# Biogeochemical drivers of soil $N_2O$, $CH_4$, and $CO_2$ emissions from alfalfa using long-term continuous measurements

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November 21, 2022

**Abstract**

Agriculture is a significant source of carbon dioxide ($CO_2$) and methane ($CH_4$) and is the dominant source of anthropogenic nitrous oxide ($N_2O$) emissions. Changes in agricultural land management practices that reduce overall greenhouse gas (GHG) emissions have been suggested to help mitigate climate change, but a better understanding of the timing, magnitude, and drivers of GHG fluxes is needed. Alfalfa agroecosystems may be significant sources of $N_2O$ given their ability to increase N inputs through symbiotic $N_2$ fixation and frequent irrigation events that create conditions for hot moments of $N_2O$ production. However, few studies have explored long-term $N_2O$ emissions and their associated drivers in alfalfa ecosystems. We collected over 108,000 $CO_2$, $CH_4$ and $N_2O$ soil flux measurements over four years using cavity ring-down spectroscopy from a conventional flood-irrigated alfalfa field in California, USA. This ecosystem was a consistent source of $N_2O$ (annual mean: 624.4 $\pm$ 27.8 mg $N_2O$ $m^{-2}$ $yr^{-1}$, range: 263.6. $\pm$ 5.6 to 901.9 $\pm$ 74.5 mg $N_2O$ $m^{-2}$ $yr^{-1}$) and a small net sink of $CH_4$ (annual mean: -53.5 $\pm$ 2.5 mg $CH_4$ $m^{-2}$ $yr^{-1}$, range: -78.2 $\pm$ 8.8 to -31.6 $\pm$ 2.5 mg $CH_4$ $m^{-2}$ $yr^{-1}$). Soil $CO_2$ fluxes averaged 4925.9 $\pm$ 13.5 g $CO_2$ $m^{-2}$ $yr^{-1}$ and were greater than other alfalfa ecosystem estimates, likely driven by elevated temperatures and plant productivity throughout the growing season. Hot moments of $N_2O$ emissions represented only 0.2% to 1.1% of annual measurements but were 31.6% to 56.8% of the annual flux. We found that both the magnitude and the contribution of $N_2O$ hot moments to annual emissions decreased over time. Normalized difference vegetation index (NDVI), soil temperature, moisture, and $O_2$ were all significantly correlated with soil $CO_2$, $N_2O$, and $CH_4$ fluxes, although associations varied across both soil depth and timescales. Our results suggest that flood-irrigated alfalfa is a significant source of agricultural $N_2O$ emissions, and that plant productivity and soil moisture effects on $O_2$ availability may modulate the net GHG budget of alfalfa agroecosystems.

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## Introduction

- Alfalfa (*Medicago Sativa* L.) is the most common perennial forage legume worldwide and the largest crop by acreage in the Western U.S.[1]
- Alfalfa is often thought of as a climate-friendly feedstock given its potential to increase soil C as a deep-rooting, perennial plant[2] and symbiotic nitrogen ($N_2$) fixer, decreasing inorganic fertilizer inputs.
- Long-term $CO_2$ and $CH_4$ studies suggest alfalfa can be a net C sink[3-4], but no continuous long-term $N_2O$ studies exist[4-5].
- Alfalfa may be a significant $N_2O$ source as enriched soil N and irrigation may stimulate hot moments of $N_2O$ production.

## Methodology

- **Jan 2016-Feb 2021:** >108,000 $CO_2$, $CH_4$ and $N_2O$ flux measurements from unfertilized alfalfa in California, USA with automated Eosense chambers and a Picarro greenhouse gas (GHG) analyzer.
- **Apr 2018-Apr 2019**: Weekly soil $NO_3^-$, $NH_4^+$ sampling.
- **Sep 2018-Feb 2021**: Continuous soil moisture, temperature, and oxygen ($O_2$) at 10, 30, and 50 cm.
- **Fluxes up to 5.7 ± 0.8 kg N-$N_2O$ ha$^{-1}$ yr$^{-1}$, and hot moments, only 1% of measurements, were 44% of total $N_2O$ fluxes**

