Monitoring the Environmental Quality of Florida Keys Canals

Final Report

Prepared for the Village of Islamorada, Monroe County, Florida

FIU
Institute of Water and Environment

Monitoring the Environmental Quality of Florida Keys Canals

Project Report

Prepared for:

The Village of Islamorada
Monroe County, Florida

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Executive Summary

A massive network of man-made canals was built in the Florida Keys during the 1950's to increase the number of waterfront homes. Since their construction, many canals have become traps for marine organic matter as well as polluted groundwater, largely due to on-site wastewater management and nutrient run-off. Many of these canals are showing typical symptoms of unhealthy, eutrophic water that violate mandated water quality standards. In their current state, many canals also disrupt the ecosystem balance in protected adjacent waters and affect human health and property value.

To improve water quality in these canals and minimize their effects on the protected waters of the surrounding Florida Keys National Marine Sanctuary, governments within the Florida Keys have integrated multiple types of technologies to determine the most feasible option for larger-scale water quality improvement efforts. This project assesses the effectiveness of these re-engineered canals by comparing post-treatment canals with nearby controls and pre-treatment conditions. Further, six canals in Islamorada have been measured as part of a separate, concurrent monitoring program which act as additional references for water quality and preliminary measurements as local communities improve wastewater management practices. This report measures the status and change in water quality using organismal and chemical indicators including seagrass, macroalgae and sediment composition that are well established proxies for water quality in South Florida.

Canal monitoring was conducted from 2014 to 2019 in 25 canals, including 8 with remediation technologies, that tested the effectiveness of installed aerators and culverts, organic removal and sediment backfilling. Air curtains and aerators offer low-cost solutions to water quality issues, though improvements from these types of remediations are expected to be gradual. Positive effects of these technologies were not measured in the short period of post-treatment monitoring that was conducted for this project. Culverts may be an effective option to remediate canal conditions, though have site-specific requirements for installation and effectiveness. The effectiveness of culverts as measured through this project show mixed results between recipient canals. Backfilling and organic removal showed immediate and drastic improvements in environmental conditions, though observations suggest further steps may need to be taken to preserve the conditions that these technologies quickly generated. Local interest and legal mandates drive water quality initiatives, though the success of improvement efforts relies not only on the technology itself, but also upon landscape configuration, larger environmental patterns, and site history.

Not all demonstrated remediation technologies can be expected to improve environmental conditions in the short period of time covered in this report, thus continued monitoring efforts are key to understanding the long-term effectiveness of remediation technologies. Further, the high-resolution benthic data presented here, compared to data collected after the devastating 2017 Hurricane Irma, will offer a rare opportunity to evaluate how nearshore environmental health and remediation respond to an intense storm event. Islamorada canals generally displayed better water quality conditions than those observed in the demonstration canals, and future monitoring will be helpful to understand how regional water quality initiatives are impacting these canals.

Contents

1 Introduction

Many homes in the waterfront neighborhoods of the Florida Keys (Monroe County, FL) sit on property adjacent to a network of residential canals. These canals provide navigational access to nearby coastal waters and should increase property value and aesthetic appeal of waterfront lots. However, many of these residential canals do not currently meet the State's minimum water quality standard, which has raised public health and environmental concerns (AMEC Environment & Infrastructure 2012). Monroe County and AMEC Environment & Infrastructure Inc. have worked to create a Canal Management Master Plan, with an objective to provide flexible and cost-effective solutions that improve canal management practices throughout the Keys that are also ecologically sound (AMEC Environment & Infrastructure 2013). The nearshore waters of Monroe County are part of the Florida Keys National Marine Sanctuary (FKNMS), a federally protected marine area. The FKNMS Water Quality Protection Program (WQPP) became concerned by the current state of these canals and has listed impaired water quality in residential canals as a priority for corrective action in the WQPP Action Plan (AMEC Environment & Infrastructure 2013). In 2014, Monroe County began the implementation of a series of demonstration restoration projects across a subset of residential canals (hereafter "demonstration canals"), aimed to improve water quality and serve as examples of the efficacy of various proposed canal restoration technologies. This report presents results from the Benthic Habitat Monitoring portion of the Water Quality Monitoring Program for Monroe County demonstration canals as well as baseline monitoring of additional residential canals in the Village of Islamorada.

1.1 Understanding Canals with Poor Water Quality

There are over 500 man-made canals in Monroe County spanning the Florida Keys, many of which exhibit signs of poor water quality and environmental conditions. These man-made canals vary widely in their length, location, use and environmental context. However, impaired canals share similar symptoms of poor water quality: high nutrients, low oxygen and high turbidity, among others (AMEC Environment & Infrastructure 2012). Poor water circulation may not be the fundamental cause of impaired waters, though it does allow unwanted chemical components like excess nutrients and man-made chemicals to accumulate. Accumulated materials can be directly harmful, like heavy metals, or cause unwanted conditions like algal blooms, turbid waters or the proliferation of harmful bacteria. Poor circulation also prevents the replenishment of oxygen required for fish, lobsters and other animals typically found in nearshore South Florida. Man-made canals are often dead ends, containing a single connection with open waters, allowing material to enter and accumulate, but preventing it from flushing out into the fresh, marine water from adjacent areas.

Further, the narrow width and relatively deep water of many canals may prevent the wind-driven mixing of water. Bottom waters and rears of canals are particularly problematic for circulation where canal length, physical configuration and bathymetric profiles (e.g. sills at the mouth) prevent any mechanisms to flush stagnant water back out to sea. The lack of circulation and flushing allows for the accumulation of organic debris from both terrestrial and marine sources. Dead seagrass and algae (referred to as "wrack") float on the surface of seawater where it can be driven into canals by wind and currents (Fig 1.1). Once it begins to decompose, wrack sinks to the bottom of canals where it evades flushing and circulation. This inorganic material continues to decompose on the bottom where it consumes oxygen required for animals and plants, releases nutrients that fuel algal blooms, produces CO_2 which forms an acid in water that corrodes limestone bedrock, and releases noxious, rotten-egg scented hydrogen sulfide gas.

Figure 1.1: Seagrass wrack blown into Canal 263 floats on the surface before it sinks to further accumulate within and impair the bottom waters

When seagrass wrack and other organic matter sinks and has not completely decomposed, the remaining material can create a fine, low-density muck that accumulates over time, and in some cases can become several meters thick (Fig. 1.2). Seagrass and algae found in South Florida are adapted to the sandy, carbonate sediments of the Florida Keys, though are poorly suited for growth in the low-density, unconsolidated organic material found in impaired canals.

Canals in Monroe County with poor water quality share similar symptoms (low dissolved oxygen, high hydrogen sulfide, lack of marine plants and animals), though the exact mechanisms that induce poor conditions can vary between canals of different sizes, shapes and orientations. For example, problems with canals downwind of seagrass meadows are likely to stem primarily from high inputs of organic material, whereas impaired canals with deep or complex bathymetries are more likely to arise from poor circulation. The various technologies showcased in the demonstration canals have been previously proven as effective for improving water quality and environmental conditions, though their effectiveness in the Florida Keys depends on whether canal-specific mechanisms of impairment are addressed by technological solutions. This report addresses the effectiveness of demonstrated technologies through the monitoring of animal, benthic and sediment characteristics.

Figure 1.2: Seagrass wrack and impaired water accumulating inside a canal. Over 80 cm of lightweight organic material has settled within this canal on eastern Big Pine Key. The sediment surface consists of dead plant material rather than sand, making it unsuitable for plant growth and as a habitat for benthic animals.

1.2 Canal Monitoring Program in Islamorada

The Village of Islamorada is interested in understanding how the ongoing changes from residential on-site wastewater management to municipal sewage will influence water quality in local canals and nearshore waters. Beginning in Fall 2015, canals in Islamorada scheduled or undergoing changes in wastewater management were monitored using indicators and methods already used in a concurrent monitoring effort in other Florida Keys canals (see Section 1.3). By winter 2016, a total of 6 canals were added to Florida Keys canal monitoring efforts as part of a separate, but concurrent monitoring program (Table 1.1). The selection of these canals was based on changes in local wastewater management rather than water quality or the likelihood for improvement unlike those in the demonstration project. Therefore, these canals varied in intensity and type of impairment.

Islamorada Canals

Six canals were monitored in Islamorada during the concurrent monitoring program of demonstration canals in the Florida Keys (Table 1.1). Of these, Canal 145 was the only one that appeared to have significant wrack accumulation like those in the Demonstration project. This canal was located on Lower Matecumbe Key, adjacent to two demonstration canals, 147 and 148, suffering from wrack loading and accumulation from the coastal Atlantic Ocean. Another canal, Canal 114 shares a similar length and shape as Canal 147, though its location within Tavernier Creek blocks the influx of material. However, as Canal 114 is located near the Overseas Highway, industry and residential homes along with poor circulation have caused the introduction and accumulation of nutrients and other unwanted materials. The remaining Islamorada canals (118, 120, 150 and 152) all face Florida Bay and are comprised of longer, branching networks of canals lined with dense construction, including residential and commercial properties. Water quality issues in these canals likely stem largely from nutrient influx, septic effluent and poor circulation more than from the influx of nearshore organic material.

Table 1.1: Canals part of the concurrent monitoring project in Islamorada

Canal	Latitude (˚)	Longitude (˚)	Location	Demonstration project
114	25.00055	-80.53331	Tavernier Creek	Small network with primarily houses
118	25.00093	-80.53887	Near Cross Bank	Contains fueling and repair stations
120	24.98946	-80.54708	Near Cross Bank	Small network with primarily houses
145	24.87440	-80.69989	Eastern Lower Matecumbe Key	Wrack influence, faces Atlantic Ocean
150	24.85927	-80.72613	Western Lower Matecumbe Key	Half-lined with natural vegetation
152	24.85748	-80.73173	Western Lower Matecumbe Key	Small network with primarily houses

1.3 Review of Demonstration Projects and Technologies

Remediation technologies are designed to mitigate issues related to wrack accumulation, poor water quality and limited circulation. Many canals in the Florida Keys exhibit these signs of impaired waters, and 10 canals were selected to demonstrate and test remediation technologies that could be deployed at a larger scale. These canals were selected based on their current water quality, potential for improvement, public benefit, and public funding support (AMEC Environment & Infrastructure 2013). Five types of technologies (Table 1.2) were matched to the 10 canals (Table 1.3), either alone (one technology in a single canal) or in combination (multiple technologies in a single canal) using preliminary knowledge of canal construction and water quality problems. Of the 10 canals selected for demonstration projects, only 8 projects were ultimately implemented.

Table 1.2: Demonstrated canal water quality remediation technologies and their characteristics

Type	Description	Issue addressed	Benefits	Drawbacks
Air curtain	Wall of mechanically driven bubbles span the canal mouth	Prevents additional wrack entry from outside canal	Modest upfront cost	Continued maintenance and power requirements, slow improvements expected
Aerators	Introduces mechanically driven air bubbles to canal bottoms	Increases oxygen in water and circulation	Modest upfront cost	Continued maintenance and power requirements, slow improvements expected
Backfilling	Adds inert sediments to fill deep canal portions	Increases circulation and light penetration to the bottom	Immediate changes in environmental conditions, no continued expenses	Expensive
Organic removal	Dredges accumulated organic material	Removes decomposing material	Immediate changes in environmental conditions, no continued expenses	Expensive
Culvert	Subaquatic connection between canal rear to adjacent water bodies	Increases circulation	Intermediate upfront cost, no continued expenses	Requires particular canal orientation and water movement to be feasible
Pumping	Mechanically drive additions of water to canal rear	Increases circulation	Modest upfront cost	Continued maintenance and power requirements, slow improvements expected

Demonstrated Technologies

Air Curtain

A wall of small bubbles spanning the width of the canal mouth prevents the entry of lightweight and slow-moving material inside. Bubbles are created by an air pump stationed on land, which is connected to a distribution system set up underwater across the canal mouth. The resulting bubble curtain prevents the entry of wrack and other organic material into the canal, while still allowing boat traffic to proceed. Air curtains require a modest upfront investment along with continued expenses in the form of maintenance and electricity. As this technology addresses incoming organic material rather than material that has already accumulated, improvements in water quality stemming from air curtains are expected to be gradual.

Table 1.3: Canals selected to demonstrate remediation technologies and their designated experimental controls.

Canal	Latitude (˚)	Longitude (˚)	Location	Demonstration project
28	25.16462	-80.38565	Key Largo	Control for 29
29	25.16392	-80.38568	Key Largo	Backfilling
132	24.95726	-80.56543	Plantation Key	Control for 137
137	24.95358	-80.57216	Plantation Key	Air curtain
147	24.87021	-80.70116	Lower Matecumbe Key	Control for 148
148	24.86823	-80.70314	Lower Matecumbe Key	Air curtain
263	24.69951	-81.34843	Big Pine Key	Control for 266
266	24.69879	-81.34821	Big Pine Key	Organic removal and air curtain
277	24.69159	-81.35619	Big Pine Key	Culvert
282	24.68451	-81.35288	Big Pine Key	Control for 277
278	24.68695	-81.37798	Big Pine Key	Pumping
287	24.67704	-81.34491	Big Pine Key	Air curtain
288	24.67627	-81.34374	Big Pine Key	Control for 287
290	24.67504	-81.34186	Big Pine Key	Organic removal and air curtain
293	24.67441	-81.34135	Big Pine Key	Control for 290
458	24.58507	-81.64876	Geiger Key	Control for 459
459	24.58432	-81.64902	Geiger Key	Culvert
472	24.57785	-81.65470	Geiger Key	Culvert
476	24.57641	-81.65692	Geiger Key	Control for 472

Aerators

Aerators introduce oxygen-rich air into the bottom of canals where high bacterial production and stagnant waters have depleted oxygen concentrations. Oxygen is a fundamental indicator of water quality as it is required for fish survival, rapid decomposition, plant health, the prevention of hydrogen sulfide formation, and a number of other important environmental conditions and processes. This technology is similar to air curtains, where an air pump on land is connected to a series of heads located on the canal bottom, which release small air bubbles into the water column. Like air curtains, aerators require a modest upfront investment for parts and installation but require continued investment for power and maintenance costs.

Pumps

In long canals where terminal sections lack circulation or mixing, pumps can be installed to force water to be replenished. Pumps actively move water into or out of terminal canal areas, forcing circulation where there previously was none. A pump was proposed for Canal 278 but was never implemented due to insufficient project funding.

Backfilling

Most canals in the Florida Keys were dug to a depth of 6-10 feet, though portions of some canals were dug deeper to provide additional fill material used in the foundations for homes. This created uneven bottoms where pockets in some canals reach depths of over 30 feet. Uneven and deep canals further prevent circulation that is already impaired in dead-end canals. Canal depths combined with poor water quality prevent light from penetrating to the canal bottom, and the low oxygen conditions that result are further exacerbated by poor circulation. This combination of water quality problems prevents plants and fish from inhabiting canals. "Backfilling" involves filling deep pockets with an inert fill material to mimic that naturally found in the area, raising the sediment up to a consistent depth, and thus encouraging circulation and benthic life. Backfilling requires high upfront costs for material and installation, though changes in water quality and environmental health are thought to be immediate. There are no continued costs.

Organic Removal

Impaired water quality in many canals is thought to stem from decomposing organic material that has accumulated to cover the canal floor. Through organic removal, the organic material that has accumulated is mechanically removed. This is a time-, labor- and cost-intensive process, though improvements in water quality are expected to be immediate and drastic. This process strictly addresses the material already accumulated within canals, not the source or influx of material.

Culverts

A lack of circulation is thought to be a primary reason for the accumulation of organic material and unwanted chemical components in canal waters. Culverts are subaquatic passages created in terminal portions of canals that result in an additional path for canal water to travel through. Canals with culverts are no longer dead ends; water can circulate through the mouth as well as the installed culvert. Increased circulation is intended to flush out impaired water along with lightweight material that has accumulated in stagnant water while introducing "fresh", unimpaired water. In order for culverts to be an appropriate option, canals need to be located next to another water body that is open for circulation. Culverts require only a modest upfront cost and improvements in water quality are expected to be gradual.

1.4 Demonstration Project Canals

The demonstration projects were intended to showcase these available technologies that, if deemed effective and suitable, could be installed in additional canals with poor water quality conditions. Out of the 10 canals selected for demonstration projects, 9 were each assigned an experimental control; an adjacent, untreated canal of similar conditions, location and arrangement that could be used as a reference (Table 1.3). Control canals are thought to have been created with similar lengths and depths and may be subjected to similar human influence as their adjacent remediated canals. Additionally, control canals likely receive similar quantities of organic material as their neighboring demonstration canals, thus the control canals should indicate that any changes in water quality within demonstration canals could be attributed to installed technologies rather than other factors. In addition to control canals for reference, comparing environmental conditions before and after technology was implemented to further assess effectiveness. Finally, the benthos was characterized directly adjacent to the canal mouth, working outwards to 250 m beyond the mouth of each canal, to observe the extent of impaired waters and determine reference conditions for the benthos under natural conditions.

