https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

Title

Eddy Covariance Evaluation of Ecosystem Fluxes at a Temperate Saltmarsh in Victoria, Australia Shows Large CO_2 Uptake

Authors

Ruth Reef[1],
Edoardo Daly[2,3],
Tivanka Anandappa[1],
Eboni-Jane Vienna-Hallam[1],
Harriet Robertson[1],
Matthew Peck[1],
Adrien Guyot[4,5]

Affiliations

1 School of Earth, Atmosphere and Environment, Monash University, VIC 3800, Australia
2 Department of Civil Engineering, Monash University, VIC 3800, Australia
3 WMAwater, Brisbane, QLD 4000, Australia
4 Atmospheric Observations Research Group, The University of Queensland, Brisbane, Australia
5 Australian Bureau of Meteorology, Melbourne, Australia

Corresponding Author

Associate Professor Ruth Reef
School of Earth Atmosphere and Environment
Monash University
9 Rainforest Walk, Clayton VIC 3800
Australia
Email: ruth.reef@monash.edu

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

Ph: +61 3 9905 8309

Key Points

This is the first study using eddy covariance to measure CO_2 fluxes at an Australian temperate saltmarsh, revealing temperature and light limitations to CO_2 uptake.

CO_2 fluxes varied seasonally; growing season net ecosystem productivity was 10.54 g CO_2 m^{-2} day^{-1}, dropping to 1.64 g CO_2 m^{-2} day^{-1} in winter.

Annual productivity at the French Island saltmarsh is estimated at 753 g C m^{-2} y^{-1}, surpassing global saltmarsh estimates but below global mangrove averages.

Abstract

Recent studies highlight the important role of vegetated coastal ecosystems in atmospheric carbon sequestration. Saltmarshes constitute 30% of these ecosystems globally and are the primary intertidal vegetation outside the tropics. Eddy covariance (EC) is the main method for measuring biosphere-atmosphere fluxes, but its use in coastal environments is rare. At an Australian temperate saltmarsh site on French Island, Victoria, we measured CO_2 and water gas concentration gradients, temperature, wind speed and radiation. The marsh was dominated by a dense cover of *Sarcocornia quinqueflora*. Fluxes were seasonal, with minima in winter when vegetation is dormant. Net ecosystem productivity (NEP) during the growing season averaged 10.54 g CO_2 m^{-2} day^{-1} decreasing to 1.64 g CO_2 m^{-2} day^{-1} in the dormant period, yet the marsh remained a CO_2 sink due to some sempervirent species. Ecosystem respiration rates were lower during the dormant period compared with the growing season (1.00 vs 1.77 µmol CO_2 m^{-2} s^{-1}) with a slight positive relationship with temperature. During the growing season, fluxes were significantly influenced by light levels, ambient temperatures and humidity. Evapotranspiration peaked at 0.27 mm h^{-1}. We cautiously

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

estimate the annual NEP budget at this marsh to be 753 (±112.7) g C m^{-2} y^{-1} which is similar to carbon uptake by temperate saltmarshes in Europe and within the range measured at some US saltmarshes. This value is higher than the value hypothesised for global saltmarshes of 382 g C m^{-2} y^{-1} but is only half the mean value estimated for global mangroves.

EGUsphere Topics

Emissions, Marine and Freshwater Biogeosciences, Earth System Biogeosciences

Short Summary

Studies show that saltmarshes excel at capturing carbon from the atmosphere. In this study, we measured CO_2 flux in an Australian temperate saltmarsh on French Island. The temperate saltmarsh exhibited strong seasonality. During the warmer growing season, the saltmarsh absorbed on average 10.5 grams of CO_2 from the atmosphere per m^2 daily. Even in winter, when plants were dormant, it continued to be a CO_2 sink, albeit smaller. Cool temperatures and high cloud cover inhibit carbon sequestration.

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

1. Introduction

Despite their relatively small global footprint of 54,650 km² (Mcowen et al., 2017), salt marshes provide a range of ecosystem services, including shoreline protection (Shepard et al., 2011), nutrient uptake, nursery grounds for fish populations (Whitfield, 2017) as well as functioning as significant carbon sinks through CO_2 uptake and storage in their organic rich sediments (McLeod et al., 2011). These 'blue carbon' habitats are recognised for their significant contribution to the global carbon cycle, as coastal wetlands more broadly are estimated to have accumulated more than a quarter of global organic soil carbon (Duarte, 2017).

Saltmarshes are a widely distributed intertidal habitat but are floristically divergent globally (Adam, 2002), such that commonalities in function and form do not extend across biogeographic realms. US saltmarshes, for example, are extensively dominated by a single grassy species, *Spartina alterniflora*, as opposed to the dominance of C_3 Chenopodioideae species in the southern hemisphere (Adam, 2002). Temperate saltmarshes occupy a latitudinal range spanning from approximately 30° to 60° (Mcowen et al., 2017) and are most commonly found along protected coastlines such as bays, estuaries, and lagoons, where they are sheltered from the full force of wave action (Mitsch and Gosselink, 2000). In the Southern Hemisphere, temperate saltmarshes have a strong Gondwanan element with high floristic similarity among the marshes of New Zealand, the southernmost coasts of South America and South Africa and the southern coastlines of Australia (Adam, 1990). These marshes are often associated with extensive seagrass meadows and mudflats, and in parts of their range, mangroves, forming complex coastal mosaics (Huxham et al., 2018). Saltmarshes have been heavily degraded across their range, and it is estimated that perhaps up to 50% of the global saltmarsh area has been lost since 1900 (Gedan et al., 2009), primarily due to land use change.

Seasonality plays a major role in the functioning of temperate saltmarshes (Ghosh and Mishra, 2017). These ecosystems experience distinct growing and dormant seasons, primarily driven by temperature, light availability, and precipitation patterns (Adam, 2000). During the growing season (typically spring and summer), increased temperatures and

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

longer daylight hours stimulate plant growth, photosynthetic activity, and decomposition processes. Photosynthesis typically outpaces decomposition during this period, resulting in the temperate saltmarsh acting as a net CO_2 sink (Chmura et al., 2003). Conversely, the dormant season (usually fall and winter) is characterized by cooler temperatures and shorter days (Adam, 2000; Howe et al., 2010). These factors lead to reduced plant growth and photosynthetic activity (Adam, 2000) and while decomposition processes also slow down due to cooler temperatures, CO_2 release through decomposition often exceeds CO_2 uptake during this period (Artigas et al., 2015).

Gross primary production (GPP) of saltmarshes is the total photosynthetic flux of CO_2 from the atmosphere to the land surface, while respiration (R_e) leads to a CO_2 flux directed back to the atmosphere. The difference between these two fluxes is the net ecosystem exchange (NEE). Saltmarsh ecosystems can act as both sources and sinks of carbon dioxide (CO_2), influencing atmospheric CO_2 concentrations (Chmura et al., 2003). However, quantifying their net exchange remains challenging (Lu et al., 2017) hindering their effective inclusion in Earth System Models (Ward et al., 2020) and confounding the incorporation of saltmarsh restoration in emission reduction targets. Eddy covariance (EC) provides a powerful method for near-continuous, high-frequency monitoring of gas exchange between a vegetated surface and the atmosphere (Baldocchi, 2003), enabling the determination of net ecosystem exchange (NEE) of CO_2, and identifying the forcings that determine how CO_2 fluxes will respond to global climate change (Borges et al., 2006; Cai, 2011).

Previous EC studies in coastal saltmarshes are limited to the Northern Hemisphere, in sites in the USA (e.g. Hill and Vargas, 2022; Kathilankal et al., 2008; Moffett et al., 2010; Nahrawi et al., 2020; Schäfer et al., 2019), France (Mayen et al., 2024), Japan (Otani and Endo, 2019) and China (Wei et al., 2020). The NEE values from these studies indicate that there is high inter-site (as well as interannual, Erickson et al., (2013)) variability in carbon dynamics of saltmarshes, with a link to species types, salinity, hydrology (Moffett et al., 2010; Nahrawi et al., 2020), site specific biochemical conditions (Seyfferth et al., 2020) and latitude (Feagin et al., 2020). While generally considered important carbon sinks (e.g. ranging between 130 to 775 g C m^{-2} yr^{-1} in the USA, according to Kathilankal et al. (2008) and Wang et al,(2016) respectively) and globally hypothesised to average 382 g C m^{-2} y^{-1} (Alongi, 2020), some EC

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

studies revealed saltmarshes to be net sources of CO_2 to the atmosphere (Vázquez-Lule and Vargas, 2021) especially in temperate saltmarshes that experience long dormant periods.

