

# Quantifying farmed kelp atmospheric CO<sub>2</sub> uptake through localized air-sea flux in the Northern Gulf of Alaska

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**Abstract.** The rapid growth of mariculture in the United States, particularly in Alaska, has ignited interest in the co-benefit of using farmed kelp as a mitigation strategy against anthropogenic carbon dioxide (CO<sub>2</sub>) released to the atmosphere. Here, we quantified the air-sea CO<sub>2</sub> flux in two kelp farms in the Northern Gulf of Alaska with differing oceanographic conditions and farming practices to determine the carbon sequestration potential over the growing season. Sensors were deployed on two subsurface moorings placed in proximity of one another at each farm site: one “inside” and one “outside” as a reference upstream of the farm. Both sensor arrays conducted hourly measurements of pH or CO<sub>2</sub>, temperature, salinity, and oxygen during the time from seed line outplanting in winter (November to January) to spring harvest (April or May) in 2024. In Windy Bay, nominal differences in carbonate chemistry parameters were detected between the inside and outside moorings from November to March, when seawater CO<sub>2</sub> within the farm decreased with respect to the reference site. In Kalsin Bay, the inside mooring displayed winter seawater CO<sub>2</sub> values 100 μatm greater than those recorded at the outside mooring, likely due to the colonization of a biofilm on the kelp lines while young sporophytes were not yet mature<sup>2</sup>, however, but seawater CO<sub>2</sub> values at both moorings converged in spring, when the frequency of variability remained consistent between moorings, but their respective magnitude diverged. Notably, apparent oxygen production, seawater CO<sub>2</sub> concentration, air-sea CO<sub>2</sub> flux, and the strength of periodic signals varied by farm site. Integrated over the entire deployment, one farm demonstrated net negative air-sea CO<sub>2</sub> fluxes strengthened the bay’s carbon flux and while one served as a net source of carbon, the other farm experienced carbon outflux over the deployment period: 800.1 ± 145.8 mol m<sup>-2</sup> in Kalsin Bay and -9.23 ± 3.6 mol m<sup>-2</sup> in Windy Bay. This study highlights the nuance of farmed kelp carbon capture by demonstrating that a farm site can influence overall air-sea CO<sub>2</sub> flux, whereby farming structures create artificial habitat and that kelp farms are not always a net sink for atmospheric carbon.

## 1 Introduction

Since the Industrial Revolution, the global ocean has absorbed almost one-third of anthropogenically produced CO<sub>2</sub> (Feely et al. 2004; Quéré et al. 2018), driving a process termed ocean acidification. OA has direct and indirect deleterious effects on marine organisms such as shell dissolution in crustaceans and mollusks (Ries et al. 2016), malfunctioning olfactory responses

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in salmon (Williams et al. 2019), and stunted growth and development across trophic levels (Kurihara et al. 2013; Bignami et al. 2013; Long et al. 2013; Alcantar et al. 2024). ~~If elevated CO<sub>2</sub> emissions to the atmosphere are not reduced, the poorest and most vulnerable human populations are most likely to suffer losses and damages as a result (IPCC 2022).~~ To help curtail the impacts of these climactic changes, efforts to sequester carbon in ocean environments have been proposed and referred to as marine carbon dioxide removal (mCDR). mCDR methods aim to enhance the flux of CO<sub>2</sub> into the ocean through techniques such as ocean fertilization, ocean alkalization enhancement, artificial upwelling, and kelp carbon sequestration (DeAngelo et al. 2023; Oschlies et al. 2025).

The burial of biomass from highly productive organisms, such as seaweed, has shown promise as a sustainable option for capturing carbon through enhanced photosynthesis (Jiang et al. 2013; Ikawa and Oechel 2015). ~~While the nearshore environment generally acts as a source of CO<sub>2</sub> to the atmosphere due to net heterotrophy (Chen and Borges 2009; Cai 2011),~~ Many kelp farms around the world have demonstrated that atmospheric CO<sub>2</sub> can be taken up by kelp and converted into seaweed biomass (Ikawa and Oechel 2015; Jiang et al. 2015; Mongin et al. 2016). In Lidao town, China, a kelp farm exhibited variation in net autotrophic activity throughout the year with the greatest drawdown of atmospheric CO<sub>2</sub> in spring and the least amount in summer (Jiang et al. 2013). However, to achieve climate benefits, kelp farming would need to expand significantly, covering over 90,000 km<sup>2</sup> (Coleman et al. 2022; DeAngelo et al. 2023). Given the scale of such efforts, other, more logistically feasible approaches have been proposed, such as implementing the use of kelp farms to locally reduce atmospheric CO<sub>2</sub> concentrations by shifting the magnitude and timing of carbon cycling and providing a local refugia from against OA. ~~However,~~ There are negative effects to consider when increasing the footprint of kelp farms as well, such as the reduction of marine recreational access, hazards to navigation, and the removal of nutrients when the kelp biomass is removed from the water (National Academy of Sciences, Engineering, and Medicine 2021).

The Northern Gulf of Alaska (NGA) has been identified as a potential site for scaling up kelp farming due to its vast coastline, highly productive waters, and the need to help transition the state economy away from heavy reliance on fossil fuel extraction and unpredictable wild fish stocks (Miller 2021; Bullen et al. 2024; Edgar et al. 2024). As a result, the NGA kelp farming industry expects to expand dramatically in the next two decades, increasing sustainable economic practices in the state with the added benefit of enabling the Alaskan coastal system and adjoining federal waters to potentially take up ~~excess~~ atmospheric CO<sub>2</sub> and buffer seawater carbonate chemistry. Local remediation of OA conditions could improve regional mariculture efforts through the co-culturing of shellfish with kelp with the added benefit of farmed shellfish utilizing macroalgae detritus as a food source (Ries et al. 2016; Haag et al. 2025; Haag et al. 2026). Empirical rate estimates of CO<sub>2</sub> drawdown by kelp from other regions are not universally applicable, due to the site-specific interaction of many physical and biological factors that affect kelp-related CO<sub>2</sub> flux rates (Ikawa and Oechel 2015; Jiang et al. 2015; Mongin et al. 2016). Accordingly, Alaska-specific values are needed, so that we may better assess the climate and local benefits of kelp farming in the NGA.

In the NGA, seeded lines are deployed between October and January, and harvested in late spring before biofouling by epiphytic organisms (Stekoll et al. 2021). Coastal marine ecosystems in the NGA are generally net heterotrophic, aside from

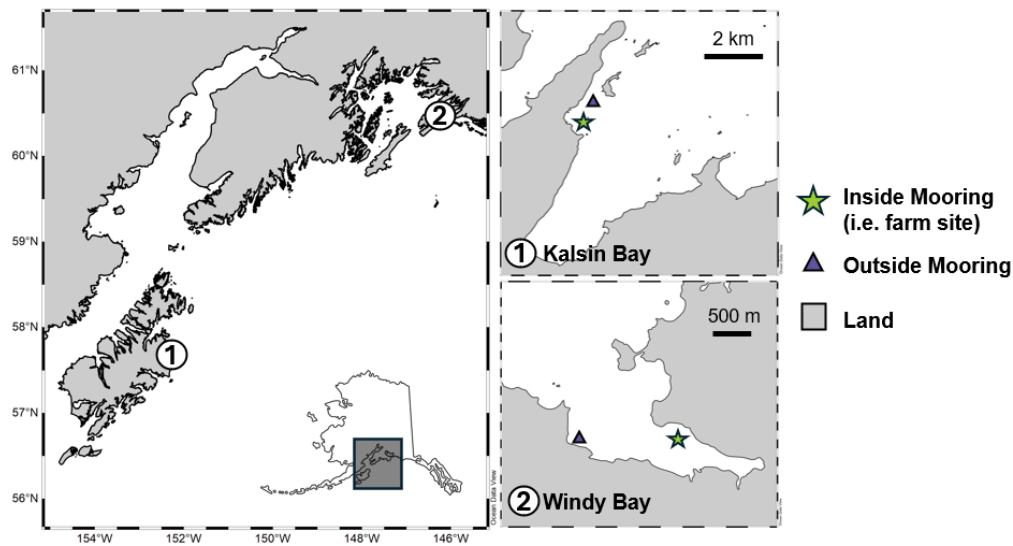
approximately sixty days of net autotrophy in summer and early fall (Miller and Kelley 2021); however, ~~offshore~~ on the continental shelf, the ocean acts primarily as a carbon sink (Evans and Mathis 2013). Currently, there are no estimates of kelp farm air-sea CO<sub>2</sub> fluxes in the NGA, although nearshore macroalgal-dominated habitats can alter carbonate chemistry and create seasonal, localized carbon sinks, ~~signaling the potential to utilize farmed seaweed as one mechanism to reduce atmospheric CO<sub>2</sub> concentrations~~ (Miller and Kelley 2021). This study quantified the air-sea CO<sub>2</sub> flux in two kelp farms in the NGA to determine the capacity of farmed kelp to take-up CO<sub>2</sub> relative to adjacent waters. This study provides empirical estimates of kelp farm-related CO<sub>2</sub> flux, thus ~~identifying-exploring~~ the role that Alaska's kelp farming industry can play in reducing atmospheric CO<sub>2</sub> and highlighting the capacity of farms to ~~offset anthropogenic CO<sub>2</sub> emissions~~ provide refugia to marine species vulnerable to OA.

## 2 Materials and methods

### 2.1 Site descriptions

Two nearshore kelp farms were selected from the Northern Gulf of Alaska (NGA) spanning a distance of 400 km: Royal Ocean Kelp Co in Windy Bay (60.5628 °N, 145.9569 °W) and Alaska Ocean Farms in Kalsin Bay (57.6581 °N, 152.4201 °W) (Fig. 1). The two farm sites varied in size, harvest period, and species grown. Alaska Ocean Farms in Kalsin Bay, in operation for three years, covered 3,200 m<sup>2</sup> and grew only *A. marginata*. Seed lines were outplanted in January and harvested in late May. The depth of the site varied from 9 to 18 m with a tidal range of up to 3 m. The substrate was largely composed of sand. Royal Ocean Kelp Co in Windy Bay covered 12,000 m<sup>2</sup> and contained two catenary arrays: one of *Saccharina latissima* and one of *A. marginata* suspended at approximately 2.2 m and 1.2 m depth, respectively. The eight lines making up each array were spaced 3 m apart. Seed lines were outplanted in October and harvested in early May. The water column depth at the farm

varied from 12 m to 22 m with a tidal range of 5.5 m. The substrate was largely made up of mud. Neither of these sites are glacier-influenced.



