AGROLOGY ARBITER DEVICE: STATIC CONTINUOUS SOIL FLUX CHAMBER

A GREEN WHITEPAPER

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Abstract

The Agrology Arbiter Device includes two components for monitoring and quantifying greenhouse gas fluxes. The first component is a Static Continuous Soil Flux Chamber. That component, which will be referred to as the "Arbiter Chamber," is the focus of this paper. The second component is the Concentration Gradient Mast, which will be discussed in a subsequent paper. Agrology's Arbiter Chamber is a new approach to monitoring soil greenhouse gas flux, based on the proven soil flux chamber lineage of fundamental physics principles and almost 100 years of field usage and study.[1] The Arbiter Chamber offers the benefits of both automated and manual chambers, with few of the drawbacks. Greenhouse gas flux calculation happens automatically based upon USDA-ARS GRACEnet Project Protocols.[2] In addition to delivering traditional soil chamber flux data, the Arbiter Chamber captures rapidly transient data features, likely due to biological interactions, that previous soil chamber designs miss.

Figure 1: Arbiter devices installed in a vineyard row (left) and vegetable crop rows (right)

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[1] Lundegårdh, H., 1927. Carbon dioxide evolution of soil and crop growth. Soil Sci. 23, 417–453.

[2] USDA-ARS GRACEnet Project Protocols. Chapter 3. Chamber-Based Trace Gas Flux Measurements November 2010 https://www.ars.usda.gov/ARSUserFiles/np212/chapter%203.%20gracenet%20Trace%20Gas%20Sampling%20protocols.pdf

Soil Chamber Background

Soil chambers have an illustrious nine-decade-plus lineage of global usage for soil gas flux analysis. Fundamentally, they are accessible devices based on simple physics principles and available as manual or automated devices. Additionally, Survey Systems split the difference with automated measurements and operators moving the devices between locations. Soil chambers can cost anywhere from less than $10 (excluding gas analysis) to six figures (for fully automated systems including onboard continuous gas analysis). In its simplest form, a soil chamber is an enclosure installed above the soil, with a collar inserted slightly into the soil, that creates a volume where gases can accumulate and concentrate. Sampling this volume for gas concentrations over time, enables measurement and calculation of the emission and sequestration of gases from the soil under the enclosure.

The fundamental simplicity of the soil chamber approach is what makes it suitable for either manual usage, which utilizes gas syringes or vials and a stopwatch, or automated usage, which relies on digital gas measurement and automated sampling.

The advantage to the manual chamber approach is the extremely low cost. A functional and accurate soil chamber could hypothetically be constructed for free from scrap materials, and have a low cost of sampling based on consumed materials like syringes and the time usage cost of gas analyzer instrumentation. The cost advantage also allows manual chamber deployment in 'high hazard' areas, like actively cultivated farms, where expensive instrumentation is at severe risk of damage from tractor strikes, agricultural sprays, and general exposure. The disadvantage of manual sampling is that it is manual. No human operator is willing to continuously sample indefinitely, so gas concentration sampling, and therefore flux calculation, tends to occur for short specific intervals which may or may not be representative of actual continuous gas flux. The operators of the manual sampling procedure may have slightly different sample handling methodologies and processes which can affect measurements. The lab instrumentation used to measure gases may have differing capabilities or calibrations. A final disadvantage is that given gaps in manual sampling continuity, manual chambers will likely miss transient gas emissions that can provide new insight into soil gas flux and the soil microbiome ecosystem.

With the disadvantages of manual chambers outlined above, the advantages of automatic chambers are evident. They gather continuous flux data without manual involvement. Automatic chambers operate autonomously and continuously. Their measurements have consistent timing. And using the same instrumentation to perform each measurement ensures consistency. The advantages of automatic chambers are extensive.

The disadvantages of automatic chambers fall into two categories. First, automatic chambers are expensive, with costs in the five to six figure range. This high cost is compounded by the fragility of these devices. As a result, automatic chambers are not generally compatible with mechanized agriculture since damage is highly likely and repairs are expensive. Since automatic chambers are generally purchased, and not leased, the operator fully takes on the operational risk and cost of automatic chamber operation. Second, automatic chambers periodically open and close during measurement. This reduces the influence on the soil system of automatic chambers, yet means that automatic chambers miss the highly transient flux signals associated with in-soil biological processes.

