Carbon Flux in a Semi-Arid Mangrove Ecosystem in Magdalena Bay, B.C.S Mexico

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Abstract

Mangrove forests are among the most productive ecosystems in the world. These tropical and subtropical coastal forests provide a wide array of ecosystem services, including the ability to sequester and store large amounts of 'blue carbon'. Given rising concerns over anthropogenic carbon dioxide (CO2) emissions, mangrove forests have been increasingly recognized for their potential in climate change mitigation programs. However, their productivity differs considerably across environments, making it difficult to estimate carbon sequestration potentials at regional scales. Additionally, most research has focused in humid and tropical latitudes, with limited studies in arid and semi-arid regions. A semi-arid mangrove forest in Magdalena Bay, Baja California Sur, Mexico was studied to quantify the average net ecosystem exchange (NEE), determine the annual carbon (C) budget and the environmental controls driving those fluxes. Measurements were taken during 2012-2013 using the eddy covariance technique, with a daily mean NEE of -2.25 ±0.4 g C m-2 d-1 and annual carbon uptake of 894 g C m-2 y-1. Daily variations in NEE were primarily regulated by light, but air temperature and vapor pressure deficit were strong seasonal drivers. Our research demonstrates that despite the harsh and arid climate, the mangroves of Magdalena Bay were nearly as productive as mangroves found in tropical and subtropical climates. These results broaden understanding of the ecosystem services of one of the largest mangrove ecosystems in the Baja California peninsula, and highlight the potential role of arid mangrove ecosystems for C accounting, management and mitigation plans for the region.

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Supporting Information for

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Introduction

This supporting information section provides additional information on our data set validation and statistical results. The first figure details information regarding the energy balance closure (H+LE vs Rn-G) within the area of eddy-covariance tower footprint. The following two figures provide insight into the creation of our neural network model, where we compare the data collected at our site with those provided by CONAGUA to input into our model, and consequently the full of our neural network model and validations. Furthermore, this section provides our statistical analysis on our half hourly data and the residual analysis performed on our daily averaged dataset. Lastly, we include a table with a summary description of other mangrove research studies and their yearly NEE productivity in comparison with our study.

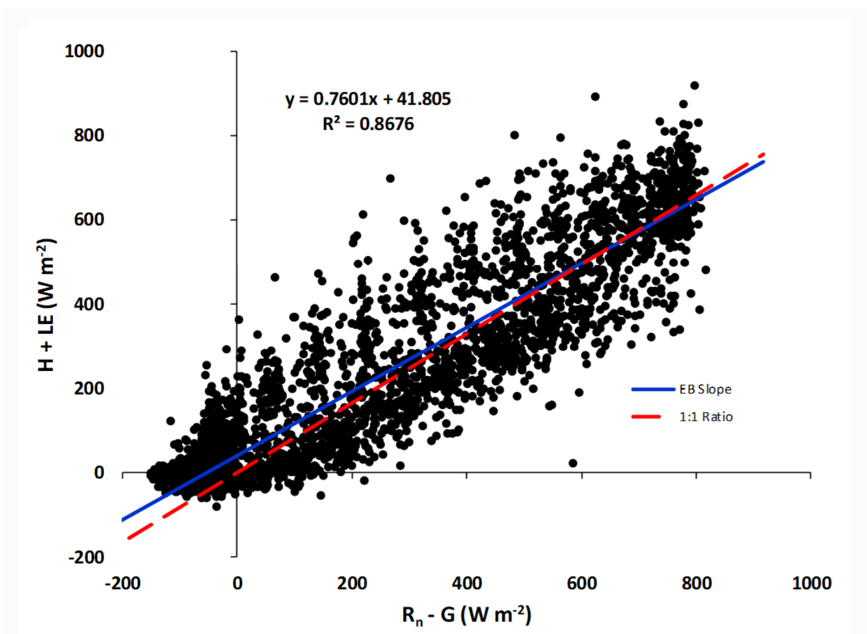


Figure S1. Energy balance for the 2012-2013 period. The above analysis shows the relationship between H (sensible heat) + LE (latent heat) measured by the eddy covariance system and R_n (net radiation) – G (ground heat flux) by the meteorological sensors with an $r^2 = 0.87$.

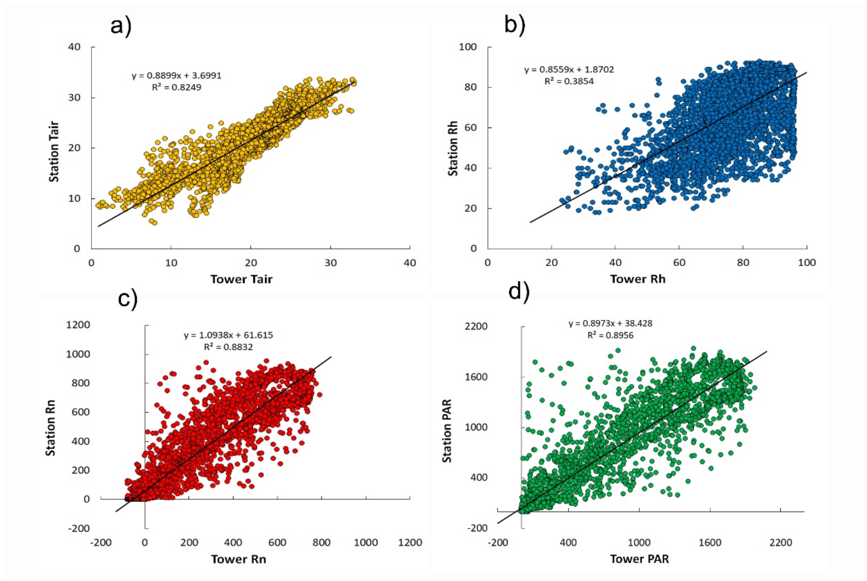


Figure S2. Data comparison between eddy covariance tower near Puerto Lopez Mateos and the ESIME meteorological tower in San Juanico, BCS. (CONAGUA). (a) Air temperature (Tair) comparison between both sites ($r^2 = 0.83$) (b) Relative humidity (Rh) comparison between both sites ($r^2 = 0.39$). (c) Net Radiation (Rn) comparison between both sites ($r^2 = 0.88$). (d) Photosynthetically Active Radiation (PAR) comparison between both sites (r2 = 0.89).

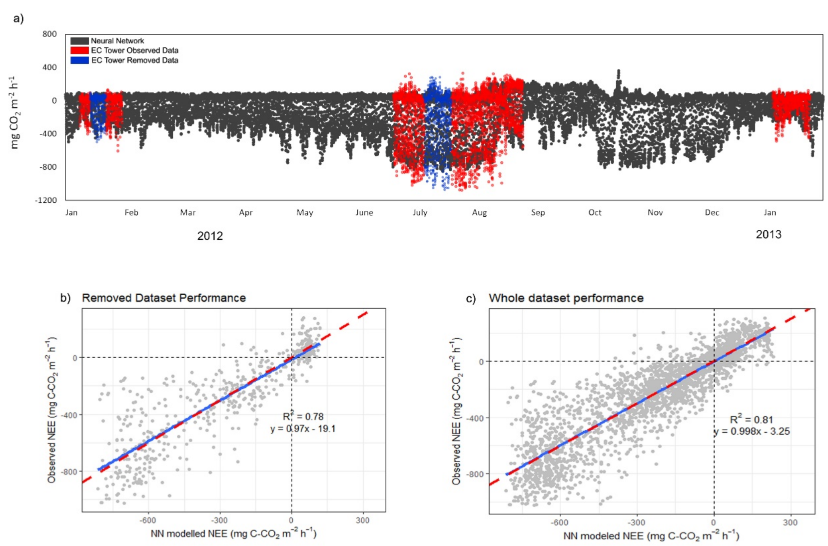


Figure S3. Yearly Measurements of observed measurements of NEE and Neural Network output (a) Half-hourly NEE output data represented in red by our direct observations, data in blue were direct observations removed to validate neural network model, data in gray depict neural network modeled NEE yearly data. (b) Removed Dataset Validation (R^2=0.78) in model performance. (c) Whole dataset performance validation ($R^2 = 0.81$).