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**Figure 1: Map of the two kelp farm study sites: Alaska Ocean Farms in Kalsin Bay and Royal Ocean Kelp Co. in Windy Bay. An “inside mooring” was deployed within the farm and an “outside mooring” was deployed upstream of the farm to act as a reference for background respiration and photosynthesis. The distance between these moorings was 100 m in Kalsin Bay and 600 m in Windy Bay. All arrays suspended 3 m below the surface, roughly the depth of the growing kelp.**

## 90 2.2 Sensor deployments, calibrations, and carbonate system calculations

A sensor array was deployed inside and outside of each farm (Fig. 1). To accurately estimate net integrated air-sea CO<sub>2</sub> flux of kelp farms through the growing season, the outside mooring must be influenced by the same water mass as the farm to capture background photosynthesis and respiration. In general, the “inside” sensor array was positioned as close to the center of the farm as possible and supported by a buoy. The “outside” sensor array was placed on a mooring a distance from the farm to ensure that it was not influenced by the biological activity of the farm while still experiencing the same water masses (Fig. 1).

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Given the different bathymetric and hydrologic features at each farm site, placement distance between the arrays varied; however, the depth of both the inside and outside mooring within the water column were similar across sites. Each sensor array was outfitted with a PME miniDOT optical oxygen logger, an Onset HOBO conductivity logger, a Sea-Bird SeapHOx™ (combination of the SeaFET™ pH sensor and the SBE 37-SMP-ODO MicroCAT CTD+DO sensor) in Windy Bay, and a Sunburst SAMI-CO<sub>2</sub>™ in Kalsin Bay. The sensor arrays were suspended roughly 3 m from the surface, which is the same

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depth as the growing kelp which may misrepresent the flux in highly stratified settings. However, NGA bays experience well-mixed water columns due to ~~the~~ strong tidal mixing (Haag et al. 2023), indicating that in locations without strong freshwater input a sensor placed at 3 m depth would be representative of the near surface. All parameters were measured on a frequency of one hour.

105 Calibration and reference seawater bottle samples were collected by farmers when they visited their farms by lowering a Science First™ 1.5L Water Sampler to the depth of the sensor array and filling 250 mL borosilicate bottles pre-spiked with 200 µl saturated mercuric chloride ~~(see Table A1 for anomalies of reference samples relative to sensor values)~~. During the retrieval of the sensors at each site in spring/summer, a survey was conducted to capture within-farm spatial variability in carbonate chemistry by collecting water samples in a grid formation at the depth of the kelp using the same methods as above.

110 The discrete bottle samples were analyzed for pH<sub>T</sub> (total scale) if complementing the pH sensors or dissolved inorganic carbon (DIC) if ~~comple~~menting the CO<sub>2</sub> sensors, and all samples were analyzed for total alkalinity (TA) and salinity. A Shimadzu 1800 spectrophotometer was used to measure seawater pH<sub>T</sub> using meta-cresol purple as an indicator dye (Acros, batch #30AXM-QN), and applying a dye impurity correction factor (Douglas and Byrne 2017). A DIC Analyzer (Apollo SciTech, Model AS-C6L) coupled to a LI-7815 CO<sub>2</sub>/H<sub>2</sub>O Analyzer measured DIC ~~as well as three different volumes of using a three-~~

115 ~~point calibration of~~ Certified Reference Material (CRM: Batch 172, A.G. Dickson, Scripps Institute of Oceanography) ~~to ensure sample volume variance remained within accuracy~~. A Metrohm 848 Titrino plus measured TA via an open-cell titration and a YSI 3100 Conductivity instrument measured salinity.

The SeaFETs were calibrated using the pH<sub>T</sub> measured from the discrete seawater samples by calculating electrode specific single-point calibration coefficients, which were then used to derive the entire pH dataset (Bresnahan et al. 2014; Miller et al.

120 2018). The HOBO loggers were calibrated with the HOBOWare® Pro software using the salinity and temperature measured by either the CTD within the SeaphOX or ~~temperature-corrected salinity measured within~~ the discrete bottle samples ~~at the lab and temperature recorded by the SAMI-CO<sub>2</sub>. The SAMI-CO<sub>2</sub> timeseries was translated up or down relative to the discrete water samples.~~ The miniDOTs were calibrated using the mean atmospheric pressure and salinity over the deployment. Data can be accessed from the DataONE repository (<https://doi.org/10.24431/rw1k9hb>).

125 Calculations were conducted in R (version 4.4.1) and MATLAB (version R2024b). The uncertainty associated with the pH<sub>T</sub> timeseries was calculated following Bresnahan et al. (2024) and Miller and Kelley (2021). In short, the propagated uncertainty incorporated all sources of possible error in the sample analysis procedure: the difference in the lab measurement of pH<sub>T</sub> and TA on a known CRM bottle versus the expected values, the standard deviation of the duplicate calibration bottle measurements, and the constants error for the CO<sub>2</sub>Sys conversions (version 2.3; Lewis and Wallace 1998). Total uncertainty was calculated

130 by adding the propagated uncertainty to the difference between a reference bottle and the calibrated pH timeseries (following Miller and Kelley 2021). The pH uncertainty was then converted to an in situ partial pressure of CO<sub>2</sub> (*p*CO<sub>2</sub>) uncertainty using a Monte Carlo simulation whereby the pH uncertainty was used to create a series of perturbed pH values for each timepoint (*n* = 10,000) that were then converted to *p*CO<sub>2</sub> using the 'seacarb' package in R (version 3.3.3; Gattuso et al. 2015). When

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summarizing the timeseries data and spatial survey to single means, the standard deviation was reported to capture the natural  
135 variability of the value and not the total uncertainty.

The 'seacarb' package can estimate any carbonate system parameters using two known values. The calibrated pH timeseries  
was used in Windy Bay as the first variable and TA was the second variable calculated from salinity using a known salinity-  
TA relationship for the nearshore of the NGA (Evans et al. 2015; see Fig. A1), while  $p\text{CO}_2$  was directly measured in Kalsin  
Bay for air-sea flux estimates. However, the decomposition analysis required a TA estimation for Kalsin Bay and the Evans  
140 et al. (2015) relationship is not a good proxy for this location based on a sensitivity analysis adapted from Fassbender et al.  
(2017) (see Appendix). A site-specific salinity-TA equation was estimated using a linear model for this purpose (Fig. A1). The  
 $p\text{CO}_2$  timeseries were subsequently used to calculate air-sea  $\text{CO}_2$  fluxes ( $\text{FCO}_2$ ) following Eq. 1 by Wanninkhof (2014):

$$\text{FCO}_2 = 0.251U^2(\text{Sc}/660)^{-0.5}K_0(p\text{CO}_{2w} - p\text{CO}_{2a}), \quad (1)$$

where  $U$  is the wind speed in  $\text{m s}^{-1}$ ,  $\text{Sc}/660$  is the dimensionless Schmidt number,  $K_0$  is the Bunsen solubility coefficient with  
145 units of  $\text{mol L}^{-1} \text{atm}^{-1}$ , and  $p\text{CO}_{2w}$  and  $p\text{CO}_{2a}$  are the  $p\text{CO}_2$  in water and air, respectively. Site-specific wind data was obtained  
from the nearest NDCB buoy to the farm site: Station CRVA2 for Windy Bay located 7 km from the farm and Station KDA2  
for Kalsin Bay located 8 km from the farm (NOAA Buoy Data Center 2024; Fig. A2). The near-surface winds at the farm may  
differ from the wind speed detected at the buoys, therefore giving first-order estimates of the exchange rates rather than precise  
local fluxes.  $p\text{CO}_{2a}$  was assumed to be  $\sim 421.2$  ppm at all sites (McKain et al. 2024).  $\text{Sc}/600$  and  $K_0$  were calculated using the  
150 polynomial equations in Wanninkhof (2014). In the absence of wind, the above equation becomes simplified as per MacIntyre  
(1995) to:

$$\text{FCO}_2 = 0.8K_0(p\text{CO}_{2w} - p\text{CO}_{2a}), \quad (2)$$

since atmospheric exchange continues even when turbulent mixing at the water surface does not occur. The net integrated  
 $\text{FCO}_2$ , a measure of the kelp farm effect, was calculated by subtracting the  $\text{FCO}_2$  estimated for the inside mooring from the  
155 outside mooring for each farm site location and integrating over the entire timeseries. An uncertainty for total net integrated  
 $\text{FCO}_2$  was calculated by propagating the errors associated with each of the sensors and the data pulled from online resources  
through the air-sea flux calculation and integration.

Because since there is no established SAMI-CO<sub>2</sub><sup>TM</sup> sensor post-calibration method—outside that from the manufacturer—  
cannot be “calibrated” like the SeaFET<sup>TM</sup> pH sensor via a single point calibration method, we utilized an independent cross-  
160 validation approach to assess SAMI-CO<sub>2</sub><sup>TM</sup> data integrity. We conducted a stoichiometric cross-validation using hourly  $\text{O}_2$   
data from co-located miniDOT sensors. Assuming a 1:1 stoichiometry ( $\text{O}_2$ :DIC), we calculated  $\text{O}_2$ -derived expected  $p\text{CO}_2$  and  
compared that to the measured time series. The relationship between measured and expected  $p\text{CO}_2$  was evaluated using  
Pearson’s correlation and ordinary least squares linear regression.