The aim of this study is to estimate CO_2 and water fluxes in a temperate saltmarsh in Victoria, southern Australia, to better characterise the effect of seasonality and environmental variables on the saltmarsh CO_2 budgets. This is the first study in an Australian coastal saltmarsh where CO_2 fluxes are estimated using the EC method.

2. Methods

2.1 Site Description

Ecosystem flux measurements were collected at the Tortoise Head Ramsar coastal wetland on French Island, Victoria (38.388°S, 145.278°E, Fig. 1) within the Western Port embayment. French Island is within the Cfb climate zone (temperate oceanic climate) and experiences distinct seasonal variations in temperature and precipitation. Long term (30 year) climate data averaged from the nearby Cerberus Station (Australian Bureau of Meteorology, site 86361) indicated that summers, spanning from December through February, are generally mild to warm, with maximum temperatures typically ranging from 17°C to 25°C although occasional heatwaves lead to temporary spikes in temperature that can exceed 30°C. Winters, from June to September, are cooler, with maximum temperatures ranging between 7°C and 14°C and a mean minimum temperature of 6°C. Frost is infrequent due to maritime influence, though crisp mornings below 0°C occur 10% of the time in winter. Rainfall, evenly distributed throughout the year, averages ca. 715 mm y^{-1}, although in 2020 the site experienced higher than average rainfall (860 mm y^{-1}). The island is exposed to weather patterns influenced by the Southern Ocean and Bass Strait, leading to occasional storm systems, particularly in winter, bringing gusty winds and increased precipitation. Western Port has semi-diurnal tides with a range of nearly 3 m, resulting in wide intertidal flats occupied by mangroves of the species *Avicennia marina* and saltmarshes.

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

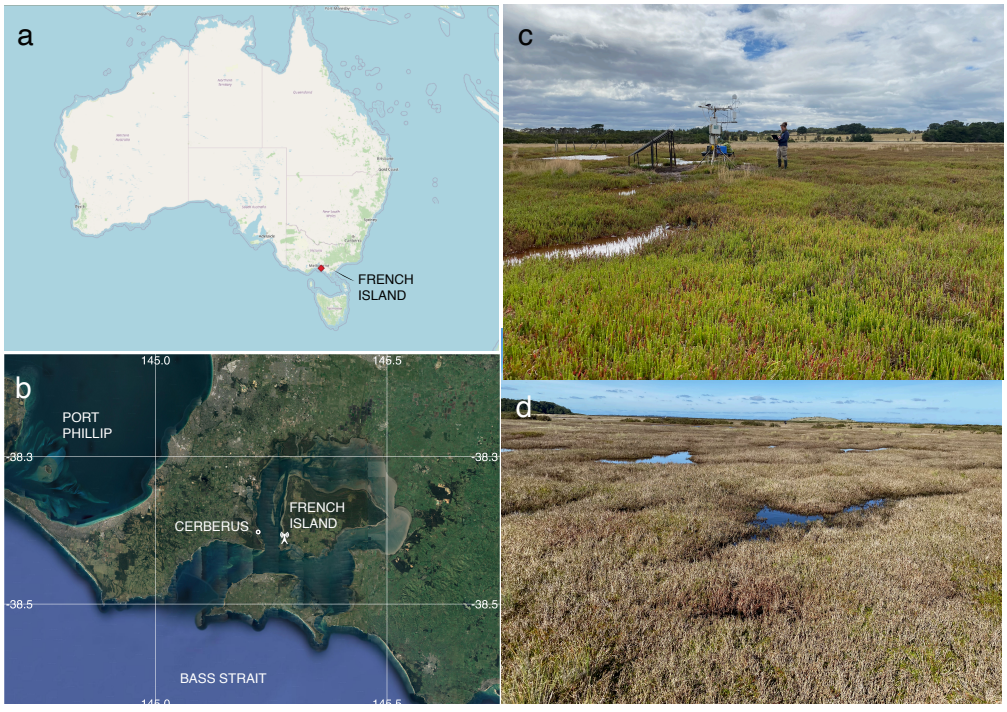

Figure 1: a) The location of French Island along the Bass Strait coast of Australia, and b) The location of the flux tower on French Island as well as the nearby Cerberus meteorological station (Bureau of Meteorology, Australia), © Google Earth. c) An image of the saltmarsh within the flux tower footprint during the growing season (with the tower and the author in the background), taken in February 2020 by Prudence Perry. d) an image of the saltmarsh during the dormant period, taken at the same location in September 2020 by Ruth Reef.

The site at French Island is dominated by an extensive temperate coastal saltmarsh community that is a particularly good natural representation of a broader biogeographic saltmarsh grouping which covers an area of ca. 7000 ha along Victoria's central coast embayments (Navarro et al., 2021). While the wetland at the site is a saltmarsh-mangrove-seagrass wetland system, the footprint of the flux tower was limited to the saltmarsh alone, which extends more than a kilometre from the shoreline in places. This geography provided the critical horizontally homogenous area with flat terrain required for ecosystem flux measurements. Floristically this saltmarsh is species poor, dominated by *Sarcocornia*

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

quinqeflora. Stands of *Tecticornia arbuscula* are common in this saltmarsh, while *Atriplex cinerea*, *Suaeda australia* and *Distichis distichophylla* can be prevalent depending on elevation and soil drainage conditions. *Sarcocornia quinqeflora* is a perennial succulent and at the temperate ranges of its distribution it has a distinct growing season from October to May (Fig. 1c) when the stems turn red, followed by a woody and fibrous dormant period during the colder months of June through September (Fig. 1d). The height of the dominant vegetation ranged between 0.3-0.6 m.

2.2 Data Collection and Analysis

Eddy covariance measurements were made between November 2019 and August 2021 capturing both the saltmarsh growing season (October-March) as well as a dormant period (April-September). An array of standard micro-meteorological instruments included a 3-dimensional sonic anemometer (CSAT3, Campbell Scientific, USA), an open-path infra-red carbon dioxide (CO_2) gas and water vapour (H_2O) analyser (Li-7500, Li-Cor, USA) and 2 data-loggers. The tower was powered by a solar array with two accompanying 12V DC storage batteries. The sonic anemometer was mounted 2.3 m above ground. The CO_2/H2O gas analyser was mounted 0.11 m longitudinally displaced from the anemometer. A CR3000 datalogger (Campbell Scientific, USA), recorded the Li-7500, anemometer, short- and long-wave radiation (CNR4, Klip & Zonen, the Netherlands), air temperature and humidity (083E, Met One, USA) readings at 10 Hz frequency. Due to the location of the site in the Bass Strait (a region that experiences regular winter storms, high wind speeds and higher than national average cloud cover) the tower sustained damage due to winter storms several times during the deployment, as well as suffered periods of poor power supply due to short day lengths and high cloud cover; this was exacerbated by poor accessibility to the remote location during COVID-19 travel restrictions. The analysis, thus focused on extended periods of continuous daily records and periods with large gaps in the dataset were removed.

Ecosystem fluxes were calculated for 30 min intervals using Eddy Pro software v.7 (LI-COR Inc., USA) Express Mode protocols. This processing step includes coordinate axis rotation correction, trend correction, data synchronisation, statistical tests for quality, density corrections and spectrum corrections. As part of this step, flux quality flags were assigned to

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

the calculated CO_2 fluxes using the 0–2 flag policy 'Mauder and Foken 2004', based on the steady state test and the developed turbulent conditions test. Only data that met the criteria of being in quality class 0 ('best quality fluxes') for CO_2 flux were chosen for further analysis. We further removed anomalous data points defined as values that exceed four standard deviations from the mean CO_2 flux; this resulted in the additional loss of ca. 1% of the dataset. Gap filling was not applied. Additional filtering was applied to night-time data due to known weak convection at night, thus CO_2 flux data during periods of atmospheric stability, i.e. when night friction wind velocities (u*) were below 0.2 m s^{-1}, were excluded. This resulted in a dataset of 674 day-time and 606 night-time flux measurements during the dormant period and 4124 day-time and 3020 night-time flux measurements for the growing period. The growing season dataset included 90 days with 85% or more flux data coverage, while the dormant season dataset included 18 days and these days were used for 24-hour flux integrations.