Canal 29 – Backfilling

Canal 29 is located in Sexton Cove, northern Key Largo, facing Florida Bay (Fig. 1.3). The canal is approximately 0.1 miles from mouth to end, lined with small, single-family homes. The mouth of Canal 29 was approximately 6 feet deep, though depth increased to a maximum of 32 feet deep in the canal's rear. The deep and uneven depth profile prohibited circulation and flushing of stagnant bottom water, allowing the accumulation of undesired chemical conditions (low O_2, high acidity, high hydrogen sulfide). Besides the consistent low water quality in the canal, there was concern that extreme weather events would occasionally flush unhealthy bottom water out, potentially influencing ecosystems in the nearby, protected waters of the Florida Keys National Marine Sanctuary and Everglades National Park. The extreme water depth in the canal also prevented the growth of benthic plants and algal communities due to the inability of light to reach the bottom. Canal 28, the neighboring canal to the north, also had a depth profile ranging from 6 feet at the mouth to 34 feet in the rear, and issues with water quality. Because of their similar construction and context, Canal 28 served as an experimental control for the demonstration canal, Canal 29. The demonstrated technology was to backfill the canal to a consistent depth of 6-7 feet using low nutrient, carbonate fill material (similar to that found naturally in the area). It was thought that the backfilling would encourage flushing and light penetration throughout the water column. Backfilling began in Spring 2015 and was completed in June 2015.

Figure 1.3: Map of Canal 29 and its experimental control, Canal 28. Imagery and map from Leaflet Tiles, ESRI, and the GIS User Community.

Canal 137 – Air Curtain

Canal 137 is located on Plantation Key in Islamorada, facing the Atlantic Ocean (Fig. 1.4). The canal is approximately 0.25 miles from mouth to rear and approximately 275 feet wide at its widest point. After a narrow, 94 feet long portion, the canal opens into a large basin surrounded by residential homes with private boat docks. This portion of the coast, including the canal itself, gets wind-driven wrack imports from the coastal ocean. Residents have noted dark turbid waters, a foul smell and a lack of sea life. This led the local home-owner's organization to install aerators which would reintroduce oxygen into the bottom waters and hopefully improve conditions. The six installed aerators were deemed inadequate to improve water quality. Therefore, this canal was designated to receive an air curtain to prevent the entry of wrack into the canal, and 6 additional aerators within the canal's basin to introduce oxygen and improve circulation. Both technologies were installed in November 2014. The neighboring canal to the northeast, Canal 132, was considered the experimental control due to its similar size, shape, exposure to the ocean, and because it contained previously installed preliminary aerators.

Figure 1.4: Map of Canal 137 and its experimental control, Canal 132. Imagery and map from Leaflet Tiles, ESRI, and the GIS User Community.

Canal 148 – Air Curtain

Canal 148 is located on Lower Matecumbe Key facing the Atlantic Ocean (Fig 1.5). The canal is approximately 0.2 miles from mouth to rear with a maximum width of 12 feet. The canal is surrounded by small homes and a hotel and is flanked by a small jetty to the northeast that serves as a parking lot and boat ramp. Wrack derived from the coastal ocean is blown into the canal where it decomposes and accumulates, negatively affecting water quality. The accumulation of lightweight, low-density sediment in this canal has caused the water column depth to shrink to a point where boat activity easily disrupts and overturns sediment. Further, foul odors likely derived from decomposing organic material were regularly noted in the area. To prevent the entry of additional wrack, an air curtain was installed at the mouth of the canal in April 2017. The adjacent Canal 147 served as a control, because of its similar length and orientation to Canal 148.

Figure 1.5: Map of Canal 148 and its experimental control, Canal 147. Imagery and map from Leaflet Tiles, ESRI, and the GIS User Community.

Canal 266 – Organic Removal and Air Curtain

Canal 266 is located on the eastern side of Big Pine Key facing No Name Key (Fig. 1.6). The canal is approximately 0.25 miles long with a consistent width of 40 feet from mouth to rear. The eastern side of Big Pine Key receives high inputs of seagrass wrack, likely from the dense, productive seagrass meadows in the area upwind of the prevailing currents. Wrack accumulates along much of this shoreline, particularly in shallow regions and small embayments, making canals along eastern Big Pine Key extremely susceptible to the wrack inputs; Canal 266 is no exception. Residents regularly note mats of floating wrack spanning most of the canal's length and wrack deposits have increased the sediment level enough to be seen from the surface. Due to the canal's poor water quality, odors of hydrogen sulfide and sewage are regular occurrences. The effect of organic removal was demonstrated in this canal, where accumulated organic sediments were dredged and removed from the canal in order to halt all of the associated water quality issues. The removal of organic sediments began in Spring 2015 and after intermittent delays, the demonstration project was completed in March 2016 along with the addition of an air curtain to prevent further wrack entry. This combination of technologies addressed not only the organic material within the canal, but the input of material that could impair water quality in the future. Canal 263, directly to the north of the demonstration canal, was used as an experimental control.

Figure 1.6: Map of Canal 266 and its experimental control, Canal 263. Imagery and map from Leaflet Tiles, ESRI, and the GIS User Community.

While the length and design of this canal is notably different than Canal 266, the location and orientation was thought to be similar enough to designate the section parallel to Canal 266 as a reference.

Canal 277 – Culvert

Canal 277 is located on the eastern side of Big Pine Key, though unlike many other canals in the area it primarily runs parallel with the coastline (Fig. 1.7). After approximately 325 feet inland, the canal takes a sharp 90˚ turn where it stretches another 0.35 miles in length. The canal is susceptible to seagrass wrack inputs from nearby waters, and poor circulation is another contributing factor to its poor water quality. The design of this canal allowed for circulation to be increased by the creation of two culverts, dug between the canal rear and adjacent water bodies. A subaquatic connection was installed between each side of the demonstration canal and the open, adjacent waters, allowing waters to flush through the canal with the intention of removing impaired water and replenishing it with a nearby clean water source. The culvert was finished in May 2016 and the demonstration canal was compared to Canal 282, a canal to the south and in the same general area as Canal 277, but different in terms of its orientation and size.

Figure 1.7: Map of Canal 277 and its experimental control, Canal 282. Imagery and map from Leaflet Tiles, ESRI, and the GIS User Community.

Canal 287 – Air Curtain

Canal 287 is a 0.25 mile long canal on the eastern side of Big Pine Key (Fig. 1.8). Like other canals on the eastern side of Big Pine Key, the exposure to wrack produced by nearby seagrass meadows causes a high input of organic material that accumulates and decomposes inside the canal. The accumulation of wrack in Canal 287 has been enough to raise the sediment beyond the depth of a boat propeller, causing interference with normal small boat operations. The decomposition of large amounts of wrack is the likely cause of sulfurous odors in the neighborhood, dark water, and the lack of fish and other sea life. To address the inputs of organic wrack, an air curtain was installed (completed in June 2016) to prevent the entry of additional material. The wall of small bubbles created at the mouth of the canal blocks the entry of light-weight organics into the canal while still allowing for boat passage. The neighboring Canal 288, located south of the demonstration canal and of similar size and orientation, was used as the experimental control.

Figure 1.8: Map of Canal 287 and its experimental control, Canal 288. Imagery and map from Leaflet Tiles, ESRI, and the GIS User Community.

Canal 290 – Organic Removal and Air Curtain

Canal 290 is a short (approximately 0.1 mile) canal on the eastern side of Big Pine Key (Fig. 1.9) and was chosen to demonstrate the combined effect of organic removal and the installation of an air curtain. The regular influx of wrack from adjacent waters prompted residents to install two physical weed gates (one at the mouth and one at the halfway point) in the canal. These gates are made of large, floating PVC rods that span the width of the canal to block entry of floating material, but which can be moved for boat passage. These physical barriers were insufficient to improve water quality and thus organic removal was undertaken as part of the demonstration technologies, completed in March 2016. The organic removal was followed by the installation of an air curtain in June 2017. The neighboring canal to the south, Canal 293, served as the experimental control, as it had similar characteristics and water quality.

Figure 1.9: Map of Canal 290 and its experimental control, Canal 293. Imagery and map from Leaflet Tiles, ESRI, and the GIS User Community.

Canal 459 – Culvert

Canal 459 is a short, straight canal (less than 325 feet long) located on Geiger Key, surrounded by a mixture of residential property and naturally occurring mangrove stands (Fig. 1.10). The canal is blocked from the nearby ocean by a mangrove island that prevents the mixing of canal and open water, but also acts as an additional source of organic input (mangrove leaf litter). Here, it is suspected that both mangrove and seagrass leaves are causing poor water quality through their accumulation and decomposition inside the canal. The proposed solution was a culvert that would connect the canal's rear to an adjacent canal to the west that has greater exposure to ocean water, intended to increase the flushing of impaired waters and organic debris. Unfortunately, this portion of the demonstration project was never completed. However, Canal 459 and its control, Canal 458, continued to be visited as part of the monitoring program to collect data and compile a baseline record useful for future work.

Figure 1.10: Map of Canal 459 and its experimental control, Canal 458. Imagery and map from Leaflet Tiles, ESRI, and the GIS User Community.

Canal 472 – Culvert

Canal 472 is 325 feet long and located on Geiger Key with a consistent width of approximately 40 feet (Figure 1.11). This canal, along with its designated control, Canal 476, face southeast towards the Atlantic Ocean. With this orientation, the canal has a propensity to collect seagrass wrack produced upwind in the coastal ocean. Both canals have depths over 15 feet and no mechanism to encourage mixing, thus poor water quality and organic-rich sediment have developed. Canal 472 was the designated recipient of a culvert, connecting the canal's rear to a neighboring canal and creating a passage for water to flush through both canals. Enhanced circulation was also thought to flush out lightweight sediments that have accumulated in stagnant waters.

Figure 1.11: Map of Canal 472 and its experimental control, Canal 476. Imagery and map from Leaflet Tiles, ESRI, and the GIS User Community.

2 Field and Laboratory Methods

Benthic monitoring of the demonstration project canals began in 2014, occurring three times a year to capture seasonal variability in environmental and ecological conditions. Monitoring trips typically occurred in January for a winter sampling and again in April/May and September/October to capture pre- and post-summer conditions. Fieldwork included identification and quantification of benthic plants and animals, fish counts, depth measurements, and sampling of plant tissues and surface sediments for chemical composition in the laboratory. Researchers on SCUBA or snorkel conducted the monitoring, though excessively poor water quality or post-hurricane debris sometimes prevented entry into the water due to safety concerns. Under these circumstances, sediments were sampled from the boat using a small box grab, but collections of sediment depth could not be made.

2.1 Monitoring Overview and Rationale

Quantifying the abundance, type, and chemical composition of marine plants is a low-cost and reliable method of assessing water quality and benthic health (Fourqurean et al. 1995; Fourqurean et al. 2001; Fourqurean et al. 2002). The community structure and condition of seagrasses and algae in the Florida Keys and Florida Bay vary with environmental conditions, thus changes in parameters such as light availability, nutrient input, sediment conditions and dissolved oxygen concentrations are linked to a shift in benthic plant community composition (Fourqurean et al. 1995; Fourqurean et al. 2001). Water quality instruments provide extremely accurate measurements of environmental conditions, though without long-term instrument deployments these data represent only a brief snapshot of conditions. Conversely, seagrass community structure and leaf chemical composition creates a long-term, integrated assessment of local environmental conditions due to relatively slow leaf growth and turnover rates. These metrics have been used to infer water quality for over 20 years in coastal South Florida and have become a fundamental monitoring tool in Florida Bay and the Florida Keys National Marine Sanctuary (Fourqurean et al. 2002).

Besides being established indicators of water quality and estuarine health, seagrasses have been identified as important habitats for commercially and recreationally important fish and lobster species (Seitz et al. 2013), tools to buffer wave and storm energy (Reidenbach et al. 2018), and a means to decrease harmful nutrients and bacteria (Lamb et al. 2017). Seagrasses provide both valuable ecological and economic services and act as a “canary in the coal mine” for water quality. Thus, the assessment of local seagrass communities before and after the installation of demonstration technologies was a fundamental component of our monitoring effort. Sponges, coral, barnacles, bivalves and other benthic animals that also help to infer environmental conditions were also identified and included in our monitoring as well. Expanding on benthic surveys, organisms attached to canal seawalls were also monitored. These communities differ from those inhabiting the sediments, though are also reflective of water quality conditions, particularly light and oxygen.

Preliminary observations of deep, organic-rich sediment in canals motivated an assessment of the sediment itself (AMEC Environment & Infrastructure 2013). The organic-rich sediments that afflicted many of the canals alter water chemistry through their decomposition and affect benthic communities via shifts to lower sediment densities that result in poor sediment stability. Sediment characteristics were assessed through the analysis of organic carbon (C_{org}), nitrogen (N), and phosphorus (P) concentrations, along with measurements of sediment density (dry bulk density) and sediment depth. Successful demonstration project technologies are expected to reduce the amount (depth) of sediment and/or change its composition to better mimic natural conditions found outside of the canals and throughout the Florida Keys.

2.2 Sampling Methods

Ten sampling sites evenly distributed from the canal mouth to the rear were randomly selected in each canal (both demonstration and control) for benthic monitoring (Fig. 2.1). These sampling sites were re-visited during each sampling campaign throughout the monitoring program (3 times per year from 2014-2017 and 2 times per year from 2018-present). At each of these sites, three 0.25 m^2 quadrats were haphazardly placed on the sediment and all species of plants, algae and animals were recorded, along with a classification of surface sediment type (Table 2.1) and a sediment depth measurement. Density of seagrass, algae and benthic animal species (Table 2.2) were measured using a modified Braun-Blanquet scale (Table 2.3; Fourqurean et al. 2002).

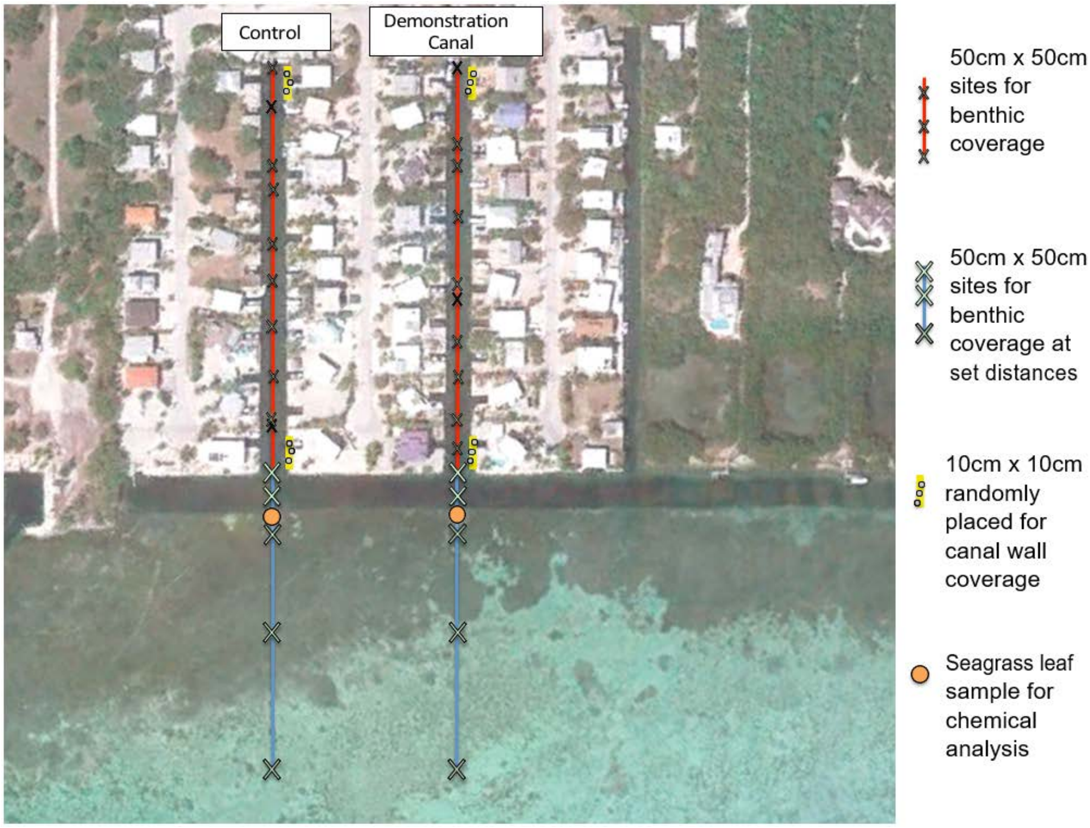

Figure 2.1: Depiction of sampling design for benthic surveys, seawall and seagrass tissue sampling

Table 2.1: Sediment categories and their assigned ranking of increasing coarseness.

Sediment Category	Numerical Value	Description
Mud	1	Individual grains indistinguishable, easily compresses in hand, sediment remains clumped after compression
Sandy mud	2	Majority of grains indistinguishable but textured upon touch, easily compresses in hand, sediment remains clumped after compression
Muddy sand	3	Sandy texture upon touch but compresses in hand, sediment dissociates upon release with most grain falling in water column
Sand	4	Clearly distinguishable grains, difficult to compress in hand, grains fall quickly in water
Coarse shell	5	Shell and shell remains dominate sediments (approximately 5-10 mm in size)
Halimeda-hash	6	Remains of carbonate segments from *Halimeda* detritus (approximately 5-10 mm in size)
Rubble	7	Medium size rock (approximately 10-25 mm in size)
Live coral	8	Continuous living coral
Rock	9	Bedrock or solid biogenic carbonate formations

Table 2.2: Organisms identified and quantified during benthic surveys using modified Braun-Blanquet density scores.