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## 2.2 Ancillary data analysis

165 Temperature-salinity (T-S) diagrams were used to determine if the inside and outside moorings experienced the same water mass, since a water mass can be defined by their salinity and potential temperature as those variables remain conserved unless experiencing mixing conditions. T-S diagrams were created by modifying the ‘ggTS’ function (Kaiser 2020), which utilized the ‘gsw’ package to calculate the potential density and plot isopycnals (version 1.2-0; Kelley et al. 2024). Similarities between the T-S diagrams for both moorings would indicate that the outside mooring can act as a reference for the inside mooring. The lag time of the water mass between the outside and inside moorings were characterized by detrending the data and applying a cross-correlation using the ‘tseries’ package (version 0.10-58; Trapletti et al. 2015).

The timeseries at each site was divided into ~~three-two~~ phases in order to compare carbonate chemistry shifts throughout the kelp growing season: heterotrophy, ~~transitional~~, and autotrophy. Net heterotrophy or autotrophy of seawater was determined by calculating the apparent oxygen production (AOP) across the timeseries, which is the difference between the measured *in-situ* oxygen versus the estimated oxygen saturation as a function of temperature and salinity (Garcia and Gordon 1992: equations corrected from Casamitjana and Roget 1993). The shift from net heterotrophy ~~or autotrophy~~ to net autotrophy in spring was estimated as the minimum of the cumulative sum of AOP measured at the outside mooring. ~~the transitional phase was characterized as the first twenty-four-hour period in which average daily AOP shifted from positive to negative or vice versa, and the shift from the transitional phase back to either heterotrophy or autotrophy was characterized as a period of time when daily averaged AOP remained either positive or negative for over one week.~~

The drivers of seawater  $p\text{CO}_2$  were assessed by doing a decomposition of monthly averages of  $p\text{CO}_2$  based on the effects of temperature (T), salinity (S), total alkalinity (TA), air-sea  $\text{CO}_2$  flux ( $\text{FCO}_2$ ), and dissolved inorganic carbon (DIC). The following equations were modified from Garcia-Troche et al. (2021), originally based on pH, to describe observed monthly changes between two consecutive months ( $t_1$  and  $t_2$ ):

$$185 \quad \Delta p\text{CO}_2 = \Delta p\text{CO}_2(T) + \Delta p\text{CO}_2(S) + \Delta p\text{CO}_2(TA) + \Delta p\text{CO}_2(\text{FCO}_2) + \Delta p\text{CO}_2(\text{DIC}) + R, \quad (3)$$

where a change in seawater  $p\text{CO}_2$  from one month to another ( $\Delta p\text{CO}_2$ ) can be described as the changes to the five variables plus a residual (R), which represents any remaining  $\Delta p\text{CO}_2$  not explained by T, S, TA,  $\text{FCO}_2$ , or DIC. Using the ‘seacarb’ package in R, the stepwise calculated change in  $p\text{CO}_2$  between  $t_1$  and  $t_2$  was derived by a single variable at a time to calculate the monthly  $\Delta p\text{CO}_2(T)$ ,  $\Delta p\text{CO}_2(S)$ , and  $\Delta p\text{CO}_2(TA)$ :

$$190 \quad \Delta p\text{CO}_2(T) = \Delta p\text{CO}_{2,2}(T_2, S_1, TA_1, \text{DIC}_1) - \Delta p\text{CO}_{2,1}, \quad (4)$$

$$\Delta p\text{CO}_2(S) = \Delta p\text{CO}_{2,2}(T_1, S_2, TA_1, \text{DIC}_1) - \Delta p\text{CO}_{2,1}, \quad (5)$$

$$\Delta p\text{CO}_2(TA) = \Delta p\text{CO}_{2,2}(T_1, S_1, TA_3, \text{DIC}_1) - \Delta p\text{CO}_{2,1}, \quad (6)$$

Due to DIC exerting an effect on both  $\Delta pCO_2(FCO_2)$  and  $\Delta pCO_2(DIC)$ , as a result of air-sea  $CO_2$  exchange and water column/benthic processes, respectively,  $\Delta pCO_2(FCO_2)$  was calculated first and subsequently used to separate its signal from  $\Delta pCO_2(DIC)$ .  $\Delta pCO_2(FCO_2)$  required an estimate of monthly  $CO_2$  air-sea exchange calculated using Eq. 1 and 2 (i.e.,  $FCO_2$ ), the change in time ( $t_2 - t_1$ , days), seawater density ( $d$ ,  $kg\ m^{-3}$ ), and water column height ( $H$ , m) from Garcia-Troche et al. (2021):

$$\Delta DIC_{air-sea} = \frac{-FCO_2 \times (t_1 - t_2)}{d \times H}, \quad (7)$$

$$\Delta pCO_2(FCO_2) = \Delta pCO_{2,2}(T_1, S_1, TA_1, DIC_1 + \Delta DIC_{air-sea,2}) - \Delta pCO_{2,1}, \quad (8)$$

$$\Delta pCO_2(DIC) = \Delta pCO_{2,2}(T_1, S_1, TA_1, DIC_2) - \Delta pCO_2(FCO_2) - \Delta pCO_{2,1}, \quad (9)$$

The monthly periodicity of  $pCO_2$  was estimated with a power spectral analysis using R package ‘spectrum’ (version 1.1; John and Watson 2020). The span was set to 20 days. A high-pass Butterworth filter (package ‘signal’; version 1.8-1; Ligges et al. 2015) was first applied to remove low-frequency components that can dominate the spectrum. The cutoff was set to 0.01 cycles per hour. The underlying periodicities were plotted to visually determine the dominant drivers of  $pH_T$  frequency.

## 3 Results

### 3.1 Comparison of inside and outside moorings

Comparison of water mass movement at the inside and outside moorings confirmed that both sensor arrays detected similar water masses, ~~allowing for a permitting the~~ calculation of net ~~integrated~~ air-sea  $CO_2$  flux ~~when paired with the inside sensor array~~. T-S diagrams were remarkably similar between inside and outside moorings across ~~all~~ sites, with distinct shifts through time driven by temperature, denoted in the ~~color~~ overlay (Fig. 2). Salinity remained relatively consistent through the deployment period ( $30.0 \pm 0.6$  in Kalsin Bay and  $31.1 \pm 0.4$  in Windy Bay) while temperature at both sites decreased from winter to early spring before warming once again (Fig. 2). The inflection of temperature warming occurred at different times depending on the site: mid-March in Kalsin Bay and mid-April in Windy Bay. The ~~within site~~ cross-correlations measured between salinity and temperature ~~at the paired moorings indicated~~ a lag time of 1 hour according to salinity and 0 hours according to temperature in Kalsin Bay, and 1 hour in Windy Bay for both variables, ~~underscoring demonstrating the~~ strong similarities ~~between~~ ~~at~~ water masses at the inside and outside moorings.

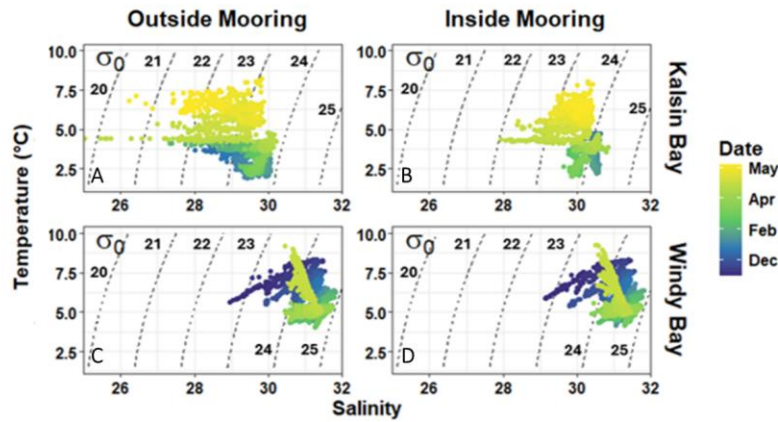
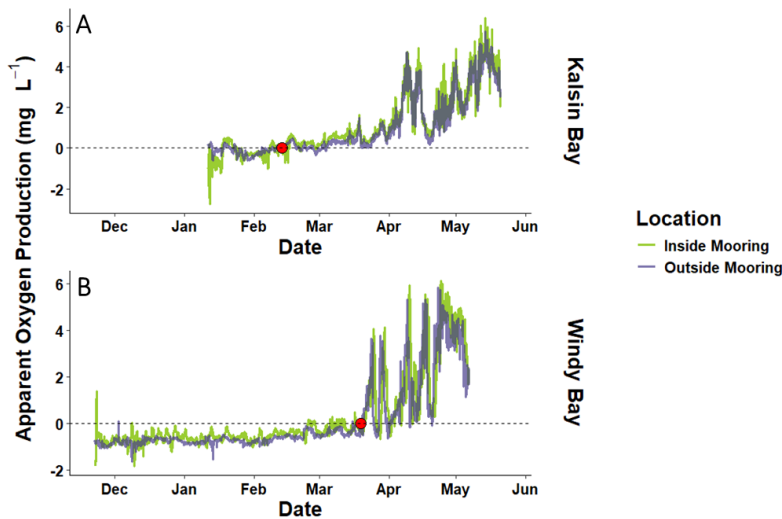


Figure 2: Temperature-salinity diagrams from two locations in the Northern Gulf of Alaska at moorings within kelp farms (inside moorings: **B and D**) and reference moorings upstream of the farm sites (outside moorings: **A and C**). Sensor arrays collected hourly data from 3 m depth. Labelled dashed lines denote isolines of potential density anomaly ( $\sigma_{\theta}$ ;  $-1000 \text{ kg m}^{-3}$ ).

Apparent oxygen production (AOP), the difference between *in situ*  $\text{O}_2$  and  $\text{O}_2$  saturation estimated as a function of temperature and salinity, indicatedemonstrated that both nearshore systems experienced a distinct shift from net heterotrophy to net autotrophy throughout the growing season (Fig. 3). Both sites experienced wintertime net heterotrophy in winter and, as spring progressed, until early spring when AOP neared the solubility compensation point (AOP = 0) where the system shifted to a transitional phase (February 13 in Kalsin Bay and March 20 in Windy Bay) and transitioned into net heterotrophy (on February 12 in Kalsin Bay and March 19 in Windy Bay. The length of this transitional phase varied depending on location: 0 days in Kalsin Bay and 13 days in Windy Bay. Kalsin Bay and Windy Bay became net autotrophic during the kelp growing season on February 13 and April 2, respectively (Fig. 3). At both sites, the inside mooring was characterized by higher net autotrophy than the outside mooring as time neared harvest (Fig. 3).