Half-hourly average CO_2 flux was measured in µmol m^{-2} s^{-1}, with positive fluxes indicating a flux direction from the Earth's surface to the atmosphere. Net ecosystem exchange (NEE) was defined as the net flux of CO_2 from the atmosphere to the marsh and was often negative during daytime, indicating that Gross Primary Productivity (GPP) was larger than ecosystem respiration (R_e). Evapotranspiration (ET) was calculated by Eddy Pro as the ratio between the latent heat flux (LE) and latent heat of vaporisation (λ). Ecosystem water use efficiency (WUEe) was then expressed as the ratio between daytime net ecosystem productivity in g CO_2 m^{-2} h^{-1} and evapotranspiration in mm h^{-1}.

A two-dimensional footprint estimation was provided according to the simple footprint parameterisation described in Kljun et al. (2015) calculating the ground position of the cumulative fraction of flux source contribution by distance for each 30-minute interval. We assessed the short-term effects of environmental factors on CO_2 fluxes at a half-hourly time scale (e.g. the effects of light, air temperature and vapour pressure deficit) using a series of non-linear or linear models. These analyses were limited to the growing season, when the plants were actively photosynthesising. The integrated CO_2 and H_2O fluxes over time (i.e., the daily sum of CO_2 or H_2O flux) were calculated for days with complete records (data

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

density>80%) as the area under the curve for each 24-hour period according to the trapezoid rule. All post-processing and statistical analyses were performed in R 4.3.2.

Because of the large data gaps, it was not possible to model the partition of the NEE in GEP and Re using common partitioning methods (Lasslop et al., 2010). For simplicity, it was assumed that NEE at night coincided with R_e. R_e was corrected for temperature effects on respiration using the linear slope of the relationship between night-time NEE and temperature. For the CO_2 budget, Net Ecosystem Production (NEP), defined as NEP=-NEE, and Gross Ecosystem Production (GEP), defined as GEP=-GPP, were used.

3. Results

The observations were divided into a growing season and a dormant season to reflect the seasonal phenology of the dominant vegetation type within the flux tower footprint, which has a relatively short growing season during the summer. During the growing season, mean temperature averaged 22.3°C. Several heatwaves occurred during this period, with temperatures exceeding 40°C on a few occasions in 2019. The dormant season was significantly colder and windier, with frequent southerly winds (Fig. 2a). Footprint models showed a slight variation in flux source between the two seasons, although in both cases the size of the footprint and the vegetation composition within the footprint was similar (Figs. 2b and 2c), but the shape was skewed to the north during winter due to the prevalent southerly winds in that season (Fig. 2a). 70% of the flux measurement source was from within 50 m of the tower, while the maximum length of the source location was 73 m.

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

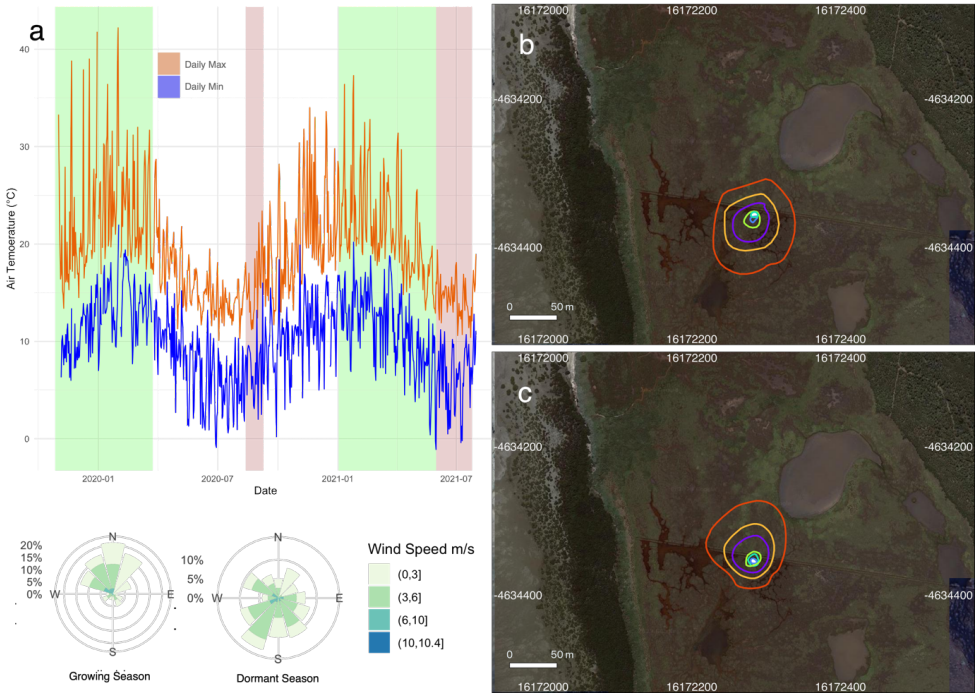

Figure 2: a) The minimum and maximum daily temperature recorded at the Cerberus meteorological station (Bureau of Meteorology, Fig. 1b) during 2019-2021. The marsh growing (Nov-Mar) and dormant (Aug-Sep) periods observed during this study are highlighted. A corresponding wind rose diagram summarises the wind speeds and directions measured at the tower site during the observation periods. The flux source footprint surrounding the tower during the dormant season (b) and the growing season (c) shows the cumulative flux source contribution to the flux measurements, with the outer red line representing the distance by which 90% of the calculated flux is sourced and the other isolines from the tower outwards correspond to 10%, 20%, 40%, 60% and 80% of the flux.

The growing season dataset included 90 days with 80% or more flux data coverage, while the dormant season dataset included 18 days. There was a strong temporal variability in net ecosystem exchange (NEE) across both short (daily) and long (seasonal) temporal scales (Fig. 3). Daytime fluxes were defined as flux points where the global radiation values in the flux averaging half-hour interval were >12 W m^{-2}. At the diurnal scale, saltmarsh NEE were

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

negative mostly during the day and positive mostly during the night and ranged between -19.1 and 10.86 µmol m^{-2} s^{-1} across the measurement periods.

