SOLAR-INDUCED CHLOROPHYLL FLUORESCENCE: A NOVEL APPROACH TO QUANTIFY PHOTOSYNTHESIS IN SALT MARSHES

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Abstract

Salt marshes serve as a large carbon sink, sequestering carbon dioxide (CO_2) from the atmosphere through efficient photosynthesis and carbon burial. Quantifying the total carbon uptake via photosynthesis, known as gross primary production (GPP), in an intertidal marsh is complicated by tidal cycles because few methods can measure photosynthesis of plants both above and below the water surface. Previous studies using eddy covariance (EC) have concluded that photosynthesis decreases when salt marsh vegetation is inundated; however, EC cannot directly discern carbon uptake during high tides and thus additional and independent approaches are needed to estimate GPP. Here, we couple EC measurements, vegetation spectra, and the solar-induced chlorophyll fluorescence (SIF) technique to study salt marsh photosynthesis. We describe concurrent measurements of vegetation spectra in the red and near-infrared regions using an automated spectrometer system and EC measurements for the 2020 and 2021growing seasons in a salt marsh on the Virginia Eastern Shore. We identify diurnal, tidal, and seasonal patterns to examine how photosynthesis is modulated by environmental factors. We also present relationships between red and near-infrared vegetation radiance and net marsh-atmosphere CO_2 fluxes during different stages of inundation to improve estimates of photosynthesis at high tides.

Motivation and background

Despite their small areal coverage, salt marshes play an outsized role in the global carbon cycle and sequester up to 70 Tg C/yr (Duarte, 2017). Organic carbon buried in the soils of salt marshes accumulates because of high rates of photosynthesis, efficient trapping of suspended particles, and hypoxic conditions that slow the rate of decomposition (McLeod *et al*., 2011; Lovelock *et al*., 2017). In contrast to terrestrial forests that sequester carbon on decadal scales, an estimated 50% of detritus (carbon originally assimilated through photosynthesis then stored as plant biomass) in salt marshes is buried in vertically accumulating sediments for millennia (McKee *et al*., 2007; Lo Iacono *et al*., 2008).

There remain large uncertainties in current inventories of salt marsh carbon storage due to high spatial variability and a general lack of measurements of photosynthesis and carbon burial. Photosynthetic rates for salt marsh vegetation are typically measured *in situ;* therefore, observations are limited in spatial coverage to just a tiny fraction of total global wetland areas. Remote sensing has the advantage of capturing larger spatial regions, longer-term trends and, in the case of space-based remote sensing, gradients across heterogeneous landscapes. Traditionally, remote sensing instruments have not been able to directly measure photosynthesis, instead relying on the proxy of vegetation greenness like the Normalized Difference Vegetation Index (NDVI). Furthermore, coastal ecosystems are especially challenging to study with space-based instruments without local ground-based measurements, as they are often narrower than most satellite pixels. These challenges require innovative methods to estimate the salt marsh carbon stock with greater certainty.