Seagrasses	Algae		Animal	
Thalassia testudinum *Syringodium filiforme* *Halodule wrightii* *Halophila decipiens*	<u>Calcifying Green Algae</u> *Halimeda* spp. *Udotea* spp. *Penicillus* spp. *Rhipocephalus* spp. *Neomeris* spp. *Cymopolia* spp. *Acetabularia* spp. <u>Red Algae</u> *Laurencia* spp. Other	<u>Other Green Algae</u> *Batophora* spp. *Avrainvilla* spp. *Dasycladus* spp. Other <u>Brown Algae</u> *Dictyota* spp. *Sargassum* spp. Other	Octocoral Stony coral Sponges Barnacles *Diadema* spp. *Lytechnius* spp. Heart urchin Other urchin Sea biscuit Sand dollar Sea cucumber	Sea star Other echnioderm Queen conch Fighting conch Other gastropod Pen shell Other bivalve Spiny lobster Stone crab Other crustacean

Table 2.3: Modified Braun-Blanquet abundance scores, their description, and their assigned percent coverage.

BB Score	Description
0	Species absent from quadrat
0.1	Species represented by a solitary shoot, < 5 % cover
0.5	Species represented by a few (< 5) shoots, < 5 % cover
1	Species represented by many (> 5) shoots, < 5 % cover
2	5 % - 25 % cover
3	25 % - 50 % cover
4	50 % - 75 % cover
5	75 % - 100 % cover

Monitoring continued outside each canal where densities of benthic species and sediment type were monitored at 10m, 50m, 100m and 250m outside the canal mouth using similar methods (Fig. 2.1). Organisms on the seawall were quantified using smaller, 10x10 cm quadrats randomly placed on the seawall at the canal mouth and rear. Organisms within 15 categories (Table 2.4) were enumerated in 3 quadrats at both the mouth and rear using the modified Braun-Blanquet scoring scale.

Fish Counts

Fish presence and diversity are important indicators of environmental health but also desired features for residents and tourism in the area. Fish assemblages were assessed using a modified Roving Diver Technique (RDT) where a diver freely swam around each of the ten monitoring sites within the canal. During this period, the diver identified and counted all fish

Table 2.4: Categories of organisms quantified on seawalls using a modified Braun-Blanquet density scores.

Category	Description
Turf green algae	Includes all species of turf-forming green algae that is not specified in other categories
Sponge	Includes all living sponges
Coral	Includes all species of living coral
Barnacles	Includes all species of barnacles
Cashm	Green algae species *Caulerpa ashmeadii*
Cmexi	Green algae species *Caulerpa mexicana*
Crace	Green algae species *Caulerpa racemosa*
Csert	Green algae species *Caulerpa sertularioides*
Halimeda	Includes all species of green algae within the genera *Halimeda*
Penicillus	Includes all species of green algae within the genus *Penicillus*
Acetabularia	Includes all species of green algae within the genus *Acetabularia*
Red algae	Includes all species of red algae
Batophora	Includes all species of green algae within the genus *Batophora*
Udotea	Includes all species of green algae within the genus *Udotea*

encountered. For encounters of over 50 individual fish, estimates were made to the nearest hundred. Given the low water quality and visibility in canals, fish encounters were rare and are likely to greatly underestimate true values.

Sampling for Laboratory Analyses

Seagrass and surface sediment samples were collected from each canal during each sampling campaign. For seagrasses, 7 shoots of *Thalassia testudinum* were collected from the mouth of each canal, or from the next closest outside sampling site from the mouth which contained *T. testudinum*. Leaf tissue samples were analyzed for carbon (C) and nitrogen (N) content using a Flash 1112 elemental analyzer (Fourqurean et al. 2001). Phosphorus (P) content was measured using a dry-oxidation, acid hydrolysis extraction followed by colorimetric analysis (Solórzano and Sharp 1980). Stable isotope ratio values $\delta^{13}C$ and $\delta^{15}N$ were measured with an elemental analyzer coupled to an isotope ratio mass spectrometer (EA-IRMS) using standard procedures (Fourqurean et al. 2005) at either Florida International University or at the University of California at Davis.

For sediments, 4-5 surface cores were taken at pre-determined monitoring sites within each canal, selected in a pseudo-random distribution from canal mouth to rear. Sediments were collected using 60 mL plastic syringes that had been modified into small piston cores (~2.6 cm diameter), able to sample the top ~15 cm of surface sediment with minimal compaction. Cores were capped and placed on ice for transportation to the laboratory, where they were processed for dry bulk density, organic material (as loss-on-ignition), organic carbon (C_{org}), N and P content (Fourqurean et al. 2012a; Howard 2018).

3 Results

3.1 Baseline Values

The following baseline data for Islamorada canals represent mean values collected over the first three sampling campaigns (winter 2016, spring 2016 and fall 2016), encompassing a year of data. For the 10 demonstration canals and 9 control canals, baseline data encompasses spring 2014, fall 2014 and winter 2015 sampling campaigns, to measure any environmental changes related to the installed technologies. Technologies were scheduled to be installed early during the monitoring effort (during 2014 and 2015), though delays in permitting pushed installation as far back as April 2017.

Seagrass meadows and macroalgae are important ecosystem engineers in coastal South Florida but were markedly absent from the sampled canals (Fig 3.1). Canals monitored in Islamorada were typically lacking SAV within the canal, despite SAV presence near canal mouths. One notable exception was Canal 150, which contained SAV throughout the entire canal. The outsides of Canals 114 and 120 were not sampled because of their bathymetry. Out of the 19 demonstration project canals sampled, only nine contained submerged aquatic vegetation (SAV; classified here as seagrass or calcifying macroalgae) within the canal during the first year of monitoring. Of those nine, only four supported SAV at more than one sampling location within the rear of the canal, the

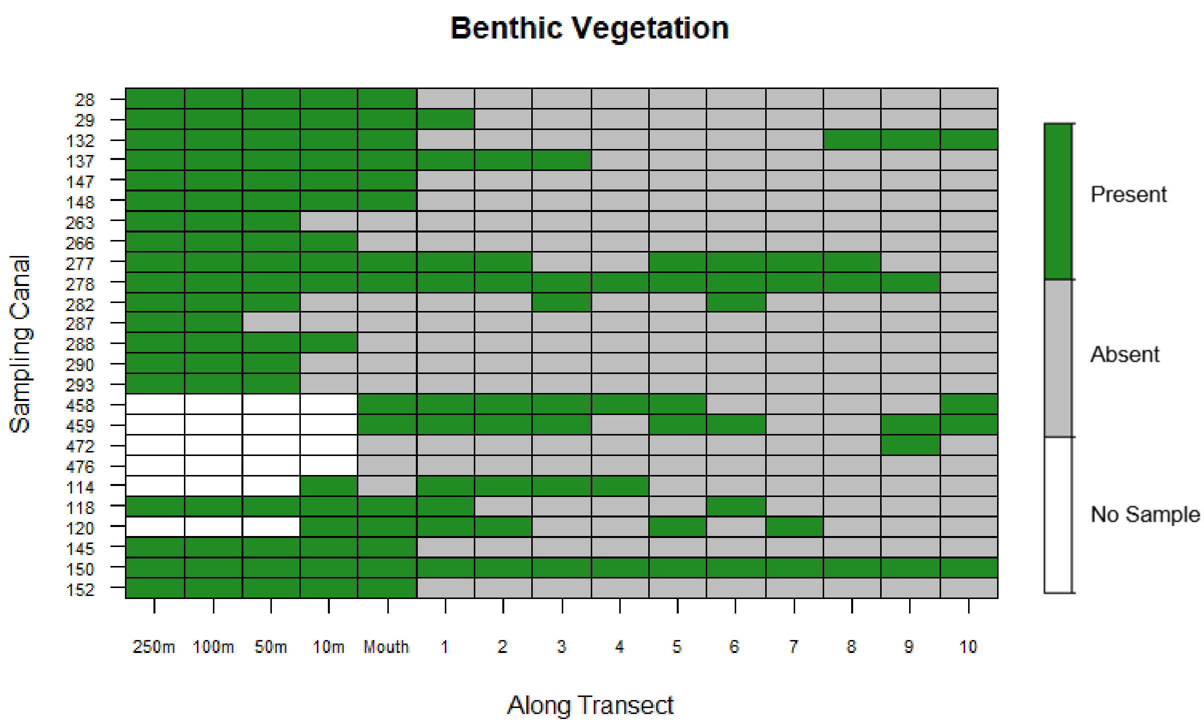

Figure 3.1: Presence of benthic vegetation along canal transects from 250m outside monitored canals until the 10th monitoring site at the canal rear. Data represents averages from the first year of monitoring.

portion of the canal that typically has the worst water quality. However, SAV was present directly outside (within 10m) of the mouth of almost all canals. The outsides of Canals 458, 459, 472 and 476 were not sampled because they contained channels for boat traffic, which may prevent hydrologic exchange between canals and adjacent seagrass meadows beyond the boat channels due to modified circulation created by the bathymetry.

Turtle grass, *Thalassia testudinum*, was found in the greatest densities between 50m and 250m outside canals, though it was found in low densities within Canals 150, 277, 278, 458 and 459 during the first year of monitoring (Fig. 3.2). Shoal grass, *Halodule wrightii*, was found at a subset of monitored canals, where it more commonly inhabited sampling sites closer to the shore (within 50m of the mouth). *Halodule* was found outside 11 of the 25 canals monitored, though three canals (278, 118 150) hosted noteworthy abundances within (Fig 3.3). Manatee grass, *Syringodium filiforme*, was found infrequently during initial monitoring efforts, only being observed at nine of the 25 monitored canals. Only the interiors two of the Big Pine Key canals, 277 and 278, were inhabited by the species; each having only a single site inhabited near the mouth. Manatee grass was found most frequently at 50 - 100 m outside the mouth (Fig 3.4).

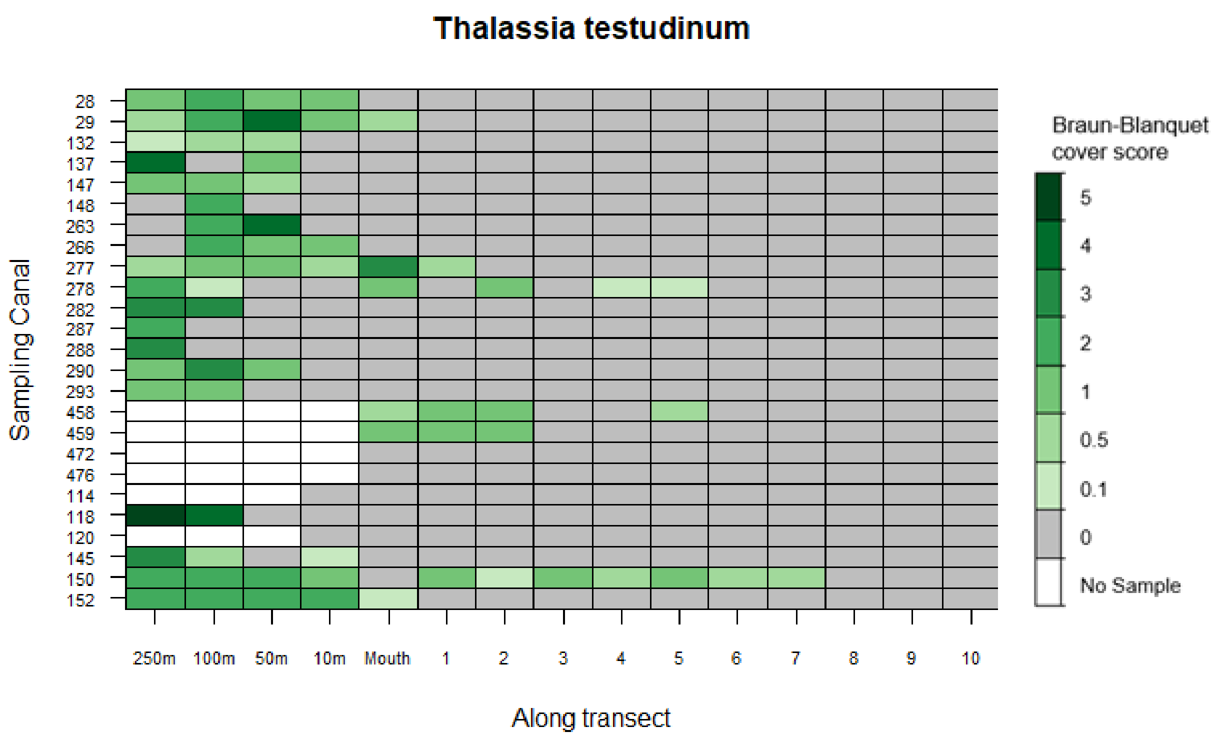

Figure 3.2: Presence of *Thalassia testudinum* along canal transects from 250m outside monitored canals until the 10th monitoring site at the canal rear. Data represent averages from the first year of monitoring.

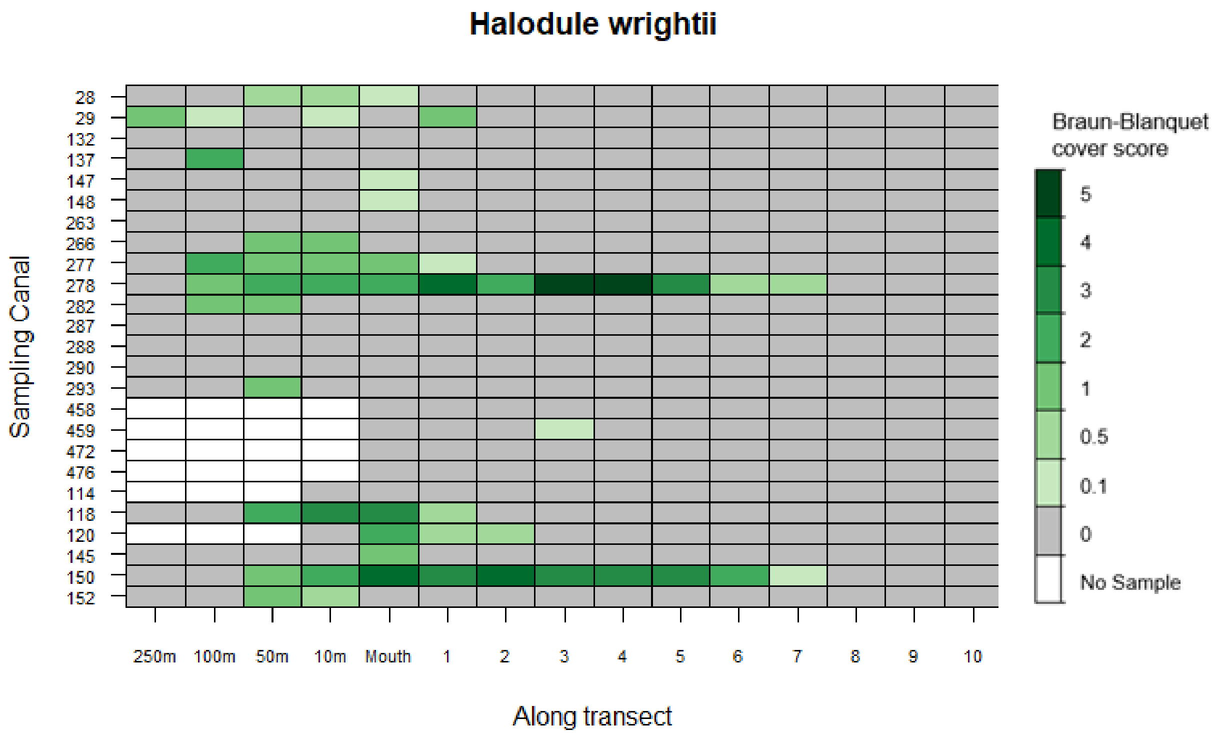

Figure 3.3: Presence of *Halodule wrightii* along canal transects from 250m outside monitored canals until the 10th monitoring site at the canal rear. Data represent averages from the first year of monitoring.

Calcifying green macroalgae (genera *Halimeda*, *Penicillus*, *Udotea*, etc.) was found outside 15 of the 25 canals, though was only found within nine canals (Fig 3.5). A higher portion of Islamorada canals had calcifying macroalgae compared to demonstration project canals during baseline measurements. The highest average densities calcifying macroalgae were found at sites 10 - 50 m outside canals, though was found sporadically at sites from the mouth to 250 m outside.