Finally, Survey Systems present a compromise between manual and automatic chambers. A portable gas analyzer moves between permanently installed chamber collars, creating a temporary chamber. This approach solves the challenges of equipment damage, as well as data quality and measurement consistency of manual chambers, but it does not generate continuous time-series data and can miss transient signals. Additionally, Survey Systems are expensive devices in terms of capital cost and operator time cost.

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Arbiter Device Description

The Agrology Arbiter Device includes two components; a concentration gradient mast and an augmented soil chamber, which is the focus of this paper. This Static Continuous Soil Flux Chamber or "Arbiter Chamber" includes differentiating features from traditional manual and automatic soil chambers to overcome the drawbacks inherent in both their designs. The Arbiter Chamber features include:

- A smaller chamber diameter, to fit within crop rows, that maximizes the chamber circumference to area ratio which in turn maximizes the influence of surrounding soil on the chamber measurements
- A built-in shallow chamber collar that eases device installation/removal and maximizes the influence of soil surrounding the chamber on chamber measurements
- A compact sensor suite, included in the chamber, to ease device installation/removal
- In-chamber measurement of atmospheric pressure, temperature, and humidity, that improves flux calculation accuracy
- No moving parts to improve reliability
- All exposed parts are durable, low cost, and modular to ensure reliability and repairability
- A proprietary venting system that ensures atmospheric equilibrium
- Other proprietary enhancements that are not publicly disclosable at this time

Figure 2 provides a visual overview of the Agrology Arbiter Device installed in a vineyard.

Figure 2: Agrology Arbiter Device, with components identified. 1 - Arbiter Chamber, 2 - Integrated chamber collar, 3 - Sensor Suite, 4 - Proprietary chamber venting system, 5 - Concentration Gradient Mast (not fully pictured)

To expand on the bullet points above, the overall size of the Arbiter Chamber, along with the built in shallow chamber collar and included compact sensor suite, enables its usage in broad acre and specialty agricultural systems. In addition to fitting within crop rows, the smaller size allows for rapid installation and removal. Without this rapidity, many broad acre and vegetable specialty crops would not be compatible due to the need for tractor passes during cultivation. The Arbiter Chamber can be uninstalled by a tractor operator, walked behind the cultivation implement, and reinstalled in less than 3 minutes. This rapid turnaround ensures compatibility with tillage, fertilization, and spraying cultivation practices. The small size maximizes the ratio of chamber circumference to chamber area, since the circumference increases linearly with size, while the area increases at an exponential rate.

$$Circumference/Area\ Ratio = \frac{2 * \pi * Radius}{\pi * Radius^{2}}$$

A high circumference to area ratio maximizes the influence of the boundary soil around the diameter of the Arbiter Chamber on the Arbiter Chamber measurements. This achieves a critical balance between soil disturbed and undisturbed by the chamber. Larger diameter chambers precisely measure a large surface area of soil, but this area is disturbed by the physical effects of the enclosure within the chamber. Automatic chambers overcome this with frequent openings and closings, with the downsides outlined in the section above.

The sensor suite in each Arbiter Chamber measures only the gas concentrations in that chamber directly. This avoids any disturbance of samples during manual sample acquisition, transport, and insertion in laboratory instrumentation, compared to manual chambers. When a gas analysis laboratory contains multiple instruments, there can be effects on data accuracy due to differences between instrumentation types, tolerances, or calibrations in measurements. Compared to automatic chambers, the internal Arbiter Chamber sensor suite measurement avoids any possible sample disturbance during transport of samples through manifolds and sampling tubes, as well as the risk of agricultural implements damaging this infrastructure and affecting measurements. The Arbiter Chamber is entirely self contained without infrastructure like manifolds and is more resistant to damage.

Manual chambers excel in durability, but are unable to deliver continuous data. Automatic chambers can deliver continuous data, but the multiple mechanical moving parts (bellows, seals, pumps) necessary to do so decreases their reliability, and increases the likelihood of damage from agricultural cultivation practices. Not to mention their very high cost. The Arbiter Chamber includes no mechanical moving parts, improving reliability and damage resistance. Given the harsh nature of agricultural environments, this resilience is critical for delivering consistent measurements.

