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TEMPORAL TRENDS IN DRYLAND SOIL CARBON FLUXES IN RESPONSE TO ARTIFICIAL AND NATURAL PULSED MOISTURE EVENTS

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Dedication

Without my mom, this thesis would not have been possible. Her unwavering support, encouragement, and love have been the foundation that has allowed me to pursue my dreams. Throughout my academic journey, she has been my constant cheerleader, my sounding board, and my guiding light. Her sacrifices, both big and small, have made it possible for me to reach this milestone. I dedicate this thesis to my mom, who has always believed in me even when I doubted myself. Thank you, mom, for everything you have done for me. I love you.

Briana

TEMPORAL TRENDS IN DRYLAND SOIL CARBON FLUXES IN RESPONSE TO ARTIFICIAL AND NATURAL PULSED MOISTURE EVENTS

by

BRIANA ALYCE SALCIDO, B.S.

THESIS

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The University of Texas at El Paso
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Abstract

Critical zone processes in drylands play a crucial role in the global carbon cycle, and one of the most important processes is soil CO_2 efflux at the interface between soils and the atmosphere, which represents a main pathway for loss of carbon. Predicting the carbon dynamics at this interface is challenging due to the complexity of belowground processes, which include both biotic (soil respiration) and abiotic (calcite precipitation) production of CO_2, as well as transport processes that include both diffusive and advective components. In this study, we aimed to investigate the contribution of soil air displacement to soil CO_2 efflux during pulsed moisture events (natural rainfall, artificial rainfall, and irrigation) in a shrubland and agricultural site. To achieve this, we took simultaneous measurements of both diffusion using soil CO_2 concentrations (Fick's Law calculations) and total CO_2 efflux at the surface (eosFD sensors) and compared the two. Our results demonstrate that the introduction of water to the soil during pulsed moisture events immediately increases CO_2 effluxes, and furthermore, these increases cannot be attributed to diffusion processes. We show that displacement plays a consistent role in both agricultural and shrubland sites during various types of pulsed moisture events, highlighting the importance of transport processes such as displacement in understanding the timing of CO_2 release from these soils.

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Introduction

Dryland ecosystems are critical to the global carbon cycle, playing a vital role in the storage and release of carbon (Poulter et al., 2015). These ecosystems are characterized by a unique dryland critical zone, which includes the zone of the Earth's surface that extends from the top of vegetation canopy to the bottom of the groundwater table (Scott & Biederman, 2018). Drylands, which cover about 40% of the Earth's surface (Guo et al., 2016; Roxburgh & Noble, 2001), rely on both inorganic and organic soil carbon as important carbon pools. In particular, dryland soils are known for their unique ability to store large amounts of soil inorganic carbon (SIC), making them key players in the carbon cycle (Gao et al., 2017). One fundamental part of the dryland carbon cycle is soil CO_2 efflux, or the release of carbon dioxide from the soil to the atmosphere (Maier et al., 2011). This process can be a major source of uncertainty in predicting the carbon dynamics of these ecosystems, as it depends on belowground processes that are less well studied and can be influenced by a wide range of factors, including temperature, soil moisture, and land use change (Kumar et al., 2020; Chamizo et al., 2022). Understanding the mechanisms controlling carbon storage and respiration in drylands is therefore essential for accurately estimating carbon budgets and assessing the impacts of environmental changes. By identifying the key drivers of soil CO_2 efflux and other components of the dryland carbon cycle, we can develop more accurate models of carbon storage and release in these systems. This, in turn, can help us develop more effective strategies for mitigating carbon emissions and managing global carbon budgets.

Unlike mesic environments, dryland systems experience infrequent and variable precipitation events followed by chronic shortages of soil moisture (Collins et al., 2014). This causes drylands to go through only short periods of water sufficiency (Knapp et al., 2008). As a consequence, the ecological processes that occur in dryland ecosystems are often described using a pulse dynamics model (Noy-Meir, 1973; Ogle & Reynolds, 2004; Collins et al., 2014) Within these dryland regions, precipitation events are known to be a major driver for important ecological activities (Huxman et al., 2004). Thus, soil activities within these moisture-limited ecosystems are closely linked to episodic rainfall pulses (Sponseller, 2007). Although previous research has emphasized the importance of understanding the short-term responses of dryland ecosystems to pulsed moisture events, there remains a need to further investigate this phenomenon (Shen et al., 2008; Huxman et al., 2004). With different biological and non-biological processes occurring simultaneously, it is challenging to determine what is the cause for such increases in soil CO_2 efflux after pulsed moisture events occur.

CO_2 efflux dynamics at the soil surface are influenced both by the *production* of CO_2 and the *transport* of CO_2. Production of CO_2 is due to two main processes in dryland soils: soil respiration and calcite precipitation. Soil respiration is due to the cellular respiration of plant roots and heterotrophs in the soil. Calcite precipitation occurs when dissolved bicarbonate (HCO_3^-) reacts with dissolved calcium (Ca^{2+}) to produce calcite, carbon dioxide, and water:

$$2HCO_3{}^- + Ca^{2+} \rightarrow \; CaCO3\;(s) + \; CO_2(g) + H_2O \qquad \text{(Reaction 1)}$$

While calcite formation is a naturally occurring process in non-agricultural areas, rates may be elevated rates in agricultural soils, especially when irrigation water contains HCO_3^- and/or Ca^{2+} (Wu et al., 2008; Nyachoti et al., 2019; Sanderman, 2012). It has also been found that higher calcite accumulation rates can lead to measurable CO_2 fluxes from agricultural soils to the atmosphere, further showing the effect inorganic carbon has on soil CO_2 efflux (Nyachoti et al., 2019). While ultimately CO_2 is always produced in the soil via respiration or by calcite precipitation, the magnitude and dynamics of the surface CO_2 flux is also influenced by the transport processes that connect the soil pores and the atmosphere (Jassal et al., 2005, Gallager & Breecker, 2020). We will consider two major classes of transport processes: diffusion and advection. The first process is diffusion, which refers to the movement of CO_2 molecules from areas of high concentration to areas of low concentration, driven by the concentration gradient (Bahlmann et al., 2020). This form of gas transport can be described using Fick's first law (Equation 1) which states that the rate of diffusion of a substance across a unit area is proportional to the concentration gradient of that same substance (Stępniewski et al., 2011; Leaist & Mehrer, 2021)

The second process is advection, which refers to the physical movement of CO_2 through soil pores due to air or water flow (Costanza-Robinson & Brusseau, 2002). Advection can occur in response to changes in pressure or temperature (Scanlon et al., 2001; Costanza-Robinson & Brusseau, 2002) While advection is generally considered to be a lesser contributor to soil CO_2 efflux when compared to diffusion, it can be an important factor under certain conditions, such as during periods of high soil moisture or in areas with high rates of air or water movement through soil pores (Roland et al., 2015). The process of displacement is a form of advection in which water enters the soil pores, pushing the CO_2-rich air out and causing an immediate increase in CO_2 efflux measurements during pulsed moisture events. This can be particularly important in dryland ecosystems, where rainfall and irrigation events may trigger significant changes in soil CO_2 efflux measurements. Understanding the role of both diffusion and advection processes in soil CO_2 efflux is important for accurately assessing the carbon balance of dryland systems and developing management strategies to mitigate climate change.

