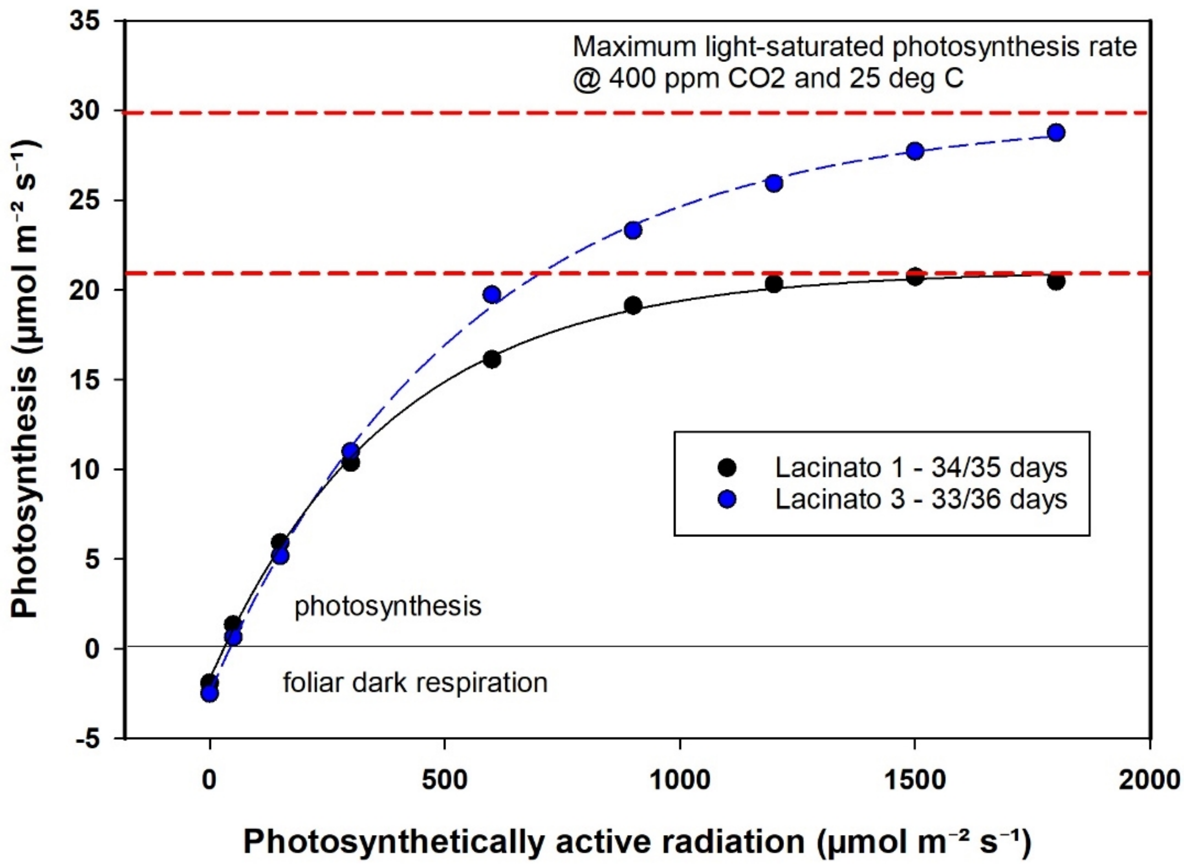

Figure 10. Photosynthetic light curves.

Figure 11 shows the photosynthetic CO_2 response curves at standard temperature (25°C) for three Lacinato kale plants grown under ambient atmospheric CO_2 concentrations. Curves reflect the rate of photosynthesis per unit internal leaf CO_2 concentration (Ci), which is a function of atmospheric CO_2 concentrations (Ca). Ca was increased from 0 to 1,200 µmol CO_2 m^{-1} s^{-1} (or up to 2,000 µmol CO_2 m^{-1} s^{-1} for Lacinato 1). Results suggest that photosynthesis can continue to increase beyond Ca > 1,100 ppm (Ca data not shown). The horizontal dashed red lines indicate a maximum rate of photosynthesis of 40–50 µmol CO_2 m^{-1} s^{-1}.

The CO_2 response curves indicate that photosynthesis increases with rising CO_2 concentrations, initially with a steep slope that then approaches a point of saturation above 1,100 ppm of atmospheric CO_2. The saturation light level varied by plant; maximum CO_2-saturated photosynthesis under ambient conditions was in the range of 40–50 µmol m^{-1} s^{-1} of net carbon dioxide removal.

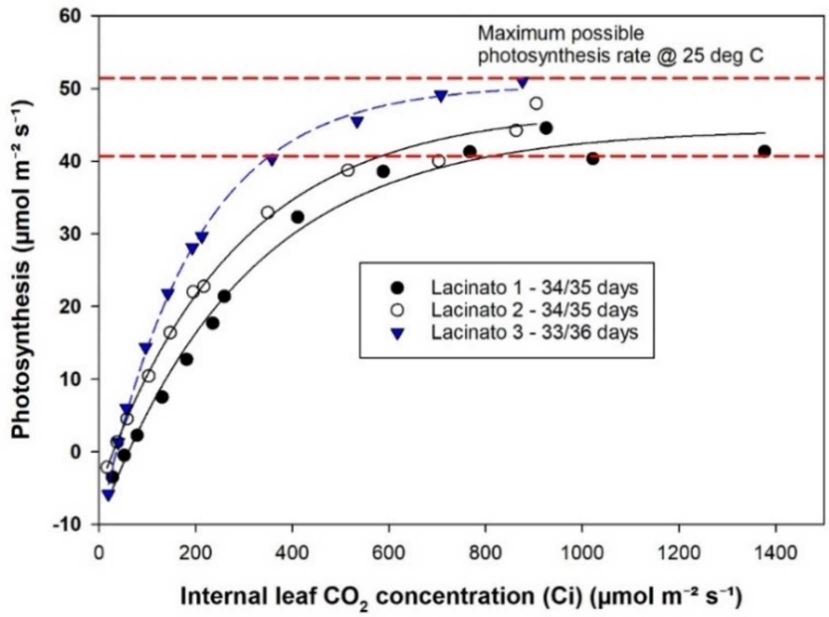

Figure 11. Photosynthetic CO_2 response curve.

