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PNNL-33489

Autonomous measurements of carbon dioxide uptake in a blue carbon habitat

September 2022

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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BATTELLE
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UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

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Abstract

A better understanding of carbon cycling dynamics in coastal ecosystems is critical to quantify “blue carbon” storage. However, obtaining the necessary measurements is complicated due to the dynamic conditions that characterize these ecosystems, and requires both spatially and temporally resolved measurements of carbon dioxide concentrations and complementary water quality parameters. In this study, we evaluate the use of a utility-class autonomous surface vehicle as a platform for measuring carbon dioxide dynamics in a shallow, intertidal, blue carbon ecosystem. We integrated a carbon dioxide sensor, a water quality sonde, and hydroacoustic sensors with an autonomous surface vehicle and performed measurements in and around a meadow of *Zostera marina* eelgrass. Results demonstrate the utility of this system to provide insight into complex carbon cycling dynamics in and around a shallow, intertidal blue carbon habitat.

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1.0 Introduction

Coastal waters play a key role in regulating the global carbon cycle (Ward et al. 2020). Despite their small global footprint, vegetated coastal ecosystems (e.g., seagrass, mangroves, marshes) sequester disproportionately large quantities of carbon, often referred to as “blue carbon,” compared to inland terrestrial ecosystems (Mcleod et al. 2011). Changes in climate and coastal management efforts will impact the location and extent of blue carbon storage in coastal ecosystems, with the potential to either increase or decrease the efficacy of this carbon sink on a global scale (Lovelock and Reef 2020). Further, targeted restoration of blue carbon ecosystems to increase carbon uptake has been proposed as an approach to enhance marine carbon dioxide removal (National Academy of Sciences Engineering and Medicine 2022). As such, the ability to accurately quantify carbon cycling dynamics that regulate blue carbon storage is an increasingly urgent priority for coastal systems. Seagrass meadows are a blue carbon habitat of particular interest, because they are experiencing global decline due to coastal development and water quality decline (Evans et al. 2018). However, seagrass may serve as an important negative feedback to climate change considering its productivity and resilience may increase in response to increasing marine CO_2 levels (Zimmerman et al. 2017; Zayas-Santiago et al. 2020).

Obtaining the necessary measurements to quantify carbon uptake by seagrass is challenging in the dynamic intertidal and subtidal environments where many blue carbon habitats are found. Sediment cores can be used to quantify historic carbon storage in a habitat (Prentice et al. 2020; Poppe and Rybczyk 2018), but quantifying present day carbon dioxide (CO_2) exchange between sediments, vegetation, the water column, and the atmosphere persists as a challenge. In addition to measurements of carbon dioxide concentrations, measurement of other key environmental variables, such as dissolved oxygen and pH, are needed to understand the biological, chemical, and physical processes controlling dissolved inorganic carbon (DIC) speciation and assess seagrass health. Existing CO_2 sensing systems capable of collecting these data are either designed for open ocean monitoring or for monitoring at a single fixed station. Neither of these solutions can capture the complex dynamics associated with changes in tidal elevation, currents, and shallow and variable bathymetry in nearshore coastal habitats. Stationary monitoring platforms can be deployed in shallow waters and provide the necessary temporal resolution (Polsenaere et al. 2012) but they are not able to capture spatial heterogeneity. Conversely, mobile platforms can provide spatial resolution, and, if surveys are repeated over an extended period of time, can capture temporal changes. However, to our knowledge, measurements of CO_2 uptake in shallow blue carbon habitats have not previously been conducted from mobile platforms aside from labor intensive boat-based surveys (e.g., Caffrey et al. 2014; Joshi et al. 2018).

A variety of autonomous mobile platforms have been used to study the global ocean carbon cycle in the open ocean including autonomous surface vehicles (ASVs) such as the Wave Glider[1] and Saildrone[2] (Sabine et al. 2020). However, these systems are designed for autonomous deployment in the open ocean and cannot function in shallow nearshore environments like eelgrass meadows or kelp forests due to their relatively deep drafts and lack of fine-scale positioning. Further, these systems require extensive engineering to operate with limited maintenance windows, increasing their cost and complexity.