The topic of diffusion of trace gases in soil has been extensively studied and measured across diverse ecosystems (Seok et al., 2009; Jassal et al., 2005; Jia et al., 2014). While these measurements are reliable under normal conditions without external factors like wind or rain, it is crucial to consider other transport processes when these elements come into play especially in a complex system such as the dryland critical zone. There is ample evidence to support the occurrence of a substantial surge in CO_2 levels during a pulsed moisture event (Emmerich, 2003; Gallo et al., 2013; Munson et al., 2009). The reason behind the CO_2 surge following the infiltration of water into soil pores remains unclear and up for question, creating a knowledge gap in the understanding of this occurrence. One phenomenon related to this topic is the Birch effect. The Birch effect entails a substantial rise in CO_2 emissions during the initial rainfall following a prolonged dry spell and is often attributed to an increase in heterotrophic respiration (Manzoni et al., 2020). Although heterotrophic respiration does increase after pulsed moisture events, we hypothesize that the displacement of CO_2-rich air from soil pores plays an important role during the initial period immediately following infiltration of water.

Several previous studies have addressed the displacement (sometimes also called degassing) process and credited it for at least a portion of the CO_2 effluxes seen after a wetting event (Emmerich, 2003; Liu et al., 2002; Lee et al., 2004; Huxman et al., 2004; Maier et al., 2010; Sánchez-García et al., 2020). Regardless of terminology, this is a physical phenomenon in which water enters soil pores, causing air pressure to increase, thus forcing CO_2-rich soil air to the surface via advection. It is important to note that any displacement effect may not account for all the CO_2 emitted after a wetting event (Lee et al., 2004; Sánchez-García et al., 2020). Due to the importance of pulsed moisture events in drylands and the rapid transition from very dry to wet, the role of soil air displacement is especially important for understanding soil CO_2 efflux at the soil-atmosphere interface within dryland ecosystems.

The goal of this study is to investigate the role of air displacement during pulsed moisture events in dryland areas at time scales of minutes to hours. We examine cases of natural rainfall, artificial rainfall, and flood irrigation. To achieve this goal, this work will address these research questions:

1. What are the magnitudes and dynamics of soil CO_2 efflux in an unirrigated shrubland over the course of a year?
2. What are the magnitudes and dynamics of soil CO_2 efflux over the course of biweekly flood irrigation cycles in a pecan orchard?
3. What is the contribution of soil air displacement's impact on soil CO_2 efflux throughout the entire process of water infiltration in soils in a shrubland and pecan orchard ecosystems during pulsed moisture events such as natural rainfall, artificial rainfall, and irrigation?

We propose the hypothesis that soil air displacement significantly influences soil CO2 efflux throughout the duration of water infiltration in dryland ecosystems following pulsed moisture events, rather than the conventional belief that chemical and biological processes alone account for fluxes at this time scale. To examine this hypothesis, we made simultaneous measurements of both diffusion using soil CO_2 concentrations and total CO_2 efflux at the surface at our shrubland and pecan orchard study sites.

Materials & Methods

STUDY SITE

This study was conducted at two study sites located in the southwestern United States, a shrubland and an agricultural system (Figure 1). These systems provide several different forms of pulsed moisture events. The shrubland system experiences natural precipitation events as well as an artificial precipitation experiment event, whereas the agricultural system experiences flood irrigation and natural rainfall events. Both study sites are located in the northern area of the Chihuahuan Desert, which is characterized by an arid climate with precipitation regimes that are dominated by summer rainfall (Muldavin 2002; Cox et al., 2018). By collecting data from both sites, this study aims to understand whether soil air displacement plays a significant role across different pulsed moisture events including natural and artificial.

The first study site is located at the Jornada Experimental Range near Las Cruces, New Mexico and is a managed rangeland. Mean annual temperature and precipitation (1991–2020) are 15.2 °C and 244 mm respectively (Menne and Williams 2012; Hernandez Rosales and Maurer 2022). Summer rains typically occur in July, August, and September, and monsoonal precipitation which lies from July to October provides more than 60% of its total annual precipitation. During monsoon season, the Jornada has a high frequency of small storm events (less than 10 mm) while having a low frequency of larger events (Snyder & Tartowski, 2006). The site is currently a shrub-dominated portion of the Chihuahuan Desert with creosote bush (*Larrea tridentata*) and honey mesquite *(Prosopis glandulosa)* being its dominant plant species. The soil material at this site contains a mixture of clay, silt, sand, pebbles, as well as a well-developed Stage IV caliche layer (calcium carbonate; Nyachoti et al., 2019). The caliche layer is often dense and thick enough that a limited amount of water or roots can penetrate. The water additions for the Jornada site will include both natural precipitation events and an artificial precipitation experiment. The artificial precipitation for the Jornada site was conducted in a 7 × 7-meter plot. Irrigation was done with a sprinkler attached to a hose feeding from a ~1200-liter water container with the use of a pump in order to simulate a 60 mm rainfall event. The eosFD sensors (for soil CO_2 efflux, described below) were deployed just before irrigation occurred.

Our second study site is a pecan orchard located in Tornillo, Texas. This orchard is on alluvial material that was deposited from the Rio Grande, is Holocene age, and contained relatively undeveloped soils before farming began (Doser et al., 2019). As this site, farmers have been practicing flood irrigation for at least 40 years, the age of the pecan trees currently growing at the site. During its growing season, which starts in April and ends in October, the pecan field is flood irrigated. During this time of the year, it receives irrigation every 2 to 3 weeks with about 1.5 m of water per growing season over 9-12 irrigation events (Ortiz & Jin 2021). The pulsed moisture events we will examine include both natural rainfall and irrigation events. The main irrigation water source is the Rio Grande, although during times of low river water supply or drought, farmers have access to two nearby wells from which they receive groundwater. Fertilizers and soil amendments are added annually to improve crop yields as well as improve soil quality. While the water quality from the Rio Grande is highly variable, the Rio Grande is known to have hard water with elevated concentrations of total dissolved solids and heavy metals (Rios-Arana et al., 2004) further affecting soil quality and drainage. The soils are high in salt content, making fluxes particularly interesting to study at this site as this is expected to have an effect on soil respiration (Ortiz et al., 2022). This study focuses on two sublocations within this pecan orchard which are referred to as Pecan Fine and Pecan Coarse. Pecan Fine has finer soil particles, higher soil salinity levels, and lower infiltration, which are associated with lower tree growth, while Pecan Coarse has coarser soil particles and larger, more productive trees.

Figure 1: Two study sites: Jornada Experimental Range in Las. Cruces New Mexico (natural dryland system) and Pecan Orchard in Tornillo Texas (agricultural dryland system)

SURFACE SOIL CO_2 EFFLUX

To measure fluxes of CO_2 from the soil to the atmosphere, Eosense eosFD forced diffusion sensors were used. The eosFD is a stand-alone sensor that measures soil CO_2 fluxes directly. It contains a single non-dispersive infra-red (NDIR) sensor, its own internal datalogger, and a diaphragm pump. This particular sensor utilizes forced diffusion technology without any external chamber movement; instead, it uses a membrane-based approach that establishes an equilibrium between the gas that is flowing in and out of the chamber through the membrane

(Risk et al., 2011). It does not require any moving parts such as other automated chambers, which allows it to be deployed in extreme climates for extended periods without intervention. Multiple eosFD sensors were deployed at different locations throughout our study site with measurements being recorded every five minutes. Additionally, the eosFD chamber at the Jornada Experimental Range site was co-located with an eddy covariance tower to provide additional context to the carbon cycle.

While these eosFD sensors are water resistant, it is not recommended that they be fully submerged in water. In order to address this concern, a floating platform was built (Figure 3) to take concurrent CO_2 efflux measurements at the agricultural site during irrigation events where flooding occurs. The platform was constructed using a 4×4 1/2″ thick sheet of plywood, a 4×4 sheet of 1″ thick styrofoam insulation, 4 3″ galvanized hex bolts, nuts, washers, and marine epoxy. A jigsaw was used to cut a small hole along the center of the plywood sheet to place the eosFD collar. The concept for this floating platform was inspired by a research paper that designed a floating platform to measure CO_2 efflux in a lake (Spafford & Risk, 2018).