Plant monitoring (Figure 12) showed that about 30 days after leaf emergence, leaf width reaches its maximum, whereas leaf length keeps extending and new leaves continue emerging. Total plant biomass monitoring has started, but data have yet to be processed. These data will be used to determine the optimal harvest time for kale.

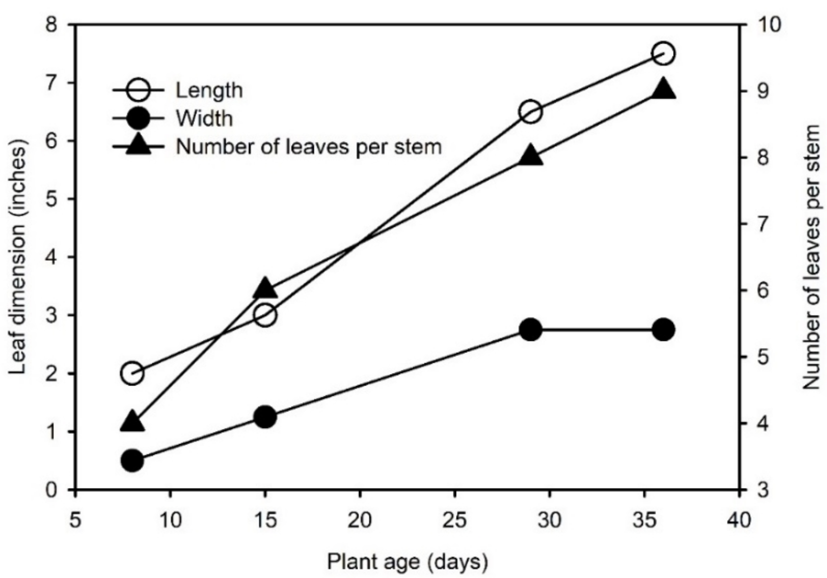

Figure 12. Leaf growth monitoring over time.

Photosynthesis measurements reveal several interesting properties of the AgPod-grown kale. First, these are very high rates of photosynthesis, suggesting that the AgPod operation has the capability to outperform field conditions in atmospheric CO_2 uptake per unit area.

Among the key research findings, short-term elevated CO_2 applied to plants grown under ambient CO_2 conditions greatly enhances maximum net photosynthesis rates, doubling the amount of CO_2 removal from the atmosphere under high CO_2 conditions. Photosynthetic rates above 40 μmol CO_2 m^{-1} s^{-1} are very high compared with rates of non-AgPod grown plants.

Results with other systems grown under elevated CO_2 indicate that there can be feedback and down-regulation of photosynthetic capacity, depending on other limitations. This would, in effect, reduce the slope of the photosynthetic CO_2 response curves such that increasing CO_2 would have a reduced response on photosynthesis for plants grown under elevated CO_2 in comparison with plants grown under ambient CO_2. This will be evaluated in the next phase when plants are grown under elevated CO_2 conditions.

Data from ambient and elevated photosynthetic CO_2 response curves will also be used to assess if the underlying mechanistic limitations to photosynthesis are impacted by CO_2 treatments. Specifically, these are derived from the curves and estimate the maximum carbonylation rate, V_{cmax} (the rate of actual capture and conversion of atmospheric CO_2 to plant metabolites), J_{max} (the rate of conversion of solar energy to chemical potential energy based on electron transport within the leaf chloroplast membranes), and TPU (triosephosphate utilization, indicating if sugars produced by photosynthesis are being used). Optimal nutrition and fast vegetative growth rates of the kale suggest this last mechanistic limitation may not be realized.

4. FY 2024 PLANS

The following major tasks are planned for FY 2024:

1. Complete the automated DAC/utilization system (ADUS)
2. Integrate the ADUS in the AgPod
3. Install the data acquisition system in the KCDC apartment complex
4. Complete crop testing in the AgPod
5. Deploy the AgPod with ADUS (dependent on funding)
6. Initiate data acquisition and analysis

5. CONCLUSIONS

Our initial results suggest that growing kale plants in the AgPod system resulted in a successful and highly productive crop. Further, the kale plants grown under ambient CO_2 conditions (415 ppm) are not CO_2 saturated and can potentially improve yield under a DAC-created elevated CO_2 environment. Further experiments will test if the theoretical productivity increases shown in the photosynthetic CO_2 response curves can be realized under an elevated CO_2 growth environment. Many large-scale field studies on elevated CO_2 plant growth enhancement show that CO_2 enhancement primarily occurs under limited conditions, such as in tandem with water limitation (Ainsworth and Long 2004). Another important consideration is plant nutrient content under elevated CO_2 conditions. Plants can acclimate to higher CO_2 by decreasing plant nitrogen (Ainsworth and Long 2004), and this can result in lower leaf nitrate and total plant protein concentration (Taub et al. 2008; Dong et al. 2018). Altered nutrient content and any rises in plant yield are both important considerations. Even so, our promising results show that this system has the potential to provide a sustainable agricultural solution that can both increase food availability, especially in urban environments, and contribute to carbon capture for a net zero carbon future.

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