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Figure 3: Apparent oxygen production (i.e., measured  $O_2$  minus saturated  $O_2$ ) across the farmed kelp growing season and the following summer in Kalsin Bay (A) and Windy Bay (B) both inside the farm (inside mooring) and at the reference site outside of the farm (outside mooring). The dashed line indicates when measured  $O_2$  is equal saturated  $O_2$  and thus denotes the solubility compensation point. The **grey boxes red dots** indicate the transition **at period** from net heterotrophy to net autotrophy in spring.

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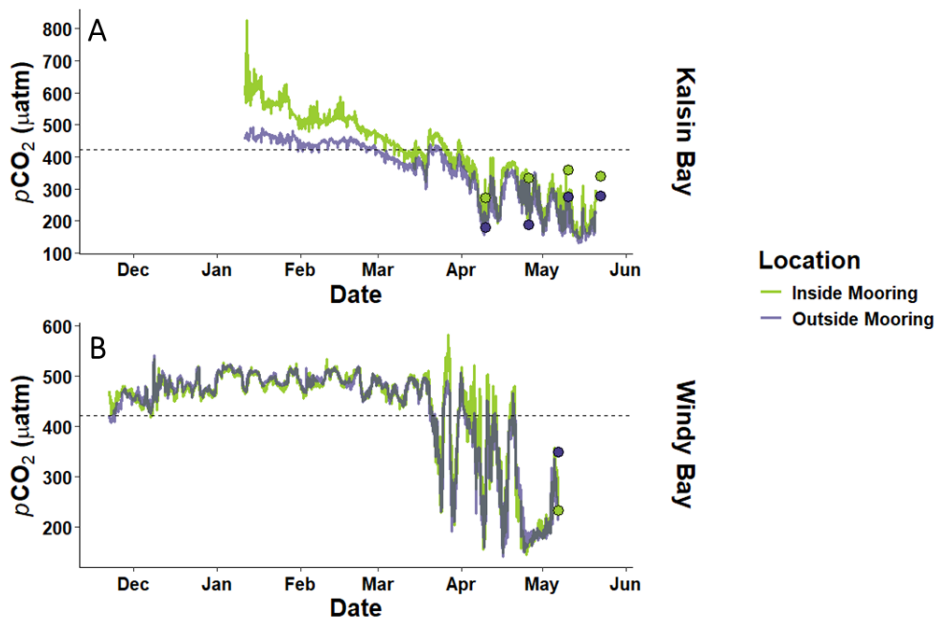
During the **period of net heterotrophy in i.e. winter-wintertime phase described by AOP**, both timeseries **measured outside of the farm** displayed **ambient seawater (i.e. the outside mooring)**  $pCO_2$  values greater than atmospheric  $CO_2$  (i.e.  $421.2 \mu atm$ ; McKain et al. 2024; Fig. 4). In Windy Bay, the inside and outside moorings had associated total uncertainties of  $69.46 \mu atm$  and  $73.73 \mu atm$ , respectively. The average  $pCO_2$  at the outside mooring during this **wintertime** net heterotrophic period was  **$453.8 \pm 15.0 \mu atm$  ( $n = 750$ ) in Kalsin Bay and  $482.2 \pm 22.4 \mu atm$  in Kalsin Bay ( $n = 2840-1175$ ) in Windy Bay and  $482.2 \pm 22.4 \mu atm$  in Windy Bay ( $n = 2854$ ). From the beginning of the transitional period to kelp harvest During the net autotrophy in **spring**, seawater  $pCO_2$  decreased below atmospheric  $CO_2$  at both sites, **Kalsin Bay and Windy Bay**, with a concurrent increase in  $pCO_2$  variability (Fig. 4). The **total** average  $pCO_2$  at the outside mooring during this time was  **$326.5301.3 \pm 94.185.3 \mu atm$  ( $n = 2336$ ) for Kalsin Bay ( $n = 1911$ ) and  $308.1283.2 \pm 100.493.3 \mu atm$  for Windy Bay ( $n = 1159858$ ).****

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The **stoichiometric cross-validation of the SAMI-CO2™ sensor using the miniDOT oxygen sensor confirmed high data integrity, with measured  $pCO_2$  exhibiting exceptionally strong, positive linear correlations with  $O_2$ -derived expected  $pCO_2$  at both the inside (Pearson's  $r = 0.95$ ,  $p < 0.001$ ) and outside (Pearson's  $r = 0.95$ ,  $p < 0.001$ ) moorings. Regression analysis indicated that biological forcing explained approximately 90% of the observed  $pCO_2$  variance ( $R^2 = 0.90$ ) at both sites (Fig. A34).**

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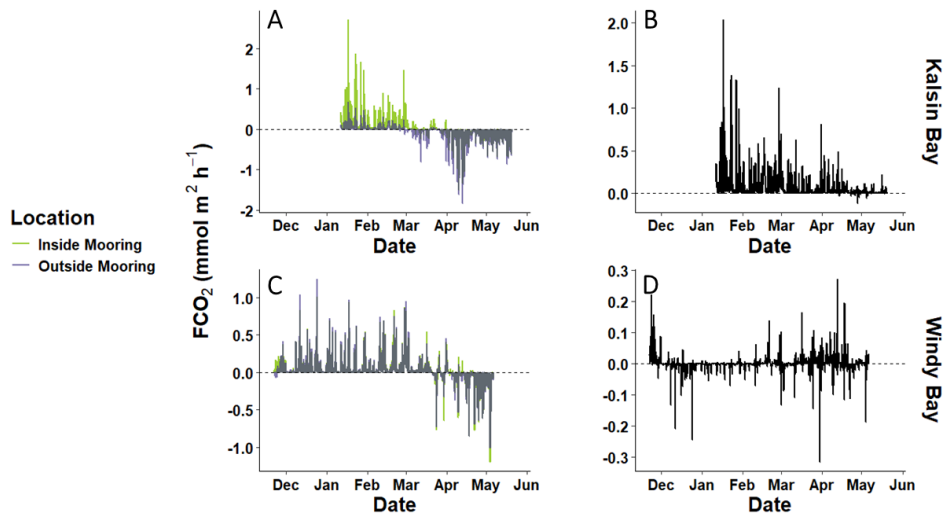


250 Figure 4: The partial pressure of carbon dioxide ( $p\text{CO}_2$ ) in seawater inside and outside of kelp farms across the kelp growing season in Kalsin Bay (A) and Windy Bay (B). The dashed line indicates the atmospheric  $\text{CO}_2$  value which has been estimated to be  $\sim 421.2$  ppm at all sites (McKain et al. 2024). The dots indicate reference samples collected at both the inside (green) and outside (purple) moorings.

### 3.2 Air-sea $\text{CO}_2$ flux timeseries

255 Air-sea  $\text{CO}_2$  flux estimations ( $\text{FCO}_2$ ) for all sites and moorings demonstrated a flux of  $\text{CO}_2$  from the ocean to the atmosphere during the net heterotrophic period indicated by AOP (Fig. 3; Fig. 5). The  $\text{FCO}_2$  for the outside mooring during this period of heterotrophy ranged between  $-0.00245$  to  $0.676599$   $\text{mmol m}^{-2} \text{h}^{-1}$  in Kalsin Bay ( $0.0497 \pm 0.08177$   $\text{mmol m}^{-2} \text{h}^{-1}$ ,  $n = 75072$ ) and  $-0.069$  to  $1.253$   $\text{mmol m}^{-2} \text{h}^{-1}$  in Windy Bay ( $0.0576 \pm 0.111$   $\text{mmol m}^{-2} \text{h}^{-1}$ ,  $n = 284054$ ). As the period of net heterotrophy ended, both sites became carbon sinks. The proportional difference in  $\text{FCO}_2$  between moorings (i.e., the  $\text{FCO}_2$  at the inside mooring divided by the outside mooring) increased at both sites over time (see Fig. A42), demonstrating that as the kelp growing season progressed, so did the difference in  $\text{FCO}_2$  estimated at the paired moorings.  $\text{FCO}_2$  at the outside mooring ranged between  $-1.8362$  to  $0.314227$   $\text{mmol m}^{-2} \text{h}^{-1}$  in Kalsin Bay ( $-0.0814 \pm 0.1748$   $\text{mmol m}^{-2} \text{d}^{-1}$ ,  $n = 2336341$ ) and  $-1.016$  to  $0.456$   $\text{mmol m}^{-2} \text{h}^{-1}$  in Windy Bay ( $-0.0467 \pm 0.1167$   $\text{mmol m}^{-2} \text{h}^{-1}$ ,  $n = 11592492$ ).

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265 Figure 5: The partial variation in air-sea CO<sub>2</sub> fluxes (FCO<sub>2</sub>) across the kelp growing season at ~~three~~ two different sites (A and C) and the net integrated FCO<sub>2</sub> representing the inside versus the outside fluxes integrated over time sensor deployment (B and D).

The influence of the kelp farms ~~created a carbon sink~~ strengthened the carbon sink at Windy Bay, but a carbon source reversed the carbon sink to a carbon source at Kalsin Bay (Fig. 5). Net FCO<sub>2</sub>, the difference in FCO<sub>2</sub> at the inside versus outside moorings representing the farm signal, integrated from the start of the ~~transitional kelp outplanting period~~ (Fig. 2) to harvest was  $800.1 \pm 145.8 \text{ mmol m}^{-2}$  in Kalsin Bay, and  $-9.2 \pm 03.6 \text{ mol m}^{-2}$  in Windy Bay. The small net positive integrated FCO<sub>2</sub> in Windy Bay was due to equal variation in FCO<sub>2</sub> above and below zero throughout the sensor deployment (Fig. 5). The net integrated FCO<sub>2</sub> across the timeseries was within the same magnitude as those of the outside mooring, indicating that large differences were experienced at the inside and outside moorings of both sites.