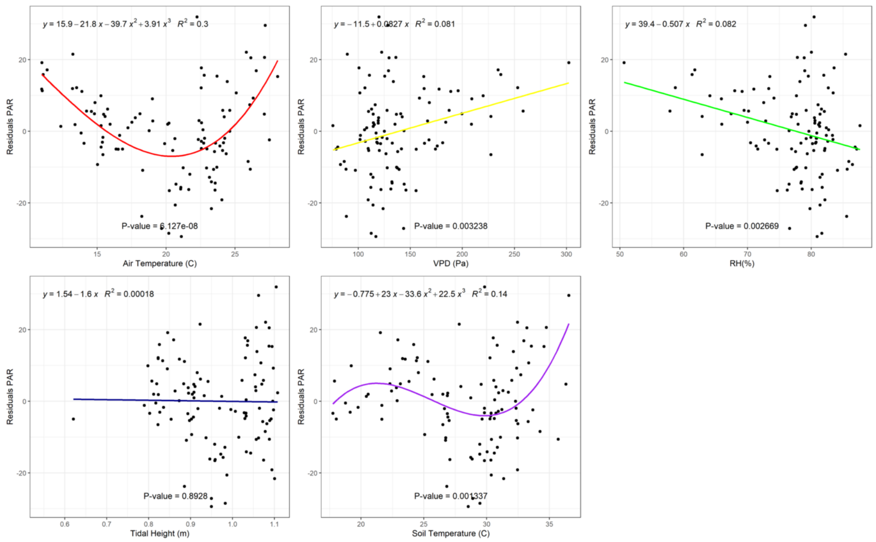
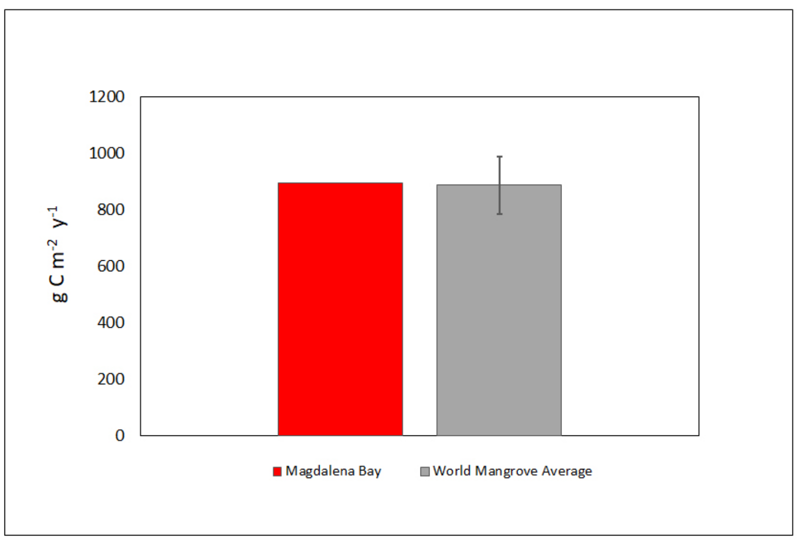


Figure S4. Residual Analysis Regressions of daily means with the influence of light removed (residual of PAR). (a)Air Temperature (b) Vapor Pressure Deficit (VPD) (c) Humidity (RH) (d) Tidal Height (e) Soil temperature.



* Magdalena Bay reports an annual NEE uptake of 894 g C m^{-2} y^{-1} and the calculated mean from other mangrove studies was calculated at 886.2 ± 101 g C m^{-2} y^{-1}

Figure S5. Yearly mean NEE from mangrove sites around the world wide and our field site in Magdalena Bay.

Time Period	Environmental Parameters	Total Regression R-square	Stepwise Backwards Regression Coefficient	Stepwise Backwards Regression P-value	Bivariate Regression Coefficient	Bivariate Regression R-square	Residual regression Coefficient	Residual regression R-square
All Data	PPFD	0.682	-0.009	0.000	-0.008	0.649	-0.008	0.649
	Air Temperature		-0.071	0.000	-0.453	0.124	-0.001	0.007
	Tide		-0.638	0.000	-1.856	0.022	-0.012	0.015
	Humidity		-0.113	0.000	0.173	0.091	-0.001	0.097
	Soil Temperature		0.037	0.035	-0.330	0.060	-0.001	0.003
Summer	PPFD	0.742	-0.01	0.000	-0.01	0.711	-0.01	0.711
	Air Temperature		0.827	0.000	-0.742	0.062	0.005	0.068
	Humidity		0.06	0.000	0.62	0.356	0.001	0.006
	Tide		-1.372	0.000	-3.174	0.044	-0.018	0.023
	Soil Temperature		-0.355	0.000	0.056	0	0.004	0.04
Winter	PPFD	0.659	-0.004	0.000	-0.004	0.585	-0.004	0.585
	Air Temperature		-0.058	0.000	-0.273	0.196	0.002	0.032
	Humidity		-0.029	0.000	0.072	0.148	-0.002	0.356
	Tide		0.819	0.000	1.305	0.068	0.009	0.015
	Soil Temperature		-0.071	0.000	-0.291	0.228	0.002	0.04

Table S1 . Multiple regression and residual models of all half hourly analyzed data for the 2012-2013 measurement period.

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Key Points:

- Large annual carbon sequestration of almost 900 g C m^{-2} in a semi-arid coastal mangrove.
- Air temperature is an important seasonal factor driving net ecosystem exchange (NEE) of CO_2 in semi-arid mangroves.
- The blue carbon storage potential of arid and semi-arid mangroves is an important resource for meeting localized climate mitigation goals.

Abstract

Mangrove forests are among the most productive ecosystems in the world. These tropical and subtropical coastal forests provide a wide array of ecosystem services, including the ability to sequester and store large amounts of 'blue carbon'. Given rising concerns over anthropogenic carbon dioxide (CO_2) emissions, mangrove forests have been increasingly recognized for their potential in climate change mitigation programs. However, their productivity differs considerably across environments, making it difficult to estimate carbon sequestration potentials at regional scales. Additionally, most research has focused in humid and tropical latitudes, with limited studies in arid and semi-arid regions. A semi-arid mangrove forest in Magdalena Bay, Baja California Sur, Mexico was studied to quantify the average net ecosystem exchange (NEE), determine the annual carbon (C) budget and the environmental controls driving those fluxes. Measurements were taken during 2012-2013 using the eddy covariance technique, with a daily mean NEE of -2.25 ±0.4 g C m^{-2} d^{-1} and annual carbon uptake of 894 g C m^{-2} y^{-1}. Daily variations in NEE were primarily regulated by light, but air temperature and vapor pressure deficit were strong seasonal drivers. Our research demonstrates that despite the harsh and arid climate, the mangroves of Magdalena Bay were nearly as productive as mangroves found in tropical and subtropical climates. These results broaden understanding of the ecosystem services of one of the largest mangrove ecosystems in the Baja California peninsula, and highlight the potential role of arid mangrove ecosystems for C accounting, management and mitigation plans for the region.

Plain Language Summary

Mangroves have been recognized as important ecosystems that can help in climate change mitigation programs. Several studies discuss the carbon dynamics and storage potential of mangroves, however, most research has focused on tropical mangroves, with few studies focusing in arid and semi-arid regions. In this study, we established an eddy covariance (EC) system and meteorological sensors, to measure carbon dioxide (CO_2) exchange between the atmosphere and a semi-arid mangrove forest in Magdalena Bay, Baja California Sur (BCS). Our analyses indicate that this mangrove was an atmospheric carbon sink during the measured period. In addition, we determined that light was the driving factor in mangrove carbon uptake on a daily basis, while temperature and vapor pressure deficit showed important seasonal controls on mangrove productivity. The above environmental conditions allowed these mangroves to be productive year-round, but with some reduction during periods of rain and high temperatures. Our findings suggest that mangroves have an optimal temperature for maximum productivity while extreme high temperatures limit and decrease net carbon uptake. The data presented here indicate that these semi-arid mangroves can be as productive as those found in wet tropical habitats and their management can be important in climate change mitigation efforts.

1 Introduction

Mangrove forests grow along many of the world's tropical and subtropical coastlines, occupying an area of almost 14 million ha (Alongi, 2009; Sanderman, 2018). Although the global area of mangroves is relatively limited, they provide a wide array of important ecological and socioeconomic services (Alongi, 2002; Laffoley, 2009). Mangroves are considered among the most productive coastal ecosystems in the world and can rival terrestrial and tropical forests in carbon production and storage per unit area (Cui, 2018; Donato, 2011; Taillardat, 2018), with global mangrove primary productivity estimated at 218 ±72 Tg C yr^{-1} (Bouillon et al., 2008). With increasing concerns over global greenhouse gas (GHG) emissions and climate change, mangrove' carbon storage potential or 'blue carbon', may have an increasingly important role in climate change mitigation (Alongi, 2014; Laffoley, 2009).

Mangroves have ecophysiological and morphological characteristics that allow them to thrive and be productive in the dynamic interface between land and sea. These characteristics include aerial roots, tidal dispersal of propagules, rapid rates of canopy production, highly efficient nutrient retention capabilities, and high water use efficiency with mechanisms for salt exclusion (Adame, 2021; Alongi, 2002). Mangroves are geographically restricted to tropical and subtropical coastlines where they have access to yearlong light and warm temperatures. In addition, access to water from the marine environment and nutrient input from land, high biodiversity, and adjacent lagoon and estuarine systems contribute to high rates of mangrove productivity. Most mangroves also fix carbon well in excess of ecosystem respiration, supporting high rates of nutrient and carbon sequestration. Carbon sequestration occurs in plant biomass and organic matter burial in sediment, resulting in potentially large carbon sinks (Alongi, 2009; 2014).