SOIL CO_2 DIFFUSION FLUX CALCULATIONS

Soil CO_2 diffusion flux calculations are an important aspect of our study as they allow us to understand the movement of carbon within the soil profile. To better understand the movement of carbon within the soil profile, we can use Fick’s first law, which describes the rate of diffusion of a substance across a unit area in relation to the concentration gradient of that substance. The equation for Fick's law:

$$J = -D\frac{dC}{dx} \text{ (Eqn. 1)}$$

where J is the rate of diffusion of the substance, D is the diffusion coefficient, C is the concentration of the substance, and x is the distance over which diffusion occurs. To collect CO_2 concentrations at different depths in the soil, we deployed eosGP CO_2 sensors at depths of 30 and 60 cm at the Pecan Orchard site and at depths of 15 and 30 cm at the Jornada site. These sensors were set up to collect data in conjunction with the eosFD sensor at 5-minute intervals. The bulk and partial density of the soil were measured to estimate pore volume, and precipitation and temperature data were collected from nearby eddy covariance towers and weather stations.

While the CO_2 diffusion coefficient needed for Fick's law was not measured empirically for this study, it was obtained using Penman's model (1940), which takes into account tortuosity, volumetric gas content, and CO_2 diffusivity. We utilized Penman's proposed tortuosity factor of 0.66 and multiplied it by (porosity - VWC) to calculate gas tortuosity. Volumetric water content values and soil temperature were measured using 5TE sensors by METER Group. We worked with a CO_2 diffusivity value of 1.381×10^{-5} obtained from Massman (1998). The CO_2 diffusion coefficient (D_s) was then calculated as follows:

$$D_s = \ gas\ tortuosity - CO_2\ diffusivity \ \text{(Eqn. 2)}$$

$$gas\ tortuosity\ = 0.66 * (porosity - VWC \ \text{(Eqn. 3)}$$

$$CO_2\ diffusivity = 1.281\ e^{-5} \text{(Eqn. 4)}$$

The gas diffusion coefficient, although challenging to obtain, is a crucial parameter in the gas diffusion equation for soils (Neira et al., 2015). It depends on various factors such as texture, structure, distribution, size, connectivity of the pores, and tortuosity (Moldrup et al., 2004; Jabro et al., 2012; Su et al., 2015). To calculate fluxes at a given time using the gradient method, we used CO_2 concentration data at multiple depths and the equation *dC/dx*, where *C* is the moles of gas over the gas volume and x is the depth we are working with (e.g., 0.15 meters). The magnitudes of the eosFD (surface) effluxes were compared with those of the calculated diffusion fluxes over time to determine their level of agreement. If the surface fluxes exceeded the calculated diffusion fluxes, it suggests that other processes, such as advection, are likely responsible.

From within the longer-term datasets, we identified and compared both surface and diffusive CO_2 efflux during several specific pulsed moisture events. While examining the long-term trends at the shrubland site, several pulsed moisture events were identified for further analysis and comparison. These included two natural rain events and one artificial rain event (artificial wetting experiment). These three events were selected for comparison with a natural rain event and two flood irrigations from the agricultural site. Thus, a total of six pulsed moisture events that were chosen based on data availability and their ability to provide a good representation of the displacement effect.

Results

Total annual soil CO_2 efflux was calculated by adding up values from 2021-03-20 to 2022-03-20. Values were in µmol m^{-2} s^{-1} and were then converted to g C m^{-2}. Linear regressions, correlations, and further statistical analysis were done using R 4.1.1 (R Core Team, 2021).

LONG TERM TRENDS IN A BAJADA SHRUBLAND

CO_2 effluxes at the bajada shrubland ranged from -0.42 to 6.12 µmol m^{-2} s^{-1} with a median value of 0.269 µmol m^{-2} s^{-1} from 2021-03-15 to 2022-07-30. The total amount of carbon emitted from the site between 2021-03-20 and 2022-03-20 was 113 g C m^{-2}. Most of the high CO_2 effluxes were recorded during pulsed moisture events between the months of June and August (Figure 2).

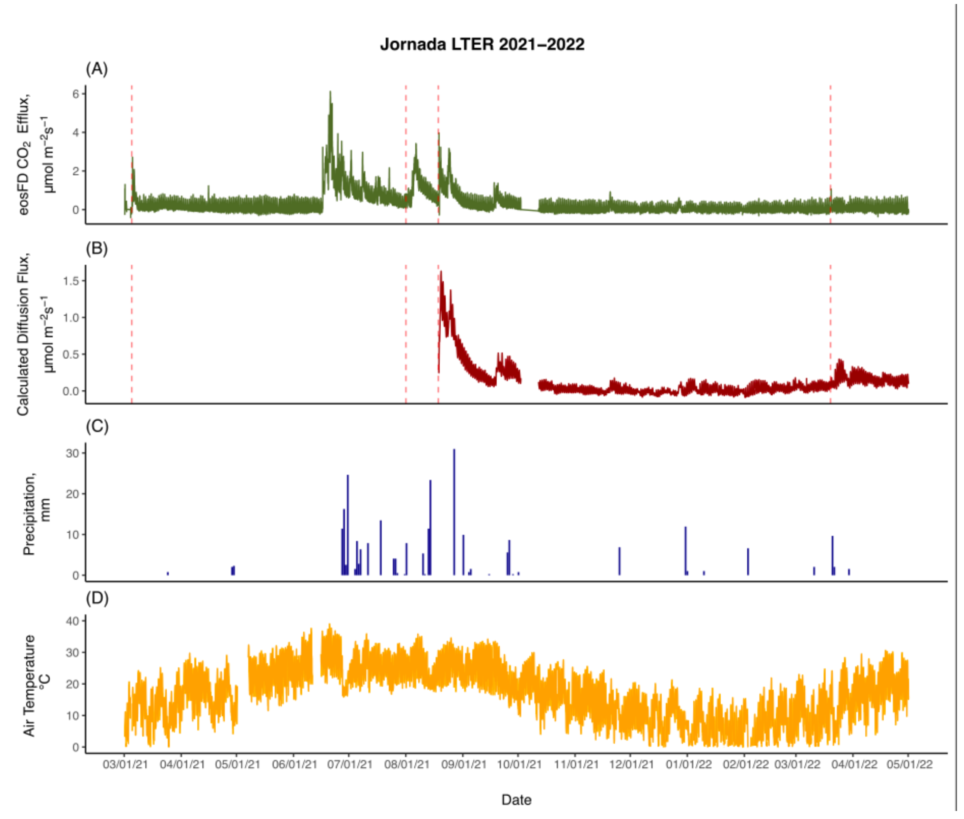

Figure 2: Time series depicting the following variables at the Jornada LTER from 2021-2022: (A) CO_2 effluxes measured by the eosFD sensor, (B) diffusion flux calculated based on the data, (C) precipitation levels, and (D) air temperature. Red dotted lines indicate the selected analysis dates.

CORRELATION AMONG SURFACE EFFLUXES, DIFFUSIVE FLUXES, AND EDDY COVARIANCE FLUXES

The surface fluxes and calculated diffusion values were positively correlated ($r^2 = 0.47$, $p < 0.001$) and the regression slope was 1.2. Whilst in different magnitudes, Figure 3 shows that A (surface fluxes) and B (diffusion fluxes) exhibited similar patterns, with low CO_2 effluxes during dry periods and high/variable effluxes during pulsed moisture events. The eosFD (surface) effluxes showed more distinct daily cycles than the calculated diffusion fluxes. Negative values were observed in both the calculated diffusion fluxes and surface effluxes, primarily during the nighttime period from 20:00 to 07:00.