275 The inside mooring value corresponded with the spatial samples collected at Kalsin Bay at the time of kelp harvest, while the mooring underestimated the FCO<sub>2</sub> of the farm spatial sampling at Windy Bay (Fig. 6). The spatial surveys at each farm indicated a FCO<sub>2</sub> of  $-0.150 \pm 0.183 \text{ mmol m}^{-2} \text{ h}^{-1}$  at Kalsin Bay (n = 8), and  $0.049 \pm 0.007 \text{ mmol m}^{-2} \text{ h}^{-1}$  at Windy Bay (n = 9). The FCO<sub>2</sub> of the sample collected at the outside mooring exceeded the farm samples in Windy Bay, but was lower at Kalsin Bay (Fig. 6). The FCO<sub>2</sub> estimate from the timeseries mooring in Kalsin Bay was within the spread of samples measured discretely at the farm, though one of the discrete bottle samples in the farm was comparable to the outside farm sample (Fig. 280 6). In Windy Bay, mooring values fell below the range measured discretely at the farm (Fig. 6). This spatial survey

demonstrated the homogeneity of FCO<sub>2</sub> at the farm and discrepancy between the mooring timeseries and discrete bottle sample FCO<sub>2</sub>.

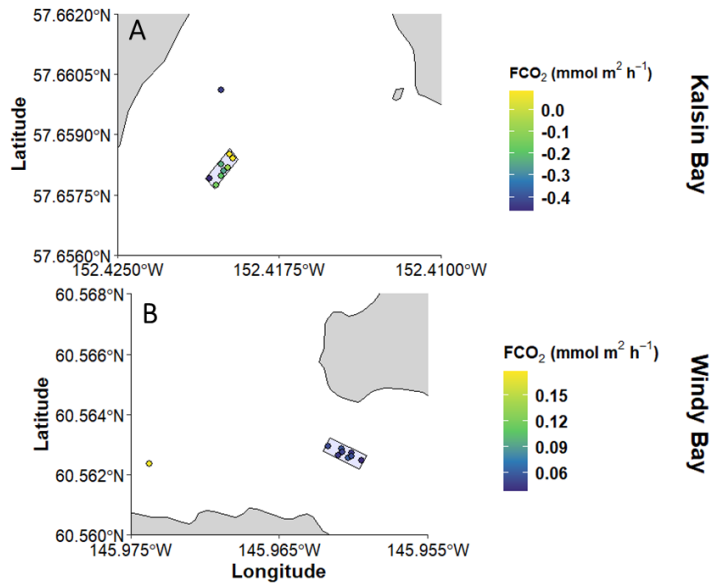
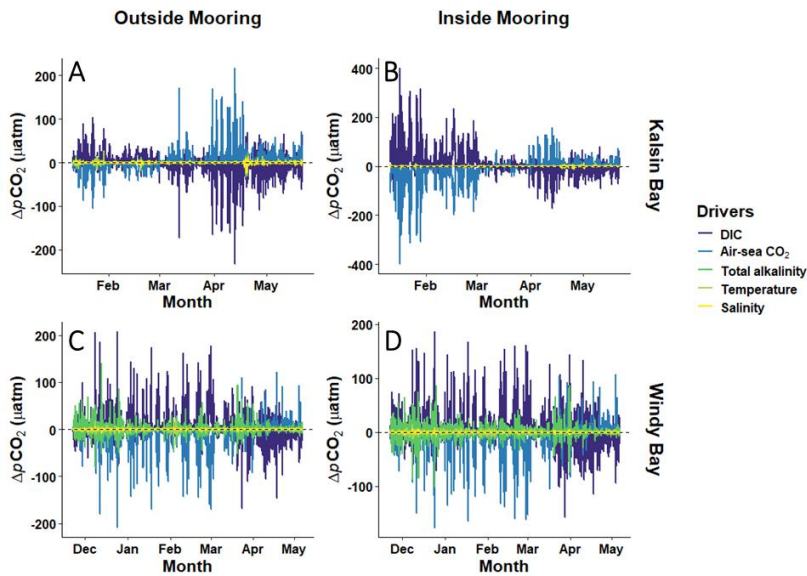


Figure 6: Histogram displaying the spatial variation in air-sea CO<sub>2</sub> fluxes (FCO<sub>2</sub>) across the a kelp farm (denoted by the shaded rectangle) at two different sites directly before harvest: May 22 in Kalsin Bay (n = 9; A) and May 6 in Windy Bay (n = 10; B). The point outside the shaded rectangle denotes the value at the outside mooring. The green rectangles indicate the samples collected as a spatial survey within the farm, the “outside” sample denoted in purple represents the ambient seawater of each bay at a mooring located upstream of the farm, and the dashed line represents the FCO<sub>2</sub> value estimated at the mooring inside the farm at the same timepoint

### 3.3 Drivers of seawater pCO<sub>2</sub>

The seawater pCO<sub>2</sub> decomposition demonstrated that hourly changes to pCO<sub>2</sub> were influenced primarily by biological processes and air-sea flux, as both ΔpCO<sub>2</sub>(DIC) and ΔpCO<sub>2</sub>(FCO<sub>2</sub>) exerted the most considerable change in pCO<sub>2</sub> (Fig. 7). DIC and FCO<sub>2</sub> applied both positive and negative changes to pCO<sub>2</sub> depending on site and time during the kelp growing season, but always as opposing forces. Salinity and temperature played a negligible role in ΔpCO<sub>2</sub> both sites during all months (Fig. 7). Therefore, the concentration of DIC in seawater, controlled primarily by biological processes, and the hourly air-sea CO<sub>2</sub> flux drove the changes in seawater pCO<sub>2</sub>. The five drivers used to decompose the hourly changes in seawater pCO<sub>2</sub> included all major sources of variability in Kalsin Bay but not Windy Bay. In Kalsin Bay, the remaining residuals ranged between -3.8 μatm to 1.04 μatm (-0.01 ± 0.14 μatm, n = 3086) at the inside mooring and -13.2 μatm to 2.6 μatm (-0.04 ± 0.33 μatm, n =

3086) at the outside mooring. In Windy Bay, the remaining residuals ranged between  $-44.5 \mu\text{atm}$  to  $2.4 \mu\text{atm}$  ( $-0.3 \pm 1.6 \mu\text{atm}$ ,  $n = 3997$ ) at the inside mooring and  $-41.5 \mu\text{atm}$  to  $0.7 \mu\text{atm}$  ( $-0.3 \pm 1.5 \mu\text{atm}$ ,  $n = 3997$ ) at the outside mooring. These residuals suggest that an additional moderate source of seawater  $p\text{CO}_2$  was present in Windy Bay but not included as a parameter and was not captured in the decomposition analysis.



305 **Figure 7: Hourly changes in  $p\text{CO}_2$  due to temperature, salinity, air-sea  $\text{CO}_2$  flux, total alkalinity, and dissolved inorganic carbon at Kalsin Bay (A and B) and at Windy Bay (C and D) at a mooring inside the kelp farm (B and D) and a reference site upstream (A and C).**

The power spectral density (PSD) analysis revealed distinct site-specific and monthly differences in seawater  $p\text{CO}_2$  periodicity that suggest diel and tidal cycling to be important drivers particularly as spring progresses (Fig. 8). Frequencies observed at  $2 \text{ day}^{-1}$  correspond to 12-hour cycles likely driven by tidal forcing. This frequency was apparent in Windy Bay, but not at Kalsin Bay (Fig. 8), suggesting that tides play a role in  $p\text{CO}_2$  variability in Windy Bay but not Kalsin Bay. Frequencies corresponding to  $1 \text{ day}^{-1}$ , observed at all sites, also indicate a diel periodicity. The most likely driver of a diel cycle would be irradiance. Although temperature and salinity may change as a product of the day/night cycle, the decomposition of  $p\text{CO}_2$  indicated that these factors played minimal roles in controlling seawater  $p\text{CO}_2$  (Fig. 7). There were multiple peaks  $< 1 \text{ day}^{-1}$ : 0.3 in Kalsin Bay, and 0.3 and 0.6 in Windy Bay. Frequencies at 0.3, and 0.6  $\text{day}^{-1}$  correspond to periodicity in seawater  $p\text{CO}_2$  every 3.3

and 1.6 days. Further, the peaks of PSD grew stronger as the spring progressed with observable peaks beginning in April for Kalsin Bay and in March for Windy Bay (Fig. 8).

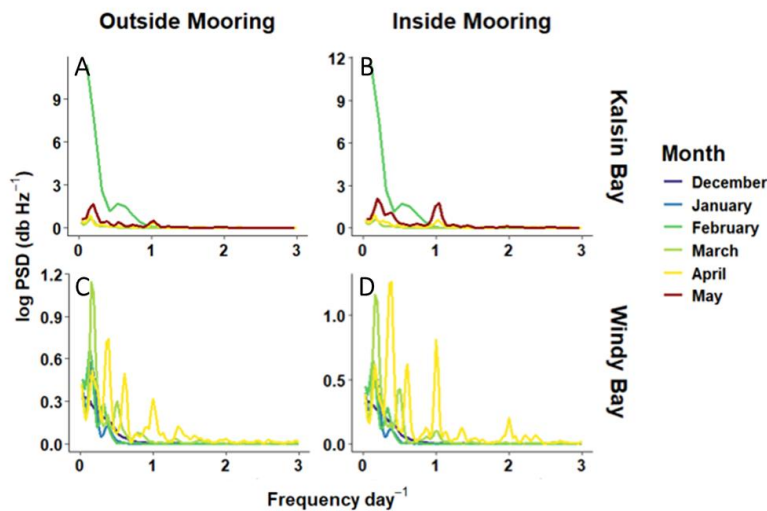


Figure 8: Monthly power spectral density analysis for Kalsin Bay (A and B) and Windy Bay (C and D), inside and outside of the kelp farm at 3 m depth (B and D, and A and C, respectively).