Seagrass Leaf Chemistry

Leaves of *Thalassia testudinum* collected outside canals, closest to the mouth were analyzed for elemental content of C, N, and P as well as stable isotope values for C and N to understand the amount and potential source of nutrients in the water column. Values of N and P content were considerably higher from seagrasses adjacent to canal mouths compared to the average values for natural waters in the Florida Keys, while C:N and C:P molar ratios are considerably lower (Table 3.1). Both N and P content of leaf tissue are high outside canals, though average N:P ratios suggest an abundance of N relative to P compared to samples from across South Florida. Nutrient values and ratios are indistinguishable between samples taken from Demonstration project and Islamorada canals. Similarly, there was no difference in baseline leaf tissue $\delta^{15}N$ between monitoring projects. Average tissue $\delta^{15}N$ during the baseline measurements were indistinguishable from the average value for the natural waters of the FL Keys (2.3 ± 0.6 ‰ compared to 2.0 ± 0.2 ‰; Campbell et al. 2009). Values of leaf tissue $\delta^{13}C$ were lower on average for samples collected outside canals compared to values for the Florida (-10.6 ± 0.5 ‰ compared

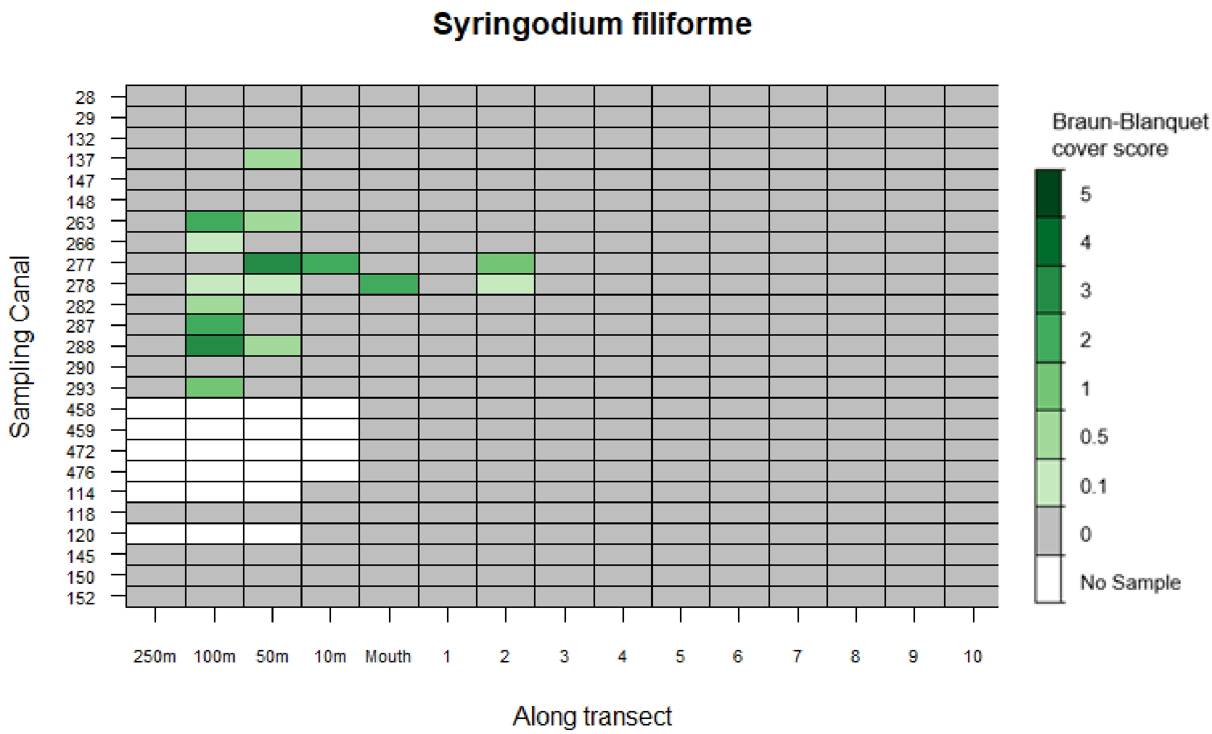

Figure 3.4: Presence of *Syringodium filiforme* along canal transects from 250m outside monitored canals until the 10th monitoring site at the canal rear. Data represent averages from the first year of monitoring.

to –8.6 ± 0.2 ‰; Campbell et al. 2009). There was also a difference in baseline $\delta^{13}C$ values between monitoring projects; Demonstration canals had lower values than samples from Islamorada canals (-10.6 ± 0.5 ‰ compared to -9.6 ± 0.6 ‰).

Baseline Sediment Conditions

Sediments assessed during baseline, pre-technology monitoring were categorized as either "unconsolidated organic material", "mud" or "sandy mud" across all sites. Average sediment density (measured as dry bulk density) within a canal ranged from 0.05 ± 0.004 g cm^{-3} in Canal 266 on Big Pine Key to 0.67 ± 0.05 g cm^{-3} in Canal 150 in Islamorada (similar to the FL Keys regional average; Howard 2018; Fig 3.6). Canal sediments from monitored canals were less dense than Florida Bay and the Florida Keys (1.0 ± 0.1 and 0.73 ± 0.04 g cm^{-3}, respectively; Fourqurean et al. 2012a; Howard 2018), though sediments of Islamorada canals were over twice the average density of those from demonstration project canals during the initial year of monitoring (0.39 ± 0.04 g cm^{-3} compared to 0.17 ± 0.02 g cm^{-3}).

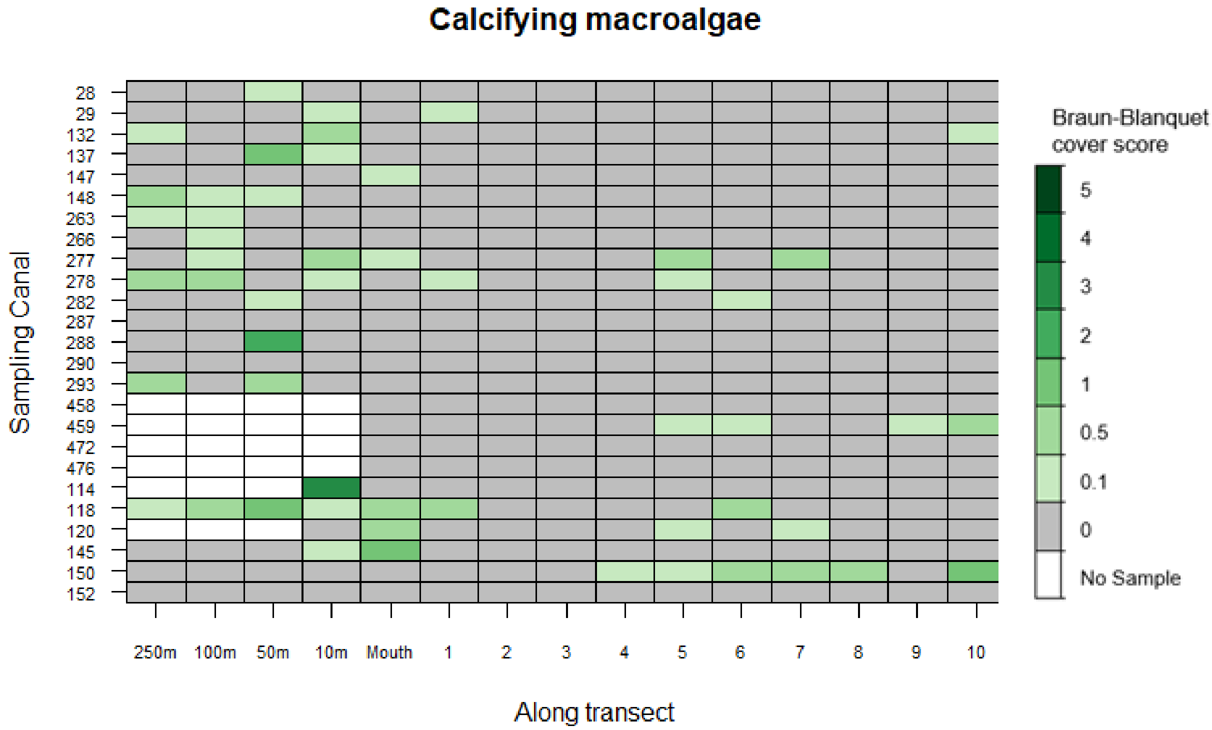

Figure 3.5: Presence of calcifying macroalgae along canal transects from 250m outside monitored canals until the 10th monitoring site at the canal rear. Data represent averages from the first year of monitoring.

Table 3.1: Baseline *Thalassia* seagrass tissue analysis. Data represent mean ± SE (min – max) for the first year of project sampling. Regional values for the Florida Keys are reported from Campbell et al. 2009.

Parameter	Unit	Demonstration project canals	Islamorada canals	Regional values for FL Keys
C	% dry wt.	37.5 ± 0.5 (34.1 - 40.6)	36.9 ± 0.6 (35.4 - 38.2)	43.4 ± 0.3 (35-46.3)
C:N	Molar ratio	16.6 ± 0.4 (14.0 - 19.2)	15.4 ± 0.9 (13.8 - 18.6)	24.1 ± 0.3 (17.1 – 33.9)
C:P	Molar ratio	714.0 ± 37.3 (474.6 - 923.8)	681.1 ± 34.3 (607.4 - 810.7)	870.8 ± 26.3 (500.3 – 1902.3)
$\delta^{13}C$	‰	-10.6 ± 0.5 (-15.7 - -8.2)	-9.6 ± 0.6 (-11.6 - -8.4)	-8.6 ± 0.2 (-13 - -5.3)
$\delta^{15}N$	‰	2.3 ± 0.6 (-0.9 - 7.2)	2.6 ± 1.1 (-1.0 - 5.7)	2 ± 0.2 (-2.2 – 5.4)
N	% dry wt.	2.7 ± 0.1 (2.3 - 3.2)	2.8 ± 0.1 (2.4 - 3.0)	1.9 ± 0 (1.4 – 2.6)
N:P	Molar ratio	43.0 ± 2.0 (33.4 - 60.1)	44.7 ± 2.7 (36.1 - 51.2)	36.5 ± 1.1 (17.1 – 76.5)
P	% dry wt.	0.1 ± 0 (0.1 - 0.2)	0.1 ± 0 (0.1 ± 0.2)	0.1 ± 0 (0.1 – 0.2)

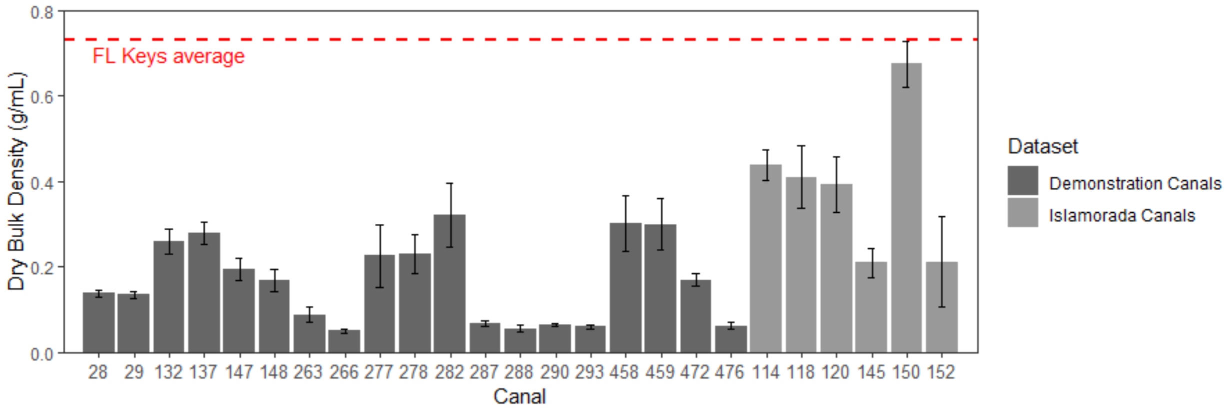

Figure 3.6: Values of sediment density (measured as dry bulk density) during the first year of monitoring, prior to demonstration technologies. Values represent mean ± SE compared to the average (red line) for natural waters in the Florida Keys from Howard (2018).

Lighter, less dense sediments correlated with a higher percentage of organic material, measured as loss-on-ignition, with density alone explaining over 50% of the variation in organic material content (Fig 3.7). As expected, material with higher percent organic material was positively correlated with C_{org} content, N, and to a lesser extent, P content (Fig 3.8), suggesting sediments rich in organic material were also high in organic carbon and the nutrients N and P. All sediments chemistry variables (density, organic content, C_{org}, N, and P) correlate with one another; lighter, less dense sediments are higher in organic material as well as C_{org}, N, and P content. Islamorada canals typically had less organic content, Corg, N and P than other Florida Keys canals.

Surface sediments ranged 3-fold in percent organic material across canals, with those on the eastern shore of Big Pine Key having the highest values (Canals 263, 266, 287, 288, 290, and 293; Fig 3.9). Sediment C_{org} and N content was also highly variable across canals with most extreme measurements on eastern Big Pine Key (data not shown). Patterns of organic material and C_{org} were similar across canals (Fig 3.10), though P varied independently, with Canal 148 having

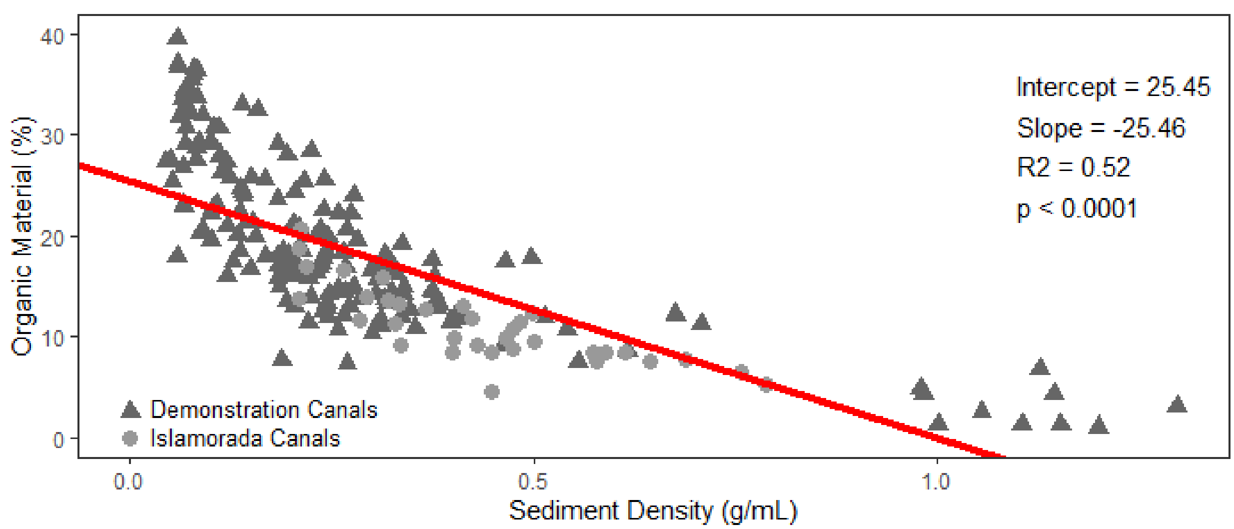

Figure 3.7: Correlation between sediment density and percent organic material of sediments. The negative slope indicates denser sediments contain less organic material.

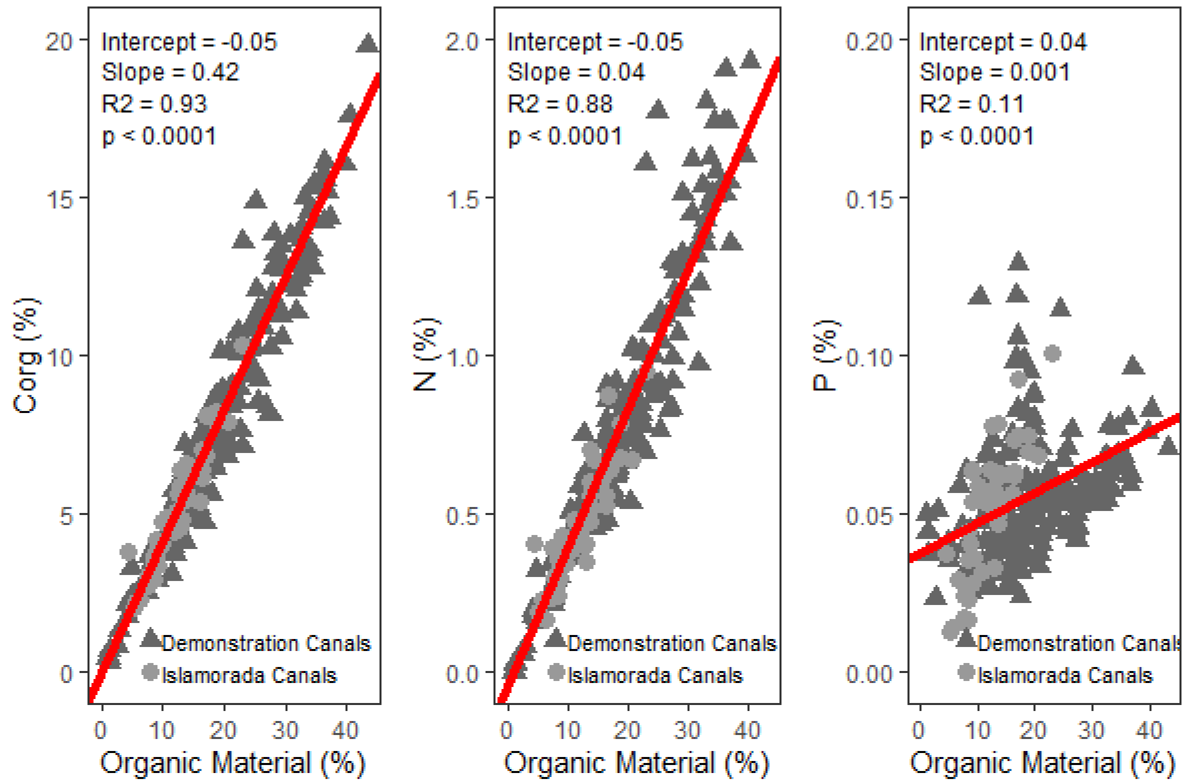

Figure 3.8: Correlations between percent organic material and C_{org}, N, and P content of sediments. There is a significant, positive relationship between all of the presented variables.

the highest average P content at 0.11 ± 0.02 % and more modest P amounts found amongst other canals (Fig 3.11). Baseline measurements were consistently higher than averages values for natural waters in Florida Bay and the Florida Keys (Fourqurean et al. 2012a; Howard 2018).