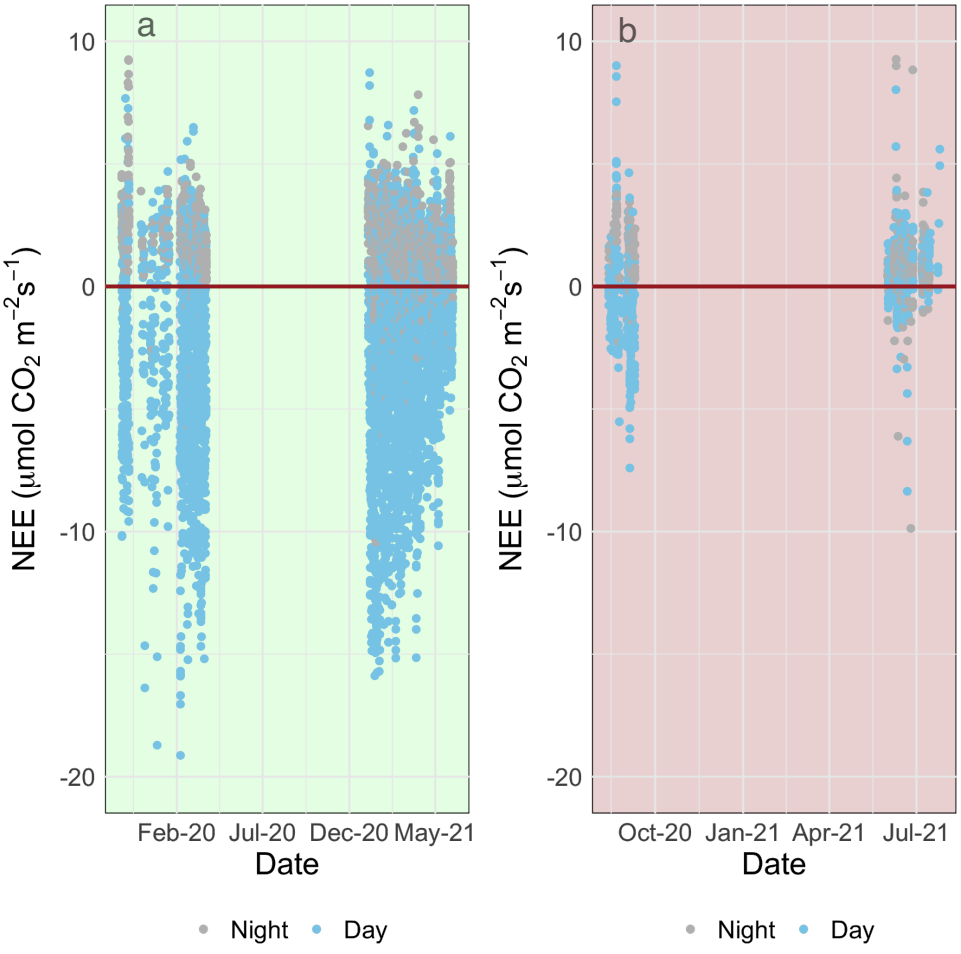

Figure 3: A time series of half-hourly measurements of CO_2 flux between a temperate saltmarsh and the atmosphere measured by eddy covariance during the marsh growing season (a) and the dormant season (b). Blue and grey points indicate measurements taken during day-time and night-time respectively. Positive fluxes indicate a direction of flux from the Earth surface to the atmosphere.

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

Flux rates varied across the day, with CO_2 uptake peaking at 11:00 during the growing season, and later in the day (14:00) during the dormant period (Fig. 4). Ecosystem respiration rates (R_e, defined as night-time CO_2 flux) were on average (±SD) 1.77 (±1.12) µmol m^{-2} s^{-1} during the growing season and 1.0 (± 0.93) µmol m^{-2} s^{-1} during the dormant period. The difference in ecosystem respiration between the growing and dormant seasons is highly significant (t-test, $p<0.01$). Daytime CO_2 flux was on average (±SD) -3.53 (± 4.15) µmol m^{-2} s^{-1} during the growing season and -0.25 (± 2.18) µmol m^{-2} s^{-1} during the dormant season. Thus, we derive that the maximum Gross Primary Productivity (GPP) of this ecosystem from NEE and temperature-corrected Re, measured during the growing season, is ca. -5.34 ± 4.3 µmol CO_2 m^{-2} s^{-1} (-5.53 ± 4.45 g C m^{-2} day^{-1}). Average R_e is thus estimated to comprise 33% of GPP.

Mean (±SD) daily evapotranspiration was 2.48 mm (±2.79 mm) during the growing season and 0.97 mm (±1.35 mm) during the dormant season (Fig. 4). Evapotranspiration peaked at noon AEST during the growing season (0.26 mm h^{-1}), and later in the day (14:00 AEST) during the dormant season (0.14 mm h^{-1}).

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

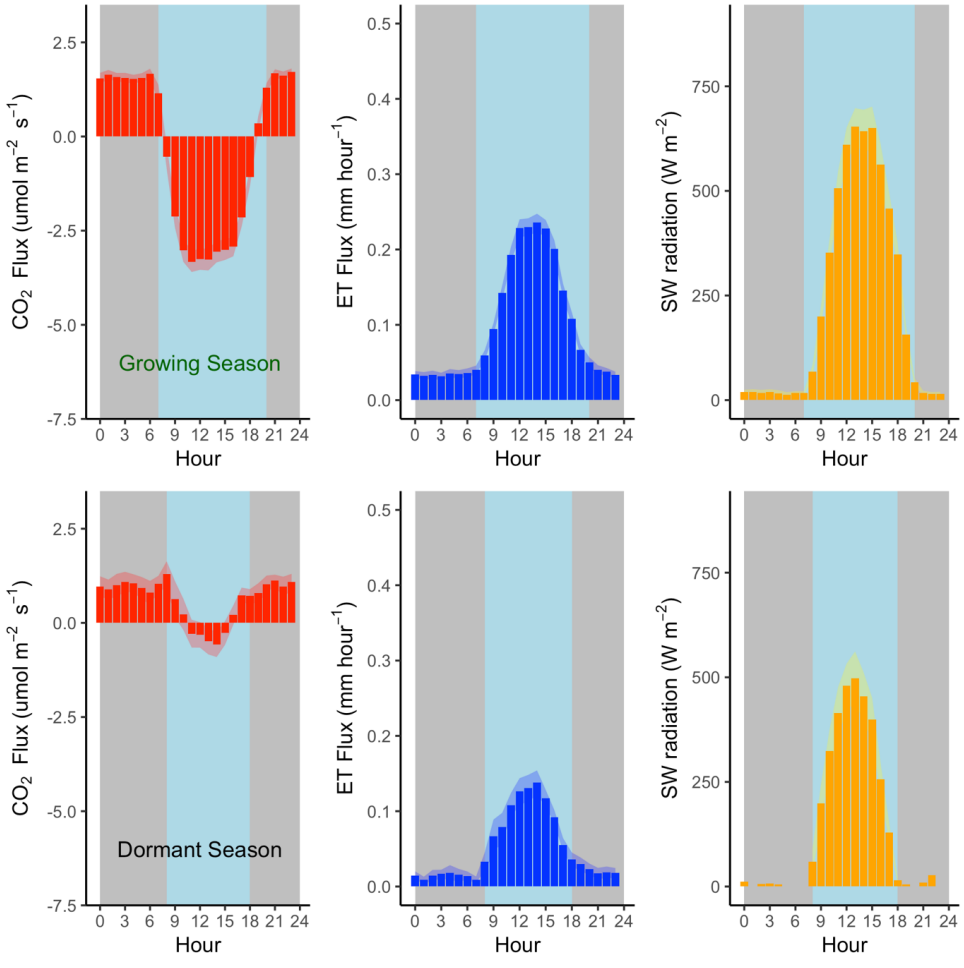

Figure 4: Mean hourly CO_2 and H_2O flux (evapotranspiration) rates during the growing season (top) and the dormant season (bottom) alongside mean short wave incoming radiation. Shading corresponds to 1 standard deviation around the mean. Grey plot background approximates night-time periods, while light blue approximates daytime (actual day length varies within each season).

The effect of some environmental forcings on daytime NEE during the saltmarsh growing season were explored (Fig. 5). To distinguish this daytime-only value from the 24-hour carbon balance integration, and to better highlight CO_2 uptake, NEP values are shown.

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

Short wave radiation (visible light) was a limiting factor to NEP below approximately 300 W m^{-2}, but radiation did not reach damaging levels that would lead to a drop in NEP throughout the measurement range, which reached a maximum level of ca. 800 W m^{-2}. Unlike light, the NEP-air temperature relationship followed a Gaussian response, with the highest NEP achieved at the optimal temperature of 25.3°C with a standard deviation of 3.8°C followed by a decline in CO_2 uptake by the marsh at higher temperatures. The minimum and maximum air temperatures for which modelled NEP nears zero (defined here as 3 standard deviations from the mean) are 13.9°C and 36.7°C respectively. Temperature also had a slight but significant positive linear relationship with ecosystem respiration (slope=0.07 µmol CO_2 m^{-2} s^{-1} $°C^{-1}$, $p<0.01$, data not shown).

NEP was positively correlated with evapotranspiration during the growing season (Pearson r = 0.59, Fig.5 C). The slope of the NEP/ET relationship was 20.0, indicating an ecosystem water use efficiency (WUE_e) of 0.86 g C kg^{-1} H_2O ($R^2 = 0.34$, $p<0.001$). The response of NEP to atmospheric vapour pressure deficit (VPD) fit a Gaussian relationship (the commonly observed inverse U-shaped curve relationship in response to VPD in plants), with NEP declining rapidly when VPD exceeded 2.39 kPa. The optimal range of VPD within which NEP was maximised in this ecosystem was 1.92 kPa (±0.73 kPa).