#### 4 Discussion

This study is the first in Alaska to directly measure, at high frequency (hourly), the effect of kelp farming two kelp farms on the seawater carbonate system using four or six-month long sensor deployments recording at high frequency (hourly). Both two kelp farms, located in Kalsin Bay and Windy Bay name them, in located in the Northern Gulf of Alaska (NGA), varied in their magnitude and direction of their influence on nearshore biogeochemistry carbon flux. This study directly measured the effect of farmed kelp on the seawater carbonate system using four or six-month long sensor deployments recording hourly. Across the kelp growing season, which extends from winter to spring, one of the two farms only Windy Bay demonstrated a net negative integrated air-sea CO<sub>2</sub> flux (i.e., carbon moved from the atmosphere to the ocean), while Kalsin Bay exhibited a net efflux of carbon to the atmosphere (Fig. 5). These differing responses are attributed to biological processes which disparately modified seawater DIC and the balance between diel cycling of drove the changes in seawater pCO<sub>2</sub>, largely on a diel cycle (Fig. 7; Fig. 8). This suggests that carbon sequestration potential of kelp farms in the NGA may

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be site-specific. Results from one site cannot be generalized across the region, highlighting the need for studies that compare CO<sub>2</sub> air-sea flux measurements from multiple sites across a heterogenous coastal landscape.

#### 4.1 Influence of site-specific differences in air-sea CO<sub>2</sub> fluxes (FCO<sub>2</sub>)

335 Each site differed in its response to apparent oxygen production, pCO<sub>2</sub> concentration, air-sea CO<sub>2</sub> flux (FCO<sub>2</sub>), and periodicity, demonstrating the need to determine site-specific influences on kelp farm carbon uptake (Fig. 3; Fig. 4; Fig. 5; Fig. 6; Fig. 7; Fig. 8). Both sites experienced a shift from net heterotrophy to net autotrophy in spring, ~~with a transitional period of a few weeks where the system remained near the O<sub>2</sub> solubility compensation point~~ (Fig. 3). The timing of the shift from heterotrophy to autotrophy coincided with the ocean changing from a carbon source to a carbon sink (Fig. 4). The ~100 μatm pCO<sub>2</sub> gradient observed between Kalsin Bay inside and outside moorings during the winter deployment was initially scrutinized given the short distance between moorings of ~100 m. However, the robust stoichiometric coupling between pCO<sub>2</sub> and O<sub>2</sub> (Fig. A34) confirms that, independently, the SAMI-CO<sub>2</sub><sup>TM</sup> sensor and the miniDOT oxygen sensor were observing biologically driven environmental signals. This high degree of correlation (Fig. 4A; Pearson's r = 0.95, p < 0.001; R<sup>2</sup> = 0.90 for both moorings) provides confidence that the observed winter differences in measured pCO<sub>2</sub> between moorings represent a real spatial decoupling and are not the result of sensor malfunction or drift. This ~~The seawater pCO<sub>2</sub> values at the outside mooring in Kalsin Bay displayed values 100 μatm lower than the inside mooring in winter (Fig. 4). The strong correlation between the pCO<sub>2</sub> and O<sub>2</sub> measured from separate sensors at both of the moorings indicate that the data is real (Pearson correlation, R > 0.95, p < 0.001; Fig. A4), suggests~~ that the biofilm observed by the farmer on their kelp lines early in the season may have contributed to the elevated pCO<sub>2</sub> values at the inside mooring (A. Pryor, personal communication, May 22, 2024). The respiration of microbial biofilms, and microbial communities in general, have been shown to significantly affect seawater carbonate chemistry (Magalhães et al. 2003). In Kalsin Bay, the presence of the farm structure allowed an opportunity for the colonization of a microbial community that strengthened the ocean's carbon efflux to the atmosphere, creating an artificial habitat of 3,200 m<sup>2</sup>. As the nearshore transitioned into a carbon sink in spring (Fig. 5), the pCO<sub>2</sub> at the kelp farm converged with the reference site but the farm still resulted in a net integrated carbon sink due to that initial wintertime respiration (Fig. 5).

355 This study ~~provided the first estimates of air-sea CO<sub>2</sub> fluxes within an Alaskan kelp farm but~~ cannot differentiate between kelp species or population level differences. In Windy Bay, both *S. latissima* and *A. marginata* were grown, while only *A. marginata* was grown in Kalsin Bay. Different kelp species exhibit different rates of photosynthesis due to physiology and diverging adaptations to preferred environment (Van der Loos 2019): *S. latissima* has adapted to low-light and low-energy environments while *A. marginata* has adapted to the high-energy, wave-exposed intertidal. Additionally, intraspecific variation in photosynthetic rates between sites may occur, with regional adaptation to local conditions at these NGA farms that are > 300 km apart (Bruhn et al. 2016).

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The farming gear and methods implemented at a given site may also have caused observable differences in the effect of cultured kelp on seawater carbonate chemistry. This study benefitted from studying two established commercial kelp farms, but the locations differed in farm size, line spacing, and seeded line source, all of which can influence kelp growth (Boderskov et al. 2021; [Lexa Meyer, unpublished Umanzor et al. 2025](#)). In Kodiak, AK, decreasing the line spacing limited the growth of kelp blades but resulted in higher total yield ([Lexa Meyer, unpublished Umanzor et al. 2025](#)). Notably, the quality of seeded line produced in hatcheries within the NGA varies significantly as these hatcheries continue to improve production for this nascent industry, and seeding method directly correlates with final yields (Boderskov et al. 2021). The variability of farming techniques across locations, paired with site- and species-specific physiology, makes decomposing the primary drivers of kelp production and subsequent FCO<sub>2</sub> difficult to achieve.

#### 4.2 Drivers of nearshore carbonate chemistry in kelp farms

The short-term periodicity observed in seawater  $p\text{CO}_2$  was accounted for by diel and tidal cycling, [and therefore a heightened biological signal](#), but the longer “event-scale” variability [observable across visible in almost all of all the timeseries](#) have not yet been explained (Fig. 4; Fig. 7; Fig. 8). Across the sites, this variability spanned 1.6 or 3.3-day intervals with periodicities strengthening in April and May (Fig. 7). [In Kalsin Bay, the high  \$p\text{CO}\_2\$ /low  \$\text{O}\_2\$  event \(825  \$\mu\text{atm}\$ , 7.22  \$\text{mg L}^{-1}\$ , respectfully\) observed 12 January 2024 deviated substantially from temporally adjacent observations. The observed anomaly corresponded to an especially high perigean spring tide event beginning 11 January, with a low tide of -0.58 m 05:00 12 January UTC, aligning perfectly with the noted  \$p\text{CO}\_2\$  spike. Tidal pumping, a dominant driver of submarine groundwater discharge flux in coastal Alaska \(Haag et al. 2023\), likely drove this excursion by forcing  \$p\text{CO}\_2\$ -enriched, oxygen-depleted porewater from the surrounding sediment into the water column during the ebbing tide. Cyronak et al. \(2014\), noted tidal pumping can be a dominant driver of  \$p\text{CO}\_2\$  variability in coastal systems, where the drainage of high  \$p\text{CO}\_2\$  groundwater or porewater during spring low tides significantly enhances local  \$p\text{CO}\_2\$ . Event-scale variability has also previously been attributed to phytoplankton blooms, advection of upwelled water, and wind relaxation \(Kapsenberg and Hofmann 2016\). Phytoplankton blooms persist on scales of two to three weeks \(Eslinger et al. 2001\)\), and wind/air-sea exchange played a minimal role in driving changes in  \$p\text{CO}\_2\$  in this study \(Fig. 7\), so these variables are likely not driving observed periodicity \(Fig. 8\). Short water residence times in recessed bays in the NGA can cause elevated mixing with offshore water \(Haag et al. 2023\), and the undersaturated seawater on the continental shelf could act to dilute the inshore  \$p\text{CO}\_2\$  with mixing \(Evans and Mathis 2013\). This mixing with offshore water might explain the event-scale periodicity and remaining residuals from the decomposition of the monthly changes in seawater  \$p\text{CO}\_2\$ . Windy Bay, in particular, demonstrated elevated residuals from the  \$p\text{CO}\_2\$  decomposition, suggesting that our analysis lacked a critical carbon sink at this site. The greatest difference between Windy Bay and Kalsin Bay is the proximity of Windy Bay to the Copper River, the single largest point source of freshwater in the NGA \(Reister et al. 2024\). \[In Kalsin Bay, the high  \\$p\text{CO}\\_2\\$ /low  \\$\text{O}\\_2\\$  event \\(825  \\$\mu\text{atm}\\$ , 7.22  \\$\text{mg L}^{-1}\\$ , respectfully\\) observed 12 January 2024 deviated substantially from temporally adjacent observations. The observed anomaly corresponded to an especially high perigean spring tide event beginning 11 January, with a low tide of -0.58 m 05:00 12 January UTC, aligning perfectly with the noted  \\$p\text{CO}\\_2\\$  spike \\(Fig.\]\(#\)](#)

4) Tidal pumping, a dominant driver of submarine groundwater discharge flux in coastal Alaska (Haag et al. 2023), likely drove this excursion by forcing  $p\text{CO}_2$ -enriched, oxygen-depleted porewater from the surrounding sediment into the water column during the ebbing tide. Cyronak et al. (2014), noted tidal pumping can be a dominant driver of  $p\text{CO}_2$  variability in coastal systems, where the drainage of high  $p\text{CO}_2$  groundwater or porewater during spring low tides significantly enhances

400 local  $p\text{CO}_2$ . While this study is speculative, further research should quantify the relative carbon fluxes in these bays and determine how long the effect of the carbon uptake by kelp persists in these nearshore sites after harvest.