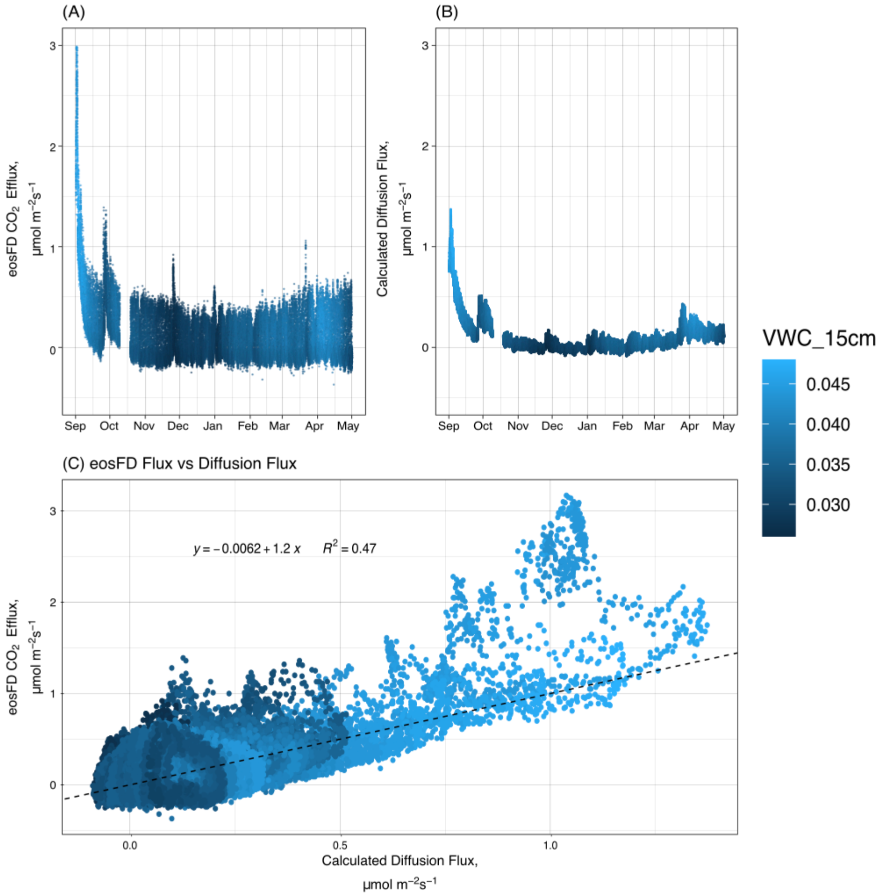

Figure 3: eosFD surface CO_2 efflux (A) vs calculated diffusion flux (B) at the Jornada LTER

The regression between the midnight CO_2 efflux values from the eosFD sensors and the nearby eddy covariance tower between 2021-09-01 and 2022-05-01 gave a positive correlation with a slope of 1.11 ($p < 0.001$; $r^2 = 0.33$; Figure 4) indicating that CO_2 fluxes from both the eosFD and the tower had comparable magnitudes and exhibited similar trends. Both methods showed values close to zero, except on days with rain events, which resulted in higher, more variable values.

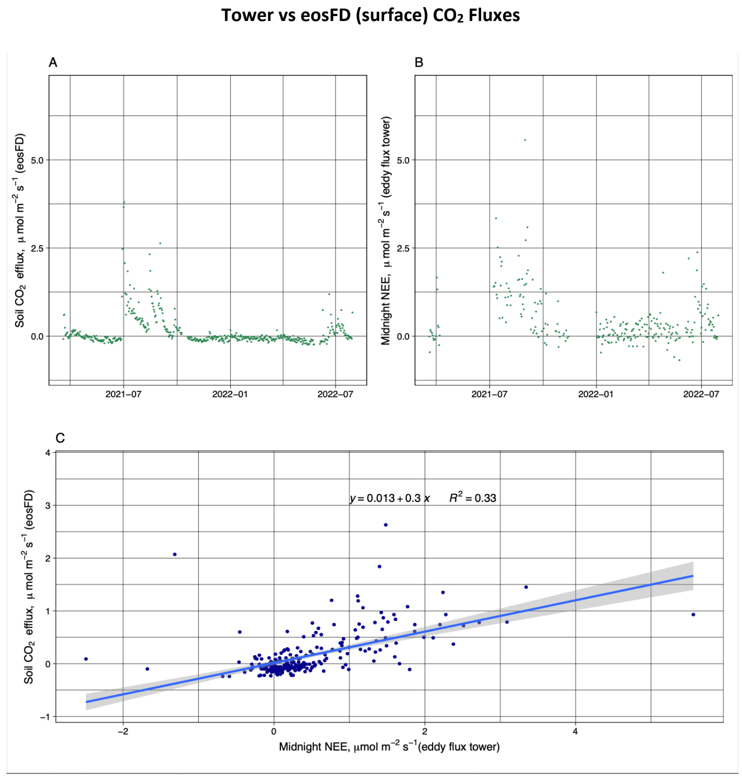

Figure 4: Comparison of Tower Midnight Net Ecosystem Exchange (NEE) and eosFD CO_2 fluxes at the Jornada Long-Term Ecological Research (LTER) site, highlighting the distinction between autotrophic fluxes related to plant leaves and ecosystem respiration (R_{eco}).

DYNAMICS OF CO_2 EFFLUX DURING BI-WEEKLY FLOOD IRRIGATION EVENTS

Calculated diffusion trends seen over four back-to-back irrigations at the agricultural location exhibited similar trends throughout the irrigations. When the irrigation began, diffusive fluxes increased slightly (never more than 16%), then immediately dropped to zero values or negative values (as seen on the first irrigation shown in Figure 5). The drops were substantial with an average drop of 95%. These values remained low (< 0.5 µmol m^{-2} s^{-1}) for about 2-3 days until they started gradually increasing again until the next irrigation where the same pattern would occur. Although there was a consistent pattern, there were some atypical variations in between the irrigation dates. These deviations happened to coincide with the days when it rained, indicating that the unusual values on those days (represented by blue lines) can be attributed to precipitation. For example, on 2022/07/26, CO_2 values had a sudden increase, followed by an immediate drop, this was also seen on 2022/08/24 and 2022/09/20. An abrupt surge in CO_2 values was observed on 2022/07/26, which was promptly succeeded by a decline. This pattern was repeated on 2022/08/24 and 2022/09/20 during which the recorded precipitation levels were 9.4 mm, 8.6 mm, and 8.1 mm respectively.

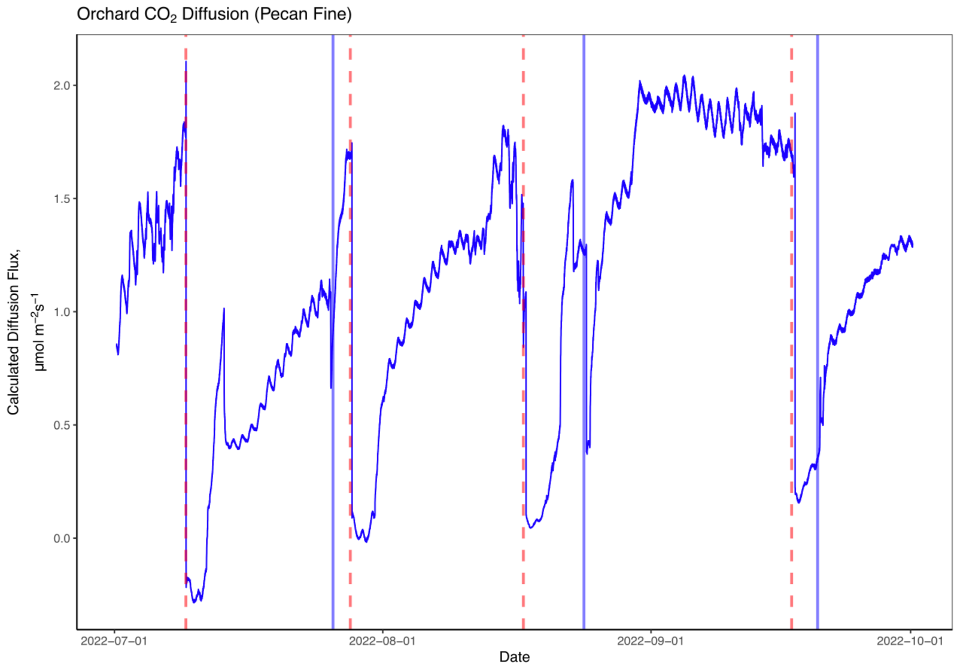

Figure 5: Calculated CO_2 diffusion fluxes through four consecutive irrigations

EXAMINATION OF CO_2 FLUX DURING PULSED MOISTURE EVENTS

Here we examine six pulsed moisture events that provide evidence of displacement across two dryland sites – an agricultural site and a shrubland site – one of which undergoes flood irrigation every growing season and one of which experiences natural rain events. We also examined pulses during the saturation (artificial wetting) experiment.