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[1] https://www.liquid-robotics.com/wave-glider/how-it-works/

[2] https://www.saildrone.com/

In this study, we developed and tested a mobile platform designed to measure CO_2 uptake in a shallow, subtidal habitat. Here, we focus on a meadow of *Zostera marina* (Pacific Northwest eelgrass), but the same approach is translatable to other blue carbon habitats. A suite of sensors was integrated with a utility-class ASV and data were collected in and around a meadow of *Z. marina* over the course of a tidal exchange. Our results show the potential of this system to provide insight into carbon dynamics in shallow, intertidal ecosystems and inform future development and application of this sensing methodology.

2.0 Methods

2.1 Autonomous Surface Vehicle

The suite of sensors described in Table 1 were integrated with a 10-foot-long Sea Robotics SR Utility 3.0, utility-class, catamaran hull ASV designed for surveying coastal waters. Sensors were mounted on adjustable pole mounts that were lowered below the hull of the ASV after deployment. A photograph of the instrumented ASV is shown in Figure 1. All sensors were integrated through the ASV data acquisition system so that data could be viewed in real-time by operators on the shore. We note that data from the acoustic Doppler velocimeter and acoustic camera are not presented in this report.

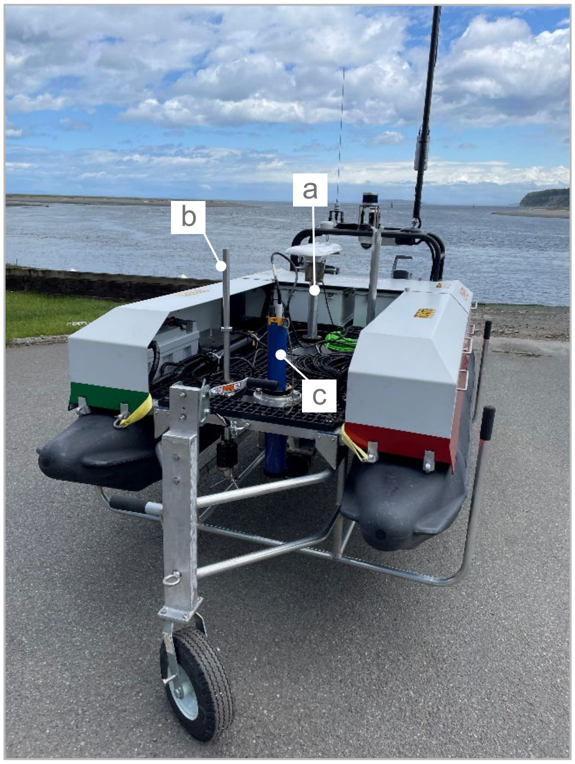

Figure 1: ASV with all instrumentation prior to deployment. Instrument mounts are labelled: a) pole mount for GNSS, ADCP, and acoustic camera, b) pole mount for ADV and CO_2 sensor, and c) water quality sonde.

Table 1: Instrumentation integrated with ASV

Sensor Type	Make	Model	Sample Rate	Position/Orientation on Vehicle

Acoustic Doppler Current Profiler	Nortek	Signature1000 VM	16 Hz	Center, downward-facing
Acoustic Doppler Velocimeter	Nortek	Vector	16 Hz	Forward, transducers oriented downwards
Vessel position and orientation	Advanced Navigation	GNSS Compass	16 Hz	Center, aligned bow-stern
Carbon dioxide sensor	Eosense	EosGP	0.017 Hz (1 sample/minute)	Forward, sensor element oriented downwards
Water quality sonde	YSI	EXO3	0.1 Hz	Forward, snesors oriented downwards
Acoustic camera	Teledyne BlueView	P900	Variable (approx.. 12 Hz)	Center, forward-facing angled approximately 45° down