Manual chambers are generally built from durable and low cost materials. This facilitates rough installation techniques, including rubber mallet pounding, and field operation. However, these chambers are rarely standardized, making repairs difficult. Automated chambers use standard parts, but these standard parts are typically expensive and can be fragile, reducing their compatibility with agricultural installations. The Arbiter Chamber uses tough, durable low-cost parts on its exterior. These parts are also all modular and standardized. This ensures that Arbiter Devices can be quickly repaired when they are inevitably damaged during agricultural cultivation, further enhancing the Arbiter Chamber's ability to handle deployment on actively cultivated farms.

Alignment With GRACEnet Design Protocols

Agrology followed USDA-ARS GRACEnet Project Protocols[3] during the mechanical design of the Arbiter Chamber:

1. Flux chambers should be fabricated of non-reactive materials.
    a. The Arbiter Chamber is made of polyethylene terephthalate glycol plastic, and high density polyethylene plastic.
2. Material should be white or coated with reflective material.
    a. The plastic is white. Agrology will experiment with reflective coatings.
3. Chambers should be large enough to cover at least 182 cm2 of the soil surface, and have a target height of 15 cm.
    a. The Arbiter Chamber is 15 cm diameter, and 15 cm height.

3 USDA-ARS GRACEnet Project Protocols. Chapter 3. Chamber-Based Trace Gas Flux Measurements November 2010
https://www.ars.usda.gov/ARSUserFiles/np212/chapter%203.%20gracenet%20Trace%20Gas%20Sampling%20protocols.pdf

Alignment With GRACEnet Design Protocols, Cont.

4. Chambers should contain a vent tube, at least 10 cm long and 4.8 mm in diameter.
    a. The Arbiter Chamber uses a patent-pending, proprietary vent design that ensures atmospheric equilibrium while reducing the effect of pressure perturbations on chamber concentration measurements.
5. Chambers should have a sampling port to enable the removal of gas samples.
    a. The Arbiter Chamber has a gas concentration sensor built in, avoiding the need to remove gas samples.

Additionally, the design of the Arbiter Chamber aligns with the GRACEnet Considerations for Chamber Construction and Deployment.

1. Soil Disturbance
    a. The Arbiter Chamber design ensures minimum soil disturbance during installation or removal.
2. Temperature Perturbations
    a. The Arbiter Chamber maximizes the surface area to volume ratio with its small size to enhance heat exchange with surroundings, and uses a reflective non-light transmitting color to avoid heat accumulation inside the chamber.
3. Pressure Perturbations
    a. The proprietary Arbiter Chamber vent minimizes the impact of pressure perturbations.
4. Humidity Perturbations
    a. The proprietary vent on the Arbiter Chamber reduces the build up of humidity inside the chamber. Additionally, the sensor array includes humidity monitoring to track perturbations.
5. Gas Mixing
    a. The Arbiter Chamber volume to surface area ratio is small, ensuring adequate gas mixing through molecular diffusion. This is evident in the sensitivity of the Arbiter Chamber to transient concentrations.
6. Chamber Placement
    a. The small size and portability of the Arbiter Chamber ensures installation compatibility with a variety of crops, including in row and inter-row.
7. Frequency and Timing of Flux Measurements
    a. The Arbiter Chamber automatically gathers time series measurements, ensuring consistent measurements.
8. Spatial Variability
    a. The Arbiter Chamber and the Arbiter Carbon Monitoring System are portable, allowing for movement to survey multiple soil points for less spatial variability sensitivity in data sets. Additionally the cost of the system allows for wider scale deployment for less spatial variability sensitivity in data sets.