The sediment depth, measured from the bedrock to sediment surface, was highly variable between sites within a single canal as well as between canals, ranging between 30 ± 10 cm measured in Canal 132 to an average of 249 ± 9 cm in Canal 293. The baseline average sediment

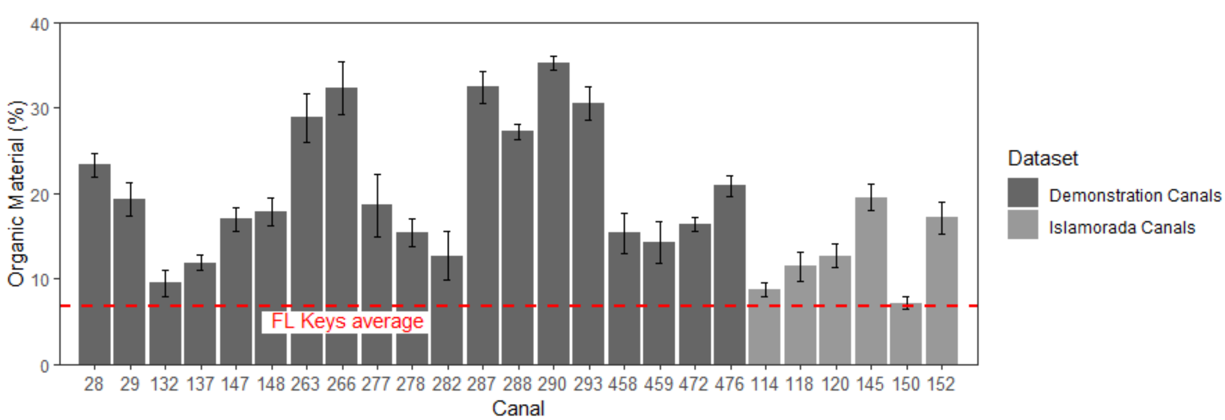

Figure 3.9: Values of sediment organic material (measured as LOI) during the first year of monitoring, prior to demonstration technologies. Values represent mean ± SE compared to the average (red line) for natural waters in the Florida Keys from Howard (2018).

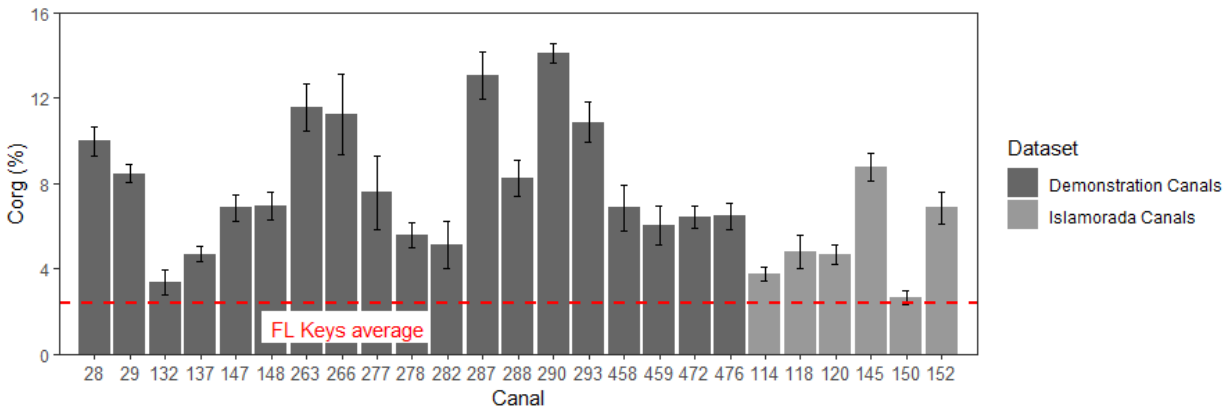

Figure 3.10: Values of sediment C_{org} content during the first year of monitoring, prior to demonstration technologies. Values represent mean ± SE compared to the average (red line) for natural waters in the Florida Keys from Howard (2018).

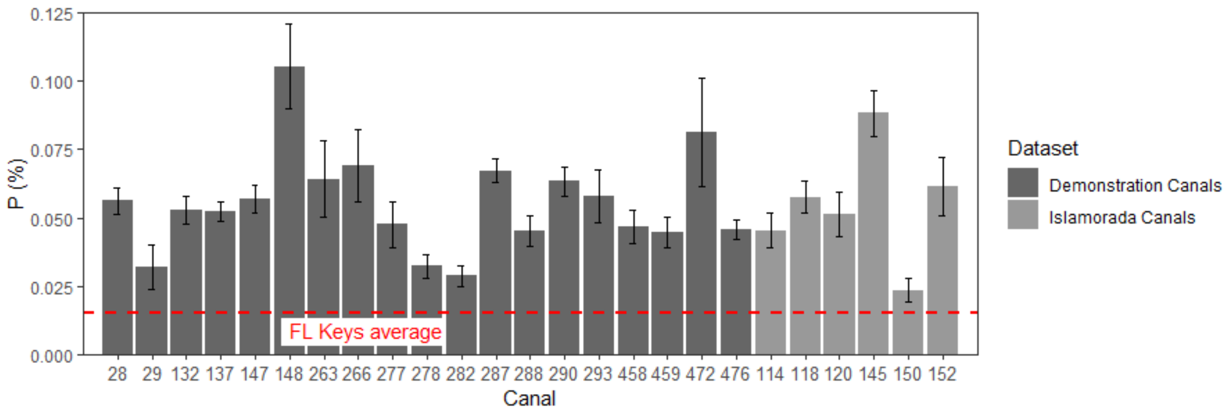

Figure 3.11: Values of sediment phosphorus content during the first year of monitoring, prior to demonstration technologies. Values represent mean ± SE compared to the average (red line) for natural waters in the Florida Keys from Howard (2018).

depth across monitored canals was 94 ± 7. Canals on the eastern shore of Big Pine had the greatest sediment depths and canals parts of the demonstration project were on average deeper than those sampled as part of the Islamorada monitoring program (Fig 3.12).

Fish Observations

During the first three sampling events (spring 2014, fall 2014, and winter 2015) of the demonstration project, significant numbers of fish were only observed in about half of the monitored canals (Fig. 3.13). There were 20 species observed across the monitored canals during this period with mangrove snapper (*Lutjanus griseus*) being the most common, followed by minnows (*Anchoa mitchilli*), barracuda (*Sphyraena barracuda*), and needlefish (family: *Belonidae*; Fig. 3.14). Other species were rare, being observed only once or twice. Only three of the Islamorada canals and six of the demonstration canals had more than one species of fish

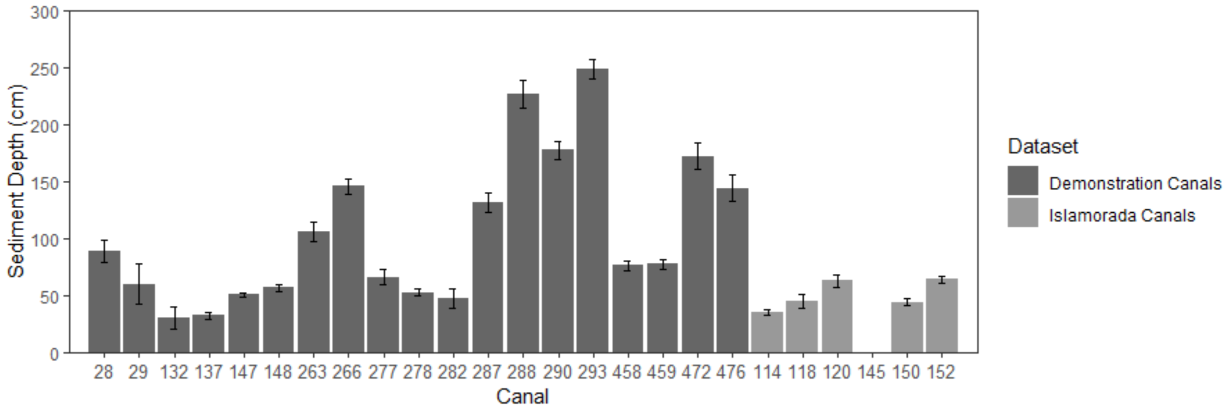

Figure 3.12: Sediment depth during the first year of monitoring, prior to demonstration technologies. Values represent mean ± SE.

observed during the first year of monitoring. Fish observations were not equally distributed across canals; less than 50 % of canals contained 90 % of the observed fish (Fig 3.13). It is important to note that fish surveys are heavily dependent on the visibility of water. As the monitored canals have been established as being impaired, varying turbidity strongly influences successful fish observation by divers.

Average fish abundance from the first year of baseline monitoring did not correlate well with average fish abundance combined across all years of our monitoring efforts ($p > 0.05$). The only canals to consistently contain more than 50 fish were Canals 28 and 459 (Fig. 3.13). For all other canals, baseline fish abundance was not a good predictor of average fish abundance across multiple years. Interestingly, the number of fish species encountered during the first year of baseline monitoring was strongly correlated with the number of fish species encountered across all years of monitoring ($p < 0.0001$; Fig. 3.14). However, data from all years of monitoring combined yielded greater numbers of fish species observed in every single canal (Fig. 3.14).

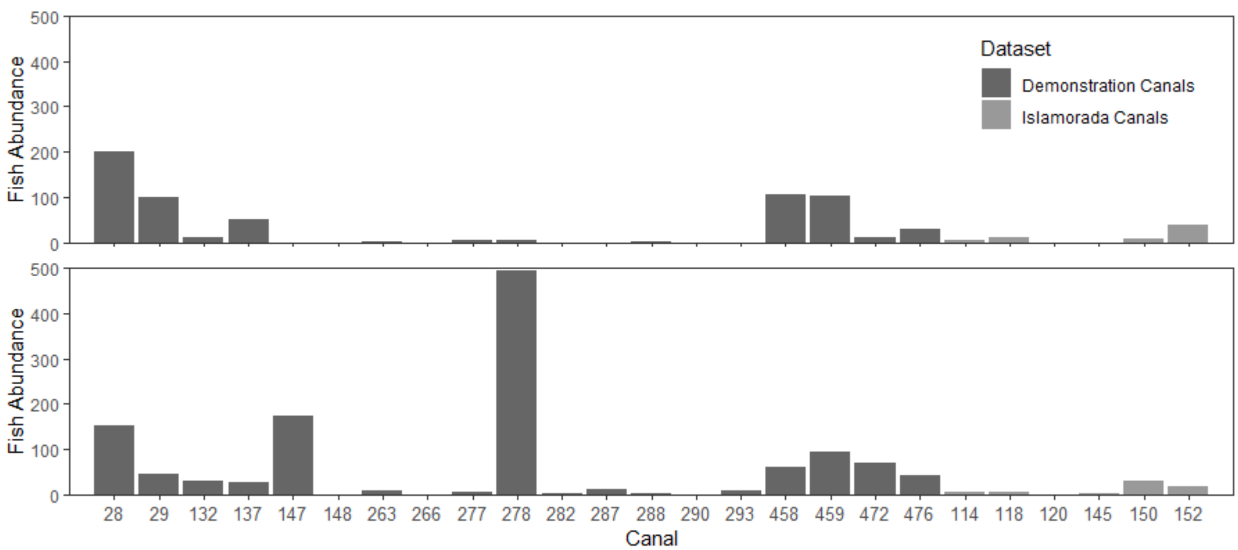

Figure 3.13: Average number of fish observed during the first year of monitoring (top) and during all years of monitoring (bottom). Counts were estimated for encounters of over 20 individuals.

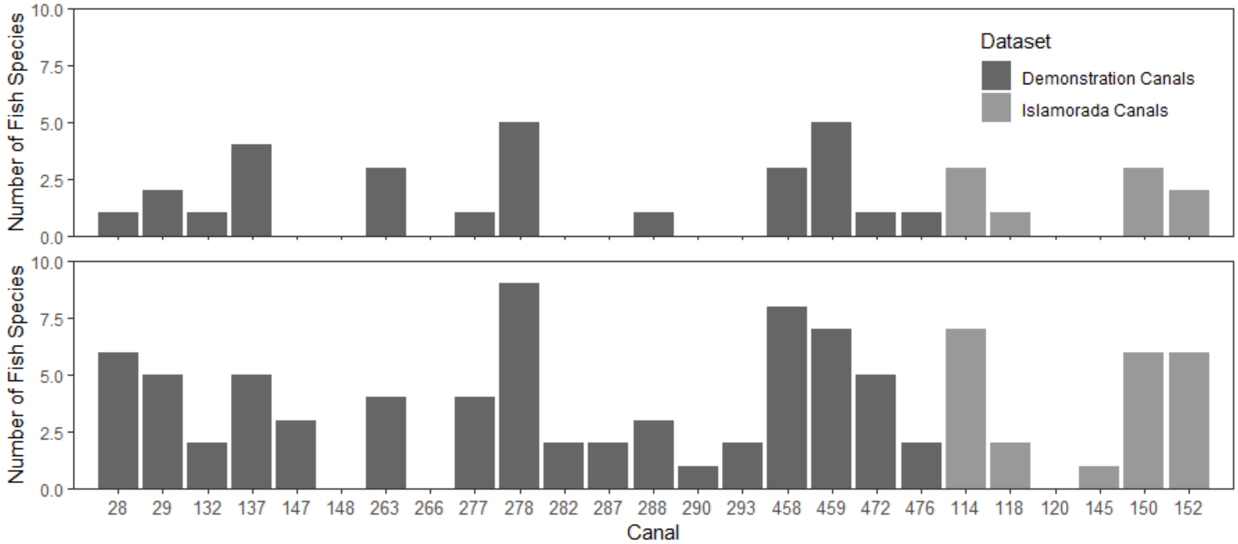

Figure 3.14: Average number of fish species observed during the first year of monitoring (top) and during all years of monitoring (bottom).

Seawall Inhabiting Organisms

In canals that contained seawalls, the seawalls were assessed for biodiversity at the canal mouth and rear. Organisms inhabiting the seawall were categorized into 15 taxonomic groups (Table 2.4) and measured for density using the 5-point, modified Braun-Blanquet scale (Table 2.3). There was a clear difference in the number of organisms inhabiting the seawall of the canal mouth compared to that of the canal rear, with more groups of organisms inhabiting the seawalls at canal mouths (Fig. 3.15a) compared to the seawalls at canal rears (Fig. 3.15b).

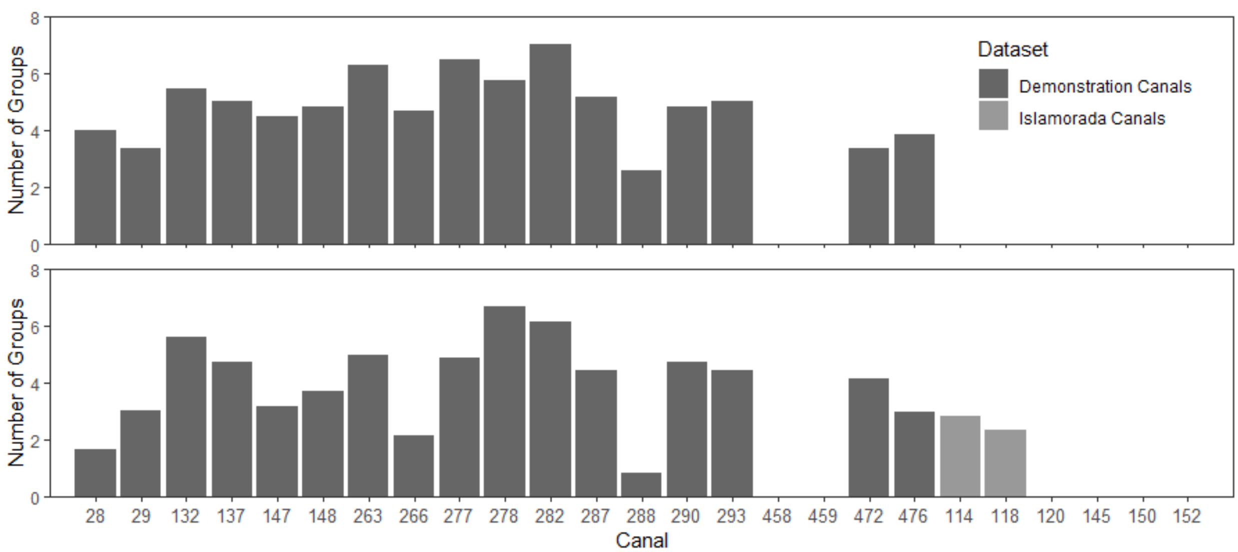

Figure 3.15a: Average number of organismal groups (of 15 categories) observed on the seawall at the mouth of each canal during the first year of monitoring (top) and during all years of monitoring (bottom). A list of organisms and abbreviations can be found in Table 2.4.

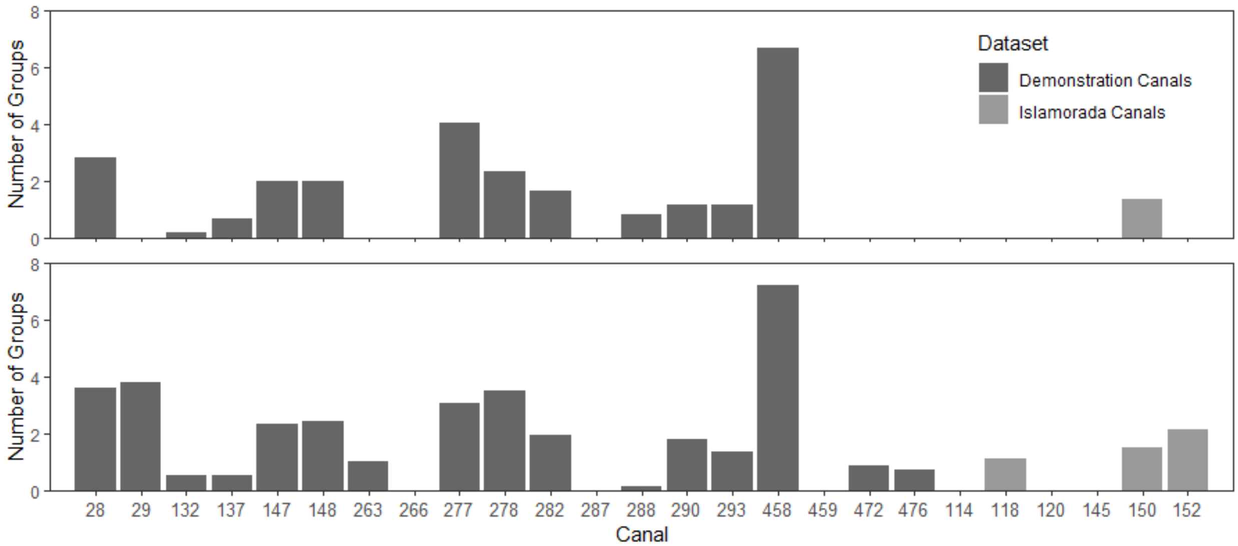

Figure 3.15b: Average number of organismal groups (of 15 categories) observed on the seawall at the rear of each canal during the first year of monitoring (top) and during all years of monitoring (bottom). A list of organisms and abbreviations can be found in Table 2.4.