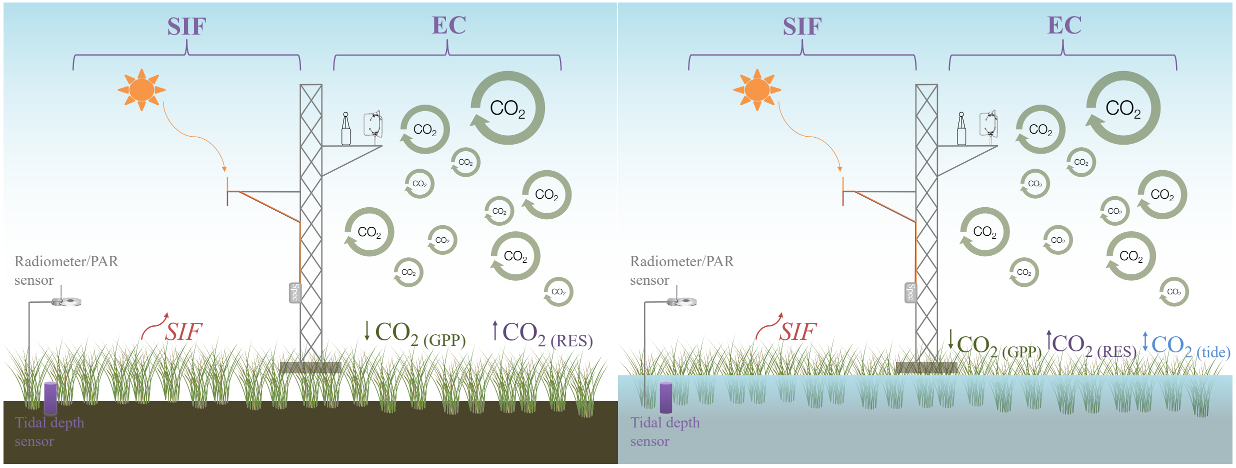

Figure 1: Experimental design at low tide (left) and high tide (right). Concurrent measurements of SIF, vegetation spectra, and EC-derived net marsh-atmosphere CO_2 exchange fluxes are collected from a 7 meter tall tower. Long and short wave radiation are collected with a net radiometer and photosynthesically active radiation (PAR) sensor, and a tidal sensor collects continues water depth depth data.

Recently it has become possible to measure solar-induced chlorophyll fluorescence (SIF) using remote sensing at the Earth's surface and from satellites. While most of the incident solar radiation absorbed by a leaf is partitioned to photosynthesis or dissipated as heat, excited chlorophyll molecules fluoresce a tiny portion of the absorbed photons (1–2%) as SIF (Frankenberg & Berry, 2018). The SIF instensity has been empirically shown to be proportional to the rate of the electron transport in photosynthesis and to correlate with photosynthesis at the canopy scale, making it a more direct probe of salt marsh photosynthesis than vegetation greenness (Porcar-Castell *et al.*, 2014; Yang *et al.*, 2015).

In my VSGC research proposal, I aimed to quantify temporal patterns of salt marsh gross primary production (GPP), the total carbon uptake by vegetation, using tower-based observations of SIF coupled with carbon (CO_2) gas exchange data determined using eddy covariance (EC). Quantifying GPP in an intertidal marsh is complicated by tidal cycles as few methods can measure photosynthesis of plants both above and below water levels. EC is a powerful approach to estimate carbon fluxes by correlating deviations in the vertical wind speed and CO_2 mixing ratio from their means (Baldocchi *et al.*, 1998). Previous studies using EC have found photosynthesis to decrease when salt marsh vegetation is inundated (Kathilankal *et al.*, 2008). However, EC cannot differentiate vertical carbon fluxes from vegetation or water during high tides, and additional and independent approaches are needed. By coupling SIF and EC, I aim to develop an approach to estimate GPP independent of the tidal cycle (Figure 1).

Current Progress

I have installed an automated spectrometer system to collect continuous measurements of salt marsh vegetation spectra and collected two full years of marsh-atmosphere CO_2 fluxes with EC. Although challenges with salt corrosion on one of my instruments and fiber angle have prevented me from calculating SIF at this point, I have found strong relationships between vegetation upwelling radiance and CO_2 fluxes. Eddy covariance net marsh-