While considering mangroves for their potential in climate change mitigation to assimilate carbon dioxide (CO_2), and sequester carbon (C), it is important to understand both the current uptake rates as well as the environmental controls on carbon flux in these ecosystems. Presently there are over 900 participating eddy covariance (EC) sites studying CO_2 fluxes on a long-term and continuous basis in the North American, European and Asian FLUXNET networks (Baldiocchi, 2001; 2020). Despite the popularity and utility of the EC technique, some regions and biomes have been studied more than others (Villareal & Vargas, 2021). In recent years, several studies have sought to measure the uptake potential of mangrove ecosystems. Barr et al. (2010) reported that mangroves in the Florida everglades were a sink for atmospheric CO_2, with an annual net ecosystem productivity (NEP) of 1170 ± 127 g C m^{-2} and was strongly influenced by available light, water salinity and tidal inundation. Chen (2014) reported the influence of large-scale environmental disturbances on a subtropical mangrove ecosystem in southern China with an NEP of 540–751 g C m^{-2}, while Leopold (2016) reported a smaller NEP of 73.8 g C m^{-2} for a semi-arid dwarf mangrove system in New Caledonia, where light temperature and vapor pressure deficit (VPD) were controlling factors of NEP. Although these studies show compelling results, the potential of mangroves as carbon sinks is understudied, especially in arid and semi-arid climates. Differences in forest size, stand age, topography, access to water, climate and geographic location can lead to differing productivity rates and carbon sequestration potential (Alongi, 2018). Here we explore the rates, patterns, and controls on net carbon sequestration in a sub-tropical, arid zone mangrove ecosystem associated with Magdalena Bay, Mexico.

Magdalena Bay is located along the Pacific coast of Baja California Sur (BCS), Mexico and is characterized by isolated and undisturbed mangroves forests and estuarine lagoons within the semi-arid and desert ecosystems of the Baja California peninsula (Lagunas-Vazquez, 2011). This mangrove lagoon system is a rich nursery and feeding ground for various species of fish, crustaceans, mollusks, birds, sea turtles, and marine mammals (Felix-Pico, 2011; Hastings, 2001). These mangroves also as an attraction for tourism, recreation, and the foundation for commercial fishing industries in the region (Aburto-Oropeza, 2008; Felix-Pico, 2011).

The Magdalena Bay mangroves are important not only for the economy, but also for the carbon reduction planning for the state of BCS and for Mexico. Our objectives were to: (1) quantify the net ecosystem CO_2 exchange (NEE) for this ecosystem, (2) determine seasonal patterns and environmental controls on NEE, and (3) evaluate the potential of mangrove management to meet CO_2 reduction targets in the state of BCS and Mexico. Measurements and productivity estimates from these mangrove forests have been previously studied using a suite of aircraft-based EC measurements and satellite remote sensing (Zulueta et al., 2013). However, ground level ecosystem fluxes have not been conducted in this system for extended periods of time. Consequently, the present study aimed to investigate the nature and magnitude of the atmosphere-biosphere CO_2 fluxes above the forest canopy and to investigate the relationship between the micrometeorological variables and CO_2 exchange.

2 Materials and Methods

2.1 Site Description

The study site is located along the northern extent of Magdalena Bay (Bahia Magdalena), which is about 10 km north of the fishing town of Puerto Adolfo Lopez Mateos, BCS, Mexico (25°15'44"N, 112° 4'48"W) (Fig. 1). The area is a contiguous series of productive and biologically diverse embayments, intertidal mud flats, and mangrove-lined canals bounded by islands and sand bars that extend for 175 km along the Pacific coast of BCS (Aburto-Oropereza, 2008; Hastings, 2001; López-Medellín, 2011). The site is located within the largest of these bays in the northwest region of Magdalena Bay in an area bordered by the sandy barrier island of Isla Magdalena, which forms a protected inner shelf lagoon that connects the inner lagoons and canals to the Pacific Ocean via the "Boca de Soledad". The interior canals and channels that constitute much of this region are narrow (0.2 - 2km) and shallow (mean depth 3.5m) (Chavez, 2006; Gonzalez-Zamorano, 2013). The tidal range is considerable and varies throughout the region, measuring between 1.46m and 1.7m on average. The tidal regime (24.8 hrs.) in the bay is mixed semidiurnal, with periods of higher water followed by those of lower water, a condition that produces greater current velocities during receding tides, however within the canals and smaller embayments current water velocities are nearly quiescent (Bizzarro, 2008; López-Medellín, 2012).

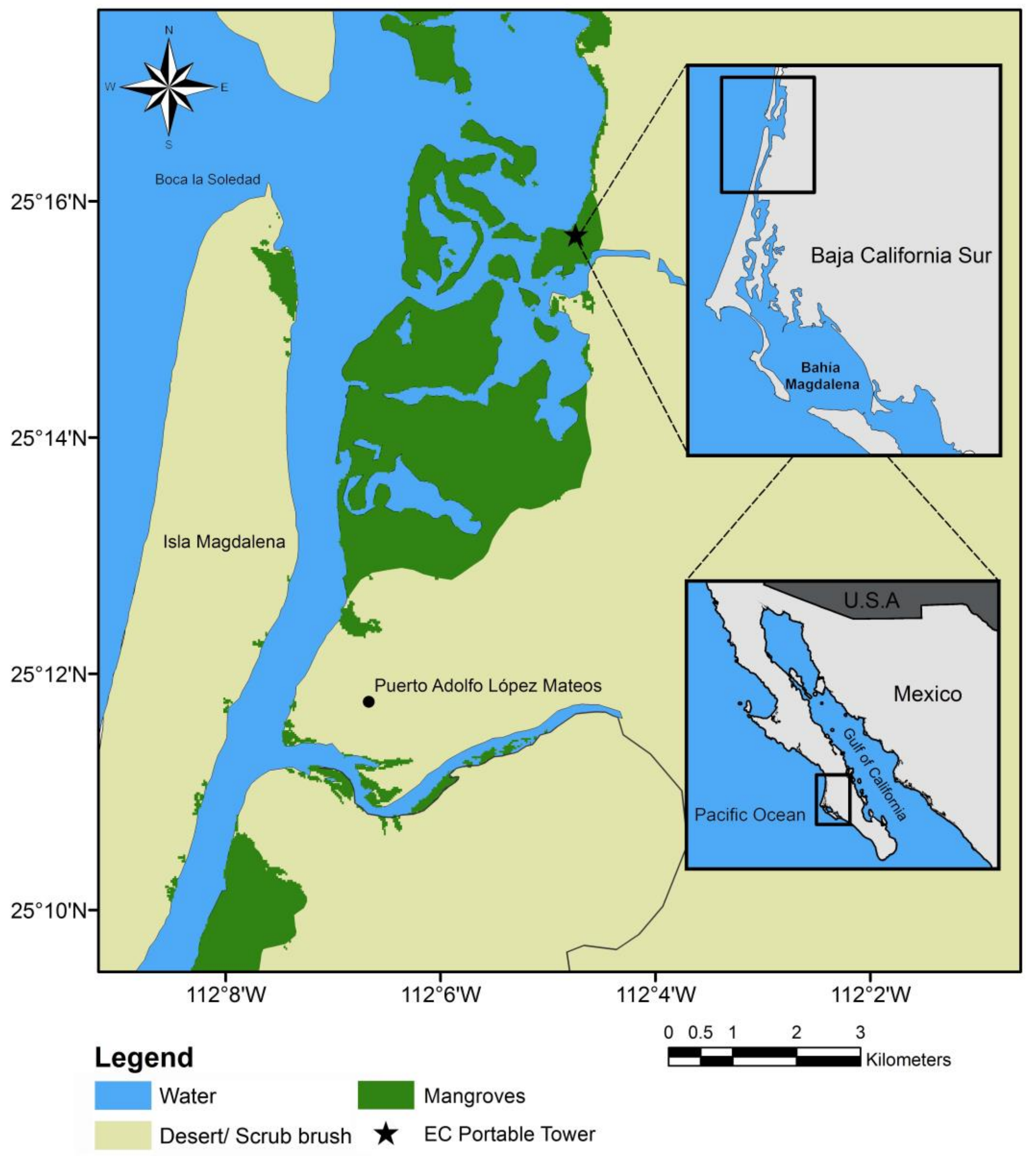

Figure 1. Location of the eddy covariance (EC) portable tower field site (black star) adjacent to a mangrove stand (25°15'44"N, 112° 4'48"W) in Magdalena Bay, BCS, Mexico.

Magdalena Bay lies within a transitional zone between temperate and tropical regions and is part of the Sonoran Desert, where the climate varies from temperate to hot and dry. Mean average air temperature is ~ 22 ^{o}C and ranges from a daily average of 12 ^{o}C during winter to ~30 ^{o}C in the late summer months. Precipitation is rare and is mostly restricted to summer and early fall where, tropical storms originating along the Pacific coast of southern Mexico may reach the bay (Bizzarro, 2008; López-Medellín, 2012). The natural desert conditions in the area produce low annual average rainfall (90 mm), high rates of evaporation, and minimal freshwater inputs contributing to a negative estuary effect where the bay's salinity concentrations generally exceed those found in the open ocean, reaching concentrations between 35 and 39 parts per thousand (ppt) in the connecting channels of the bay (Chavez, 2006; Zulueta, 2013).

Magdalena Bay is characterized by a high floral and faunal diversity, where the arid desert region transitions into a coastal area (Fig. 2). Seasonal upwelling in the sub-tropical California Current allows high rates of productivity in the bay, which is dominated by surf grass, eel grass, intertidal mud flats, salt marshes, and mangrove lined coastlines (Bizzarro, 2008; Gonzalez-Zamorano, 2013). The dominant mangroves species found in this area are red (*Rhizophora mangle)*, white (*Laguncularia racemosa*) and black (*Avicennia germinans*) mangrove trees (Chavez, 2006; Felix-Pico, 2011). The total coverage of mangrove forests in Magdalena Bay has been estimated at 178.64 km^2 (±14.15) with an average canopy height of 3.5 m and an average tree stem diameter of 4.09 cm (Chavez, 2006) (Fig 2).