While one of the two kelp farms ~~provided a net drawdown of~~ strengthened the atmospheric drawdown of  $\text{CO}_2$  across the growing season, the hourly  $\text{FCO}_2$  varied from being a source to a sink of carbon, sometimes within the same twenty-four-hour period (Fig. 5). Coastal oceans exhibit strong diel cycles in  $p\text{CO}_2$ , and the NGA was not an exception (Fig. 8; Torres et al. 405 2021). The diel photosynthesis/respiration cycle of primary producers can alter the availability of TA and DIC in seawater, and was the dominant driver of  $p\text{CO}_2$  in the region such that it could drive both positive and negative  $\text{FCO}_2$  should seawater  $p\text{CO}_2$  rise above and fall below atmospheric  $\text{CO}_2$  (Fig. 7; Torres et al. 2021). Wind speed dominates the magnitude of these fluxes, therefore an increasing differential between seawater and atmospheric  $\text{CO}_2$  would still require strong winds to drive  $\text{FCO}_2$  (Eq. 1 and 2). However, wind forcing weakens through spring, which can slow air-sea  $\text{CO}_2$  equilibration (Stabeno et al. 410 2004). Therefore, the timing of wind and air-sea  $\text{CO}_2$  differentials are important when considering the ability of kelp farms to draw down atmospheric  $\text{CO}_2$ , as a mismatch between seasonal winds and the farmed kelp growing season would result in a reduction of  $\text{CO}_2$  uptake (see wind speed in Fig. A2):-

#### 4.3 Carbon credit and ocean acidification mitigation

If one were to consider the uptake of carbon from seawater by a kelp farm, with the assumption that the kelp will be removed 415 from the system through harvest, an estimate of carbon credit capacity can be made using the farm dimensions. The  $\text{FCO}_2$  within each farm was fairly homogenous at the timepoint sampled (Fig. 6), further bolstering the notion that the timeseries measured at the mooring was representative of the entire farm. To account for the ability of Alaskan farmed kelps to use  $\text{CO}_2$  or bicarbonate as a source of carbon, we calculated the carbon credits two ways: we multiplied both the (1) net integrated dissolved inorganic carbon (DIC) and (2) the net integrated  $\text{FCO}_2$  between the inside and outside moorings by the area of the 420 farm assuming the kelp occupied a conservative 1 m depth in the water column. Over the growing season this produced an uptake of DIC into kelp tissue of 4289 tons  $\text{CO}_2$  eq in Windy Bay and a release of 18,269 tons  $\text{CO}_2$  eq in Kalsin Bay, an atmospheric  $\text{CO}_2$  drawdown of 4995 tons  $\text{CO}_2$  eq in Windy Bay, and an atmospheric  $\text{CO}_2$  release of 115,465 tons  $\text{CO}_2$  eq in Kalsin Bay. To sell farmed kelp as a carbon credit, farmers would be required to prevent the harvested biomass from being remineralized by sinking their product off the continental shelf in locations of periodic or permanent anoxia (Pederson et al. 425 2021; Duarte et al. 2025), or by other means, which would leave the carbon credits as the sole source of income for farmers choosing this route. This method would also remove fixed nutrients from the nearshore system and potentially degrade the marine system (citationCampbell et al. 2019), especially if the kelp were grown at scale in this region.

Kelp farms may also act as local refugia against ocean acidification by creating a halo effect of lower-higher pH water in their vicinity, altering the seawater chemistry so that biocalcification is more favorable (Krause-Jensen et al. 2015; Ries et al. 2016).

430 When aragonite is at saturation with respect to seawater, the mineral solubility product in seawater, the aragonite saturation state ( $\Omega_{\text{arag}}$ ) is 1, and seawater  $\Omega_{\text{arag}}$  remained above that value across most of the NGA, except for within the Kalsin Bay farm in winter (Fig. 9). However, the presence of kelp farms reduced-appeared to reduce the aragonite saturation of seawater in Windy Bay both farms which may increase the exposure of organisms to conditions favouring dissolution in future OA conditions if the kelp farm were to scale up, especially during brief windows of opportunity when organisms experience sensitive life stages (Ross et al. 2011). However, in contrast, the Kalsin Bay kelp farm demonstrated no observable change in aragonite saturation (Fig. 9), indicating that this may not be a universal effect of kelp farms in this region.

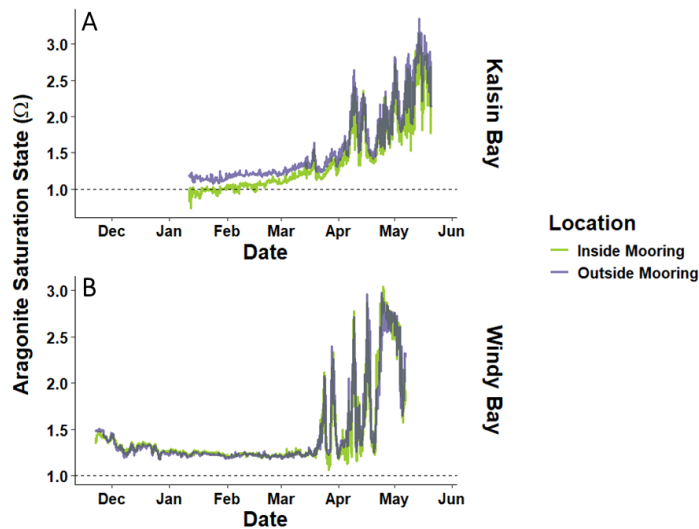


Figure 9: The aragonite saturation in seawater ( $\Omega_{\text{arag}}$ ) inside and outside of kelp farms across the kelp growing season in Kalsin Bay (A) and Windy Bay (B). The dashed line indicates when seawater is at saturation with respect to aragonite ( $\Omega_{\text{arag}} = 1$ ).

440 Estimates of other sources and sinks of kelp-derived carbon in the marine environment are needed to contextualize the effect of farmed kelp, particularly the effect of phytoplankton in controlling the seawater carbonate chemistry. There are extended periods of time during summer where farmed kelp is not present, as it is harvested in early spring and not reseeded until the following winter (Stekoll et al. 2021); however, there are no current estimates in the NGA to the residence time of kelp detritus in the water column. To ascertain the role of kelp farms in carbon cycling, further research should seek to quantify the longevity of kelp influence after harvest and natural drivers of carbon in the nearshore. For example, submarine groundwater

discharge plays a dominant role in nutrient cycling in southcentral NGA due to the high tidal forcing in the area (Haag et al. 2023)—and tides were also demonstrated to be an important driver of seawater  $p\text{CO}_2$  (Fig. 8)—but there are no current estimates for advective carbon fluxes at the sediment-water interface. Future deployments ~~should~~ could pair sensor arrays with current profilers to more directly resolve tidal advection dynamics as this study could not account for the additional uncertainty of tidal reversals and ~~with-measure~~ chlorophyll measurements to determine the ~~abundance~~-biomass of phytoplankton in the water column.

## 5 Conclusions

Kelp farms influenced the seawater carbonate chemistry and air-sea  $\text{CO}_2$  flux in two bays in the NGA. During the growing season, which extends from winter into late spring, the farmed kelp at one of the farms increased the capacity for the nearshore to act as a  $\text{CO}_2$  sink, while the second farm had the opposite effect. A higher capacity of atmospheric carbon drawdown may be attainable at targeted farm sites where kelp farms increase the carbon sink capacity of the ocean if mariculture activities were to scale, though further studies into intraspecific- and interannual variability would be required to actualize a carbon credit market from Alaska's kelp farming industry.

## 6 Appendix

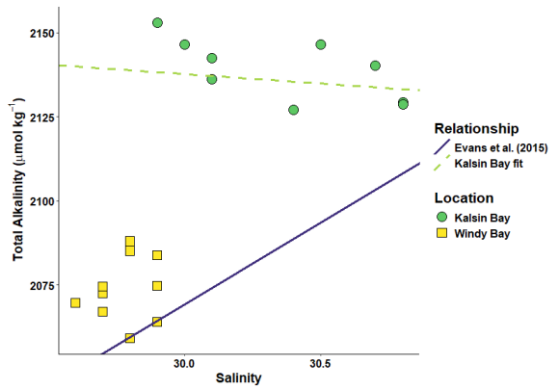
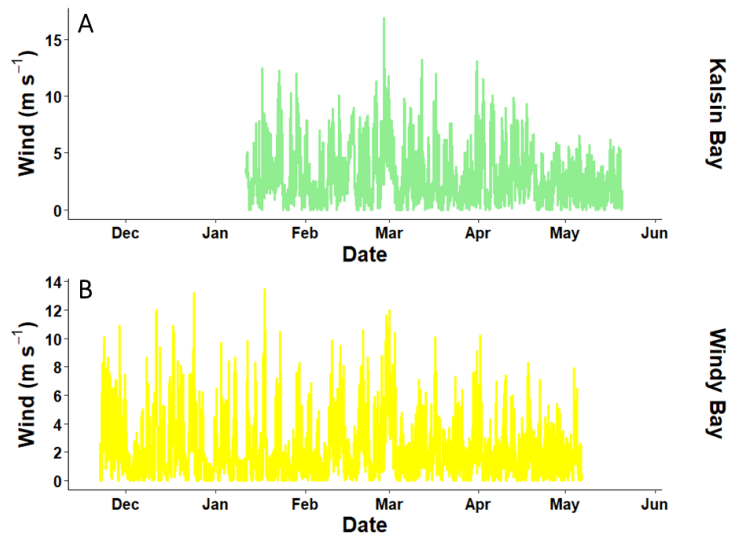


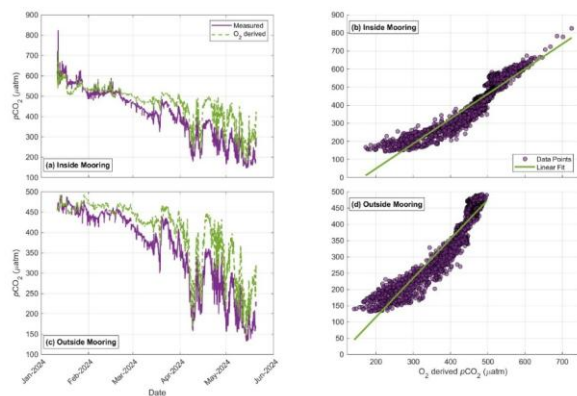
Figure A1. The spread of discrete samples taken at the farm sites at the end of the sensor deployments (May 22 in Kalsin Bay and May 6 in Windy Bay) according to their total alkalinity and salinity. Two salinity-temperature relationships are denoted: one devised by Evans et al. (2015) and one created specifically for Kalsin Bay using the displayed discrete samples.