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

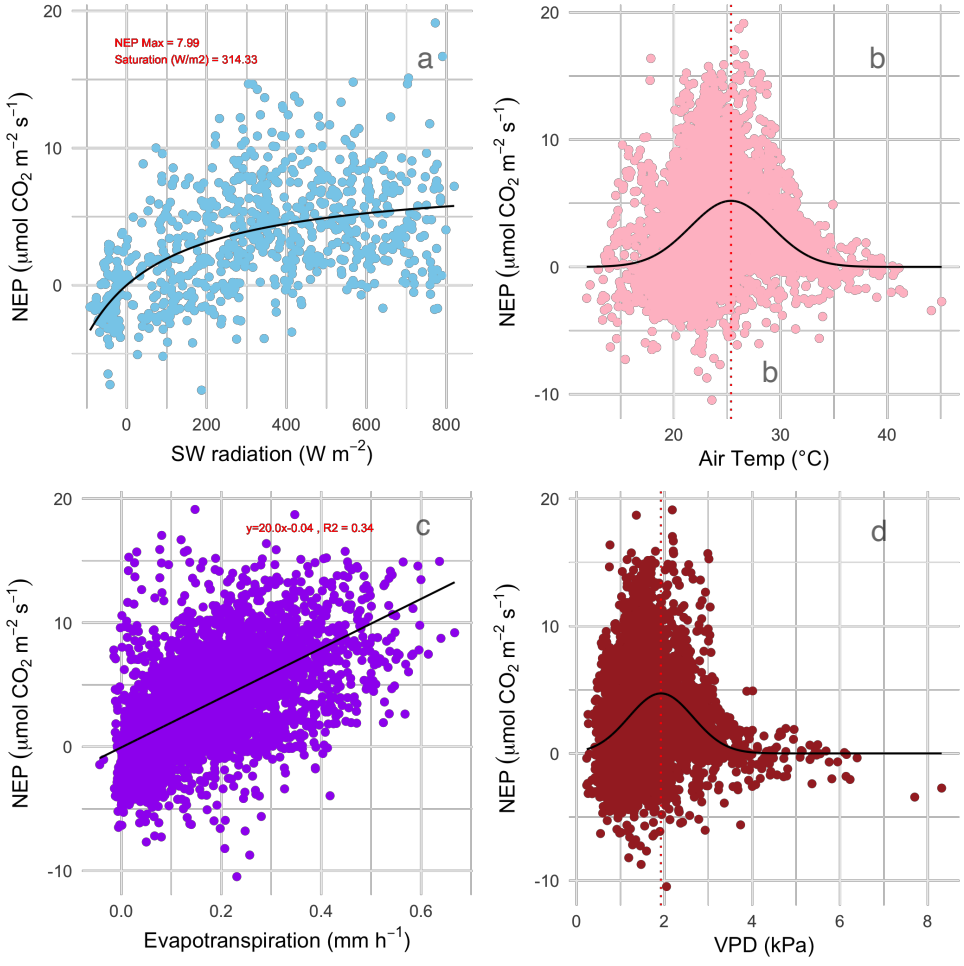

Figure 5: The relationship between growing season net ecosystem CO_2 uptake (NEP, µmol CO_2 m^{-2} s^{-1}) and corresponding environmental variables. a) Shortwave radiation (visible light); black line is the Michaelis-Menten model of best fit. The coefficient of saturation is at 314 W m^{-2} and maximum net productivity is 8.0 µmol CO_2 m^{-2} s^{-1}. b) Air temperature; black line is a Gaussian model of best fit with a temperature optimum at 25.3°C. c) Evapotranspiration; linear model (R^2 = 0.34) has a slope of 20.0. d) Vapour Pressure Deficit; black line is a Gaussian model of best fit with a VPD optimum at 1.92 kPa.

When integrated over a 24-hour period, the saltmarsh is on average a CO_2 sink during all canopy phenological phases (Fig. 6), although during the dormant season the sink is weaker, with an average uptake of -2.42 g CO_2 m^{-2} day^{-1} (±2.54). During the growing season (defined

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

as the non-dormant period and thus reflecting several phenological stages), the marsh is a substantial sink with a mean (±SD) daily NEP of 10.95 g CO_2 m^{-2} day^{-1} (±4.98) over a 24-hour period (ranging between -22.8 and 4.3 g of CO_2 emission to the atmosphere m^{-2} day^{-1}) . The daily CO_2 budget during the growing season showed some variability among days (CV=0.46, Fig. 6) and days with lower average light levels (i.e. cloudy days) had a significant negative impact on the CO_2 budget (multiple linear regression, $p < 0.02$, $R^2 = 0.27$). Daily maximum air temperatures did not have a significant impact on the daily CO_2 budget ($p = 0.77$) at this location, although NEE was significantly affected by temperature at finer temporal scales (Figure 5). Assuming the dormant period spans a third of the year, we cautiously estimate an annual NEP value of 753 (±112.7) g C m^{-2} yr^{-1} .

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

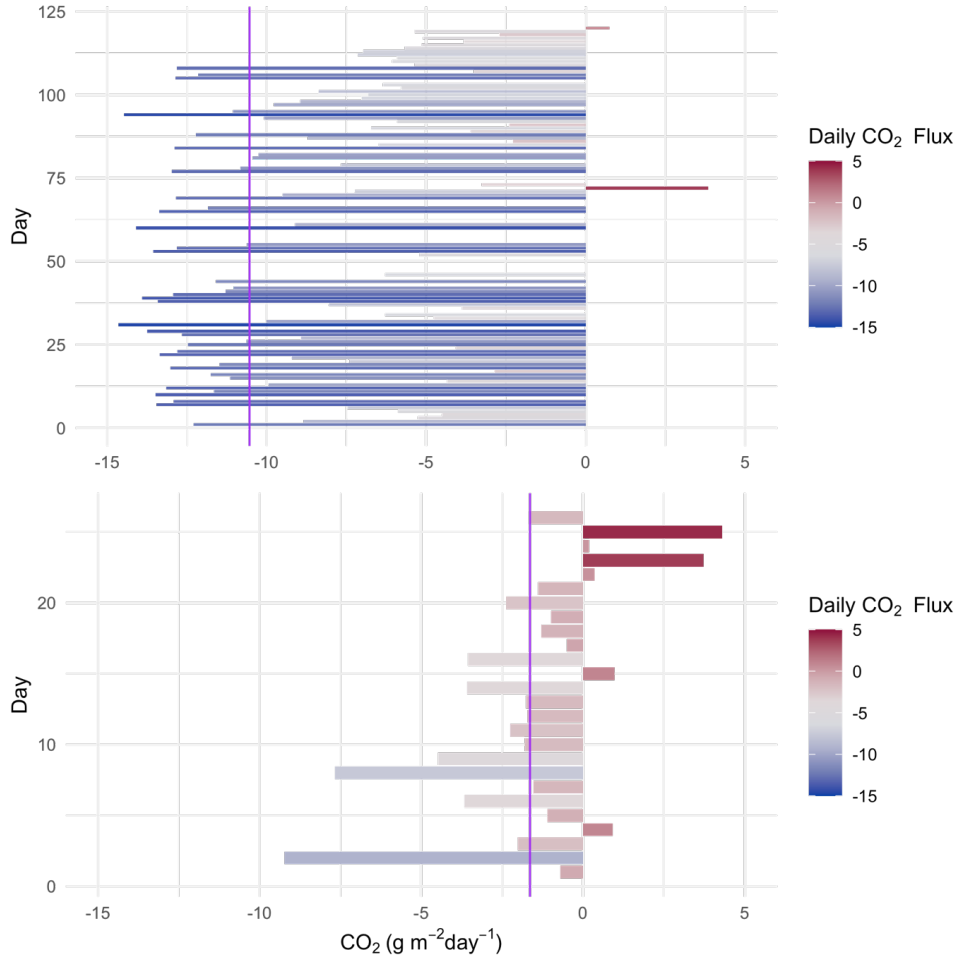

Figure 6: Daily (24 h) integrated NEE in g CO_2 m^{-2} day^{-1} during the saltmarsh growing season (top) and the dormant season (bottom) for days with data density > 85%. Purple lines indicate the mean daily integrated flux for each season (-10.54 and -1.64 g CO_2 m^{-2} day^{-1} with an SD of 4.98 and 2.54 for growing and dormant respectively). A positive balance indicates an integrated net flux of CO_2 from the Earth's surface to the atmosphere over the 24-hour period. Assuming the dormant season period spans one third of the year, we cautiously estimate an annual NEP value of 753 g C m^{-2} yr^{-1} (±weighted sum of SD of 5.9).