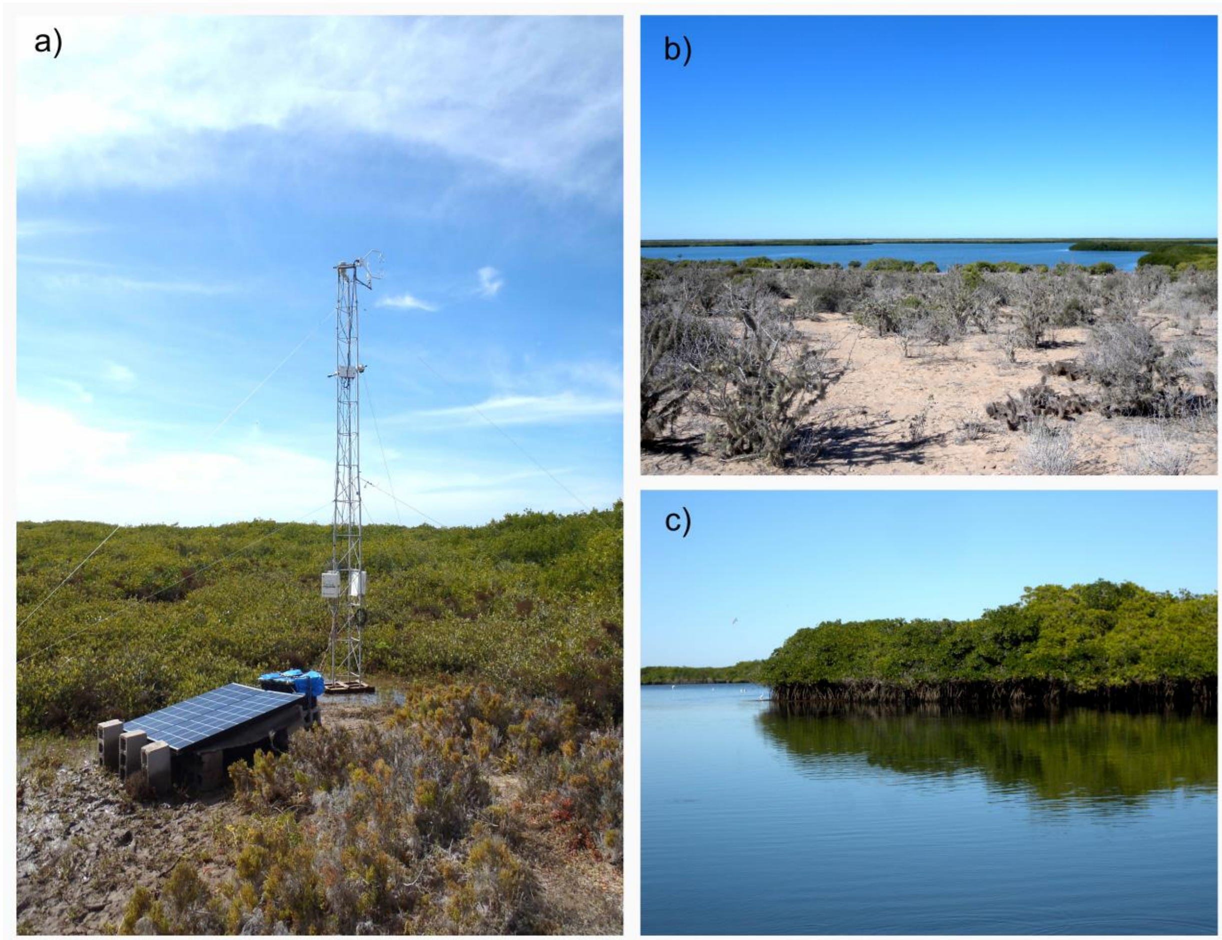

Figure 2. (a) Portable eddy covariance (EC) tower setup adjacent to mangrove forest. (**b)** land side view of adjacent desert ecosystem and its transition to the mangrove lined lagoon. **(c)** Lagoon side view of flooded red mangrove forest (*Rhizophora mangle)* along the coastlines of Magdalena Bay.

2.2 Eddy Covariance and Meteorological data.

Ecosystem flux measurements were done using the EC technique (Baldocchi et al. 1988; 2003). A portable flux tower was placed adjacent to a large mangrove stand (Fig. 1; 25° 15'45" N, 112° 04'46" W) as determined by a suitability analysis. The site suitability model was created using Geographic Information Systems (GIS) software (ArcGIS® and Model Builder) to identify a suitable location that included requirements of the area for the EC method and safety of the equipment (Burba, 2010). Data was collected for 22 days between January 8 and 30, 2012; for 69 days during summer between June 20 and August 28th, 2012; and for 19 days between January 5 and 24 in 2013. January 2012, and January 2013 were grouped together as winter and the months of June through August were grouped as Summer for seasonal period analysis.

The EC system included a fast response (10Hz) three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, UT, USA) used to measure wind velocity and sonic temperature fluctuations. Atmospheric CO_2 and water vapor concentrations were measured by a fast response (10Hz) open-path infrared gas analyzer (IRGA) (LI-7500, LI-COR Inc., Lincoln, NE, USA) at 5 m above the ground (Fig. 2). Power for the system was provided by 3 rechargeable deep cycle batteries connected to 2 solar panels (135W each). The portable tower measurement height was 5 m above ground level, and approximately 1.5 m above the mangroves canopy with an average tree height 3.5 m. A prevalent onshore windflow from west to east and northwest to southeast was recorded during the majority of the study period (Chavez, 2006; Zulueta, 2013). A footprint analysis (Schuepp et al., 1990) indicated that 90% of the flux measurements originated within 100 m of the tower.

Meteorological variables were averaged over 30-minute intervals from measurements taken every 10 seconds and stored using a datalogger (CR3000, Campbell Scientific Inc.) with a removable 2 GB compact flash memory card: Air temperature (T_{air}), and relative humidity (RH), (HMP45c, Vaisala, Helsinki, Finland) were measured at 4.5 m in a radiation shield. Vapor pressure deficit (VPD) was calculated from air temperature and relative humidity. Incoming photosynthetic active radiation (PAR) was measured by a quantum sensor (LI-190 SB, LI-COR, Lincoln, NE, USA) at 4m above the ground. Net radiation (R_n) (Q-7.1, REBS Inc., Seattle, WA, USA) was measured within the upwind sampling area at 4 m above the ground. Ground heat flux, G, (HFT3, REBS Inc., Seattle, WA, USA) was measured at a depth of 5cm below the ground surface, and copper-constantan thermocouples were placed at depths of 2, 5, and 10cm below the surface to measure soil temperature.

2.3 Data Analysis

Fluxes were calculated as half hourly means of CO_2 and H_2O fluxes as the covariance between the vertical wind speed and the appropriate mixing ratio (Vourlitis and Oechel, 1997) via the post processing software *EDIRE* (version 1.5.0.9, University of Edinburgh; http://www.geos.ed.ac.uk/abs/research/micromet-/EdiRe/). The percentage of reliable EC data collected during the measurement periods varied from 60% to 80% among each measurement period. Data gaps were primarily caused by power, computer, or sensor failures, instrument calibration, and data rejection following quality assessment during data processing. The processed data yielded half-hourly values that were filtered and rejected based on the following conditions: (1) evidence of condensation or precipitation on the IRGA or sonic anemometer, (2) wind vectors with a standard deviation (SD) >6, (3) IRGA and sonic anemometer error flags, (4) sensible heat (H) (>600 or <-50 W m^{-2}) or latent heat (LE) (>700 or <-50 W m^{-2}) values, and (5) critical friction velocity (u^* <0.18 m s^{-1}) (Bell, 2012; Falge et al., 2001a) determined as the point where increases in u^* had little apparent effect on nighttime CO_2 flux and we can avoid the underestimation of carbon source strength under calm wind conditions (Zulueta, 2013). Low u^* values were invariably associated with night-time measurements and low wind speed (low turbulence) (Schedlbauer, 2010). Monthly means of half-hour flux data over the diurnal cycle were used to calculate monthly and seasonal sums of carbon exchange (Hastings and Oechel, 2005). Data gap periods of less than 30 minutes to 3 hours were filled by linear regression (Falge et al., 2001b). Gap-filling of periods greater than 3 hours, flux-partitioning, and the uncertainty estimates were all done by using the online EC tool available at https://www.bgc-jena.mpg.de/~MDIwork/eddyproc/ for observed data, which incorporates the techniques described in Falge et al. (2001b) and enhanced algorithms that consider the temporal autocorrelation of fluxes and the co-variation with meteorological variables as described in Reichstein et al. 2005.

2.4 Neural Network

Due to logistical reasons, including site security, we were not able to collect continuous local climatic data, so to complete an annual data set we obtained meteorological data from the Mexican national weather service, Coordinación General del Servicio Meteorológico Nacional (CGSMN) and the department of water, Comisión Nacional del Agua (CONAGUA) who provided climatic data for our study period (January 2012- January 2013) from 2 of their meteorological stations within 200km of our site.