The first moisture pulse we examined was a small rain event (5.08 mm) at the Jornada LTER. Although small, the initial rain pulse resulted in an increase of CO_2 effluxes that were not evident in the diffusion flux calculations (Figure 6). From 20:00 to 21:00 on 03/21/22, the rain gauges recorded a rainfall amount of 5.08 mm, with the corresponding eosFD (surface) readings rising from -0.1 to 0.13 µmol m^{-2} s^{-1} within the same time frame. Although not immediately apparent in the surface readings, the daily maximum values increased gradually in the days

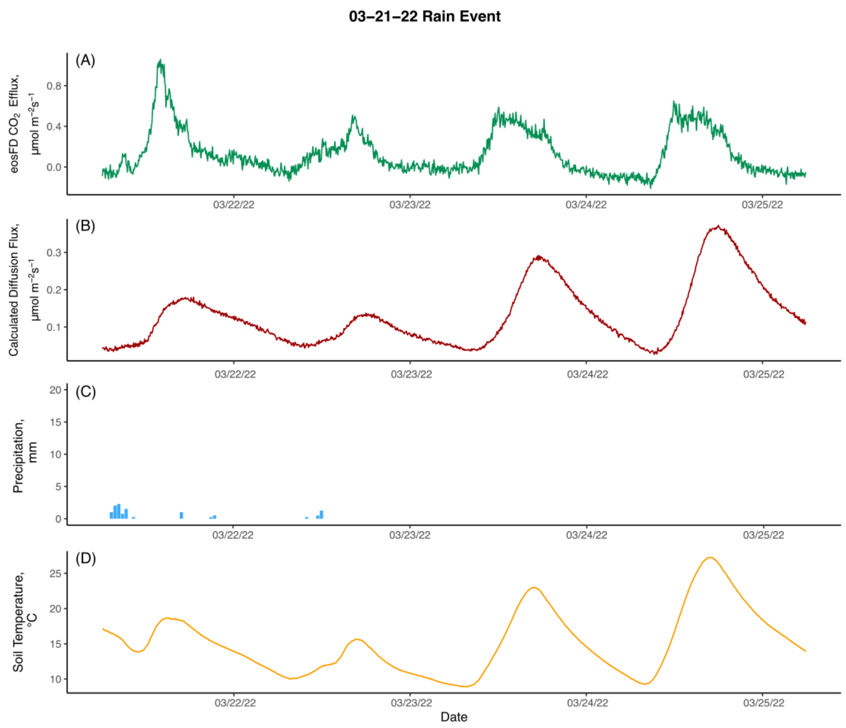

Figure 6: Time series of (A) measured CO_2, (B) calculated diffusion flux, (C) precipitation, and (D) soil temperature at the Jornada LTER during a rain event on 03/21/2022

following the first rain event. This increase was more noticeable in the calculated diffusion flux values (Figure 6B). As seen with other rain events, calculated diffusion fluxes did not increase until hours after the rain event.

The second event we examined was a larger rain event at the Jornada LTER on 2021-08-27. The initial rain pulse of ~7 mm caused CO_2 readings to increase from 0.6 µmol m^{-2} s^{-1} to 3.97 µmol m^{-2} s^{-1}. Three hours later, another rain event occurred that was larger in magnitude at ~20 mm of rain. This second pulse caused CO_2 effluxes to increase from 1.27 to 2.47 µmol m^{-2} s^{-1}. In the days following these events, the daily maximum and minimum values decreased gradually until they returned to their baseline measurements after approximately 5 days. Although multiple rain events occurred in a single day, the diffusion flux values did not correspond with the measured eosFD (surface) efflux values during the rain events. The diffusion fluxes were lower

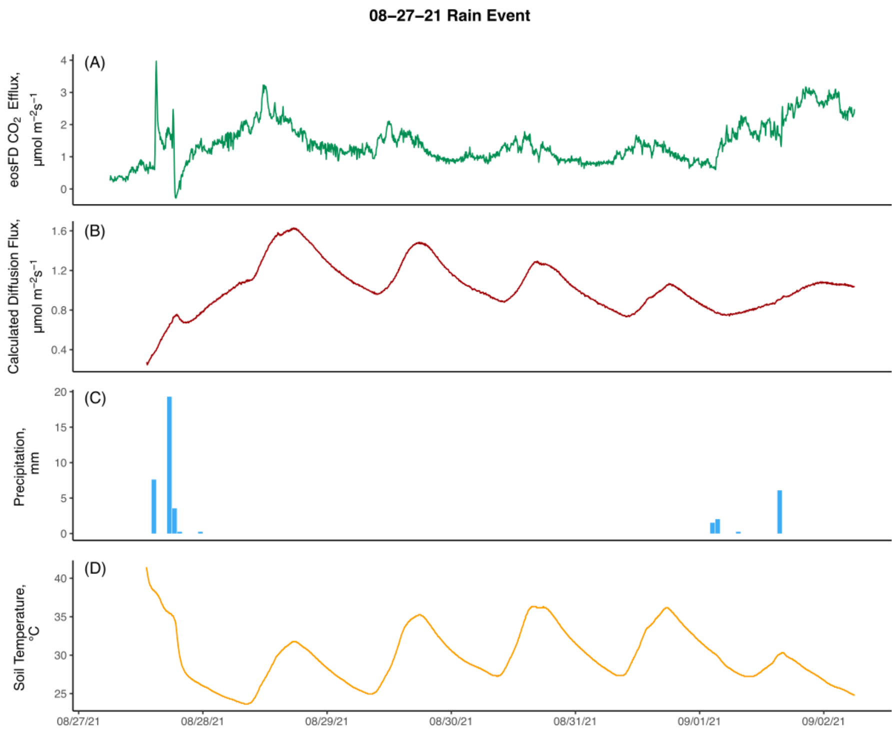

Figure 7: Time series of (A) measured CO_2, (B) calculated diffusion flux (C) precipitation, and (D) soil temperature at the Jornada LTER during a rain event on 08-27-2021

in magnitude throughout the time series and did not exhibit an immediate increase in CO_2 when water entered the soil pores during the first rain event.