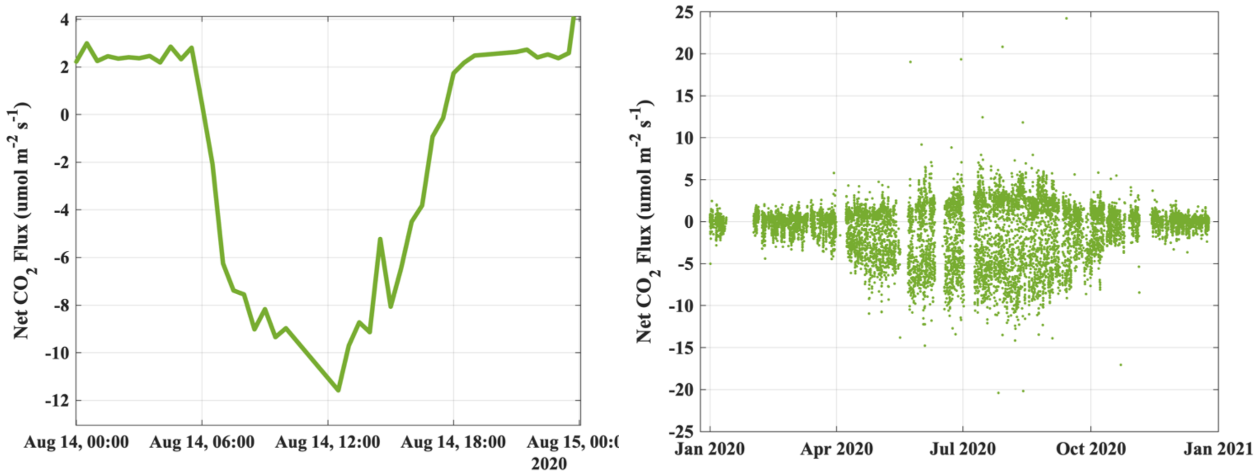

Figure 2: 2020 CO_2 fluxes. Example plot of daily net marsh-atmosphere CO_2 flux from August 15, 2020 (left). Full time series of CO_2 flux across all of 2020. A more negative flux indicates greater photosynthesis and a net flux of carbon down into the marsh.

atmosphere CO_2 fluxes have shown expected diurnal and seasonal patterns, with carbon uptake peaking in summertime at rates of up to 20 μmol m^{-2} s^{-1} and reaching daily peaks at midday (Figure 2). In 2020, the marsh was a net carbon sink and sequestered up to 325 g C m^{-2}. I'm currently processing the 2021 data before proceeding to partitioning the GPP flux component from the net ecosystem flux.

Salt marsh vegetation radiance has shown promising results in utilizing both SIF in the red and near-infrared wavelengths to estimate GPP across tidal conditions. Our spectrometer design has captured expected vegetation radiance and incoming solar irradiance spectral shapes and intensities, such as the red edge that results from vegetation increasing reflectance as wavelength increases beyond 700nm (Figure 3). Vegetation radiance in near-infrared wavelength was strongly attenuated by tidal height, while radiance in red wavelengths remained consistent across all tidal conditions (Figure 4). Since water strongly absorbs wavelengths >700nm, this is not a surprising result. However, the resilience of radiance in the red wavelengths indicates we can reliably draw conclusions about vegetation physiology independent of the tide. This suggests SIF red wavelengths may be a better proxy for photosynthesis during

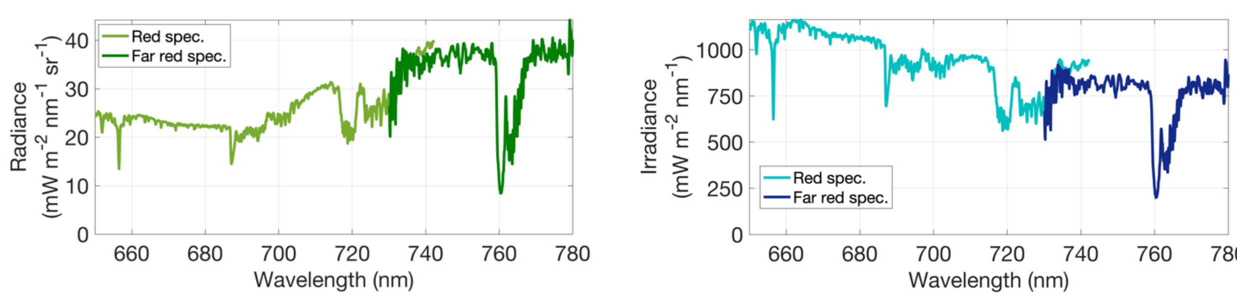

Figure 3: Example vegetation radiance (left) and sky irradiance spectra (right). Red spectrometer covers red wavelengths. Near-infrared spectrometer covers near-infrared wavelengths.