We used these data to predict our local site's meteorological conditions throughout the study period. We performed simple linear regressions of our site data to each remote site and selected the datasets with the best 1:1 relationship, and with the highest r^2 as the source data for our artificial neural network (ANN) (See SI). The datasets used included environmental data for air temperature, humidity, solar radiation, air pressure, precipitation, and wind direction. The resultant estimated site environmental data was then used in the ANN to gap fill the annual NEE record for the site and to estimate the annual carbon balance of the ecosystem using the "neuralnet" package (Günther & Fritsch, 2010) in R v.4.0.4 (R Core Team, 2021). This method has been shown to be robust for modeling and gap filling carbon exchange in natural ecosystems (Moffat et al., 2007) as ANNs are well suited for finding patterns in non-linear relationships (Wu et al., 2009). Models were validated on 25% of removed data not used to train the model, the validation data included one week of the flux data in January 2012 and three weeks in the summer period 2012 (See SI).

2.5 Statistical Analysis

All statistical analyses were performed with the statistical software SYSTAT (Version 12, Cranes Software Inc., Chicago, IL, USA) and R (v.4.0.4 R Core Team, 2021). In order to assess for multicollinearity in our measured variables we calculated the variance inflation factor (VIF), variables with a VIF of 5 or greater were removed from the analysis models (Kasambara, 2018). We then continued carbon flux pattern analysis with a backward stepwise multiple linear regressions to determine significant meteorological variables to half-hour averaged NEE each month and season. All statistical models were defined as significant at $p < 0.05$. Once the significant variables were identified, the correlation coefficient between each variable and to carbon flux was found by individual linear regression. The variables with the largest r^2 values were selected as the most important meteorological variables to carbon uptake and efflux for each measured period (Bell, 2012).

Additionally, nonlinear regression (rectangular hyperbola Michaelis–Menten model, described in Ruimy et al. 1995, was used to estimate the light response of the half-hourly averaged NEE and to derive the residual. We then performed a residual analysis on the NEE light response curve to estimate the significance of temperature (air and soil), tide, humidity and VPD, on the half-hourly averaged data overall and seasonal periods. All models were tested for normal distribution and equal variance of the residuals, and tested for collinearity using the VIF. Once the residuals were modeled, a linear model was then used to test the significance and the explanatory power of VPD, tide and humidity and an exponential model to test the explanatory power of air temperature (Zona, 2013).

3 Results

3.1 EC System Performance

EC system performance was assessed by examining the degree of closure of the surface energy balance (Wilson, 2002; Bell, 2012). The sum of half-hourly values of latent (LE) and sensible (H) heat flux were compared against the sum of half-hourly net radiation ($R_{n)}$ minus ground heat flux (G) over the whole for the measurement periods in 2012 and 2013 (See SI). Least square regression curves were fitted to the graphs and a goodness of fit was quantified with an r^2 of 0.87, the slope of regression was 0.76 and the intercept was 41.8. These values represent typical good system performance as reported for other FLUXNET sites (Baldocchi et al., 2001).

3.2 Environmental Conditions

Over the study period between Jan 8th 2012 and Jan 24th 2013, annual data provided by CONAGUA and used for our artificial neural network showed that Tair, RH, PAR, and tidal height, averaged 21 ±0.04 ºC, 70 ±0.11 %, 476 ±4.55 µmol m^{-2} s^{-1}, and 0.86 ±0.02 meters respectively. Although meteorological conditions remained relatively constant on a day-by-day basis, the environmental variables showed strong seasonal differences at the study site. (Table 1). The winter season had lower average solar radiation (R_n 97 W m^{-2} and PAR 365 µmol m^{-2} s^{-1}) than the summer season (R_n 192 W m^{-2} and PAR 566 µmol m^{-2} s^{-1}). Both air and soil temperature at the surface were highest during summer (23.2 and 30.9 ºC, respectively), with lower values during the winter (14.9 and 23.6 ºC, respectively). RH showed only a slight difference between winter and summer (74% and 79%). Tidal height varied between winter and summer, with higher mean tidal height during summer than in winter (1.03, 0.86 meters, respectively). Precipitation was very scarce in the arid desert regions adjacent to Magdalena Bay. During winter there were no major rain events recorded, while in summer between August 14 and August 17 a large rain event precipitated by tropical storm Hector brought approximately 32mm of rain into the site.

Additional information provided by CONAGUA showed a large number of precipitation events occurring in later days beyond our study period between the months of August and October with total of 149mm of rain (Fig. 3), which is above the yearly annual mean of 90mm for Magdalena Bay.

Table 1. Meteorological variables during summer and winter measurement periods 2012 - 2013.

Study Period	Tair (°C)	RH (%)	PAR (μmol m^{-2} s^{-1})	R_n (W m^{-2})	Tsoil (°C)	Tidal Height (m)	VPD (kPa)	Precipitation (mm/day)	Precipitation (mm sum)
Summer*	**23.2** ±0.05	**79.4** ±0.14	**566** ±12.61	**192** ±5.08	**30.9** ±0.05	**1.03** ±0.01	**0.61** ±0.01	**0.49** ±0.19	**33.3**
Winter†	**14.9** ±0.11	**73.5** ±0.38	**365** ±12.9	**97** ±4.98	**23.6** ±0.11	**0.86** ±0.01	**0.49** ±0.01	**0.08** ±0.01	**3.3**

*Summer season measurements were made from June 20th to August 27th, 2012.
†Winter season measurements were made between January 8th – 30th, 2012 and January 5th - 24th, 2013.
Air temperature (Tair); relative humidity (RH); photosynthetic active radiation (PAR); net radiation (R_n); soil temperature (Tsoil,); vapor pressure deficit (VPD).

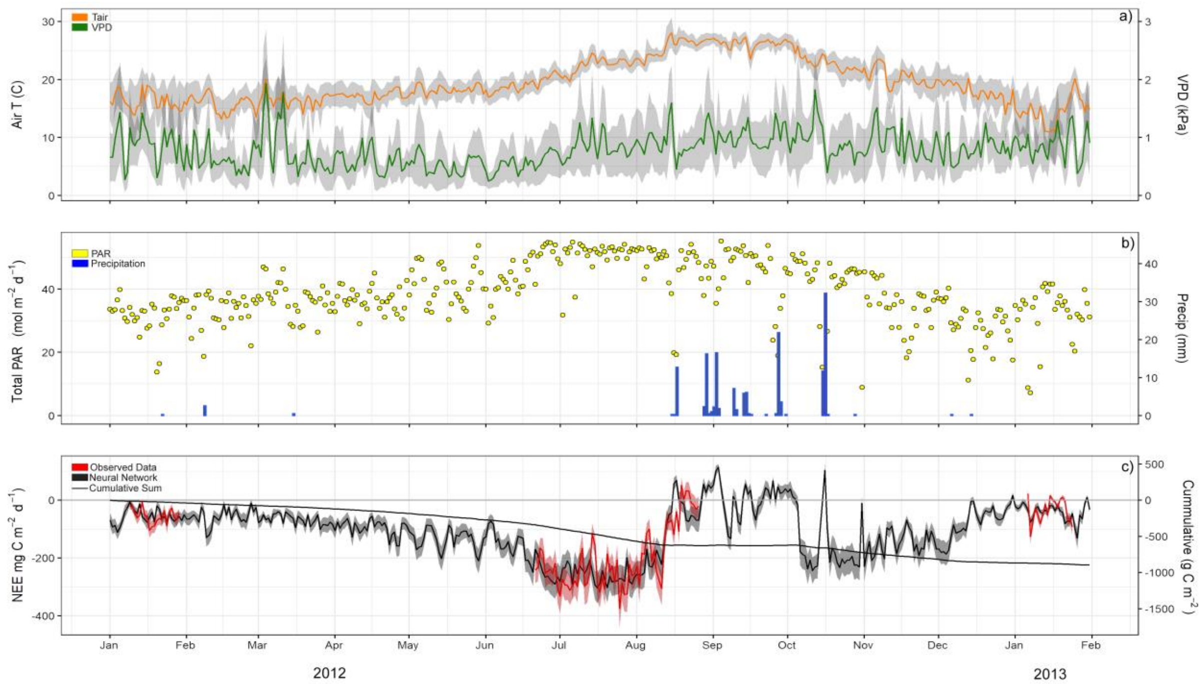

Figure 3. Data displayed from January 1, 2012 to January 31, 2013 **(a)** Daily mean air temperature (Tair) (^{o}C) and Vapor Pressure Deficit (VPD) (kPa). **(b)** Daily total sum of photosynthetic active radiation (PAR) and precipitation (mm). **(c)** Observed daily means of net ecosystem exchange (NEE) fluxes (mg C m^{-2} d^{-1}) from our eddy covariance (EC) tower and the artificial neural network (ANN) output (g C m^{-2}) for yearly estimates with a daily cumulative sum trendline.