The third pulsed moisture event we examined was an artificial wetting experiment. Prior to conducting the wetting experiment, the baseline measurements during a dry period at night were negative values that were almost equal to 0. The average night-time value on the day prior to the experiment was -0.128 µmol m^{-2} s^{-1}. The peak values observed during dry periods were approximately 0.5 µmol m^{-2} s^{-1}. During the experiment, irrigations were made in two stages to mimic a 65 mm rain event. The first water addition began at 15:56 and ended at 17:11 and included a water addition of 35 mm. Between 15:55. and 16:00, the eosFD (surface) effluxes increased from 0.38 to 2.08 µmol m^{-2} s^{-1}. They continued to rise and reached their maximum value of 2.71 µmol m^{-2} s^{-1} at 16:15. At 16:15, the CO_2 effluxes peaked at 2.71 µmol m^{-2} s^{-1}, marking a 673% increase in just 10 minutes. Effluxes began to steadily decrease after reaching their maximum values, dropping to 1.56 µmol m^{-2} s^{-1} by 17:00. One hour after the peak (at 17:15), the CO_2 effluxes had decreased by 44%. During the period from 20:12 to 21:30, when the second round of water was added, there was no rise in CO_2 efflux. Instead, the values exhibited a consistent trend of decline, continuing along the same pattern observed prior to the water addition. After the saturation (artificial wetting) experiment, the daily maximum values gradually decreased over a period of 4 days until they returned to values similar to pre-irrigation on the fifth day following the experiment.

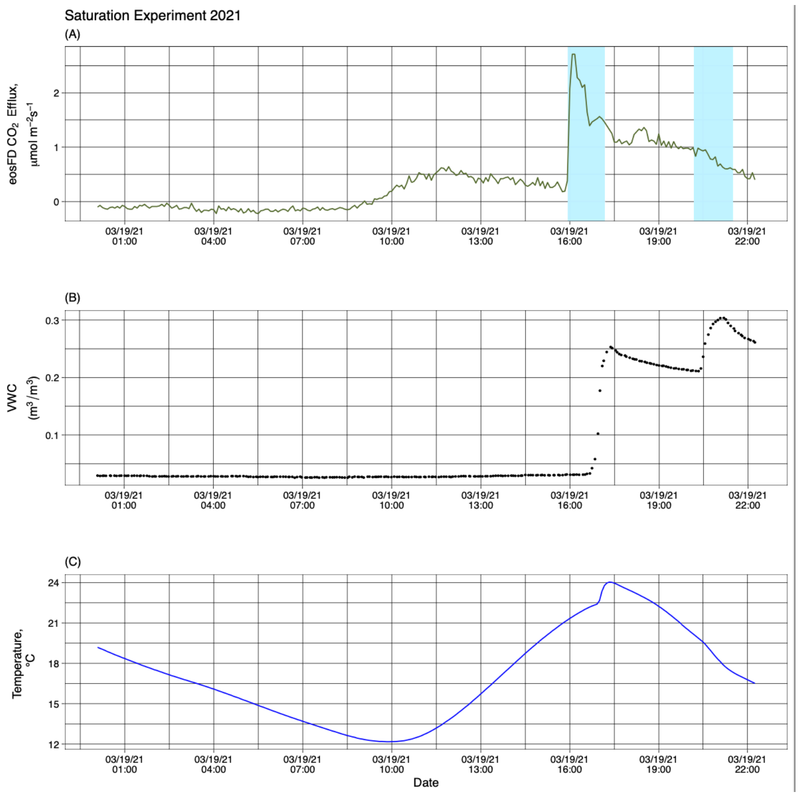

Figure 8: Time series of CO_2 efflux measurements during a "Saturation Experiment" at the Jornada LTER in 2021

The fourth pulsed moisture event we examined was a natural rain event on 2021-08-10 at the agricultural site, with a total precipitation of 1.55 mm (Figure 9). Rain began around 20:00; therefore, the 1.5 mm of rain occurred during a span of 4 hours. At 20:15, the eosFD (surface) efflux value was 1.53 µmol m^{-2} s^{-1} and by 20:40, efflux readings had increased to 5.38 µmol m^{2} s^{-1}. By 21:35 eosFD (surface) values had reached 14.4 µmol m^{-2} s^{-1} and by 23:40, CO_2 measurements had reached its max readings at 17.29 µmol m^{-2} s^{-1}. Subsequently, the measurements started to decrease and eventually returned to values similar to its baseline readings (around 2 µmol m^{-2} s^{-1}) by 3:00 the next day. Over the next few days, the efflux values persisted within the range of 2-5 µmol m^{-2} s^{-1}.

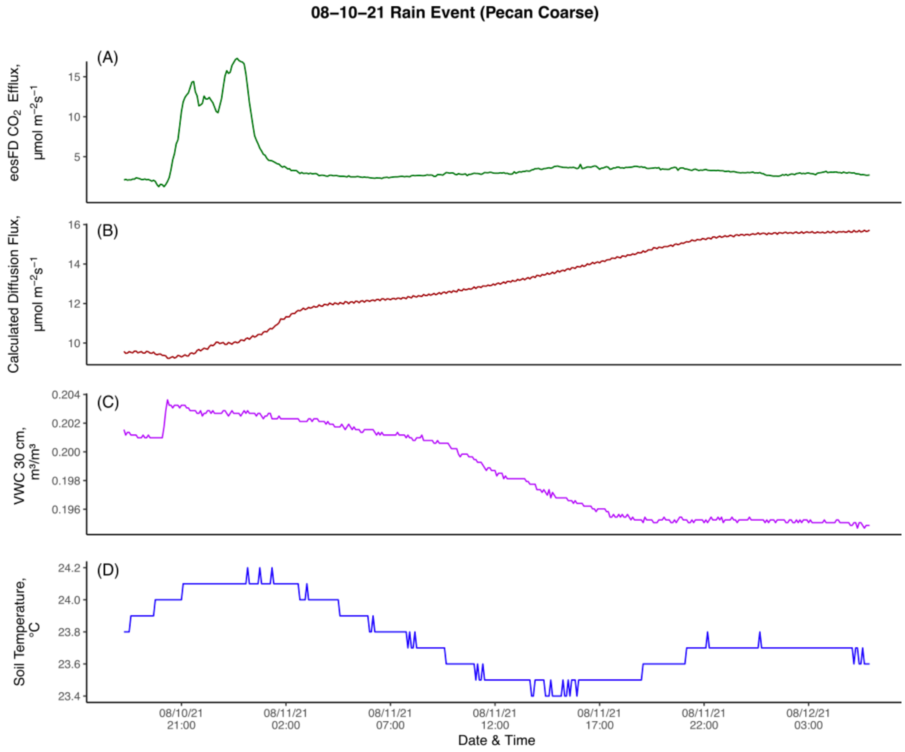

Figure 9: Time series of (A) CO$_2$ efflux from eosFD, (B) calculated diffusion flux, (C) volumetric water content at 30 cm, and (D) soil temperature at 30 cm during a rain event at our Pecan Orchard site in August 2022. This data was collected from the Pecan

The fifth moisture event investigated was a flood irrigation event at the Fine agricultural site on 2022-07-09 (Figure 8). eosFD (surface) sensors detected a rapid increase in CO$_2$ levels as soon as water was introduced during flood irrigations, which was observed consistently across the recorded flood irrigations. During this irrigation, readings jumped from 22.04 to 31.24 µmol m^{-2} s^{-1} at the pecan fine site in a span of 5 minutes of water entering the soil pores, giving us a ~42% increase. Following the initial spike, the CO$_2$ readings rapidly declined, dropping below 1 µmol m^{-2} s^{-1} within an hour. Subsequently, the values remained low for 22 hours until a slight increase was observed, peaking at 6.44 µmol m^{-2} s^{-1} the morning after the irrigation. At around 19:40 on the day following the irrigation, the CO$_2$ effluxes started to increase and followed similar trends and magnitudes that were observed prior to the irrigation. Another irrigation at the Fine site on 2022-08-17 followed a similar trend in that CO_2 readings increased from 1.17 µmol m^{-2} s^{-1} to 7.42 µmol m^{-2} s^{-1}, yielding a 533% increase within 5 minutes of the water entering the soil. The high fluxes observed during the irrigation were not sustained for long, as they peaked at 21.31 µmol m^{-2} s^{-1} within 20 minutes of the water addition, but then rapidly decreased to values lower than 1 µmol m^{2} s^{-1} within 40 minutes of the initial water addition. Values began to return to base readings 2 days later during the hours of the late afternoon. Despite the high magnitudes of the readings throughout our recordings at this site, it is noteworthy that the trends were still consistent with our hypothesis.