2.2 Data Collection

The ASV was deployed on July 29, 2022 in the vicinity of an eelgrass meadow located west of the entrance to Sequim Bay, WA, USA (Figure 2). The entrance to Sequim Bay forms a narrow tidal channel with peak currents exceeding 2 m/s, but the eelgrass habitat is relatively sheltered by Gibson spit and experiences relatively low flow velocities. The seafloor around the eelgrass bed is predominantly sandy and transitions to gravelly sand and cobble in the channel. Previous surveys of the eelgrass bed using differential GPS have indicated relatively little year-to-year variability of the extent of the eelgrass, though some variation has been observed towards the north end of the site where water flows out from a lagoon (Personal communication, Amy Borde). A tide gage deployed on the MCRL pier (Whiting et al. 2021) was used for concurrent measurements of tidal elevation.

The ASV was programmed to repeat two survey track lines throughout the tidal exchange. The first track was a curved, south to north transect that followed the shoreline in shallow water over the eelgrass meadow. The second track was a straight line returning north to south, positioned to the east in the deeper tidal channel to facilitate collection of baseline measurements while returning to the start (see a representative survey in Figure 2). Operators kept the speed of the vehicle low (around one knot) over the eelgrass meadow to allow sensors to equilibrate and to minimize the introduction of entrained air bubbles that could interfere with the sensors. Data collection began around low tide (11:05) and continued as the tide rose until 15:00. As the tide rose, the extent of the first track was moved closer to shore to maintain survey depth over the eelgrass. We note that preliminary data collection and operations on July 25 and 28, 2022 informed the final survey strategy.

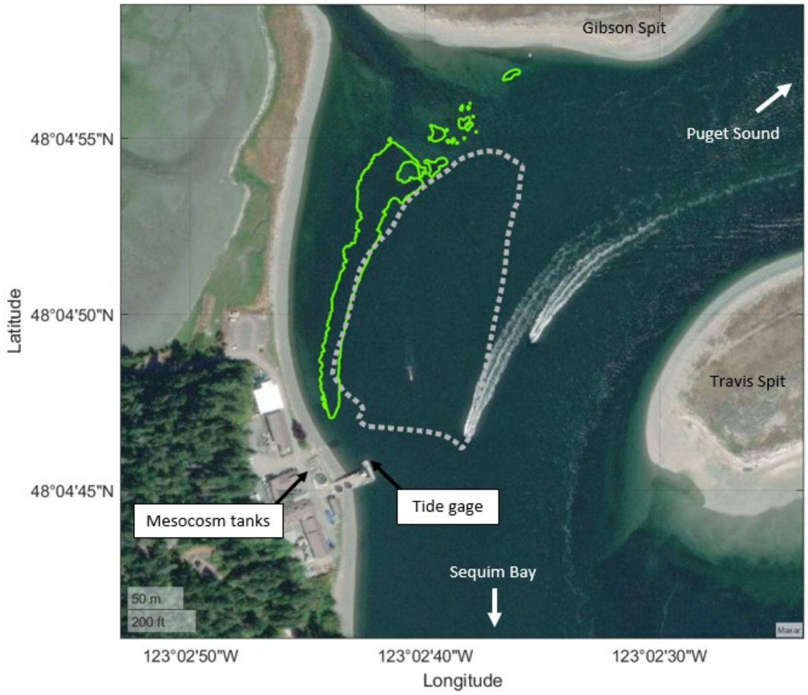

Figure 2: Study area map. The green line indicates the extent of the eelgrass bed measured by differential GPS in 2021 (Personal communication, Amy Borde), and the grey, dashed line indicates a representative survey transect.

2.3 Data Analysis

2.3.1 ADCP

The Nortek Signature1000 VM ADCP has 5 beams – four are used for water velocity measurement and a fifth, downward facing “echosounder beam” is designed for measurements of sediment mobilization, but also provides a measurement of water column backscatter. Both water velocity data and echosounder beam data from the ADCP were used to inform interpretation of the water quality and CO_2 data.