3.3 Net Ecosystem Exchange of Carbon

Controls over NEE were determined by examination of daily average patterns of meteorological variables from observed data for each measured month and season at the half hourly scale. PAR had the strongest correlation in all of the measured months (r^2 = .65, P <0.001) however, air temperature was found to be the environmental factor driving the seasonal variation of carbon uptake (r^2 = .12, P <0.001) (See SI). Using the environmental variables with the strongest significant correlation to daily NEE allowed for comparison of seasonal NEE magnitudes (Fig 4). During winter, ecosystem sink activity began at 0800 MST and lasted until the evening at 1800 MST. Ecosystem activity would reach a midday peak of -253.8 ±19.6 mg C m^{-2} h^{-1} while nighttime ecosystem respiration of 44.78 ±3.5 mg C m^{-2} h^{-1} was recorded from our EC measured data. The average NEE of the winter season showed a daily sink of -0.97 ± 0.06 g C m^{-2} d^{-1} or a seasonal estimated total of -87.3 g C m^{-2} (Table 2). During summer, ecosystem sink activity began at 0700 MST and lasted until the evening 1930 MST with a midday peak rate of -682.2 ±30.7 mg C m^{-2} h^{-1} while a nighttime ecosystem respiration of 110.8 ±8.8 mg C m^{-2} h^{-1} was recorded. The average NEE for summer was of -4.32 ± 0.13 g C m^{-2} d^{-1} or an estimated seasonal total of -388.8 C m^{-2} $season^{-1}$. The overall averaged NEE for the study period in 2012-2013 was calculated to be a sink of -2.25 ± 0.04 g C m^{-2} d^{-1} (Table 2). In Zulueta et al. (2013), aircraft-derived C flux measurements were taken alongside a portable tower during July 2004 in the same site in Magdalena Bay. They recorded a mean C uptake of -350.6 mg C m^{-2} h^{-1} and -531.8 mg C m^{-2} h^{-1}, respectively which falls within the same range we measured. With this information we are able to determine that during both the winter and summer seasons these mangroves were a large sink of carbon.

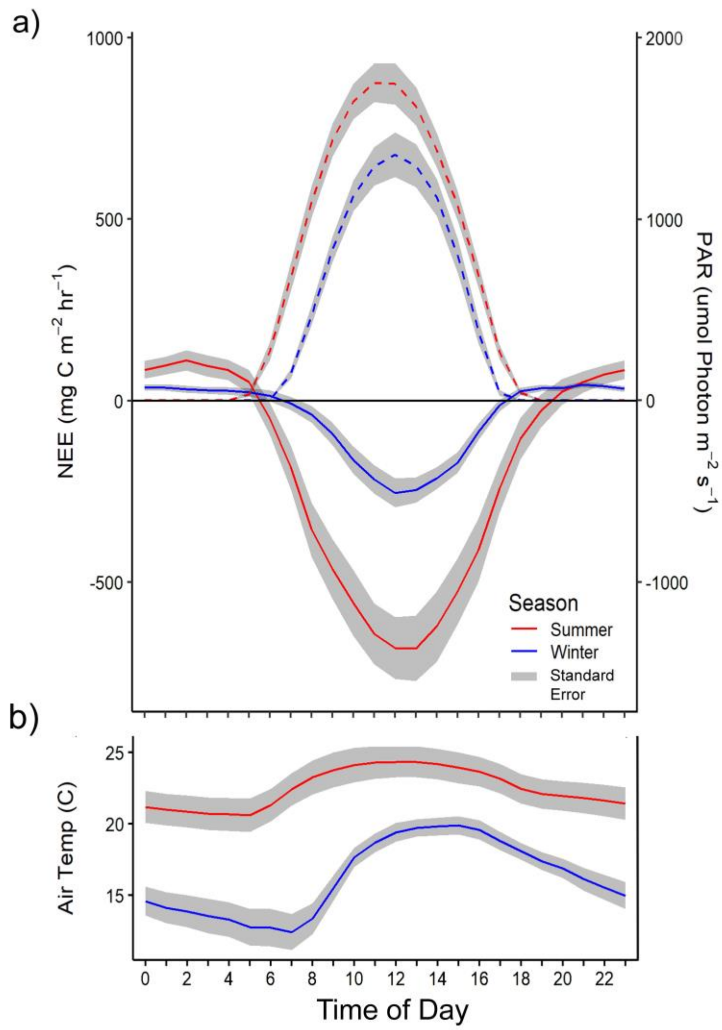

Figure 4. (a) Average diel seasonal C flux (NEE) shown by solid lines and Photosynthetic Active Radiation (PAR) shown by dashed line. **(b)** Average diel air temperature flux.

Table 2. Seasonal and annual mean estimates of Net Ecosystem Exchange (NEE) in the measurement periods of 2012- 2013.

Season	NEE ($g C m^{-2} d^{-1}$)	Month	NEE ($g C m^{-2} d^{-1}$)
Winter	-0.97 ± 0.06*	January 2012	-1.17 ± 0.09*
		January 2013	-0.74 ± 0.08*
Summer	-4.32 ± 0.13*	June 2012	-5.01 ± 0.32*
		July 2012	-5.74 ± 0.20*
		August 2012	-2.40 ± 0.18*
Yearly Mean Estimate†	-2.25 ± 0.04*		

*Negative values denote carbon uptake from atmosphere.

† Yearly mean estimate calculated from Artificial Neural Network (ANN) output.

3.4 Seasonal Factors Controlling NEE

As noted above, PAR showed the strongest environmental correlation on a daily basis across all measured months. To determine the seasonal variation, we examined the NEE daily totals against the daily mean of each environmental parameter, and from these regressions we calculated the residuals to see their effect on NEE with the influence of light removed. Soil temperature covaried with air temperature (VIF>5), so we excluded it from the model due to its lower explanatory power. Our stepwise multiple regression model showed that PAR, air temperature, VPD and tide were all significant in controlling daily total NEE ($r^2 = 0.43$), however we saw each variable influence on NEE differ at the seasonal scale. During summer, PAR and air temperature primarily influenced NEE ($r^2 = 0.45$) while in winter, PAR, air temperature and VPD had a combined impact on NEE of ($r^2 = 0.33$) (Table 3).

Table 3. Stepwise multiple regression and residual analysis of daily mean averages of photosynthetic active radiation (PAR), air temperature (Tair) , vapor pressure deficit (VPD) and tide against daily total NEE, partitioned for all measured values and on a seasonal scale.

Time Period	Stepwise Regression				Residual Regression			
	Environmental Parameters	r^2	Coefficient	P-value	Environmental Parameters	r^2	Coefficient	P-value
All Data	PAR	0.433	-0.707	0.000	--			
	Tair		-1.694	0.002	Tair	0.300	-1.660	0.000
	VPD		30.923	0.001	VPD	0.028	29.791	0.087
	Tide		45.029	0.047	Tide	0.000	40.439	0.893
Summer	PAR	0.453	-0.470	0.000	--			
	Tair		3.520	0.000	Tair	0.312	3.413	0.000
					VPD	0.131	34.796	0.003
					Tide	0.177	90.934	0.000
Winter	PAR	0.330	-0.225	0.002	--			
	Tair		-1.120	0.002	Tair	0.156	-0.825	0.013
	VPD		10.194	0.034	VPD	0.043	6.411	0.204
					Tide	0.063	-19.136	0.122

Looking at the regression analysis of each variable between seasons (Fig. 5), air temperature showed a positive relationship with net uptake with $r^2 = 0.28$ in winter, while in summer, air temperature showed a negative relationship with net uptake $r^2 = 0.46$. Tide showed no impact on NEE during winter ($r^2 = 0.003$) with a stronger relationship in summer ($r^2 = 0.11$). VPD showed no relationship with NEE in winter ($r^2 = 0.01$), while in summer, VPD showed a positive relationship with NEE ($r^2 = 0.25$). We then removed the effect of light from the model by a residual analysis where overall air temperature explained 30% of the residuals and VPD explained 3% of the residuals. At a seasonal scale, air temperature explained 16% of the residuals, VPD an additional 4% and tide 6% of NEE during winter. In summer, air temperature explained up to 31% of the residuals, VPD explained 13% and tide explained 18% of the residuals (Table 3).

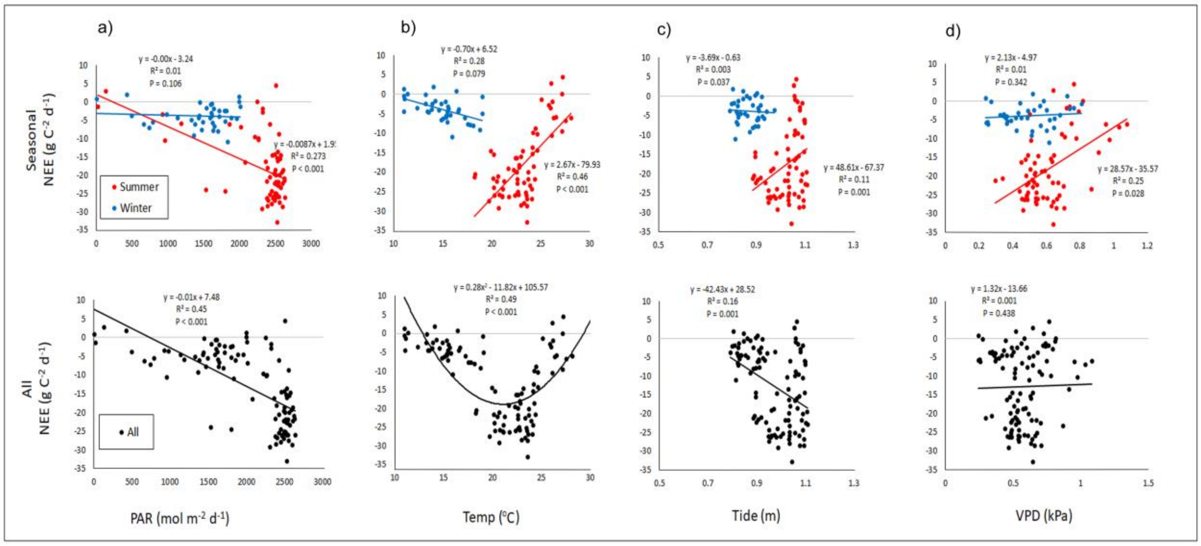

Figure 5. Yearly and Seasonal regressions of daily means of carbon (C) flux (NEE) for each environmental parameter: **(a)** photosynthetic active radiation (PAR), **(b)** air temperature (Tair), **(c)** tidal height and **(d)** Vapor Pressure Deficit (VPD). NEE values less than zero indicate net C uptake.