| Site Year | Annual mean (mg $N_2O$ m$^{-2}$ y$^{-1}$) | Hot moment mean (mg $N_2O$ m$^{-2}$ d$^{-1}$) | Hot moment % of flux |
|---|---|---|---|
| 1 (2017-18) | 611 ± 68 | 496 ± 67 | +56.8% |
| 2 (2018-19) | 902 ± 74 | 457 ± 43 | +55.3% |
| 3 (2019-20) | 777 ± 52 | 363 ± 46 | +37.5% |
| 4 (2020-21) | 264 ± 6 | 20 ± 1 | +31.6% |
| All years | 624 ± 28 | 401 ± 27 | +44.4% |

**Table 1.** Mean ± SE annual and hot moment (>4 SD) $N_2O$ fluxes.

## Daily mean $CO_2$, $CH_4$, and $N_2O$ fluxes

- **Hot moments (fluxes > 4 SD) were 57% of $N_2O$ fluxes, largely associated with flood irrigation.**
- **Strong seasonal trends in soil $CO_2$ fluxes closely followed air temperature and plant respiration.**
- **Alfalfa was a small net $CH_4$ sink with the largest sinks in 2020-21.**

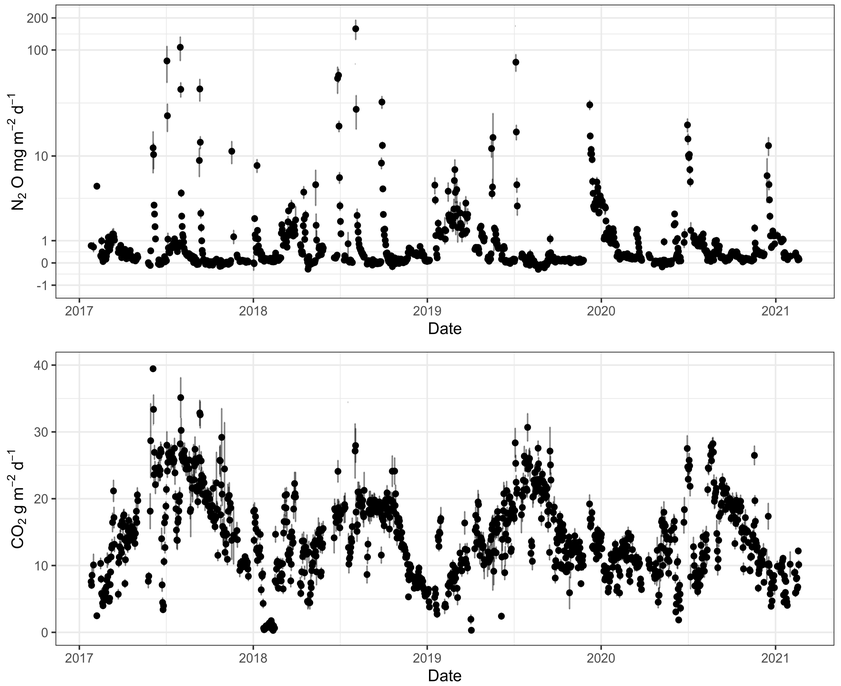
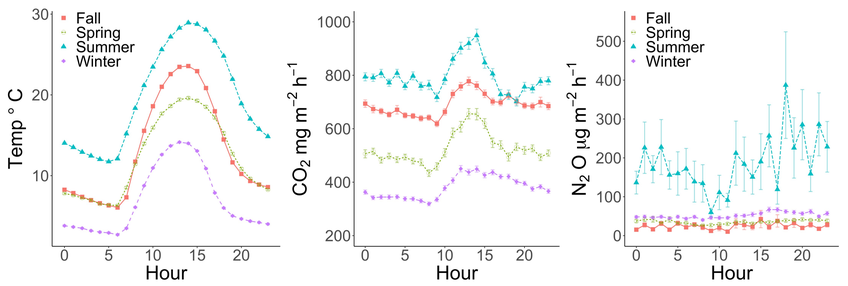


