THE UNIVERSITY OF ARIZONA
Cooperative Extension

az2074 December 2023

Evaluating an *in-situ*, Low-Cost Soil CO_2 Sensor as a Soil Health Assessment Tool in Agricultural Soils

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Abstract

Measurements of carbon dioxide (CO_2) emissions from agricultural soils are essential to understand the journey of an agricultural operation toward sustainability. Existing commercial technologies to measure CO_2 emissions are expensive and require advanced technical knowledge. A new, low-cost, in-situ CO_2-measuring device was designed and standardized by the authors to upscale CO_2 emission measurements in commercial agricultural operations, spatially and temporally. We present an initial report from our preliminary studies as we measured CO_2 emissions in different agroecosystems and compared different management strategies. Diurnal soil respiration or CO_2 emission was also measured under different weather conditions. We coined the term, Potential Soil Respiration or PSR, to indicate the CO_2 emission from soils with actively growing crops. Our data revealed that cover cropping influenced carbon storage in the soil while fallowing continued to lose soil carbon in a cotton production system, which was correlated with plant vigor. We are also working toward integrating this sensory system with other existing or new sensory systems to be deployed in commercial agricultural operations for effective natural resource management and environmental stewardship.

Introduction

Soil carbon mineralization, i.e., the release of carbon dioxide (CO_2) from soils, is a biogeochemical process that exhausts carbon levels in the soil. Soil respiration (SR), also defined as carbon dioxide (CO_2) emission from soils due to biological activities, is considered a major soil health indicator (Schlesinger and Andrews 2000; Ditzler and Tugel 2002). In arid and semi-arid environments of the desert southwest, agricultural soils observe low levels of carbon due to high rates of soil carbon mineralization, intensive tillage (soil disturbance), and irrigation regimes under an extremely arid climate for crop production (Jabro et al. 2008). Therefore, it is necessary to understand optimum levels of SR, which is indicative of biological activities in healthy soil or excessive soil carbon mineralization indicative of carbon loss from soil ecosystems. Soil health has been prioritized by agricultural stakeholders in a recent needs assessment survey conducted by the University of Arizona Cooperative Extension (CRED 2023). Therefore, measuring and monitoring SR, soil CO_2 emission, can potentially be an essential way to determine soil health.

Existing instruments required to measure in-situ CO_2 emission from soils are not only expensive but also require specialized technical expertise. In addition, there are not many options available to measure soil biological respiration alone excluding the CO_2 emission from crop canopies and other sources. We have built a low-cost, soil CO_2 sensor that is designed to measure SR from commercial agricultural soils and requires minimum effort and skillset to operate by practitioners, agricultural professionals, and producers. The objective of this research was to monitor *in-situ* soil CO_2 emissions using a 'cost-effective' sensory system to measure soil biological activities under different cropping systems.

Materials and Methods

The CO_2 sensor used in this instrument is a nondispersive infrared (NDIR) sensor. These sensors are built on the principle that when infrared light passes through an enclosed chamber filled with gas mixtures, specific gases absorb specific wavelengths of the spectrum; CO_2 absorbs wavelengths between 2,000 and 15,000 nanometers. The detector then analyzes how much light of a pre-determined wavelength within that range was absorbed. The sensory system (Figure 1) was made of stackable electronic boards with a CO_2 sensor, Arduino-based microcontroller, SD memory card slot, and dimensions of 5.1 cm (H) x 6.0 cm

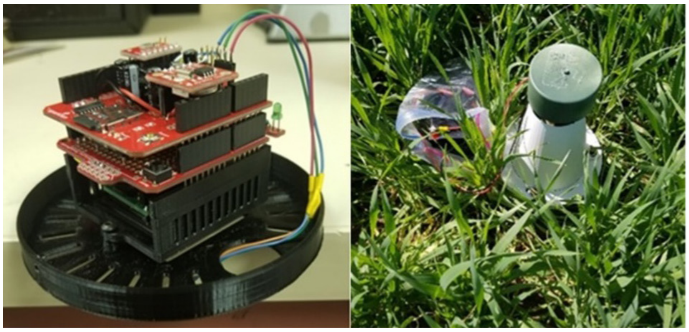

Figure 1. The CO_2 sensory system (left) and on-farm deployment of the sensors in a protective housing (right)

(W) x 6.7 cm (L). For on-farm deployment, the sensory system was placed in a PVC plastic housing along with a 12V power source to enable continuous data collection (Figure xx); this portable system was then deployed in commercial agricultural fields.