The ADCP was configured to collect velocity data in 0.5 m bins with a 1 m blanking distance (i.e., the first bin represented mean water velocity 1-1.5 m below the sensor) and echosounder beam data in 0.2 m bins. Motion correction to subtract the velocity of the ASV was implemented in the Nortek Signature VM Review software before exporting the data to MATLAB (MathWorks) for further analysis. The Nortek Signature VM Review software also calculates the water depth, which was used to inform the interpretation of data from other sensors.

A thresholding scheme was used to automatically identify whether the ASV was over eelgrass or bare seafloor. First, a 1.5 m window around the depth reported by the Nortek software was isolated. Then, the width, *w*, of the bottom return (determined as the envelope above 71 dB) was determined. Eelgrass was assumed to be present when *w* exceeded 0.7 m and the maximum intensity of the bottom return envelope did not exceed 80 dB. The upper threshold was set to avoid detection of rocks or other instrumentation on the bottom, which had higher intensity returns than eelgrass. An overview of this process is shown in Figure 4. Thresholds were tuned and validated empirically based on correspondence with previously mapped limits of the eelgrass meadow. We note that the echosounder beam was not calibrated so all measurements use the nominal calibration value in the Nortek software and dB values are relative. Further, this approach may require tuning or refinement in different environments with different seafloor substrates or marine flora.

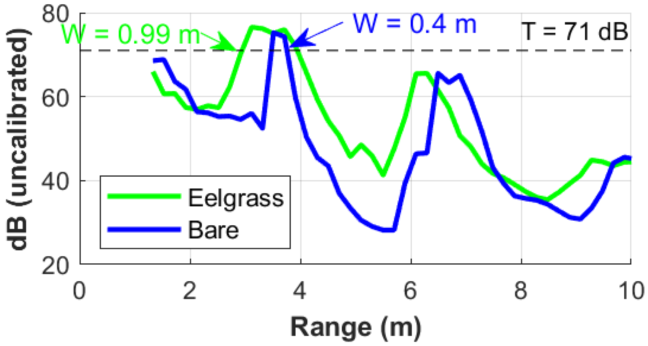

Figure 3: Representative echosounder beam pings showing one ping containing eelgrass and one ping where the ADCP was over bare seafloor. The threshold used in eelgrass detection, T, and the calculated widths of the bottom returns, W, are indicated. The first peak in the signal represents the bottom, while the second, less intense peak, is a reflection on of the surface.

2.3.2 Water Quality Measurements

For CO_2 measurements made underway while mounted to the ASV, a time lag is required to account for the time the sensor takes to equilibrate. We applied a 5-minute lag time (Personal communication, EoSense) to all underway data to correct for the difference in sensor location and water it was equilibrated to when measuring. For the EXO, all sensors are optical or chemical and do not require lagging to account for equilibration.

Because the CO_2 sensor had the slowest sample rate of all sensors (1 minute, Table 1), data from all other sensors (EXO and ADCP) were resampled to the same frequency using the arithmetic mean of each measured variable. Each one-minute sample was determined to be taken over eelgrass if any ADCP pings collected during that minute were determined to contain eelgrass.

3.0 Results

After validating our sensor system in the mesocosms, we integrated CO2 and water quality sensors onto the ASV, as described in the methods. Figure 4 presents measurements made during two survey paths: one at the beginning of the rising tide (“Low”; Figure 4A) and one at the end of the rising tide (“High”; Figure 4B). At lower tidal elevation (“Low”), pCO$_2$ was consistently below atmospheric saturation (mean: 373 ppm) and was lower for measurements over eelgrass (mean: 358 ppm) compared to measurements not over eelgrass (mean: 377 ppm). In addition, temperature, DO, and pH were all consistently higher for measurements over eelgrass (14.6 ºC, 12.1 mg L^{-1} and 8.22, respectively) relative to measurements not over eelgrass (13.6 ºC, 11.2 mg L^{-1} and 8.14, respectively). We note that oxygen saturation for temperatures of 13.6 ºC and 14.6 ºC for ambient salinity and pressure is 10.2-10.4 mg L^{-1}, indicating consistent O$_2$ super-saturation was observed during low-tide conditions.