**Figure A2.** The wind speed measured by NDCB buoys (Station CRVA2 for Windy Bay located 7 km from the farm and Station KDA2 for Kalsin Bay located 8 km from the farm) used to calculate the air-sea CO<sub>2</sub> flux at the two farm sites.

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470 Figure A3. Comparison of autonomous  $p\text{CO}_2$  and  $\text{O}_2$ -derived expected  $p\text{CO}_2$  at the Kalsin Bay kelp farm. Panels (a) and  
(c) display the time-series observations for the inside mooring and outside control mooring, respectively, illustrating  
the coupled oscillations between dissolved gases. Panels (b) and (d) show the linear regression analysis between  
measured  $p\text{CO}_2$  and  $\text{O}_2$ -derived expected  $p\text{CO}_2$  for the inside and outside sites. Tight stoichiometric coupling ( $R^2 > 0.90$ ,  
 $p < 0.001$ ) across both the kelp farm and the reference site confirms sensor functionality.

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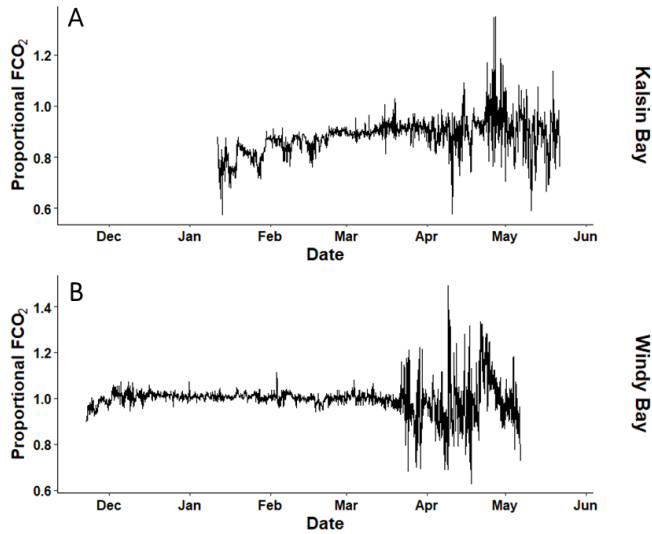
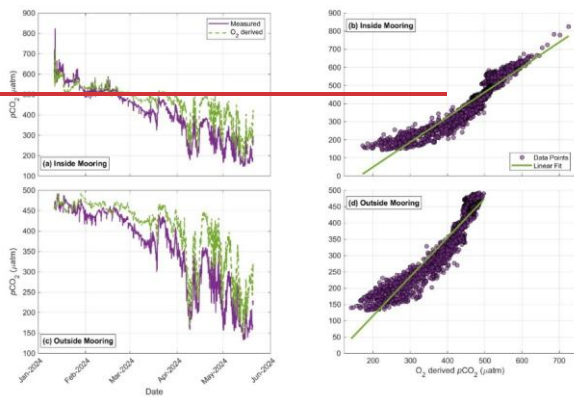


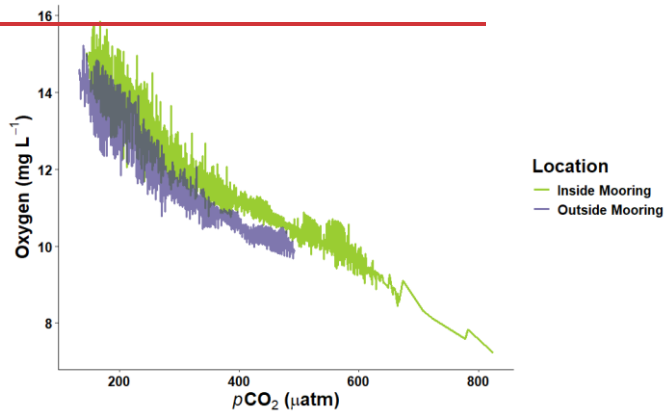
Figure A42. The proportional difference in air-sea  $\text{CO}_2$  fluxes ( $\text{FCO}_2$ ) between the inside of a kelp farm relative to ambient conditions at three Kalsin Bay (A) and Windy Bay (B) different sites calculated by dividing the inside mooring by the outside mooring.

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**Comparison of autonomous  $p\text{CO}_2$  and  $\text{O}_2$ -derived expected  $p\text{CO}_2$  at the Kalsin Bay kelp farm. Panels (a) and (c) display the time-series observations for the inside mooring and outside control mooring, respectively, illustrating the coupled oscillations between dissolved gases. Panels (b) and (d) show the linear regression analysis between measured  $p\text{CO}_2$  and  $\text{O}_2$ -derived expected  $p\text{CO}_2$  for the inside and outside sites. Tight stoichiometric coupling ( $R^2 > 0.90$ ,  $p < 0.001$ ) across both the kelp farm and the reference site confirms sensor functionality.**

**Table A1. The absolute anomalies between sensor-derived  $p\text{CO}_2$  and bottle-derived  $p\text{CO}_2$  at Kalsin Bay and Windy Bay.**

<b>Location</b>	<b>Outside mooring anomaly</b>	<b>Inside mooring anomaly</b>
<b>Windy Bay</b>	<b><math>67.07</math> (<math>n = 1</math>)</b>	<b><math>16.98</math> (<math>n = 1</math>)</b>
<b>Kalsin Bay</b>	<b><math>40.6 \pm 35.5</math> (<math>n = 4</math>)</b>	<b><math>59.5 \pm 58.0</math> (<math>n = 4</math>)</b>

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## 6.1 TA-salinity sensitivity analysis

We adapted the methods of Fassbender et al. (2017) to estimate the sensitivity of  $p\text{CO}_2$  values derived from predicted total alkalinity (TA) values. The sensor arrays deployed in this study did not measure TA, so we wanted to use a known salinity-TA relationship established by Evans et al. (2015) for the region to estimate a timeseries of TA to then estimate  $p\text{CO}_2$  as estimations of the carbonate system require two known variables. We utilized discrete samples measured for TA and one other carbonate chemistry parameter in the lab for this purpose. First, we predicted the TA values for the bottle samples only using salinity and the Evans et al. (2015) relationship. Next, we calculated the residual for the bottle samples predicted TA and the measured TA. Then, we used the ‘seacarb’ package in R to estimate the  $p\text{CO}_2$  for each sample twice, once using the predicted TA and once the measured TA, and compared again the final  $p\text{CO}_2$  values for the sensitivity. The results demonstrated that the Evans et al. (2015) relationship would work for one of the two sites only (Table A2<sup>†</sup>).

**Table A2<sup>†</sup>.** The residuals associated with the difference between the measured total alkalinity and resulting estimated  $p\text{CO}_2$  value and a total alkalinity value predicted by Evans et al. (2015) and its resulting estimated  $p\text{CO}_2$  value. Values are shown as the mean  $\pm$  standard deviation.

Location	TA residual ( $\mu\text{mol kg}^{-1}$ )	$p\text{CO}_2$ residual ( $\mu\text{atm}$ )
Windy Bay	$-15.22 \pm 9.85$	$3.76 \pm 2.47$
Kalsin Bay	$-51.65 \pm 24.32$	$-140.53 \pm 58.49$

We calculated a site-specific salinity-TA relationship for Kalsin Bay as the Evans et al. (2015) relationship massively underestimated the resulting  $p\text{CO}_2$  values (Table A1). Using 6 of the 9 discrete bottle samples, a linear model was created:

$$\text{Total alkalinity} = \text{Salinity} * (-5.613) + 2306.137, \quad (\text{A1})$$

The last 3 discrete samples were treated the same as above, and the final residual for  $p\text{CO}_2$  demonstrated a much better match than the Evans et al. (2015) relationship (Table A2).

**Table A2.** The residuals associated with the difference between the measured total alkalinity and resulting estimated  $p\text{CO}_2$  value and a total alkalinity value predicted by Equation A1 and its resulting estimated  $p\text{CO}_2$  value. Values are shown as the mean  $\pm$  standard deviation.

Location	TA residual ( $\mu\text{mol kg}^{-1}$ )	$p\text{CO}_2$ residual ( $\mu\text{atm}$ )
Kalsin Bay	$-9.62 \pm 4.74$	$-15.40 \pm 6.79$

## 7 Code availability

The code utilized in this project was minorly modified from pre-existing packages or code already publicly available, so it has not been published anywhere.

## 8 Data availability

Data can be accessed from the DataONE repository (<https://doi.org/10.24431/rw1k9hb>).

## 9 Author contribution

AK acquired the funding and designed the project with JH. The investigation and data processing was conducted by JH, AK, and JJ. Formal analysis and writing of the original draft was conducted by JH with aid from AK and CM. All authors contributed to the reviewing and editing of the manuscript.

## 10 Competing interests

The authors declare that they have no conflict of interest.

## 11 Acknowledgments

Samples were collected on the unceded traditional homelands of the Dena'ina, Alutiiq, Eyak, and Sugpiaq and samples were processed on the unceded traditional homelands of the Lower Tanana Dené. Thank you to the kelp farmers who worked with us: Lindsay Olsen and Larry Lansdowne of Spinnaker Sea Farms, Alf Pryor and Lexa Meyer of Alaska Ocean Farms, and Thea Thomas and Cale Herschleb of Royal Ocean Kelp Co. Thank you to Dr. Sarah Mincks, [Dr. Marina Alcantar](#), Jonah Jossart, Alorah Bliese, and Emily Ortega for aid in sample collection/processing, data analysis, and manuscript edits. This research was financially supported by the Rasmuson Fisheries Research Center, the Exxon Valdez Oil Spill Mariculture Research and Restoration Consortium, and the Northern Gulf of Alaska Applied Research Award. [We thank the reviewers, Dr. Simone R. Alin and Dr. Wiley Evans, for their constructive comments and suggestions that greatly improved this manuscript.](#)

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