In the initial phase, we deployed the sensors in different cash crop fields (Figure 2) to understand the ranges of CO_2 emission levels and to design an effective protocol for field deployment. In this report, however, we did not report any data from the lettuce crop. We were also cautious about measuring SR excluding other CO_2-emitting above-ground sources. The housing is made using a technology that allows continuous air movement from soil to atmosphere through the sensory system inside, making sure we are detecting 'real-time' soil CO_2 emissions.

All data was collected from the fields at regular intervals. The duration of deployment varied depending on the crops and farms' irrigation schedules. In this article, we will report CO_2 emission data from two different cash crops: cotton (broadleaf) and wheat (grass), along with a non-cropped/fallow area as the reference CO_2 emission. For the cotton study, we also collected data from two different rotations: 1) Cover crop – Cotton, and 2) Fallow – Cotton. Raw data was processed and reported in parts per million (ppm) for easy communication with the industry. We also collected in-season Normalized Difference Vegetation Index data for cotton to correlate with CO_2 emissions.

Figure 2. In-situ soil CO_2 sensor deployment in different commercial crop fields and fallow grounds for comparisons

Results and Discussion

Soil CO_2 emissions: Influence of crop and weather

Soil biological activities such as microbial decomposition of soil organic matter, and root respiration can be assessed by CO_2 emissions. Generally, CO_2 emissions are correlated with the intensity of soil biological activities (Yerli et al. 2019). In Figure 3, we report an example of diurnal soil CO_2 emissions during one day in spring 2022 under a commercial wheat crop compared to fallow ground. As plant roots exude carbon-rich products, this might trigger soil biological activities, eventually resulting in higher CO_2 emissions. We also observed signature diurnal patterns of CO_2 emissions depicting dynamics of soil biological activity. During the warmer part of the day, especially under sunlight, we documented lower CO_2 emissions as compared to the cooler part of the day, between sunset and sunrise. One possible explanation is that soil biological respiration is reduced under heat stress, which ramps up as the soil environment cools down. This is a well-reported phenomenon (Buyanovsky et al. 1986; Sanyal et al. 2021). As we eliminated any chance of measuring ambient atmospheric CO_2 concentrations that are influenced by crop canopy and any potential above-ground CO_2-producing activities, we believe the regulation of CO_2 levels is predominantly impacted by soil biological activities.

Gas emission measurements are also influenced by ambient climatic variables; therefore, weather is an important variable when measuring CO_2 concentrations (Hernandez-Ramirez et

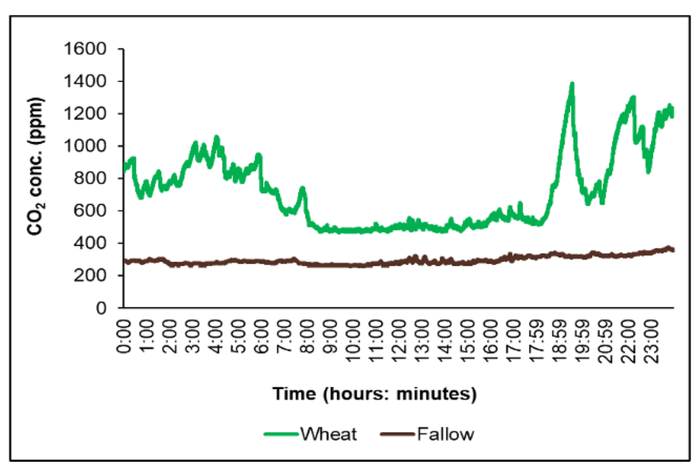

Figure 3. An average diurnal signature of CO_2 emissions from a cropped field in comparison to a non-cropped field