Flux Calculation Methodology

In order to benefit from the many decade lineage of soil chamber development, Agrology also followed the USDA-ARS GRACEnet Project Protocols during development of the Arbiter Chamber flux calculation algorithm. This algorithm evaluates each approximately 10min measurement interval using linear regression. Since each sample time interval produces a linear gas concentration delta, the linear regression flux calculation approach implemented across each sample interval is most accurate. Additionally, since gas flux is tracked continuously, there is no risk of linear regression producing a non-representative flux based on a small sample set. The linear regression yields the flux of carbon dioxide per second, in microlitres per liter (CO_2 µL/L/s). Multiplying by the volume of the Arbiter Chamber gets the volume flux of carbon dioxide per second in microlitres per second (µL/s).

$$Volume\ Flux,\ \mu L/s = \frac{Concentration1 - Concentration0}{Time1 - Time0} * Chamber\ Volume$$

Since the Arbiter Chamber is a vented chamber, laboratory benchtop testing yielded a “diffusion factor” representing the decrease in CO_2 ppm concentration per second at different levels of CO_2 concentration. This “diffusion factor” improves the accuracy of measurements by accounting for the major non-soil leakage of CO_2 from the Arbiter Chamber. The appropriate diffusion factor based on the Arbiter Chamber concentration incorporates CO_2 loss from the chamber vent into the flux calculation. Figure 3 shows a lab bench calibration curve used to develop the diffusion factor dK.

Figure 3: CO_2 Concentration versus time for diffusion factor dK development

After determining the volume flux of carbon dioxide in microlitres per second, the Ideal Gas Law allows conversion of this volumetric flow to a mass flux.

$$Mass\ Flux,\ \mu g/s\ = 12.011\ g/mol * \frac{Pressure * Volume\ Flux}{R * Temperature}$$

The Arbiter Chamber logs chamber pressure and chamber temperature during each concentration measurement. Averaging these measurements yields the average temperature and pressure per concentration measurement interval. Applying the ideal gas law to the measurements from each interval converts volume flux to mass flux. All calculations use measurements, not assumptions to deliver the highest possible accuracy.

Finally, the software server side of the Arbiter Carbon Monitoring System stores all raw values, so Agrology can adjust flux calculation methodology as necessary.

Data

With flux calculation methodology covered above, it's time to share sample data from the Arbiter Chamber installed in a vineyard and pictured in Figure 1.

Figure 4 shows data for a period of carbon sequestration during a day with net carbon sequestration. The data shows generally decreasing CO2 concentration in the Arbiter Chamber, along with stable enough chamber temperature and pressure that this decrease manifests as sequestration. Here the diffusion factor dK is zero due to the low CO2 concentrations in the chamber, which are not high enough to result in significant diffusion losses of CO2.

timestamp	device ID	airTemp	barometricPressure	co2Concentration	K (ppm diffusion coefficient, deltaPPM/s)	lin mass flux per interval per area (g C/m^2/interval)
1676092903	70B3D57BA000393B	8.2	996.1	1203	0.000	0.0005837668374
1676093502	70B3D57BA000393B	8.1	996	1208	0.000	0.0002433226508
1676094105	70B3D57BA000393B	8	996	1187	0.000	-0.001022267241
1676094704	70B3D57BA000393B	7.9	996.1	1164	0.000	-0.001120080554
1676095301	70B3D57BA000393B	7.8	996.1	1146	0.000	-0.000876940752
1676095902	70B3D57BA000393B	7.7	996.1	1095	0.000	-0.002485550001
1676096501	70B3D57BA000393B	7.6	996	1054	0.000	-0.001998798525
1676097106	70B3D57BA000393B	7.5	996.1	1092	0.000	0.001853204948
1676097705	70B3D57BA000393B	7.3	996.1	1079	0.000	-0.0006343619808
1676098302	70B3D57BA000393B	7.2	996.1	1061	0.000	-0.0008788172301
1676098905	70B3D57BA000393B	7	996.1	994	0.000	-0.003272903863
1676099505	70B3D57BA000393B	6.8	996.1	1014	0.000	0.0009776839505
1676100106	70B3D57BA000393B	6.6	996.3	1008	0.000	-0.0002935442676
1676100703	70B3D57BA000393B	6.4	996.2	991	0.000	-0.0008323453532
1676101303	70B3D57BA000393B	6.3	996.2	973	0.000	-0.0008817355629
1676101902	70B3D57BA000393B	6.2	996.2	984	0.000	0.0005390312551
1676102500	70B3D57BA000393B	6	996.2	986	0.000	0.0000980583268
1676103100	70B3D57BA000393B	5.9	996.2	985	0.000	-0.00004905551372
1676103701	70B3D57BA000393B	5.8	996.2	927	0.000	-0.002846239588
1676104301	70B3D57BA000393B	5.8	996.2	870	0.000	-0.002797667866
1676104903	70B3D57BA000393B	5.7	996.2	934	0.000	0.003141804261

Figure 4: Sample data for a day with net carbon sequestration.