Turf green algae was by far the most common seawall-inhabiting organism group in the first year of baseline monitoring, followed by *Caulerpa sertularioides*, red algae and barnacles (Fig 3.16a-b). There was no correlation between the density of organismal groups found on seawalls during the first year of baseline monitoring compared with the average density of organismal groups observed during all years of monitoring. But, during both the baseline and subsequent monitoring efforts, there were consistently greater densities of organisms found on seawalls at the mouths of canals compared to those found on seawalls in the rears of canals, following the same trend as the number of organismal groups present on seawall mouths and rears described above.

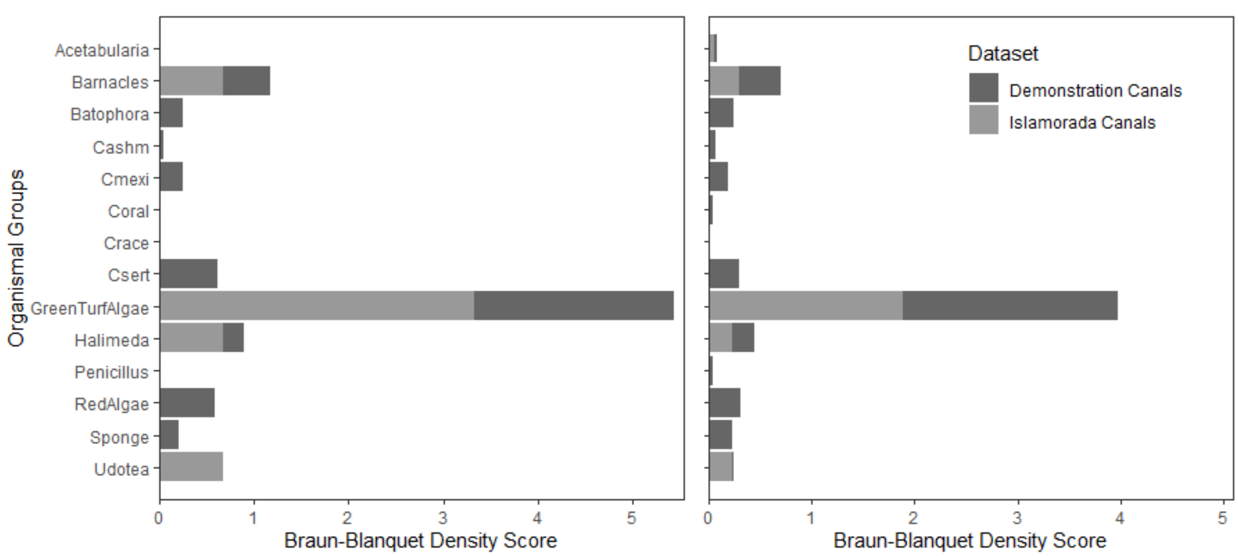

Figure 3.16a: Average density of organisms inhabiting canal seawalls at the mouth of each canal during the first year of monitoring (left) and during all years of monitoring (right). A list of organisms and abbreviations can be found in Table 2.4.

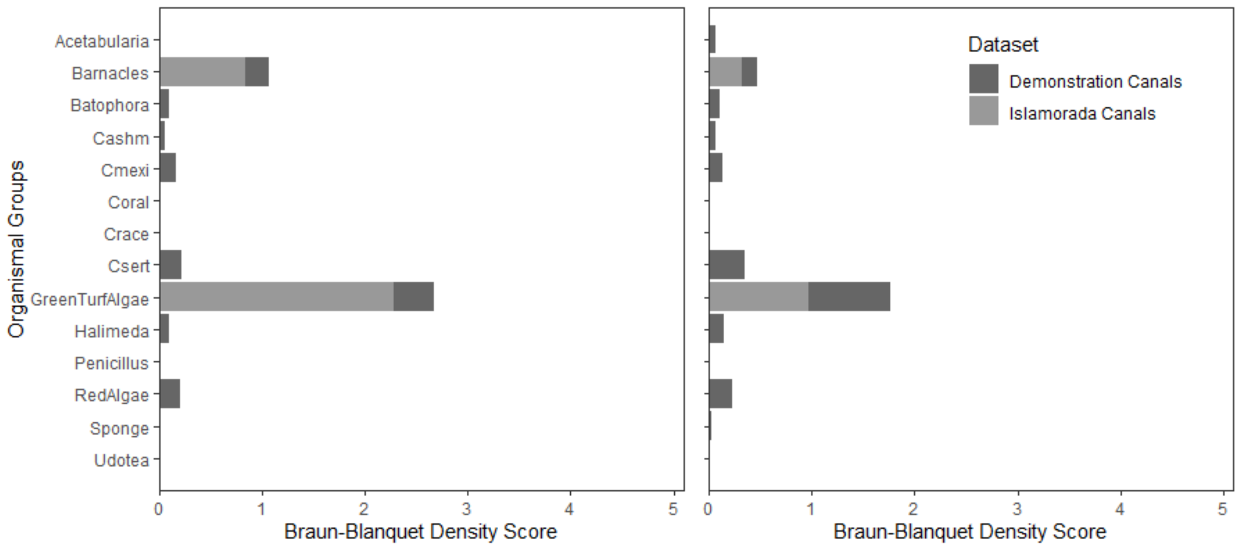

Figure 3.16b: Average density of organisms inhabiting canal seawalls at the back of each canal during the first year of monitoring (left) and during all years of monitoring (right). A list of organisms and abbreviations can be found in Table 2.4.

3.2 Monitoring Results from Islamorada Canals

Baseline sediment conditions in Islamorada canals are better than those in Demonstration canals, with denser sediments containing lower organic material and nutrient content (Table 3.2). However, sediments in Islamorada canals have lower density and greater nutrient content than regional sediments of the Florida Keys (Table 3.2).

There are clear differences in sediments characteristics between Islamorada canals; Canal 145 (facing the Atlantic Ocean) has sediments with the highest organic, Corg, and phosphorus content, while Canal 150 consistently has the lowest nutrient values and highest sediment density

Table 3.2: Sediment characteristics between Demonstration project canals, Islamorada canals, and regional averages. Data represent mean ± SE (min – max). Regional values for the Florida Keys are reported from Fourqurean et al. 2012 and Howard 2018.

Parameter	Unit	Demonstration project canals	Islamorada canals	Regional values for FL Keys
Sediment density	g cm^{-3}	0.27 ± 0.1 (0 – 1.3)	0.43 ± 0.08 (0.214 – 0.79)	0.7 ± 0 (0.2 – 1.5)
Sediment depth	cm	98 ± 14 (8 – 279)	49 ± 10 (27 – 75)	N/A
Organic content	% dry wt.	19.5 ± 3.0 (1.0 – 43.3)	12.0 ± 2.1 (4.5 – 23.1)	6.9 ± 0.6 (3.3 – 19.5)
Corg	% dry wt.	8.0 ± 1.4 (0.3 – 19.8)	5.0 ± 0.9 (2.1 – 10.3)	2.4 ± 0.3 (1.7 – 8.6)
N	% dry wt.	0.80 ± 0.13 (0 – 2.14)	0.46 ± 0.08 (0.16 – 0.95)	N/A
P	% dry wt.	0.06 ± 0.01 (0.02 – 0.13)	0.05 ± 0.01 (0.01 – 0.10)	0.1 ± 0.02 (0.004 – 0.344)

(Fig 3.17). Sediment density was different between canals ($p < 0.0001$), with Canal 150 having greater sediment density than all other Islamorada canals ($p < 0.05$ for all; Fig. 3.17). Sediment organic content was also different between canals ($p < 0.0001$), with Canal 145 having higher organic content than all other Islamorada canals except Canal 152 ($p < 0.05$ for all), and Canal 152 typically having higher organic content and Canal 150 typically having lower organic content compared to all other Islamorada canals (Fig. 3.17). Organic content was also different between canals ($p < 0.0001$), with Canal 145 having greater organic carbon content than all other Islamorada canals ($p < 0.05$ for all), followed by Canal 152 ($p < 0.05$ for all), and Canal 150 typically having lower organic carbon content than all other Islamorada canals (Fig. 3.17). Finally, sediment P content was also different between canals ($p < 0.0001$), with Canal 145 having higher P content than all other Islamorada canals ($p < 0.05$ for all), and Canal 150 having lower P content than all other Islamorada canals ($p < 0.05$ for all; Fig. 3.17). Sediment characteristics have not changed for any parameter over time in any canal ($p > 0.05$ for all; Fig. 3.17).

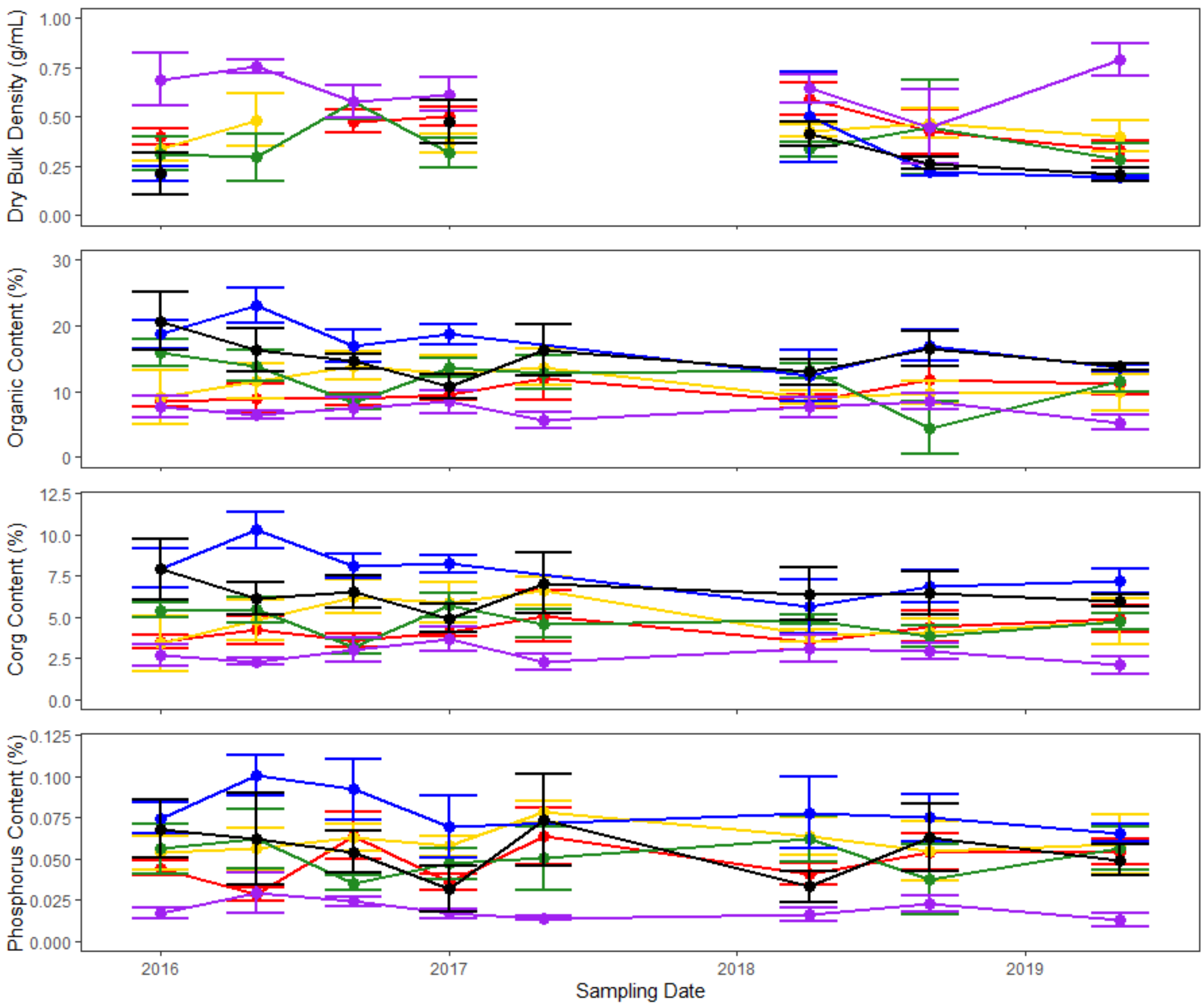

Figure 3.17: Changes in sediment characteristics over time in canals part of the Islamorada monitoring program (Canal 114: red; Canal 118: gold; Canal 120: green; Canal 145: blue; Canal 150: purple; Canal 152: black). Data represent mean ± SE.

3.2.1 Canal 114

Sediment density, organic content and depth in Canal 114 varied greatly from the mouth of the canal to the rear (Fig. 3.18). Generally, sediment density and depth decreased from mouth to rear, while organic content increased from mouth to rear (Fig. 3.18). SAV in Canal 114 was never observed beyond monitoring station 6 and was only observed at low densities in the front portion of the canal (Fig. 3.19). No SAV measurements were collected outside the mouth of Canal 114 because the canal is located off Tavernier Creek (Fig. 3.19).

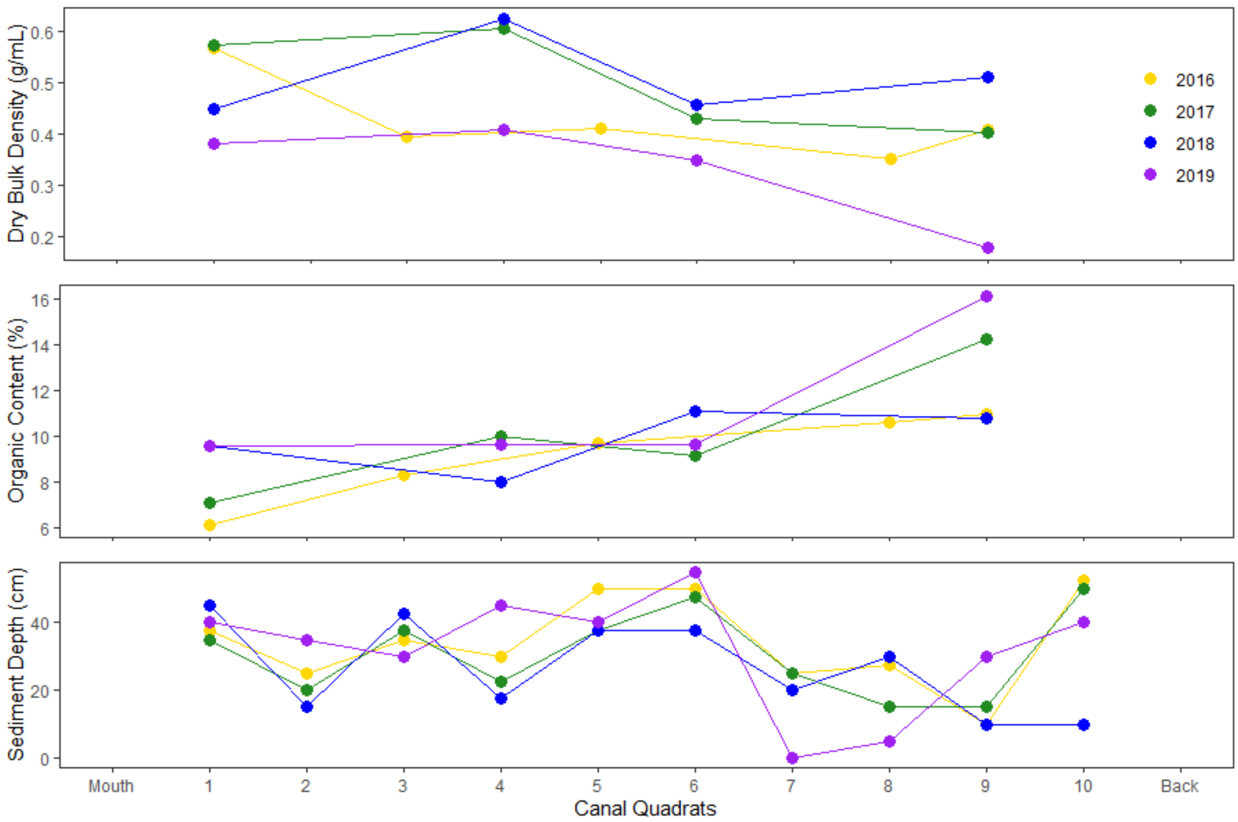

Figure 3.18: Changes in sediment dry bulk density (top), organic content (middle) and sediment depth (bottom) throughout Canal 114 over time.