4 Discussion

4.1 Annual and Seasonal Drivers of NEE

Mangrove photosynthetic rates vary widely among species and location and are strongly regulated by the local environmental conditions (Alongi, 2009). For example, Barr et al. 2005 reported that mangrove leaves and foliage in the Florida everglades were nearly as active during midday in the winter and summer, where the differences associated with the assimilation for carbon were mostly based on the changes in daylight periods and daily light availability. In our study, PAR was the main driver in NEE fluxes on an annual and seasonal scale (See SI), however, we do see a seasonal influence from additional meteorological variables including air temperature and VPD. During the winter, mangrove productivity is strongly limited by temperature, with low NEE uptake during periods of low temperature and NEE uptake increases as temperatures rise above15 C^o (Fig 4). During summer, mangrove productivity reaches its peak uptake when temperatures range between 20-25 C^o but once temperatures rise beyond that range, NEE uptake decreases and the mangroves become a carbon source. This can be an important factor to consider in response to rising global temperatures, where we could see higher uptake of carbon beginning to occur during colder months and warmer months decreasing their carbon uptake efficiency and possibly becoming sources of carbon. VPD had a positive relationship with NEE during both winter and summer, showing a greater influence during the summer period. The models show that at lower VPD with a lower transpiration rate, the plants are more productive with ahigher water use efficiency.

Based on our multiple regression model, overall mangrove ecosystem respiration decreased with tidal inundation, though we were not able to detect the direct mechanisms of its influence on NEE. Li et al. 2014, reported that mangrove forest respiration was reduced during tidal inundation, and reported that during summer periods, tidal activity may become a more important driving factor of respiration than temperature. It is possible that during tidal inundations, respiration may be lower due to soil anoxic conditions or reduced soil diffusivity, which would tend to reduce gas exchange from the soil to the atmosphere. More local monitoring and experimental studies are needed to fully understand these ecosystem dynamics.

Based on our ANN, throughout the year this mangrove ecosystem acted primarily as an atmospheric carbon sink, with increasing uptake beginning in late spring which corresponds with an increase in available daylight, and rising in uptake with optimal temperature conditions, reaching its peak uptake during the month of August. From August through November the area is commonly impacted by the tropical storm season, becoming exposed to sudden and large precipitation events. These rain events introduce a large quantity of fresh water into the system, and coincide increased cloud cover and a general decrease in available sunlight. As a result, the ecosystem shifts from an NEE sink to a source in association with these rain events in our model. The decrease in light, increase in moisture and consistent high temperatures may lead to depressed photosynthesis and higher ecosystem respiration, extending for several days after each rain event. Though there are no major watershed drainages at the study site, we assumed storm related C loading was minimal, however C loading from runoff by large rain events may also contributed to C efflux. As conditions stabilize, our model indicates a return of the ecosystem to a net carbon sink. Additional data coverage during this rainy season would be ideal to constrain fluxes, however our estimates show a similar annual total to other mangrove ecosystems (Table 4).

Although this mangrove's carbon balance is primarily driven by many of the same factors regulating terrestrial forests, as a coastal habitat, the carbon balance is also influenced by tidal cycles, water availability, and episodic coastal disturbances. Improved understanding of these factors will enable more precise determinations of the role of mangrove forests in global carbon budgets. Based on our observed data and the ANN output (Fig. 3), we estimated an annual carbon uptake of 894 g C m^{-2} y^{-1}. We reviewed an additional 21 studies on mangrove productivity and ranked them by the amount of rainfall they received and NEE (Table 4). Surprisingly, despite having the second lowest amount of rainfall in comparison to other regions, this semi-arid mangrove ecosystem had an estimated annual carbon uptake within 1% of the global mean for mangroves of 886.2 ± 101 g C m^{-2} y^{-1} (Table 4).

Table 4. Estimated carbon budget of mangrove forests. Units in g C m^{-2} y^{-1}.

Mangrove Forest	NEP	Climate	Rainfall per year (mm)	Location	Reference
Sonneratia-Avicennia forest	954	Tropic	5102 - 5332	East Thailand	Poungparn et al., 2012
Rhizophora forest	1050	Tropic	5102 - 5332	East Thailand	Poungparn et al., 2012
Xylocarpus and Bruguiera forest	775	Tropic	5102 - 5332	East Thailand	Poungparn et al., 2012
Mature mangrove ecosystems	2142	Sub-Tropic	2000-3500 [1]	Hinchinbrook Channel, Australia	Alongi et al., 2011
Disturbed mangrove forest	1524	Tropic	2000 -3000 [2]	Matang Mangrove Forest Reserve, Malaysia	Alongi et al., 2011
Mature mangrove ecosystems	1219	Sub-Tropic	~2500 [3]	Missionary Bay, Australia	Alongi et al., 2011
Immature mangrove ecosystems	1351	Tropic	>2000 [4]	Southern Thailand	Alongi et al., 2011
Estuaries mangrove ecosystem	1116	Sub-Tropic	~1700	Darwin Harbour, N. Australia	Burford et al., 2008
Kandelia-obovata mangrove	890	Sub-Tropic	1700	Mai Po, Hong Kong	Liu et al., 2019
Kandelia-obovata mangrove	758	Sub-Tropic	1700	Mai Po, Hong Kong	Liu et al., 2019
Avicennia- Bruguiera - Rhizophora mangroves	249	Tropic	1,650	Sundarban, India	Rodda et al., 2016
Everglades mangrove ecosystem	800	Sub-Tropic	1,600	Florida, USA	Barr et al., 2006
Everglades mangrove ecosystem	1170	Sub-Tropic	1,600	Florida, USA	Barr et al., 2010
Everglades mangrove ecosystem	1000	Sub-Tropic	1,600	Florida, USA	Barr et al., 2012
Kandelia-Avicennia & Bruguiera-Avicennia forests	708	Sub-Tropic	1240	Southern China (Yunxiao, Fujian, China)	Chenet al., 2014
Rhizophora and *Conocarpus forest*	709	Tropic	1222	Puerto Morelos, Quintana Roo, México	Alvarado-Barrientos et al., 2021
Avicennia- Rhizophora mangroves	74	Semi-Arid	< 800	Coeur de Voh, New Caledonia	Leopold et al., 2016
Rhizophora-Avicennia forest	183	Tropic	653	Pichavaram, India	Gnanamoorthy et al., 2020
Rhizophora-Avicennia forest	745	Arid	300	Navopatia, Sonora Mexico	Granados-Martínez et al., 2021
Rhizophora-Avicennia forest	307	Arid	300	Navopatia, Sonora Mexico	Granados-Martínez et al., 2021
***Rhizophora-Avicennia* forest**	**894**	**Semi-Arid**	149 (~90)	**Magdalena Bay, BCS, Mexico**	**This Study**
Rhizophora-Avicennia forest	878	Arid	125	El Sargento, Sonora, Mexico	Delgado Balbuena et al., 2019
Global Mean	886.2 ± 101				

Mangrove forest studies organized and ranked down from greatest to least amount of rainfall.
NEP – Net Ecosystem Production, units in g C m^{-2} y^{-1}
*Precipitation data obtained from the following sources: [1] Bureau of Meteorology, 2021; [2] Goessens et al. 2014; [3] Alongi, 1997; [4] Gale, 2013

4.2 Global scale and importance.

Undegraded mangrove forests are generally strong carbon sinks (Barr, 2012; Jha, 2014; Poungparn, 2012), however their productivity varies widely based on latitude and corresponding regional and local climates (Osland, 2017). Most studies have focused on tropical and subtropical mangrove ecosystems in humid climates, with limited research occurring in semi-arid or arid climates (Leopold, 2016; Ochoa-Gomez, 2019). Mangroves in humid areas see large amounts of rainfall and have been measured to grow over 20 meters tall, whereas those in arid zones show smaller tree size caused by less rain and exposure to more extreme temperatures and water stress conditions. Despite these differences, arid and semi-arid mangroves can be important in blue carbon sequestration projects. This study showed that these undisturbed mangroves can be as productive as mangroves in areas with higher rainfall and less extreme temperatures (Table 4; See SI).