Figure 5 shows the Agrology Arbiter Chamber CO_2 concentration curve for this day.

Figure 5: Agrology Arbiter Chamber CO_2 concentration curve in PPM (blue) for a day with net carbon sequestration.

Figure 6 shows data for a period of carbon emission during a day with net carbon emission. The data shows generally increasing CO_2 concentration in the Arbiter Chamber, along with stable enough chamber temperature and pressure that this increase manifests as emission.

timestamp	device ID	airTemp	barometricPressure	co2Concentration	K (ppm diffusion coefficient, deltaPPM/s)	lin mass flux per interval per area (g C/m^2/interval)
1678681290	70B3D57BA000393B	11.3	995.9	3229	0.333	0.01154724958
1678681888	70B3D57BA000393B	11.2	996	3268	0.333	0.01147080398
1678682486	70B3D57BA000393B	11.2	996.1	3307	0.333	0.01147397294
1678683085	70B3D57BA000393B	11.2	996.2	3342	0.367	0.01225992714
1678684289	70B3D57BA000393B	11.2	996.3	3416	0.367	0.02482085945
1678684887	70B3D57BA000393B	11.2	996.3	3452	0.333	0.01133238893
1678685485	70B3D57BA000393B	11.1	996.4	3478	0.333	0.01085329566
1678686087	70B3D57BA000393B	11.1	996.4	3501	0.333	0.01077545551
1678686687	70B3D57BA000393B	11	996.5	3516	0.333	0.01036026884
1678687287	70B3D57BA000393B	11	996.6	3531	0.400	0.01229115628
1678687884	70B3D57BA000393B	11	996.6	3552	0.400	0.01252314752
1678688490	70B3D57BA000393B	11	996.7	3576	0.400	0.01284193178
1678689085	70B3D57BA000393B	11	996.8	3593	0.400	0.01229362302
1678689685	70B3D57BA000393B	11.1	996.8	3618	0.400	0.01277411898
1678690287	70B3D57BA000393B	11.1	996.9	3638	0.400	0.01257008036
1678690887	70B3D57BA000393B	11.1	996.9	3666	0.367	0.01195374345
1678691484	70B3D57BA000393B	11	996.9	3673	0.367	0.01089042631
1678692086	70B3D57BA000393B	11	997	3686	0.367	0.01127061195
1678692685	70B3D57BA000393B	11	997	3700	0.367	0.01126635497
1678693283	70B3D57BA000393B	11	997	3716	0.367	0.01134511819
1678693884	70B3D57BA000393B	11.1	997	3722	0.367	0.01091401855

Figure 6: Sample Agrology customer data for a day with net carbon emission.

Figure 7 shows the Agrology Arbiter Chamber CO2 concentration curve for this day.