4. Discussion

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

At this temperate saltmarsh, seasonality had a significant effect on carbon and water flux. Growing season net ecosystem productivity was five times greater than during the dormant period. Seasonality in Australian marshes has not been previously reported in the scientific literature, and assumptions were made that Australian saltmarshes do not exhibit the growing and dormant phenology observed on other continents (Clarke and Jacoby, 1994). Seasonality might be an overlooked important characteristic of this habitat and in addition to affecting flux estimations, can have broader implications. For example, in the USA, the saltmarsh greening up period was shown to be an important range-wide timing event for migratory birds (Smith et al., 2020) with plant-growth metrics predicting the timing of nest initiation for shorebirds. Saltmarshes in Australia are important roosting and feeding sites along the East Asian Australasian Flyway, particularly waders, thus potentially a similar relationship between migration timing and saltmarsh phenology could be occurring. Seasonality also affects other significant ecosystem functions such as the bio-geomorphological feedback between saltmarshes, coastal hydrodynamics and landscape evolution (Reents et al., 2022).

We derived the light-response and associated coefficients of light regulation of saltmarsh NEE using the Michaelis Menten model (Chen et al., 2002). Quantum (or production) efficiency is the predominant input in remote sensing techniques to model productivity, and is specific to the biome (Hilker et al., 2010). While not directly comparable to leaf level quantum efficiency measurements, the quantum efficiency (α) of the NEP light response curve was estimated from the slope of the Michaelis-Menten model to be 0.025 μmol CO_2 J^{-1}. The ecosystem reached light saturation at an insolation of 314 W m^{-2}, but daytime insolation was below this value more than 50% of the time suggesting that light might be a significant limiting factor to NEP at this marsh, especially during winter. The level of light limitation we observed is an underestimation, due to the loss of high-quality EC data during periods of rain. The solar geometry at this latitude and the length of day result in an annual average top of atmosphere SW radiation of 250 W m^{-2}, but clouds can strongly modulate the SW radiation balance (SWCRE), and apart from the months of January and February when cloudy days are less frequent (10-12 days per month), cloudy days are frequent at this

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

site, averaging 15-17 days per month (Bureau of Meteorology) and could significantly impact on NEP.

Temperature is another forcing that significantly impacts NEE at this marsh, with an optimal range for maximum NEP at 25.3°C (21.5°C-29.1°C). Data for Australian saltmarshes is not available, but this optimal temperature response range is similar to that measured experimentally in a saltmarsh species in an equivalent climate zone (e.g. Georgia, (Giurgevich and Dunn, 1981)) and to the values hypothesised for the habitat from data collected along the US Atlantic Coast, (Feher et al., 2017). The long-term average maximum daytime temperature at this site is 19.2°C, which is cooler than the optimal range for NEE suggesting temperature can be a significant limiting factor to productivity, especially during the dormancy period where average monthly maximum temperatures are only 13.7°C to 16.6°C (Bureau of Meteorology). During the growing season the average maximum temperatures are within the range of optimal NEE (20.6°C to 23.1°C), although hot days (>30°C) significantly depress NEE and depending on the year, can be common during summer months (averaging 2-6 days per month).

In saltmarshes, evapotranspiration occurs from plant mediated transpiration but also from soil pores (which tend to be saturated), wetted leaves and open water. We observed average evaporation rates of 2.48 mm day^{-1} during the growing season and 0.97 mm day^{-1} during the dormant season. Actual evapotranspiration in this region modelled using the CMRSET algorithm is estimated to range between 0.6 and 3.2 mm day^{-1} during winter and summer respectively (McVicar et al., 2022); these values are consistent with our field measurements. Overall, rainfall is in excess of the requirements for maintaining ET at this site, although deficits can develop for short periods during the growing season.
Long term rainfall excess could be contributing to the complicated hydrology at this location, where inundation is not strictly associated with tidal stage (data not shown). Growing season ET rates are significantly higher than those of the dormant season, partly due to the solar configuration in winter as opposed to summer, but also due to phenological changes. A big leaf model estimation of evapotranspiration from saltmarshes in New South Wales estimates ET to be highly sensitive to vegetation height, increasing by more than 1 mm day^{-1} as vegetation height increases from 0.1 to 0.4 m (Hughes et al., 2001) and

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

transpiration in saltmarsh plants in the cold season has been shown to account for only 20% of the annual transpiration budget (Giurgevich and Dunn, 1981) following the same pattern as the seasonal distribution of productivity.

The rate of carbon uptake per unit of water loss (WUE) is a key ecosystem characteristic, which is a result of a suite of physical and canopy physiological forcings, and has direct implications for ecosystem function and global water and carbon cycling. Mean water use efficiency (WUEe) of this saltmarsh was estimated at 0.86 g C kg^{-1} H_2O, which is markedly lower than for grass dominated saltmarshes in China (2.9 g C kg^{-1} H_2O, Xiao et al. (2013)) but similar to the value for WUEe based on NEP and ET in mangroves (0.77 g C kg^{-1} H_2O, Krauss et al. (2022)). The chenopod *Sarcocornia quinqueflora* has been suspected to have higher evapotranspiration rates than saltmarsh grasses by approx. 15% (Hughes et al., 2001), but while *Sarcocornia quinqueflora* dominates at this site, the footprint is a mix of species and the lower WUEe cannot be directly linked to the presence of *Sarcocornia quinqueflora*. Furthermore, like most wetlands, the wetland surface is a mixed composition of emergent vegetation, unsaturated soil and water bodies thus the spatial scale at which WUEe is determined encompasses both the canopy (Ec) as well as any open water present in the footprint. Transpiration is predicted to account for only 55% of ET in these systems (Hughes et al., 2001), which is an Ec to ET ratio similar to that of mangroves (Krauss et al., 2022) but significantly lower than terrestrial forests where more than 90% of ET can be attributed to transpiration. Thus, regional variations in WUEe can be attributed to multiple forcings that form complex spatiotemporal patterns.

Saltmarshes are considered among the most productive ecosystems on Earth with an estimated global NEP of 634 Tg C y^{-1} (Fagherazzi et al., 2013). Productivity of southern Australian marshes was previously estimated at 0.8 kg m^{-2} y^{-1} by repeated measurements of above ground standing crops (Clarke and Jacoby, 1994), which is remarkably similar to the values reported here, where we extrapolate an approximate annual mean of 0.75 kg C m^{-2} y^{-1}. Similar studies on saltmarshes in France report lower productivity than the marshes at French Island (-483 g C m^{-2} y^{-1}, (Mayen et al., 2024)) but our values are within the range reported for mid-latitude saltmarsh sites in the USA (-775 g C m^{-2} y^{-1}, (Wang et al., 2016)) and China (-668 g C m^{-2} y^{-1}, (Xiao et al., 2013)). It is clear that productivity across climate

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

zones and biogeographic regions varies widely with some studies even reporting net emissions over an annual period from some marshes and a global average estimated between -382 (Alongi, 2020) and -1,585 g C m^{-2} y^{-1} (Chmura et al., 2003), albeit based on a small subset of studies. An analysis of GPP across latitudes in the USA show that warmer sites (including mangrove wetlands in southern USA) had significantly higher GPP than mid-latitude saltmarshes such as the one on French Island (Feagin et al., 2020). Mangroves have higher NEE than saltmarshes, estimated by (Krauss et al., 2022) to average 1200 g C m^{-2} y^{-1}. The data presented here is the exchange of carbon between the land surface and the atmosphere, but saltmarshes, like other marine connected communities, exchange carbon also through dissolved carbon pathways, which can be significant (Cai, 2011). Thus, the fluxes presented here do not constitute the entire carbon budget of this ecosystem.

5. Conclusions

The response of the French Island saltmarsh to environmental drivers is indicative of the complex interactions determining saltmarsh productivity. While the overall carbon sequestration rate we measured was in the range of other temperate saltmarsh estimates (ca. 750 g C m^{-2} y^{-1}), the unique long-term, high-resolution record enabled us to derive temperature, VPD and light response functions, thus formulating equations that describe how climate-change sensitive parameters such as temperature, relative humidity, and cloud cover, affect CO_2 uptake, respiration and evapotranspiration. The marsh operated as a CO_2 sink throughout the various canopy phenological phases, but during the dormant period, CO_2 uptake was less than 25% that of the growing season. Seasonality has not been previously considered in Australian saltmarshes and it should not be overlooked when estimating saltmarsh carbon budgets.