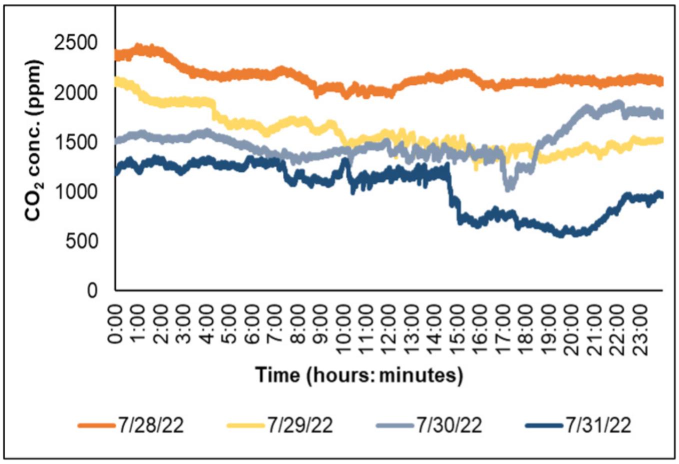

Figure 4. Weather patterns influencing the diurnal patterns of soil CO_2 emission from a cotton field

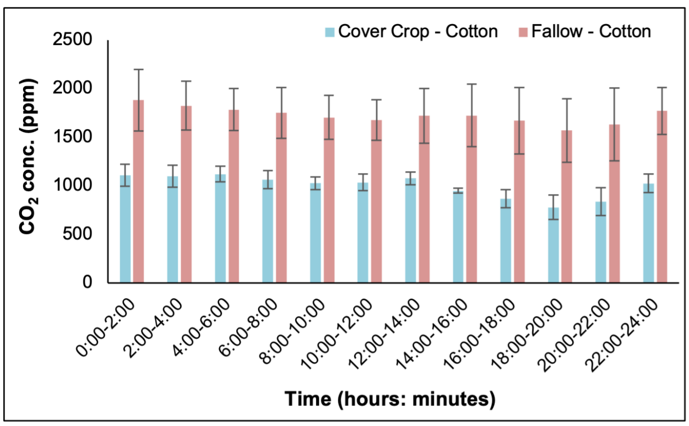

Figure 5. Soil CO_2 emissions from two cotton rotations: a) cover crop – cotton rotation and b) fallow – cotton rotation

al. 2009; Dhadli et al. 2015). We monitored soil CO_2 emissions with the same sensory system from the same location inside a cotton field for 4 consecutive days, following a thunderstorm event on July 28, 2022, that lasted more than 48 hours. Figure 4 shows the variability in soil CO_2 emission and the range of values, possibly due to weather dynamics during an extreme weather event. As the weather variables began to reach an equilibrium, the CO_2 emission data started taking the signature shape, as depicted in Figure 3. More analyses need to be done to identify weather patterns responsible for this variation, especially during extreme weather events, to guide more effective and reliable soil CO_2 emission measurements.

Effect of cover cropping on soil CO_2 emissions in cotton

Cover cropping is a soil conservation tool used to improve soil health and soil carbon storage (Joshi et al. 2023). Conversely, 'fallowing' is reported to be detrimental to soil health and carbon sequestration (Tiefenbacher et al 2021). As soil CO_2 emission is an indicator of soil health, we deployed sensory systems in two neighboring cotton fields managed differently. Figure 5 depicts mean 2-hour CO_2 emissions from two cotton fields laid out in Maricopa Agricultural Center, Maricopa, AZ, followed by: a) green manure cover cropping (cover crop residues incorporated in the topsoil) in the previous season, and b) a long-term (>10 years) fallowed land. Data was collected between irrigation events in May through June 2022. In the cotton field under fallow, the C mineralization rate as measured from soil CO_2 emissions was significantly higher (~1900 ppm) compared to typical Arizona soils (Figure 3), indicating carbon loss from the system during summer. While in the field where cotton followed cover cropping, the carbon mineralization rate was much lower, indicating lower carbon and potentially better soil health. Future studies should be designed to identify relationships between soil CO_2 emissions with soil health indicators (Laffely et al. 2020).

The phenotypic characteristics of the cotton plants under two different rotations were measured using a reflectance-based indicator, Normalized Difference Vegetation Index (NDVI). NDVI is one of the universal indicators for plant health, vigor, and other phenotypic responses (Stamford et al. 2023). Our NDVI data showed that the cotton crop under the cover crop-cotton rotation had more plant vigor than the cotton crop after a fallow period, and the difference was more pronounced as the growing season progressed (Figure 6). This information was valuable in identifying the importance of soil health as revealed by the soil CO_2 emissions measured from cotton fields under different soil management practices. Studies have reported similar findings indicating cover cropping improved soil health, as well as plant health and vigor (Manici et al. 2015; Novara et al. 2014).

Potential soil respiration (PSR): A new soil health indicator?