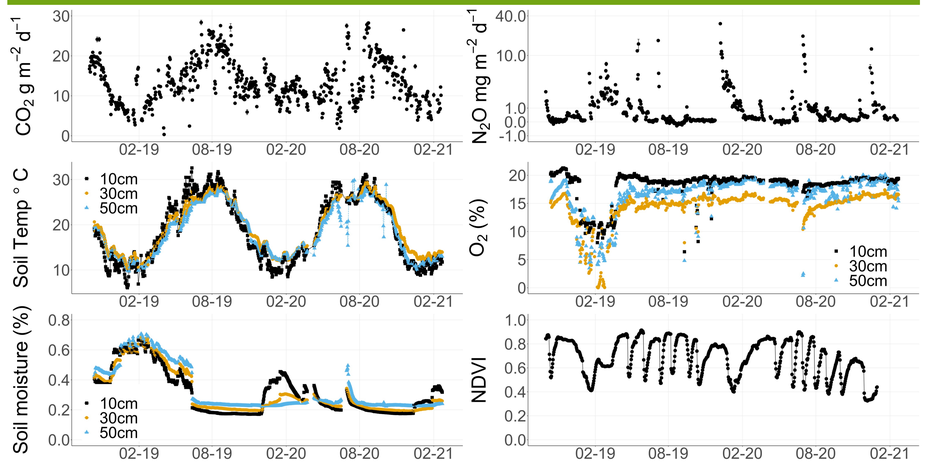

**Fig. 1** Daily mean fluxes (± standard error) for $N_2O$ and $CO_2$. Black circles represent daily mean flux measurements.

## Diels trends in soil greenhouse gas emissions

- **Diel $CO_2$ fluxes followed similar trends to temperature**
- **$N_2O$ fluxes significantly higher in summer, lagged temperature**




## Drivers of soil greenhouse gas emissions




- **$CO_2$ coupled with temperature and normalized vegetation index (NDVI)**
- **$N_2O$ coupled with soil $O_2$, moisture, and NDVI**
- **Significant wavelet coherence of all three GHGs with NDVI, temperature, moisture, and $O_2$, but varied across timescales.**

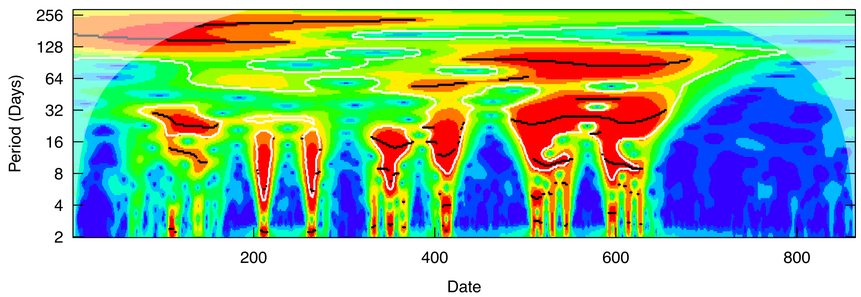



**Fig. 4** Example wavelet coherence of $N_2O$ and $O_2$ at 10 cm. Red = significant.

## Conclusions

- **Alfalfa is a significant $N_2O$ source (up to 5.7 ± 0.8 kg N-$N_2O$ ha$^{-1}$ yr$^{-1}$), and hot moments are up to 57% of annual $N_2O$ flux.**
- **$N_2O$ fluxes offset net ecosystem $CO_2$e sink by 10-20% even without N inputs**
- **Significant coherence with NDVI, temperature, moisture, and $O_2$ suggest plant productivity and soil $O_2$ modulate GHG budgets.**

## Acknowledgments

Thank you to the members of the Silver and Baldocchi Labs at UC Berkeley. This work was supported by a California Department of Water Resources Contract (award 4600011240). This was also supported by the California Sea Grant Delta Science Fellowship by the Delta Stewardship Council Delta Science Program under Grant No. 5298 and California Sea Grant College Program Project R/SF-89. *

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