Competing interests

The contact author has declared that none of the authors has any competing interests.

Acknowledgments

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

The work was carried out with the permission of Parks Victoria (Permit 10008684). We thank Phil and Yuko Bock for logistic support and accommodation on French Island. We thank Leigh Burgess, Kiri Mason and Ian McHugh for technical support and the Australian OzFlux community for ongoing collaboration. This work was funded by an Australian Research Council Discovery Award to RR and ED (DP220102873) as well as a Monash University Networks of Excellence award to RR.

Data Availability

Data used for this analysis is available at https://figshare.com/s/ba62aafd1a4049248a08 (note that this is a temporary private link to an embargoed dataset which will be replaced with a publicly available DOI upon publication).

Author contribution

RR conceptualised the study, acquired funding, prepared the manuscript, designed and carried out the field campaign, and performed the analysis. ED acquired funding, developed methodology and prepared the manuscript. AG developed methodology and prepared the manuscript. TA, EJVH, HR and MP were involved in the field investigation and administration of the project and provided edits on the manuscript.

References

Adam, P.: Saltmarsh Ecology, Cambridge University Press, 1990.

Adam, P.: Morecambe Bay saltmarshes: 25 years of change, in: British Saltmarshes, Forrest Text, Cardigan, UK, 81–107, 2000.

Adam, P.: Saltmarshes in a time of change, Environ. Conserv., 29, 39–61, https://doi.org/10.1017/S0376892902000048, 2002.

Alongi, D. M.: Carbon balance in salt marsh and mangrove ecosystems: A global synthesis, J. Mar. Sci. Eng., 8, 767, 2020.

Artigas, F., Shin, J. Y., Hobble, C., Marti-Donati, A., Schäfer, K. V. R., and Pechmann, I.: Long term carbon storage potential and CO_2 sink strength of a restored salt marsh in New Jersey, Agric. For. Meteorol., 200, 313–321, https://doi.org/10.1016/j.agrformet.2014.09.012, 2015.

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

555 Baldocchi, D. D.: Assessing the eddy covariance technique for evaluating carbon dioxide
556 exchange rates of ecosystems: past, present and future, Glob. Change Biol., 9, 479–492,
557 https://doi.org/10.1046/j.1365-2486.2003.00629.x, 2003.

558 Borges, A. V., Schiettecatte, L.-S., Abril, G., Delille, B., and Gazeau, F.: Carbon dioxide in
559 European coastal waters, Trace Gases Eur. Coast. Zone, 70, 375–387,
560 https://doi.org/10.1016/j.ecss.2006.05.046, 2006.

561 Cai, W.-J.: Estuarine and coastal ocean carbon paradox: CO_2 sinks or sites of terrestrial
562 carbon incineration?, Annu. Rev. Mar. Sci., 3, 123–145, https://doi.org/10.1146/annurev-
563 marine-120709-142723, 2011.

564 Chen, J., Falk, M., Euskirchen, E., Paw U, K. T., Suchanek, T. H., Ustin, S. L., Bond, B. J.,
565 Brosofske, K. D., Phillips, N., and Bi, R.: Biophysical controls of carbon flows in three
566 successional Douglas-fir stands based on eddy-covariance measurements, Tree Physiol., 22,
567 169–177, https://doi.org/10.1093/treephys/22.2-3.169, 2002.

568 Chmura, G. L., Anisfeld, S. C., Cahoon, D. R., and Lynch, J. C.: Global carbon sequestration
569 in tidal, saline wetland soils, Glob. Biogeochem. Cycles, 17,
570 https://doi.org/10.1029/2002GB001917, 2003.

571 Clarke, P., J. and Jacoby, C. A.: Biomass and above-ground productivity of salt-marsh plants
572 in South-eastern Australia, Aust. J. Mar. Freshw. Res., 45, 1521–1528, 1994.

573 Duarte, C. M.: Reviews and syntheses: Hidden forests, the role of vegetated coastal habitats
574 in the ocean carbon budget, Biogeosciences, 14, 301–310, https://doi.org/10.5194/bg-14-301-
575 2017, 2017.

576 Erickson, J. E., Peresta, G., Montovan, K. J., and Drake, B. G.: Direct and indirect effects of
577 elevated atmospheric CO_2 on net ecosystem production in a Chesapeake Bay tidal wetland,
578 Glob. Change Biol., 19, 3368–3378, 2013.

579 Fagherazzi, S., Wiberg, P. L., Temmerman, S., Struyf, E., Zhao, Y., and Raymond, P. A.:
580 Fluxes of water, sediments, and biogeochemical compounds in salt marshes, Ecol. Process.,
581 2, 3, https://doi.org/10.1186/2192-1709-2-3, 2013.

582 Feagin, R. A., Forbrich, I., Huff, T. P., Barr, J. G., Ruiz-Plancarte, J., Fuentes, J. D., Najjar,
583 R. G., Vargas, R., Vázquez-Lule, A., Windham-Myers, L., Kroeger, K. D., Ward, E. J.,
584 Moore, G. W., Leclerc, M., Krauss, K. W., Stagg, C. L., Alber, M., Knox, S. H., Schäfer, K.
585 V. R., Bianchi, T. S., Hutchings, J. A., Nahrawi, H., Noormets, A., Mitra, B., Jaimes, A.,
586 Hinson, A. L., Bergamaschi, B., King, J. S., and Miao, G.: Tidal wetland gross primary
587 production across the continental United States, 2000–2019, Glob. Biogeochem. Cycles, 34,
588 e2019GB006349, https://doi.org/10.1029/2019GB006349, 2020.

589 Feher, L. C., Osland, M. J., Griffith, K. T., Grace, J. B., Howard, R. J., Stagg, C. L.,
590 Enwright, N. M., Krauss, K. W., Gabler, C. A., Day, R. H., and Rogers, K.: Linear and
591 nonlinear effects of temperature and precipitation on ecosystem properties in tidal saline
592 wetlands, Ecosphere, 8, e01956, https://doi.org/10.1002/ecs2.1956, 2017.

593 Gedan, K. B., Silliman, B. R., and Bertness, M. D.: Centuries of human-driven change in salt
594 marsh ecosystems, Annu. Rev. Mar. Sci., 1, 117–141,
595 https://doi.org/10.1146/annurev.marine.010908.163930, 2009.

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

Ghosh, S. and Mishra, D. R.: Analyzing the long-term phenological trends of salt marsh ecosystem across coastal Louisiana, Remote Sens., 9, https://doi.org/10.3390/rs9121340, 2017.

Giurgevich, J. R. and Dunn, E. L.: A comparative analysis of the CO_2 and water vapor responses of two Spartina species from Georgia coastal marshes, Estuar. Coast. Shelf Sci., 12, 561–568, https://doi.org/10.1016/S0302-3524(81)80082-5, 1981.

Hilker, T., Hall, F. G., Coops, N. C., Lyapustin, A., Wang, Y., Nesic, Z., Grant, N., Black, T. A., Wulder, M. A., Kljun, N., Hopkinson, C., and Chasmer, L.: Remote sensing of photosynthetic light-use efficiency across two forested biomes: Spatial scaling, Remote Sens. Environ., 114, 2863–2874, https://doi.org/10.1016/j.rse.2010.07.004, 2010.

Hill, A. C. and Vargas, R.: Methane and carbon dioxide fluxes in a temperate tidal salt marsh: comparisons between plot and ecosystem measurements, J. Geophys. Res. Biogeosciences, 127, e2022JG006943, https://doi.org/10.1029/2022JG006943, 2022.

Howe, A. J., Rodríguez, J. F., Spencer, J., MacFarlane, G. R., and Saintilan, N.: Response of estuarine wetlands to reinstatement of tidal flows, Mar. Freshw. Res., 61, 702–713, 2010.

Hughes, C. E., Kalma, J. D., Binning, P., Willgoose, G. R., and Vertzonis, M.: Estimating evapotranspiration for a temperate salt marsh, Newcastle, Australia, Hydrol. Process., 15, 957–975, https://doi.org/10.1002/hyp.189, 2001.