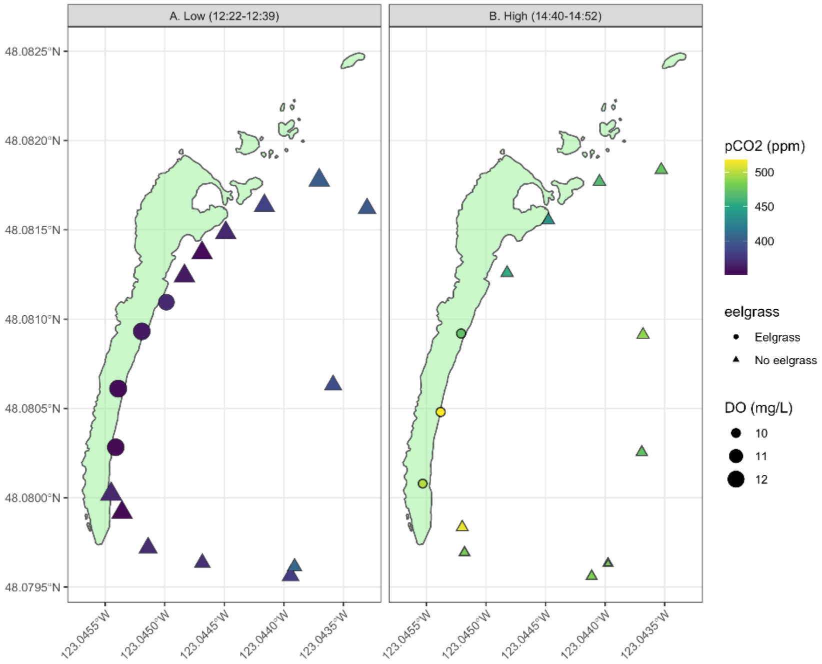

Figure 4: pCO$_2$ and DO measurements collected during two survey paths at different tidal elevation levels: one at lower tidal elevation (“Low”; left panel) and one at higher tidal elevation (“High”; right panel). The shape of each point represents whether eelgrass was detected during the one-minute sampling period, the size of the shape indicates DO, and the color indicates pCO2.

In contrast, at higher tidal elevation (“High”), pCO$_2$ was consistently above atmospheric saturation (mean: 480 ppm) and higher over eelgrass (mean: 496 ppm) compared to not over eelgrass (mean: 475 ppm). Also in contrast to low tide conditions, temperature and pH were the same regardless of proximity to eelgrass (means of 12.3 ºC and 8.02, respectively), while DO was slightly higher over eelgrass (mean: 9.80 mg L^{-1}) relative to not over eelgrass (mean: 9.77 mg L^{-1}). We note that oxygen saturation for 12.3 ºC is 10.7 mg L^{-1}, indicating consistent O$_2$ under-saturation.

To further explore temporal changes in CO_2 dynamics through the tidal cycle, we examined measurements of pCO_2 exchange collected while the ASV was over eelgrass, averaged for each survey path conducted over the deployment period (Figure 5). As tidal elevation increased, pCO_2 consistently increased from below atmospheric saturation to above atmospheric saturation). Concurrent with the increase in pCO_2, we observed decreasing pH, consistent with higher acidity associated with higher pCO_2 levels.

These results indicate that the sensor package was able to measure differences in pCO_2 and water chemistry associated with eelgrass presence at lower tidal elevation, but not at higher tidal elevation. This is consistent with photosynthetic activity during low tide by eelgrass (under-saturation of CO_2 and super-saturation of DO despite warmer temperatures). These patterns are likely also a function of increased water depth, which 1) moves sensors vertically away from the eelgrass bed, 2) increases light attenuation, and 3) increases water circulation and velocity, which complicates measurement of concentration gradients.