As we measured CO_2 emission or soil respiration (SR) from cropped fields, we also deployed a sensory system in the neighboring fallow field, on top of bare soil. To develop

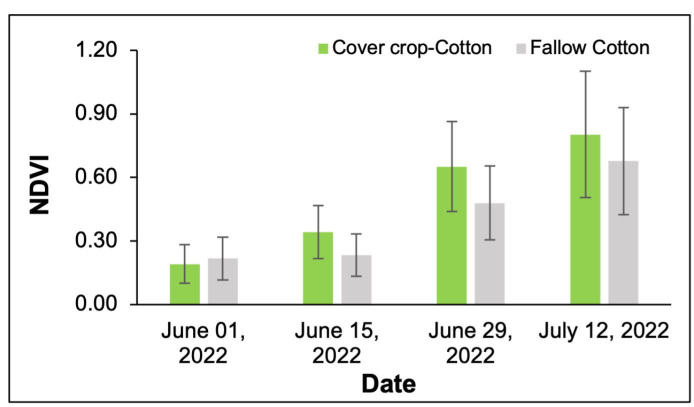

Figure 6. Cotton crop health as indicated by Normalized Difference Vegetation Index (NDVI) values in two cotton rotations: n = 180, row length = 55 m; the error bars depict the standard deviation values

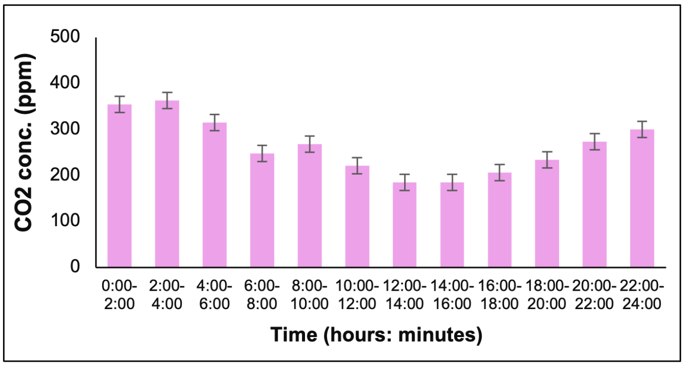

Figure 7. Potential soil respiration (2-hour averages) from a wheat field; the error bars depict the standard deviation values

a more effective indicator, we calculated Potential soil respiration (PSR). PSR was calculated by subtracting mean CO_2 concentrations in the fallow ground from the mean CO_2 concentration in a cropped field. If we subtract the magnitude of CO_2 emission from a fallow field while measuring CO_2 emissions or SR from a cropped field, the values may provide a more realistic depiction of CO_2 release from soils due to plant-soil-microbial interactions. Figure 7 presents mean PSR values in a wheat field during the 2022 spring growing season at every 2-hour interval. In this figure, the mean 2-hour CO_2 concentrations were calculated by averaging soil CO_2 emission data over 10 consecutive days. This bar diagram indicates that PSR values are higher during the early and late hours, and lower in the middle of the day. We can speculate that microbes are most active when the soil temperatures are optimum (lower) during a 24-hour period, and at extremely high temperatures, soil biological activities shut/slow down. However, more research is required to establish PSR as a soil health indicator in soils with vegetation.

Conclusion

Our preliminary study looked into in-situ soil respiration or soil CO_2 emissions from different perspectives in order to gain insight into using this low-cost, in-situ, soil CO_2 sensor at multiple spatiotemporal scales. Especially if the CO_2 emission data can be used to indicate essential soil health attributes, PSR values can be integrated into decision-making systems in commercial agricultural operations. Through this research, we validated the soil CO_2 sensor's capability in diverse cropping systems during different seasons in a year. We confirmed that the sensors are able to capture quality emission data on a large temporal scale and we found correlations between CO_2 emission and crop vigor. However, future research will look into relationships with recognized soil health indicators. Overall, the soil CO_2 data collected in this study suggests that this sensor has tremendous potential to be used by farmers and ranchers in identifying soil health and soil carbon status in their operations as we continue to fine-tune this technology and its applications. Future research will investigate the relationships among soil CO_2 emissions, soil health, plant vigor, and crop yield to guide agronomic management and potential development decision support tools.

Acknowledgments

We acknowledge *Arizona Grain Research* and *Promotion Council and Cotton Incorporated* for funding parts of this research. We also acknowledge all producer cooperators like JV Farms for partnering with us on this project.

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