Huxham, M., Whitlock, D., Githaiga, M., and Dencer-Brown, A.: Carbon in the coastal seascape: how interactions between mangrove forests, seagrass meadows and tidal marshes influence carbon storage, Curr. For. Rep., 4, 101–110, https://doi.org/10.1007/s40725-018-0077-4, 2018.

Kathilankal, J. C., Mozdzer, T. J., Fuentes, J. D., D'Odorico, P., McGlathery, K. J., and Zieman, J. C.: Tidal influences on carbon assimilation by a salt marsh, Environ. Res. Lett., 3, 044010, https://doi.org/10.1088/1748-9326/3/4/044010, 2008.

Kljun, N., Calanca, P., Rotach, M. W., and Schmid, H. P.: A simple two-dimensional parameterisation for Flux Footprint Prediction (FFP), Geosci Model Dev, 8, 3695–3713, https://doi.org/10.5194/gmd-8-3695-2015, 2015.

Krauss, K. W., Lovelock, C. E., Chen, L., Berger, U., Ball, M. C., Reef, R., Peters, R., Bowen, H., Vovides, A. G., Ward, E. J., and others: Mangroves provide blue carbon ecological value at a low freshwater cost, Sci. Rep., 12, https-doi, 2022.

Lasslop, G., Reichstein, M., Papale, D., Richardson, A. D., Arneth, A., BARR, A., STOY, P., and WOHLFAHRT, G.: Separation of net ecosystem exchange into assimilation and respiration using a light response curve approach: critical issues and global evaluation, Glob. Change Biol., 16, 187–208, https://doi.org/10.1111/j.1365-2486.2009.02041.x, 2010.

Lu, W., Xiao, J., Liu, F., Zhang, Y., Liu, C., and Lin, G.: Contrasting ecosystem CO_2 fluxes of inland and coastal wetlands: a meta-analysis of eddy covariance data, Glob. Change Biol., 23, 1180–1198, https://doi.org/10.1111/gcb.13424, 2017.

Mayen, J., Polsenaere, P., Lamaud, É., Arnaud, M., Kostyrka, P., Bonnefond, J.-M., Geairon, P., Gernigon, J., Chassagne, R., and Lacoue-Labarthe, T.: Atmospheric CO_2 exchanges

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

measured by eddy covariance over a temperate salt marsh and influence of environmental controlling factors, Biogeosciences, 21, 993–1016, 2024.

McLeod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarte, C. M., Lovelock, C. E., Schlesinger, W. H., and Silliman, B. R.: A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2, Front. Ecol. Environ., 9, 552–560, https://doi.org/10.1890/110004, 2011.

Mcowen, C. J., Weatherdon, L. V., Bochove, J.-W. V., Sullivan, E., Blyth, S., Zockler, C., Stanwell-Smith, D., Kingston, N., Martin, C. S., Spalding, M., and Fletcher, S.: A global map of saltmarshes, Biodivers. Data J., 5, e11764, https://doi.org/10.3897/BDJ.5.e11764, 2017.

McVicar, T., Vleeshouwer, J., Van Niel, T., Guerschman, J., and Peña-Arancibia, J. L.: Actual Evapotranspiration for Australia using CMRSET algorithm. Version 1.0, 2022.

Mitsch, W. J. and Gosselink, J. G.: The value of wetlands: importance of scale and landscape setting, Ecol. Econ., 35, 25–33, https://doi.org/10.1016/S0921-8009(00)00165-8, 2000.

Moffett, K. B., Wolf, A., Berry, J. A., and Gorelick, S. M.: Salt marsh–atmosphere exchange of energy, water vapor, and carbon dioxide: Effects of tidal flooding and biophysical controls, Water Resour. Res., 46, 2010.

Nahrawi, H., Leclerc, M. Y., Pennings, S., Zhang, G., Singh, N., and Pahari, R.: Impact of tidal inundation on the net ecosystem exchange in daytime conditions in a salt marsh, Agric. For. Meteorol., 294, 108133, https://doi.org/10.1016/j.agrformet.2020.108133, 2020.

Navarro, A., Young, M., Macreadie, P. I., Nicholson, E., and Ierodiaconou, D.: Mangrove and saltmarsh distribution mapping and land cover change assessment for south-eastern Australia from 1991 to 2015, Remote Sens., 13, https://doi.org/10.3390/rs13081450, 2021.

Otani, S. and Endo, T.: CO_2 flux in tidal flats and salt marshes, Blue Carbon Shallow Coast. Ecosyst. Carbon Dyn. Policy Implement., 223–250, 2019.

Reents, S., Möller, I., Evans, B. R., Schoutens, K., Jensen, K., Paul, M., Bouma, T. J., Temmerman, S., Lustig, J., Kudella, M., and Nolte, S.: Species-specific and seasonal differences in the resistance of salt-marsh vegetation to wave impact, Front. Mar. Sci., 9, 2022.

Schäfer, K. V. R., Duman, T., Tomasicchio, K., Tripathee, R., and Sturtevant, C.: Carbon dioxide fluxes of temperate urban wetlands with different restoration history, Agric. For. Meteorol., 275, 223–232, https://doi.org/10.1016/j.agrformet.2019.05.026, 2019.

Seyfferth, A. L., Bothfeld, F., Vargas, R., Stuckey, J. W., Wang, J., Kearns, K., Michael, H. A., Guimond, J., Yu, X., and Sparks, D. L.: Spatial and temporal heterogeneity of geochemical controls on carbon cycling in a tidal salt marsh, Geochim. Cosmochim. Acta, 282, 1–18, 2020.

Shepard, C. C., Crain, C. M., and Beck, M. W.: The protective role of coastal marshes: a systematic review and meta-analysis, PLoS ONE, 6, e27374, https://doi.org/10.1371/journal.pone.0027374, 2011.

https://doi.org/10.5194/egusphere-2024-2182
Preprint. Discussion started: 14 August 2024

Smith, J. A. M., Regan, K., Cooper, N. W., Johnson, L., Olson, E., Green, A., Tash, J., Evers, D. C., and Marra, P. P.: A green wave of saltmarsh productivity predicts the timing of the annual cycle in a long-distance migratory shorebird, Sci. Rep., 10, 20658, https://doi.org/10.1038/s41598-020-77784-7, 2020.

Vázquez-Lule, A. and Vargas, R.: Biophysical drivers of net ecosystem and methane exchange across phenological phases in a tidal salt marsh, Agric. For. Meteorol., 300, 108309, https://doi.org/10.1016/j.agrformet.2020.108309, 2021.

Wang, Z. A., Kroeger, K. D., Ganju, N. K., Gonneea, M. E., and Chu, S. N.: Intertidal salt marshes as an important source of inorganic carbon to the coastal ocean, Limnol. Oceanogr., 61, 1916–1931, https://doi.org/10.1002/lno.10347, 2016.

Ward, N. D., Megonigal, J. P., Bond-Lamberty, B., Bailey, V. L., Butman, D., Canuel, E. A., Diefenderfer, H., Ganju, N. K., Goñi, M. A., and Graham, E. B.: Representing the function and sensitivity of coastal interfaces in Earth system models, Nat. Commun., 11, 2458, 2020.

Wei, S., Han, G., Jia, X., Song, W., Chu, X., He, W., Xia, J., and Wu, H.: Tidal effects on ecosystem CO2 exchange at multiple timescales in a salt marsh in the Yellow River Delta, Estuar. Coast. Shelf Sci., 238, 106727, 2020.

Whitfield, A. K.: The role of seagrass meadows, mangrove forests, salt marshes and reed beds as nursery areas and food sources for fishes in estuaries, Rev. Fish Biol. Fish., 27, 75–110, https://doi.org/10.1007/s11160-016-9454-x, 2017.

Xiao, J., Sun, G., Chen, J., Chen, H., Chen, S., Dong, G., Gao, S., Guo, H., Guo, J., Han, S., Kato, T., Li, Y., Lin, G., Lu, W., Ma, M., McNulty, S., Shao, C., Wang, X., Xie, X., Zhang, X., Zhang, Z., Zhao, B., Zhou, G., and Zhou, J.: Carbon fluxes, evapotranspiration, and water use efficiency of terrestrial ecosystems in China, Agric. For. Meteorol., 182–183, 76–90, https://doi.org/10.1016/j.agrformet.2013.08.007, 2013.