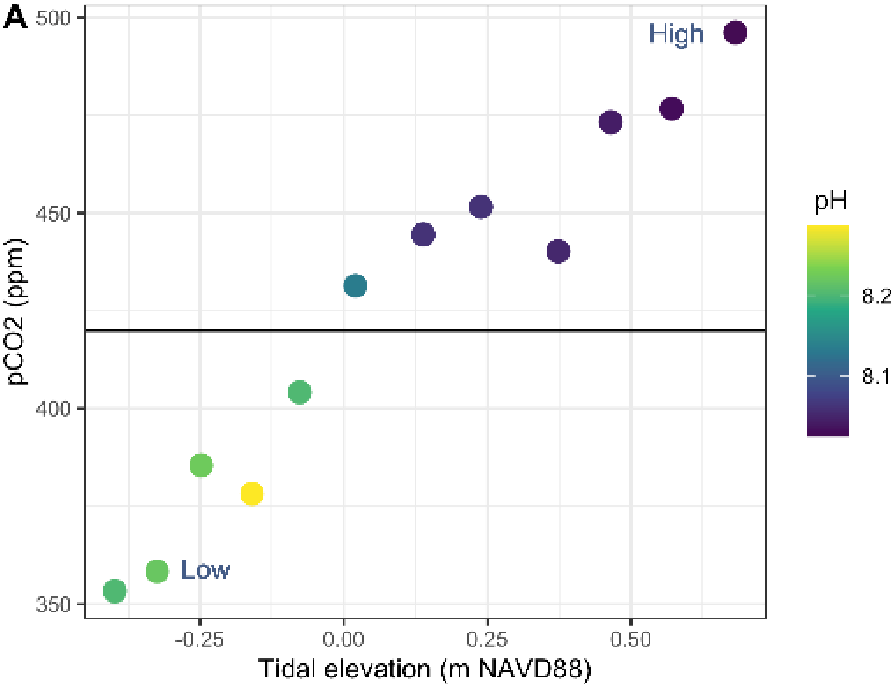

Figure 5: Average pCO_2 for measurements made over eelgrass for the 12 survey paths conducted on July 29, 2022. We note that each point represents the mean value for measurements made over eelgrass, and does not include values not over eelgrass (i.e., in the tidal channel). The two survey paths shown in Figure 8 are indicated.

4.0 Conclusions

In this work, we have demonstrated the utility of a small ASV to quantify carbon dioxide uptake in blue carbon habitats. The autonomous nature and spatiotemporal resolution of the ASV platform pair well with current approaches to monitoring coastal carbon cycling, including underway ship measurements, underwater autonomous platforms, fixed stations, and remote sensing (e.g., Bai et al. 2015; Fassbender et al. 2018; Joshi et al. 2018; Lohrenz et al. 2018; Todd et al. 2019). Fixed stations are spatially limited but would provide benthic measurements to compare with ASV surface measurements. This is of value in hydrologically complex systems like Sequim Bay, where changes in CO_2 are likely a combination of eelgrass activity and changing currents and tidal elevation. Likewise, remote sensing can only detect what is visible from the surface, and requires in-situ measurements (like those made by the ASV) to accurately estimate CO_2 concentrations and fluxes. Remote sensing approaches have typically been deployed over large areas of the coastal ocean (e.g., Valerio et al. 2021) with nearshore environments often masked; however higher resolution optical satellite products may prove useful for the spatial scales covered by this type of ASV survey. We see the ASV platform as an integral component for a system that also includes fixed monitoring stations and remote sensing to scale our understanding of blue carbon from site to regional scales at high spatial and fine temporal resolution.

Acknowledgments

The authors wish to thank Amy Borde and James McVey at PNNL for productive discussion about the sensors and test site, and Madison Bowe for assistance with sensor maintenance, and Alex Turpin for assistance with ASV operations. The research described in this paper was conducted under the Energy and Environment Directorate (EED) Mission Seed Laboratory Directed Research and Development Program at Pacific Northwest National Laboratory, a multiprogram national laboratory operated by Battelle for the U.S. Department of Energy. PNNL is a multi-program national laboratory operated for the U.S. Department of Energy (DOE) by Battelle Memorial Institute under Contract No. DE-AC05-76RL01830.

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National Laboratory

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