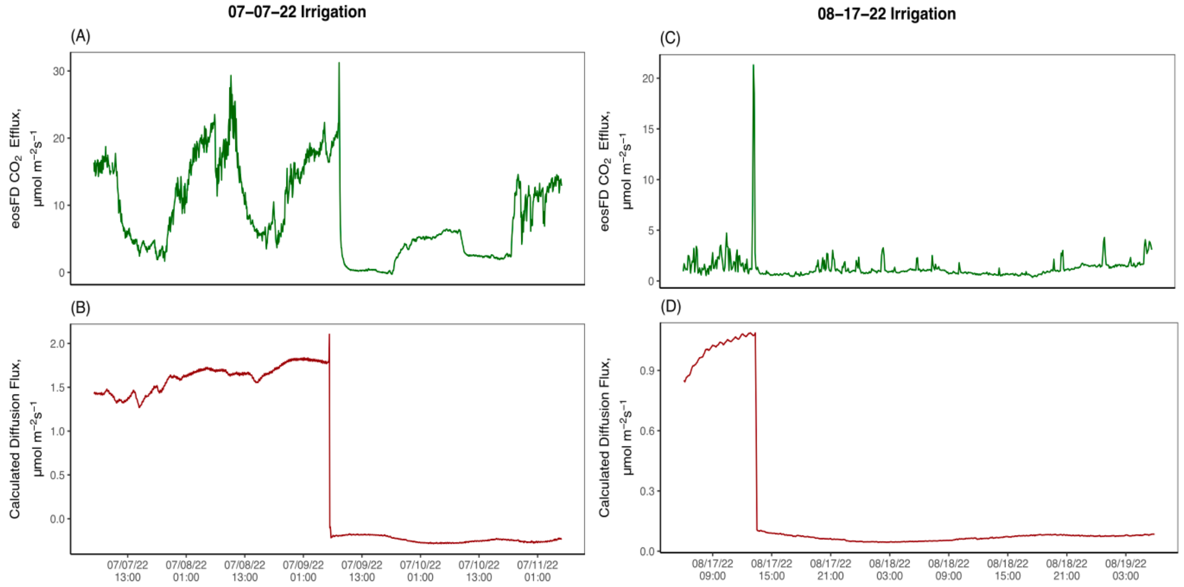

Figure 10: Time series of CO_2 efflux from eosFD and calculated diffusion efflux during two irrigation events at the Orchard site

Discussion

The aim of our study was to investigate the dynamics of CO_2 release into the atmosphere following precipitation, irrigation, and artificial precipitation events. Our results showed that the addition of water to the soil, regardless of the source, immediately increased CO_2 effluxes, which was consistent with the displacement effect we hypothesized in which water enters the soil pores and pushes out CO_2-rich air out via advection. When observing the soil CO_2 efflux data through the course of a year at the Jornada shrubland site, it was observed that the highest efflux values were associated with rain events. Similarly, at the Tornillo Orchard site, high CO_2 values were associated with flood irrigation events but right after irrigation CO_2 efflux was low due to inundation. Due to challenges with the implantation of the floating chamber that was built for this site, we did not get a complete picture of dynamics over the course of the irrigation event. Nonetheless, we consistently observed spikes in CO_2 immediately after each irrigation, followed by an abrupt decrease. The comparison of the diffusion and surface flux data suggested that the role of displacement played a consistent role at both the shrubland and orchard sites, and the different types of pulsed moisture events. This is a noteworthy finding as it provides empirical evidence for the role of soil air displacement, a phenomenon that has been addressed in some papers but not studied in detail. Specifically, our study sheds light on the short-term effects of water additions on CO_2 emissions, which can have important implications in understanding the carbon cycle in dryland ecosystems.

At the bajada shrubland site, slight negative CO_2 values were recorded during the nighttime, indicating nighttime uptake of CO_2. These characteristics of slight nighttime carbon uptake are consistent with other dryland papers (Hastings et al., 2005; Hamerlynck et al., 2013; Fa et al., 2014). As plants exhibit dormancy during nighttime, other mechanisms must account for these measurements. Temperature variations observed between day and night at our locations could potentially be a contributing factor (Hamerlynck et al., 2013). A literature review of CO_2 influx in drylands supports this idea, as negative CO_2 effluxes have been linked to low air and low soil temperatures (Sagi et al., 2021). Another possible explanation is carbonate dissolution driven by ventilation, which is relevant to our study sites due to the significant presence of calcium carbonate in our soils. During this process, atmospheric turbulence triggers pronounced daily patterns (Roland et al., 2013). In our study, we explored this mechanism and found that the daily pattern of calcium carbonate precipitation could affect nighttime CO_2 values. During the day, ventilation causes a disruption to the soils carbonate equilibrium and causes an increase in carbonate precipitation which then leads to CO_2 production. Conversely, during nighttime when ventilation ceases, carbonate dissolution increases, resulting in the uptake of CO_2 and associated negative effluxes.

High CO_2 pulses following a pulsed moisture event are commonly observed and have been well documented. However, the specific relationship between water infiltration and the displacement of CO_2-rich air has not been extensively studied at high temporal resolution, and thus our goal here was to establish its validity and contribution to overall carbon dynamics. Throughout the different pulsed moisture events we examined, we observed a consistent relationship between soil air displacement and the increase of CO_2 levels. Our findings closely mirrored those of Norman et al. (1992) who credited the displacement effect for their observed soil CO_2 level increase from 2 to 18 μmol m^2 s^{-1} following a thunderstorm. Similarly, at our agricultural location, the soil CO_2 levels increased from ~2 to ~17 μmol m^{-2} s^{-1} (Figure 7) following a rain event that closely resembled the thunderstorm observed by Norman et al. (1992). Water infiltration, as suggested by other studies, can affect gas fluxes by reducing diffusivity through filling soil pores with water, resulting in blocked gas exchange between soil and atmosphere during waterlogging (Rochette et al., 1991; Pan et al., 2021). This displacement effect results in the release of CO_2 that had previously accumulated in soil pore spaces, causing it to exit the soil (Kim et al., 2012).

A related topic that has been extensively studied is the Birch effect. This phenomenon refers to a sudden increase in CO_2 efflux in response to soil rewetting after a drought (Unger et al., 2010). As previously mentioned, the CO_2 pulses observed during the Birch effect have been attributed to heterotrophic respiration. However, our results are also to some extent consistent with trends seen during the Birch effect, and thus we propose that displacement may play a role during this phenomenon. It can be argued that the early CO_2 efflux following a wetting event is unlikely to be solely attributed to microbial respiration, as research has shown that microbial reactivation takes hours to days rather than seconds to minutes (Salazar et al., 2018; Meisner et al., 2017). The release of high CO_2 levels after wetting events that we observed was brief, but consistent with earlier findings that attributed the phenomenon to soil air displacement (Sánchez-García et al., 2020; Kim et al., 2012; Gallo et al., 2013). As the displacement effect occurs rapidly, it is consistent with our values that peaked within 10 minutes of adding water, whether naturally or artificially irrigated. This trend is consistent with a study which found CO_2 values peaked within 15 minutes of applying rainfall in their experiments (Rey et al. ,2019). The rapid nature of this process aligns with previous findings in the literature, further supporting that the displacement effect has a quick impact on CO_2 values.