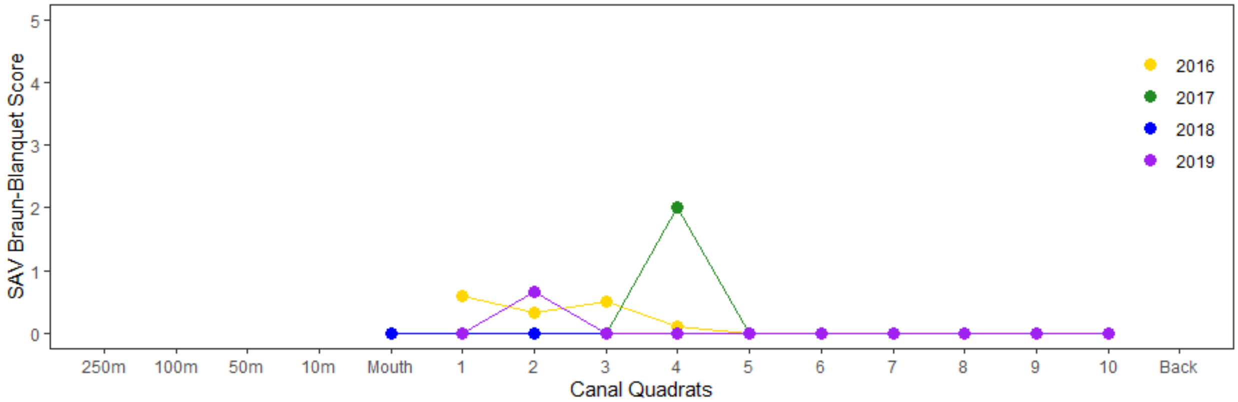

Figure 3.19: Changes in total submerged aquatic vegetation (SAV) throughout Canal 114 over time.

3.2.2 Canal 118

Sediment density, organic content, and depth were all variable throughout Canal 118 (Fig. 3.20). Sediment density typically increased from mouth to rear, while organic content decreased from mouth to rear (Fig. 3.20). Sediment depth was greatest at monitoring station 1 near the mouth in 2017 and 2018, but highest at monitoring station 6 in 2019 and monitoring stations 2 and 10 in 2016 (Fig. 3.20). Moderately dense SAV was observed outside the mouth of the canal and sometimes in through monitoring station 2 (Fig. 3.21). SAV was not observed further into the canal, except for one instance in 2016 at monitoring station 6 (Fig. 3.21).

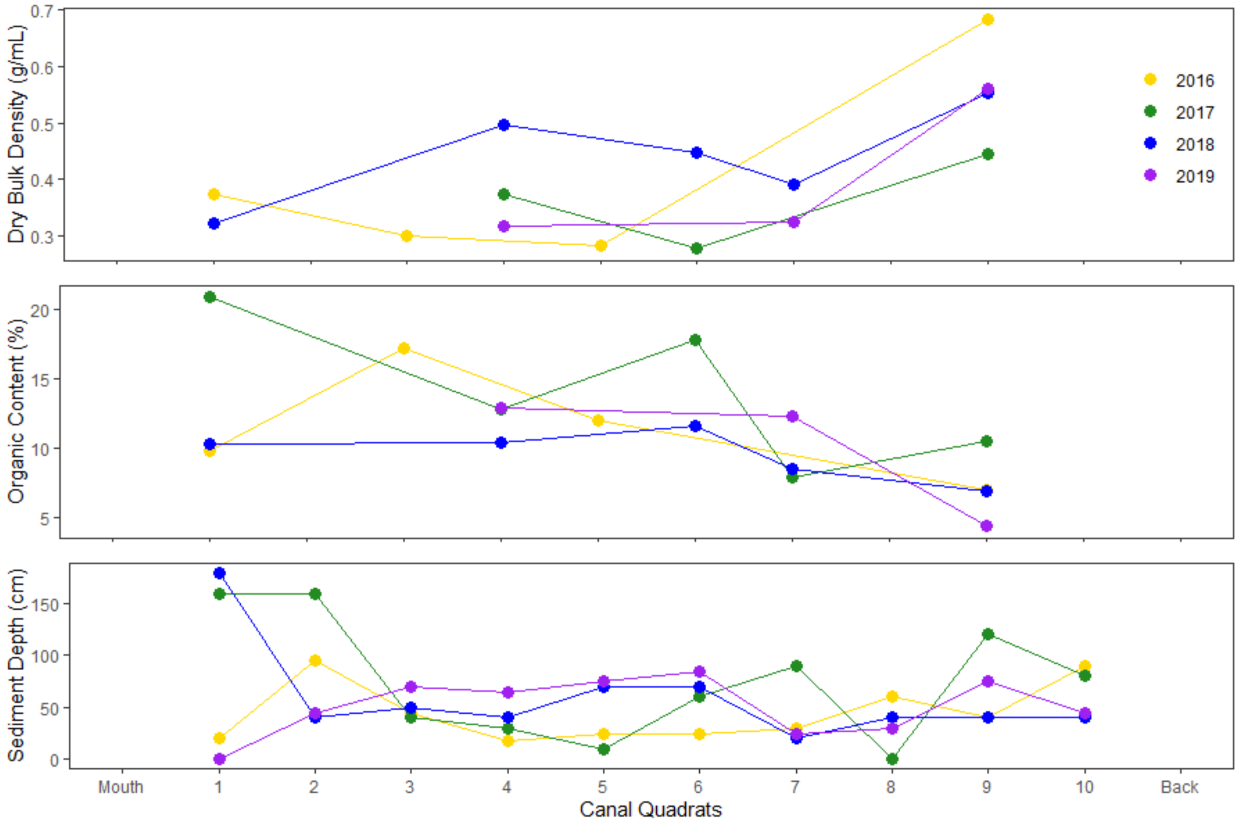

Figure 3.20: Changes in sediment dry bulk density (top), organic content (middle) and sediment depth (bottom) throughout Canal 118 over time.

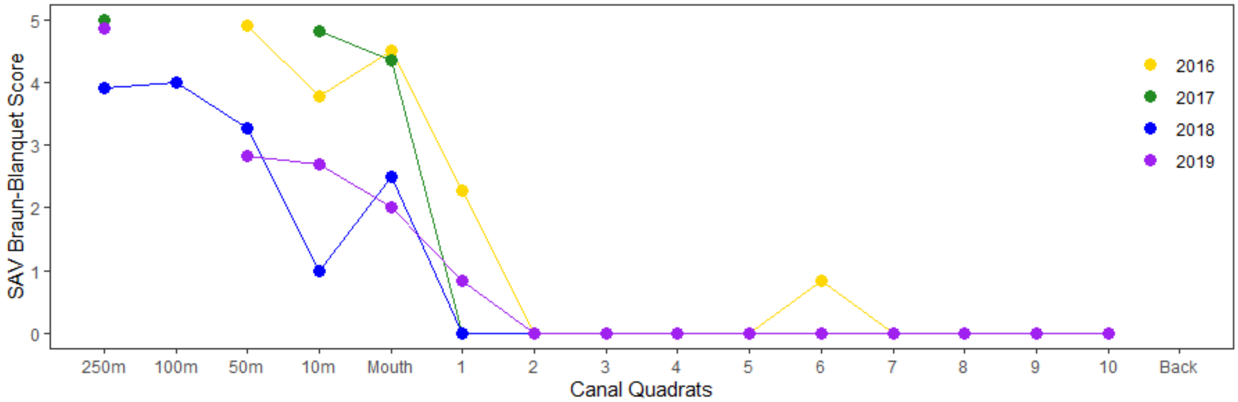

Figure 3.21: Changes in total submerged aquatic vegetation (SAV) outside of and throughout Canal 118 over time.

3.2.3 Canal 120

Monitoring in Canal 120 usually showed lower sediment density and higher organic content from monitoring stations 5 through 9 (Fig. 3.22). Sediment depth was typically greatest at monitoring station 3 (in 2017 and 2018) or at monitoring station 10 at the rear of the canal (Fig. 3.22). SAV was not measured outside the mouth of the canal because of the orientation of a bank near the mouth (Fig. 3.23). SAV was sometimes seen at monitoring stations 1 and 2 near the mouth of the canal, and throughout at monitoring stations 5 and 7 in low abundances (Fig. 3.23).

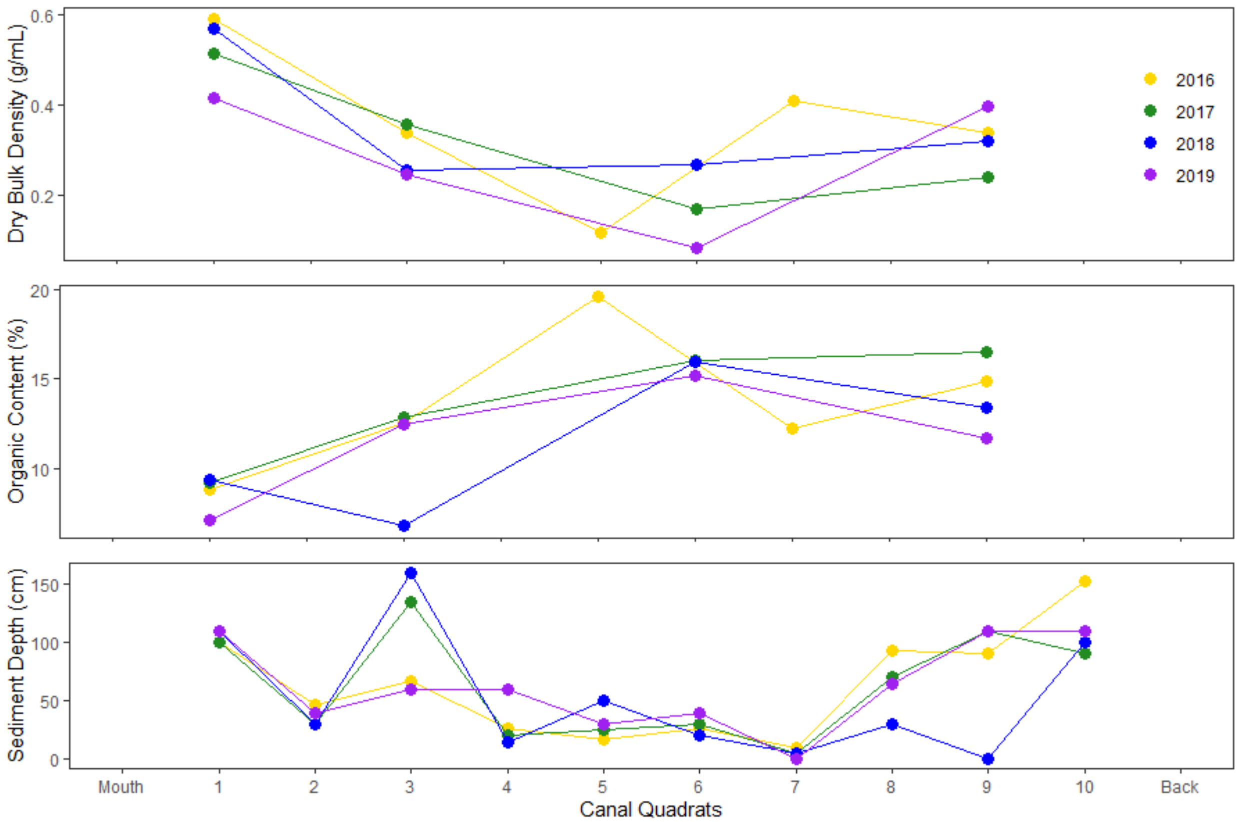

Figure 3.22: Changes in sediment dry bulk density (top), organic content (middle) and sediment depth (bottom) throughout Canal 120 over time.

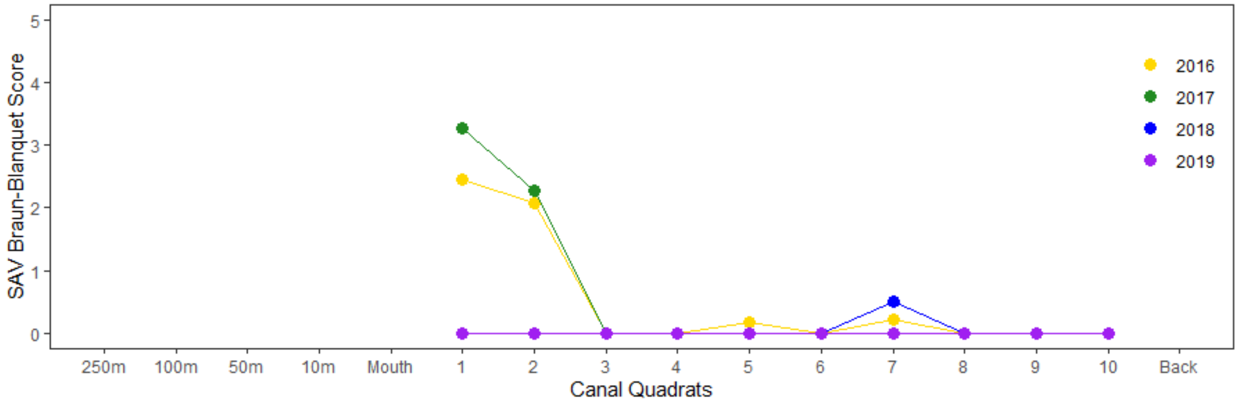

Figure 3.23: Changes in total submerged aquatic vegetation (SAV) throughout Canal 120 over time.

3.2.4 Canal 145

Generally, sediment density and organic content remained strikingly similar throughout the extent of Canal 145 across all years, except for notably higher density and lower organic content recorded at monitoring station 1 near the mouth in 2018 (Fig. 3.24). Sediment depth and SAV were never measured in Canal 145 due to unsafe diving conditions, but SAV was observed outside of the canal (Figs. 3.24 and 3.25).

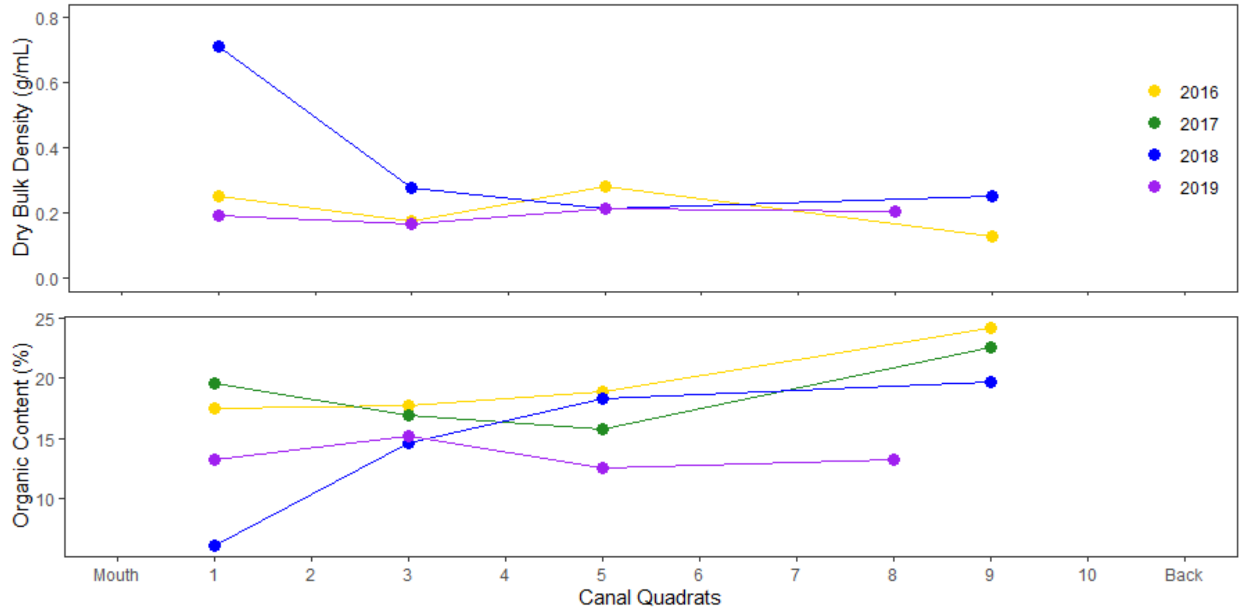

Figure 3.24: Changes in sediment dry bulk density (top) and organic content (bottom) throughout Canal 145 over time.

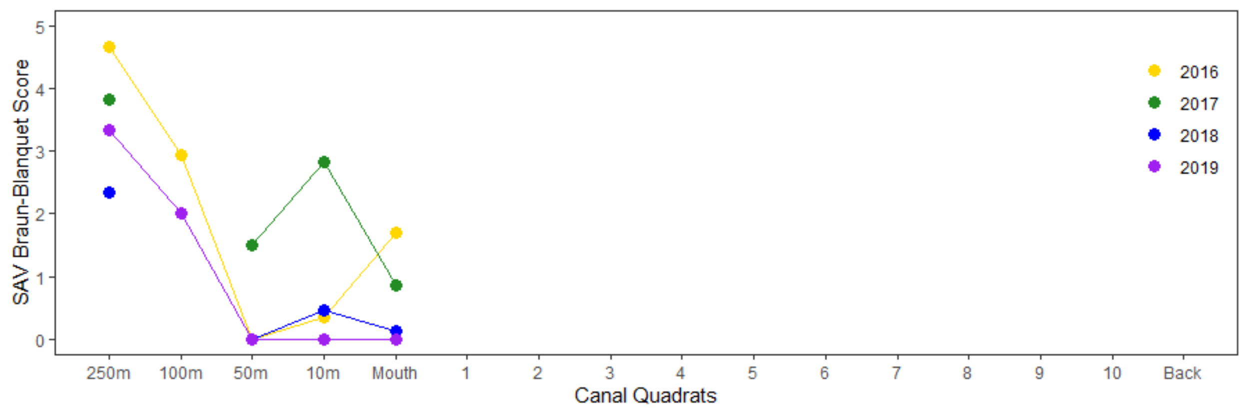

Figure 3.25: Changes in total submerged aquatic vegetation (SAV) outside of Canal 145 over time.