Baja California Sur is a region of the Sonoran Desert, where most of the terrain is comprised of sand and rocky outcroppings, populated with sparce vegetation primarily composed of desert shrubs, small trees and succulents. Hastings et al. 2005, evaluated the annual carbon flux of a similar desert shrub ecosystem in BCS, near La Paz, and found a small sink of C ranging from -39 g C m^{-2} y^{-1} to -52 g C $m^{-2}y^{-1}$ while Bell et al. 2012, reported a carbon source with values ranging from 62 g C m^{-2} y^{-1} to 258 g C m^{-2} y^{-1} from the same site. While mangrove-lined bays and canals in BCS occupy only 287 km^2 or less than 1% of the State's area (Ruiz-Luna, 2010), they are highly productive and efficient carbon sinks per unit area. Magdalena Bay is one of the largest mangrove-lined lagoon systems in all of the Baja California peninsula with an estimated mangrove area of 22,600 ha (Laguna-Vazquez, 2011; Watson, 2017). Assuming the CO_2 flux values from our site and scaling to the mangrove cover of Magdalena Bay, we estimate a total carbon uptake of 8.94 t C ha^{-1} y^{-1} or 0.20 Mt C y^{-1} for the mangrove areas of Magdalena Bay. According to Muhlia-Melo et al. 2012, GHG emissions for Baja California Sur were estimated to total 1.1 Mt C as CO_2 in 2010. The primary contributors to these emissions were the transportation and energy (electricity and gas) sectors. If the rate of increased emissions at that time (3.48% per year) have persisted to 2021, we estimate a total of 1.6 Mt C as CO_2 emitted per year. With the yearly area estimate of 0.20 Mt of C uptake per year, Magdalena Bay mangroves are estimated to be offsetting emissions for BCS by approximately 12.5%. The limited spatial extent of mangroves habitats reduces their potential for global scale carbon sequestration projects. However due to their efficiency as natural carbon sinks, they can significantly mitigate fossil fuel emission for smaller countries and localized regions (Taillardat, 2018).

While mangrove forests are highly effective in carbon sequestration due to their relatively high levels of primary production, their value as blue carbon sinks is due to their capacity to steadily accumulate and bury that carbon in waterlogged sediment (Taillardat, 2018). Despite their importance, it is estimated that up to 50% of the world's mangrove forests have been lost over the past half century, with a current rate of loss of 1-2 % per year (Alongi, 2009; Sharma, 2020). Rising sea-levels are placing these ecosystems in a 'coastal squeeze', as their ability to adapt to anthropogenic changes is severely restricted by urban development and land use change (Gilman, 2008; Giri, 2011), pollution, mining, aquaculture, and changes in the natural hydrology of these systems, have led to substantial losses and degradation of mangrove habitats worldwide (FAO, 2007; Sharma, 2020; Thomas, 2017). It is of increasing concern if these ecosystems are removed or lost, as they can disproportionately contribute to GHG emissions.Additionally, when mangroves are disturbed or removed, this destabilizes the underlying sediment and exposes it to increased aeration, which can release up to four times as much organic carbon per unit area than other terrestrial forested ecosystems (Hamilton & Friess, 2018). With the potential complete loss of the world's mangrove forests by the end of the century, it is estimated we could see a global loss of 0.21 - 0.45 Gt C y^{-1} as CO_2 to the atmosphere (Hamilton & Friess, 2018).

On a local scale, the loss of mangroves in Magdalena Bay has been minimal compared to parts of Southeast Asia, such as Myanmar and Indonesia (Erickson-Davis, 2018). Mangroves in the bay remain relatively pristine as coastal development is restricted to larger urban centers on the peninsula (Watson, 2017). Historically, mangrove habitat loss in the region was due to the use of the area as a gunnery range by the U.S. Navy in the early 1900s (Whitemore, 2005). Since 1985, mangrove loss has been primarily associated with commercial fisheries, aquaculture, tourism and urban city development (Ochoa-Gomez, 2019; Paez-Osuna, 2003; Whitemore, 2005). On a positive note, Avila-Flores (2019) reports that despite urban growth and development, mangrove area in the La Paz Bay had a 15% overall increase in area of 17 ha from 256 ha to 273 ha between 1974 and 2019. This increase in mangrove area could mean an additional 149 t C y^{-1} in carbon sequestration to offset GHG emissions from the La Paz area.

While this increase in mangrove cover may reflect the unique situation seen in BCS, it provides a good example of the benefits of halting mangrove deforestation, restoring degraded mangroves and implementing conservation plans to reverse the extensive loss of these ecosystems (DFN, 2010; Laffoley, 2009; Romanach, 2018). Some proposed strategies involve using the carbon storage potentials of mangroves as an economic incentive or their inclusion in blue carbon management plans to mitigate GHG emissions (Alongi, 2011; Espinoza-Tenorio, 2019; Gevaña, 2018; Locatelli, 2014). One such proposal is presented by Adame (2018), whose project seeks to secure land along the coast of the Gulf of California, which would enable mangrove adaptation to changes brought on by rising temperatures and provide protection from human activities within a Ramsar Natural protected network area. The project estimates avoided carbon emissions worth \$508,500 per year (Adame, 2018) (\$15 per t CO2; World Bank 2020).

Beyond the avoided emissions of blue carbon sinks, mangroves provide a wide array of important ecological and socioeconomic benefits (Alongi, 2002; Laffoley, 2009). Mangroves provide protection from hurricanes and tsunamis (Alongi, 2008; EJF, 2006); recycle terrestrially derived nutrients and pollutants (Alongi, 2009); act as important nursery and breeding sites for birds, reptiles, mammals, fish and various other marine species, (Alongi, 2002; Nagelkerken, 2008); and extensively contribute to coastal, estuary and deep-sea fisheries (Aburto-Oropeza, 2008; Barbier, 2000). In southeast Asia these ecosystem services have been estimated at an average of \$4,200 US ha^{-1} yr^{-1} (Sanderman, 2018) and globally have been estimated to contribute an annual yield of US \$1.6 trillion in ecosystem services (Aburto-Oropeza, 2008).

4.3 Challenges and future research

The results presented in this study are an important first step in analyzing and quantifying the carbon sequestration potential of Magdalena Bay's mangroves. Further analysis of the importance of tidal regimes, salinity and water chemistry on C sequestration can provide greater insight into this ecosystem's potential to sequester carbon. The results of this study primarily focus on the vertical flux of carbon between the mangrove canopy and the atmosphere. In order to fully determine C sequestration, the fate of tidal transport of litter, particulate and dissolved organic material from the mangroves to the adjacent lagoon and ocean systems needs to be determined. Mangrove forests link terrestrial and marine environments and are important filters and processors of nutrients, toxic materials, and sediments from the upslope terrestrial areas. As a result, mangroves contribute in a major way to the health and productivity of adjacent marine environments (Adame, 2011). Mangroves also export carbon in the form of leaves, plant litter, particulate organic carbon (POC), dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) through lateral flow and tidal effects. It has been estimated that litter export from mangroves averages 202 g C m^{-2} y^{-1}, and is primarily driven by rainfall and temperature (Alongi 2014; Adame 2011). Across all mangroves the mean DOC export is 26.6 g C m^{-2} y^{-1} and is primarily driven by tidal flushing (Alongi 2014; Adame 2011). The lateral export of carbon from mangrove forests to the marine environment is important to consider in future research for its importance in long term C storage.

From our neural network model and data provided by CONAGUA, we saw the importance of performing long term measurements of this ecosystem. Seasonal and annual changes in local climate, rising tides, and extreme weather events can significantly influence these ecosystems potential to sequester carbon, and is important to account for in future research. Although mangroves have been previously protected from exploitation in Mexico by strict environmental laws, management efforts and regulation of natural resources have been largely inefficient due to lack of enforcement and stakeholder conflicts (Hastings & Fischer, 2001). The growing carbon market has created an opportunity to mitigate ecosystem degradation, preserve carbon stocks, quantify ecosystem services and finance environmental conservation (Watson, 2017). Research and the quantification of carbon sequestration potential within mangrove forests, along with the expansion of the blue carbon market can bridge local and international interests and engage local people. This could offer sustainable opportunities for GHG mitigation, biodiversity preservation, and the generation of local livelihoods (Roe et al., 2008; Malagrino, 2008).

5 Conclusions

Efforts around the world to mitigate GHG emissions have increasingly focused on protecting and restoring blue carbon forests and wetlands. These projects provide strong benefits to wildlife and humanity in addition to those of sequestering carbon. Our results demonstrate the importance of the eddy covariance technique as a valuable tool to estimate ecosystem-scale fluxes, over longer temporal scales than previously measured in the area. We estimate that carbon uptake (894 g C m^{-2} y^{-1}) from a semi-arid mangrove ecosystem to be as productive as those of terrestrial ecosystems and mangroves growing in humid climates. PAR, air temperature and VPD appeared to be the major factors determining NEE at a yearly scale, however at a seasonal scale we see their relative contribution shift between winter and summer months. Additionally, in our neural network model we observed that during the latter part of summer large precipitation events coincided with periods of decreased NEE uptake. These rain events during the wet season in conjunction to decreased available light and high temperatures may account for the ecosystem becoming a carbon source during this period.

Further research will be necessary to understand the complete carbon dynamics at this site due to annual and seasonal changes as well as its interaction with the adjacent lagoon to determine the ultimate fate of the carbon. While Mexico has developed strong environmental laws for coastal wetlands protection, these policies have not been broadly enforced at preventing wetland destruction. As wetlands in an already harsh arid environment these coastal ecosystems are especially vulnerable to future impacts from development and climate change. The results presented here represent a first step in the quantitative assessment of mangrove carbon dynamics for Magdalena Bay and their consideration in blue carbon projects. In addition to their beauty, and the multiple ecosystem and economic benefits these mangrove forests provide, their potential as blue carbon sinks warrants their continued protection, conservation and restoration.

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