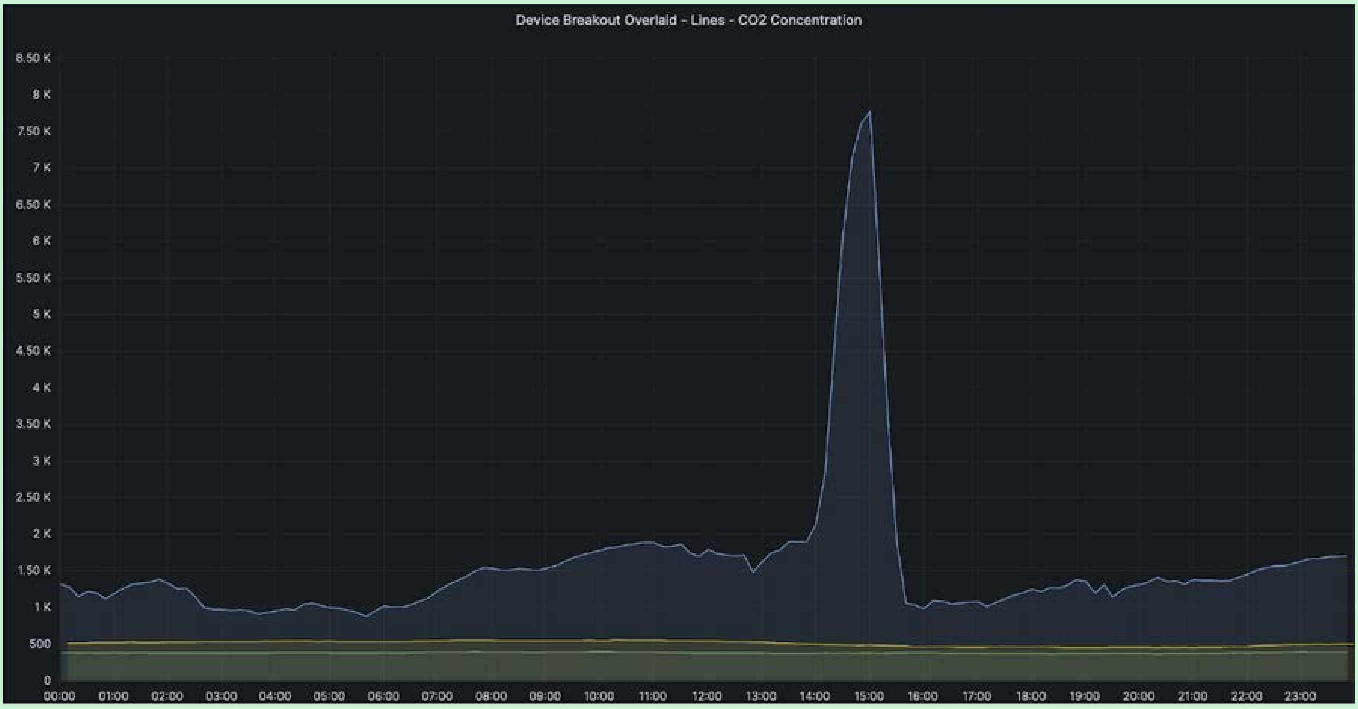

Figure 7: Agrology Arbiter Chamber CO2 concentration curve in PPM (blue) for a day with net carbon emission.

New Capabilities

In addition to quantifying carbon sequestration and emissions, the Arbiter Chamber shows significant sensitivity to transient data features that manual and automatic soil chambers can easily miss. This is significant since transient features may be biological in origins and indicative of soil health. Figure 8 shows a 10-day period of Arbiter Chamber CO2 concentration with rapid transient CO2 concentration features.