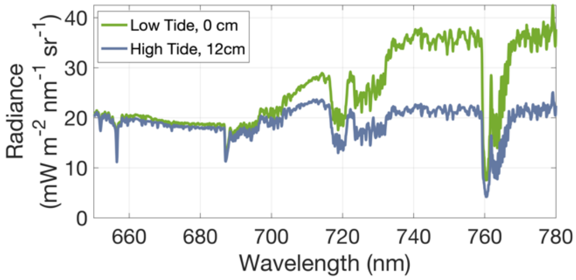

Figure 4: Two example vegetation radiance spectra from environmental conditions aside from tidal height. There is a clear divergence of the two spectra beginning at 700nm due to water strong light absorption in the near-infrared wavelengths.

high tide conditions and is an important result for retrieving SIF with satellite observations.

We also find correlations between the net ecosystem CO_2 flux and vegetation radiance (Figure 5). Radiance in the near-infrared wavelengths correlated with CO_2 flux across all tidal conditions remarkedly well for this point in the data processing. The tide physically attenuating CO_2 exchange between the marsh and atmosphere and absorbing near-infrared light likely drives this relationship. It's important to note the net ecosystem flux in the sum of photosynthetic (GPP) and respiration fluxes. When we complete the data processing to partition GPP and retrieve SIF, we expect the red vegetation radiance to correlate more strongly with GPP and red SIF.

Next Steps

My next steps are to finalize the post processing of eddy covarience net ecosystem CO_2 fluxes and partition the GPP and ecosystem respiration componenets of the net flux. Additionally, I am planning a new SIF instrument design with more salt-resistant instrumentation and adjustable fiber angle components to allow me to change the angle of view of my optic fibers and optimize the fiber field of view. This should address the salt corrosion and spectral reflectance shape

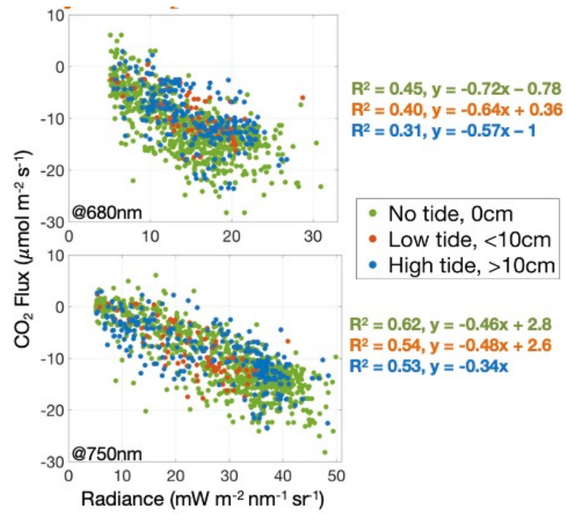

Figure 5: Vegetation radiance at 680nm (top) and 750nm (bottom) plotted against

errors that have prevented me from retrieving SIF this past summer.

During the coming growing season, I will determine how tidal conditions impact the ability of SIF to escape the water's surface by calibrating my remote sensing observations with an LED light as described by Burkart *et al.* (2015). This approach will allow me to understand how tidal fluctuations modulate SIF and develop a correction model for vegetation-based SIF that adjusts for the current tidal level. The LED light source will emit light in the SIF infrared emission region (760 nm) and serve as reference to determine a SIF signal attenuation factor for a given tidal depth.

Next, I will use low-tide data periods to determine the slope of the linear fit between SIF and the eddy covariance GPP flux. The SIF signal attenuation factors derived from the LED light experiment will allow me to extrapolate the low tide SIF-GPP relationship to high tide conditions and calculate a SIF-derived GPP when eddy covariance does not yield reliable results. I will apply this method across the 2022 growing season to estimate the annual amount of CO_2 entering the salt marsh through photosynthesis. Additionally, I will calculate a GPP estimate from my eddy covariance data. Comparing these two estimates will detect any longer-term differences in SIF- and eddy covariance-derived GPP that arise at seasonal scales.

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