While other factors may also play a role in CO_2 emissions after a wetting event, soil air displacement is believed to be a primary contributor as found by studies that found that 64% of emission following a wetting event was attributed to soil air displacement. (Marañón-Jiménez et al., 2011). Our high-resolution data and direct comparison with diffusive fluxes provides strong evidence of the processes occurring when water enters the soil pores. Specifically, the entry of water into soil pores results in the displacement of CO_2 from the pores, leading to elevated CO_2 efflux measurements that cannot be explained by diffusion fluxes alone.

Different CO_2 production and transport processes take place over the course of a pulsed moisture event. While we propose that soil air displacement plays a role immediately after the water enters the soil, it is unlikely it contributes significantly to the rest of the pulsed period. It is important to consider the broader context of flux dynamics beyond the immediate displacement pulses. At the bajada shrubland location, we frequently observed a distinct pattern of CO_2 emissions following large water pulses. After reaching its peak, the CO_2 values gradually declined over the next 24 hours, which was consistent with findings from a related study that also saw a gradual decrease over the next day after their experimental water addition (Rey et al., 2019). This is likely attributed to most of the CO_2 rich air being pushed out by the displacement effect. CO_2 values following the day of the wetting event resulted in higher CO_2 values than the day before the wetting event, likely due to heterotrophic respiration as the microbes have had time to become activated (Salazar et al., 2018; Meisner et al., 2017). Furthermore, the restoration of diffusion processes in the soil due to the absence of water filling up the pore spaces may also contribute to the elevated CO_2 values observed after the wetting event. As the soil dries out, gases can move more freely through the soil matrix, potentially resulting in increased CO_2 emissions from an increase in CO_2 production.

In the broader picture, fluxes a few days after wetting events are crucial to understanding the overall dynamics and putting the displacement pulses into context. Our study focused on high-resolution data immediately following wetting events and within a small area of our sites.

Automated soil CO_2 flux chambers, which allow continuous monitoring and provide high-resolution datasets, have been more widely used in such studies. For example, foundational work by Fierer and Schimel (2003) demonstrated that post-wetting respiration pulses can be attributed to the mineralization of microbial biomass. Their measurements were conducted at a daily frequency, thereby missing most of the dynamics that our report captured.

Conversely, at the agricultural site, we saw a steep drop in CO_2 values after the initial pulse from the displacement effect; as with the shrubland site, this is likely due to most of the CO_2-rich air being pushed out. The rate of this drop is a lot faster than that of the shrubland site as this site experiences flood irrigation, which is a larger amount of water in a shorter period of time. Our flood irrigation cycles were similar to those of Liu et al. (2013). They observed an immediate increase in CO_2 fluxes following flood irrigation, with values exceeding pre-flood levels by over 50%. Moreover, they noted a reduction of 70-90% in their values within an hour of water addition, which is comparable to our measurements that exhibited a decline of around 95% within the same time frame after adding water. After this, the CO_2 values tend to drop to values close to zero, likely due to soil pore oversaturation with water, which creates unfavorable conditions for microorganisms or diffusion to contribute to CO_2 effluxes. Nevertheless, as the drainage phase initiates on the subsequent day, CO_2 efflux levels gradually rise, possibly on account of heightened diffusivity and microbial activity, as well as root respiration.

While not empirically separated in this study, the role of inorganic carbon is also likely to contribute to efflux readings after wetting events as carbonates are found at our study sites. Irrigation practices at the agricultural site have been known to transport substantial quantities of dissolved Ca^{2+} and HCO_3^- to soils which then leads to the formation of pedogenic carbonates (Ortiz et al., 2022). Previous studies have demonstrated that rapid calcium dissolution and precipitation can occur following episodes of pulsed moisture. Interestingly, Gallagher & Breecker, (2020) found that CO_2 concentrations decreased up to 72% after water addition due to calcium dissolution, followed by an increase in CO_2 of up to 166% due to calcite precipitation. This may be applicable to our research as our numbers immediately increased due to displacement but could have also been taken up by nearby calcium carbonate in the soil. Conducting more research and measurements would help to accurately assess the relative contributions of displacement and calcium carbonate presence, allowing for a more robust and well-supported argument. Furthermore, the gradual increase in CO_2 fluxes in the days following the wetting event could be attributed to the role of calcium precipitation especially since this study reported that calcite dissolution occurs when soil respiration rates are elevated within the first 30 hours (Gallagher & Breecker, 2020). Therefore, it is important to consider the potential impact of inorganic carbon on soil CO_2 measurements, especially in regions where pedogenic carbonates are common as these carbonates can lead to either over- or underestimates of soil CO_2 efflux.

Future Directions

Moving forward, there are several research avenues that can enhance our understanding of the dynamics of CO_2 release following moisture events and contribute to a broader comprehension of carbon cycling in dryland ecosystems. To delve deeper into diffusion flux calculations, further exploration of different diffusion coefficient equations is warranted. This endeavor involves refining existing models or devising novel approaches to estimate diffusive fluxes more accurately. By incorporating additional factors such as soil properties, moisture content, and temperature, we can enhance the precision of diffusion flux calculations and better differentiate the contributions of displacement and diffusion processes to overall CO_2 emissions. Moreover, addressing the limitations encountered during the implementation of the floating chamber in our study highlights the need for improved measurement techniques. Therefore, ongoing efforts to develop a new floating platform for the eosFD sensor are underway. This innovative design will enable more accurate and reliable measurements of CO_2 efflux by overcoming the challenges associated with the previous implementation. The new platform will ensure comprehensive monitoring of carbon dynamics during moisture events, providing better coverage and minimizing disturbances to soil-air interactions. By pursuing these future research directions, we can refine our understanding of CO_2 dynamics following moisture events, advance measurement techniques, and deepen our knowledge of carbon cycling in dryland ecosystems. These endeavors will contribute to more precise predictions and effective management strategies concerning carbon balance and climate change mitigation in these critical environments.

Conclusions

Our findings consistently demonstrated that the introduction of water pulses to the soil, regardless of its source, resulted in an immediate increase in CO_2 effluxes, which could not be attributed to diffusion fluxes alone. Thus, we conclude that displacement is the dominant process causing rapid CO_2 efflux increases in the seconds and hours following a moisture pulse. During a year-long observation of soil CO_2 efflux data at the shrubland site, it was noticed that the highest efflux values were linked to rain events. Similarly, at the agricultural site, high CO_2 values coincided with flood irrigation events, but the efflux dropped immediately after irrigation due to inundation. By comparing the diffusion and surface flux data, we found evidence indicating that displacement played a consistent role at both the shrubland and agricultural sites during various types of pulsed moisture events. Moreover, flood irrigations at the agricultural site resulted in CO_2 effluxes of higher magnitudes than those from natural rain events at the shrubland site, likely due to the copious amounts of water introduced and the presence of calcium carbonates at the site. These results highlight the importance of understanding the complex interactions among moisture pulses, displacement, and soil carbon dynamics within the dryland critical zone.

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Vita

Briana Alyce Salcido received her Bachelor of Science degree in Environmental Science from The University of Texas at El Paso in December of 2020. As an undergraduate student, she conducted research on the Comparison of Methods for Quantifying Fungal Biomass in Soils Using Ergosterol and FAME under the guidance of Dr. Anthony Darrouzet-Nardi. In the Spring of 2021, Briana was admitted into the master's Environmental Science program in the Department of Earth, Environmental and Resource Sciences. During her graduate studies, Briana focused on dryland soil carbon fluxes during pulsed moisture events, which formed the basis of her thesis. She received a travel grant to present a poster at the Fall 2022 AGU conference in Chicago, Illinois. Briana has experience in teaching as a teaching assistant for Intro to Environmental Science, Field Methods in Environmental Science, and Organismal Biology Lab. She is interested in pursuing a career in conservation, remediation, or sustainability.

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