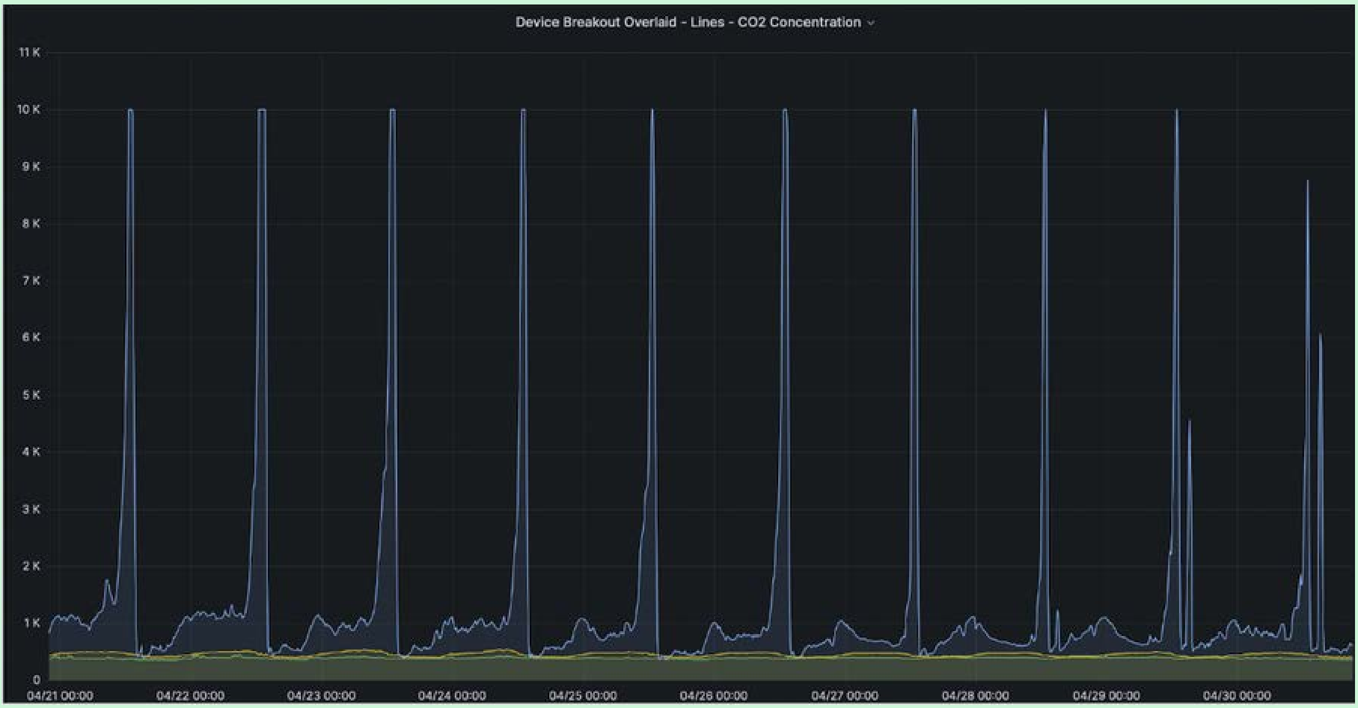

Figure 8: transient CO2 concentration in PPM (blue) in the Arbiter Chamber.

Each day, nearly exactly 24 hours apart, the chamber experiences a rapid spike in CO2 concentration, followed by a rapid plummet in CO2 concentration. Correlations with other data sets that measure plant biological activity (photosynthetically active radiation and ambient air Volatile Organic Compound levels) indicate that this transient feature is likely a root-exudate and soil microbiome interaction occurring when leaf stomata open and plants begin transpiring. Simultaneously, plant roots release carbohydrates to stimulate the soil microbiome and initiate nutrient exchange and uptake. The microbiome, in turn, releases a burst of respiration captured in this transient feature.

By quantifying the amplitude and duration of this root-exudate respiration spike transient feature, Agrology offers daily feedback of soil health and microbial activity. This real-time soil health monitoring is a capability that manual and automatic soil chambers cannot replicate. And real-time soil health monitoring will hopefully prove an essential tool for farmers who are targeting improved soil health outcomes.

The Concentration Gradient Mast

In addition to the Arbiter Chamber, the Arbiter Device includes a Concentration Gradient Mast. The Arbiter Concentration Gradient Mast will augment the Arbiter Chamber to provide better data on net ecosystem carbon exchange beyond soil carbon flux. While all Agrology devices use machine learning to calibrate, improve accuracy, and deliver forecasts, machine learning is the key enabler of the Arbiter Concentration Gradient Mast. The underlying datasets for machine learning development are currently accumulating, so Arbiter Carbon Monitoring Devices currently do not share Concentration Gradient Mast data with customers. When ready, the Concentration Gradient Mast will extend the area of influence of the Arbiter Chamber as well as better quantify net ecosystem carbon exchange.

Conclusion

The Agrology Arbiter Chamber is a new approach to monitoring soil greenhouse gas flux, based on the proven soil flux chamber lineage of fundamental physics principles and almost 100 years of field usage and study. The Arbiter Chamber offers the benefits of automated and manual chambers, with few of the drawbacks. With the Agrology Arbiter System, flux calculation happens automatically based upon USDA-ARS GRACEnet Project Protocols. In addition to delivering traditional soil chamber flux data, the Arbiter Chamber also captures rapidly transient data features that are likely due to biological interactions and that previous soil chamber designs miss.