3.2.5 Canal 150

Similar to the other Islamorada canals, Canal 150 showed fluctuations in sediment density and organic content from mouth to rear (Fig. 3.26). While there were no statistical differences through time ($p > 0.05$), density was higher and organic content was lower in the outer half of canals in 2019 compared to other years (Fig. 3.26). Sediment depth ranged from approximately 10 to 50 cm from the mouth of the canal back to monitoring station 8, increased greatly at monitoring station 9, then decreased again at monitoring station 10 (Fig. 3.26). SAV measurements fluctuated greatly throughout Canal 150 during all years of monitoring, though SAV was consistently observed from 250 m outside to the canal to at least monitoring station 8, and sometimes all the way to monitoring station 10 at the rear of the canal (Fig. 3.27).

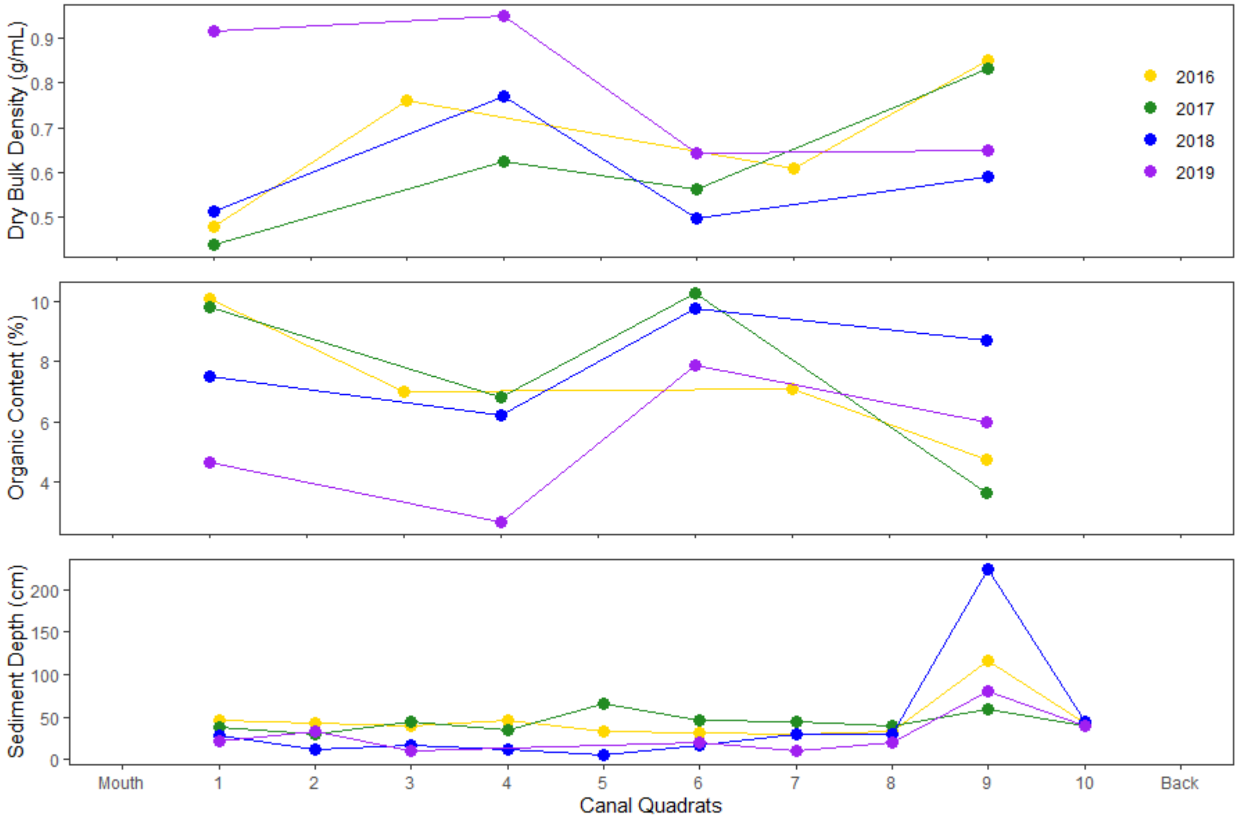

Figure 3.26: Changes in sediment dry bulk density (top), organic content (middle) and sediment depth (bottom) throughout Canal 150 over time.

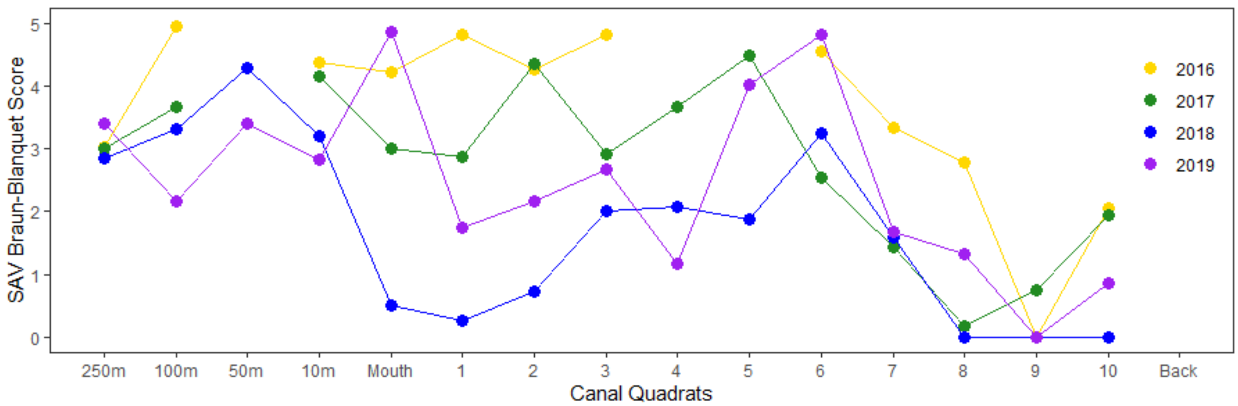

Figure 3.27: Changes in total submerged aquatic vegetation (SAV) outside of and throughout Canal 150 over time.

3.2.6 Canal 152

Sediment density, organic content, and depth varied greatly for Canal 152, both between monitoring stations within the canal and across years (Fig. 3.28). Sediment depth was typically higher in the middle of the canal and quite low at monitoring station 8 (Fig. 3.28). SAV was found in moderate to high densities outside of Canal 152 but was typically not found inside the canal except for on a few occasions near the mouth and once at monitoring station 5 in 2019 (Fig. 3.29).

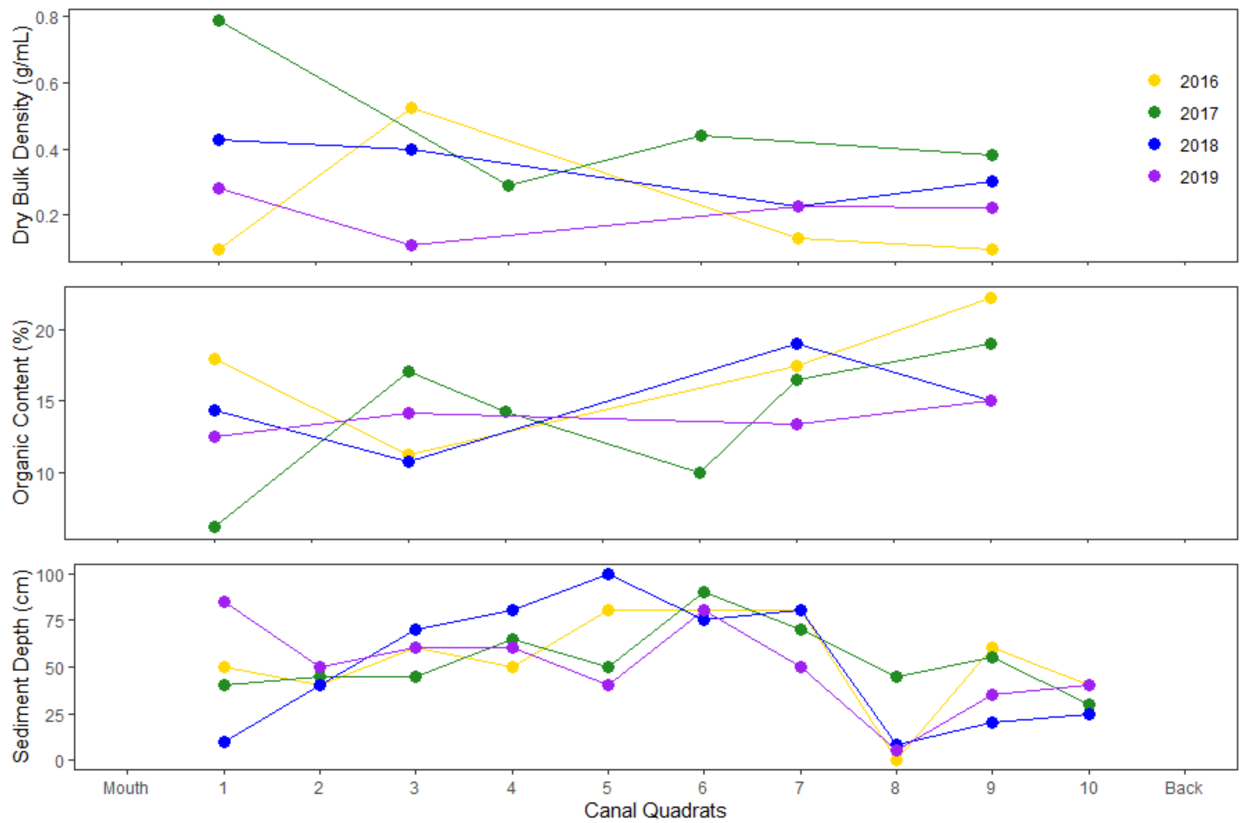

Figure 3.28: Changes in sediment dry bulk density (top), organic content (middle) and sediment depth (bottom) throughout Canal 152 over time.

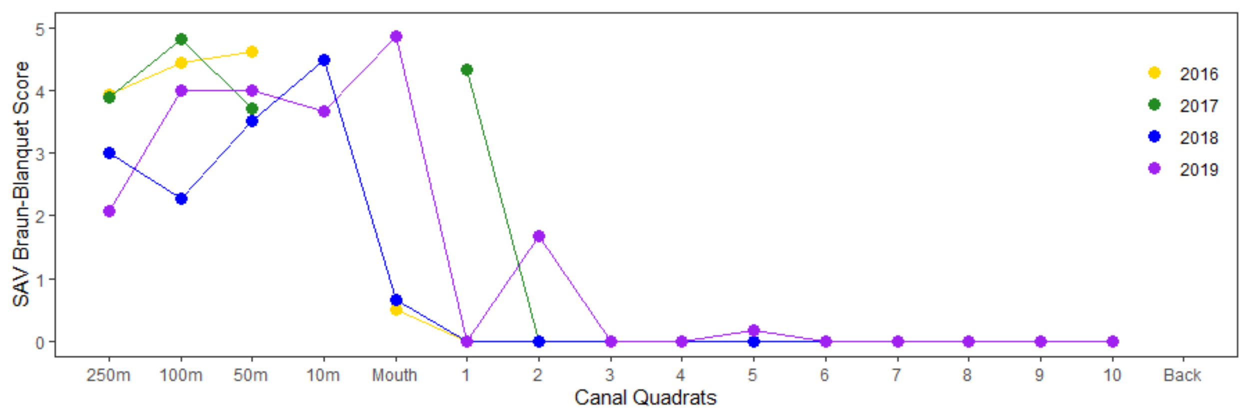

Figure 3.29: Changes in total submerged aquatic vegetation (SAV) outside of and throughout Canal 152 over time.

Seagrasses were not collected outside the mouths of Canal 114, which opens to Tavernier Creek, nor Canal 120, which has a bank adjacent to its mouth. C:P and N:P molar ratios were not different between canals ($p > 0.05$ for both) and no changes were observed through time for any canal ($p > 0.05$ for all; Fig. 3.30). C:P ratios ranged from 573.2 to 1,293.9, averaging 808.6 ± 47.0, and N:P ratios ranged from 35.9 to 69.7, averaging 46.0 ± 2.1 (Fig. 3.30). There were significant differences in $\delta^{13}C$ signatures between canals ($p < 0.01$), where Canal 118 was different from Canals 150 and 152 ($p < 0.05$ for both), but not from Canal 145 ($p > 0.05$; Fig. 3.30). The $\delta^{13}C$ signatures for Canal 118 and 152 increased through time ($p < 0.05$ for both; Fig. 3.30). There were also differences in $\delta^{15}N$ between canals ($p < 0.001$), with seagrasses outside the mouth of Canal 118 having higher $\delta^{15}N$ signatures than the other Islamorada canals ($p < 0.05$; Fig. 3.30).

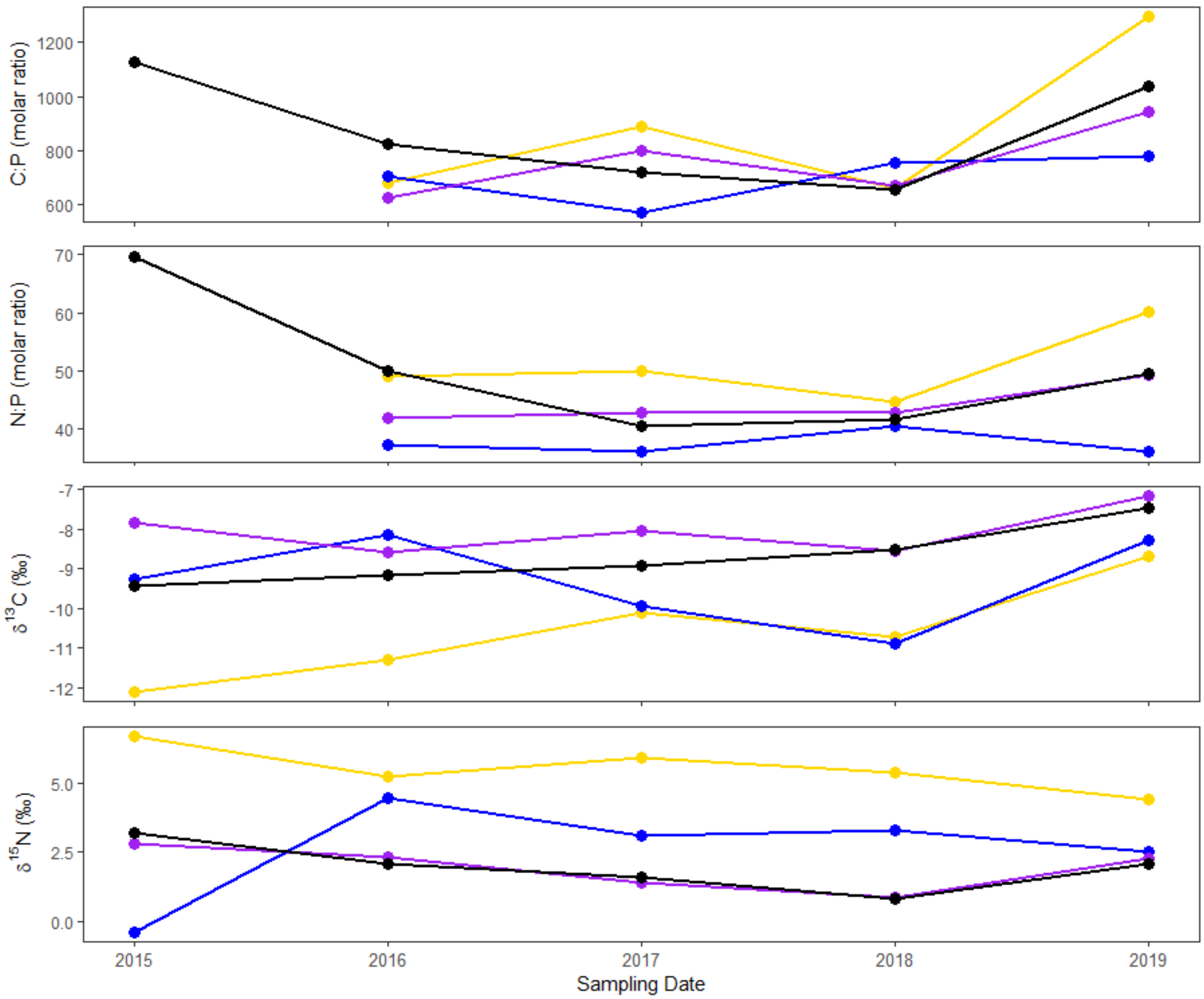

Figure 3.30: Changes in *Thalassia testudinum* leaf tissue nutrient content and stable isotope values over time in canals part of the Islamorada monitoring program (Canal 118: gold; Canal 145: blue; Canal 150: purple; Canal 152: black). Leaf samples were collected at the point closest to the canal mouth with seagrass, 10m – 250m outside canal.

Seawall inhabiting organisms were only observed at the mouth in Canals 114 and 118, and at the rear in Canal 118 (Fig. 3.15a-b). The Islamorada canals are heavily used and densely occupied by docked boats. Seawall space typically monitored for organisms was frequently shadowed by docked boats or cleaned of organisms in such a way to prevent fouling. Fish were observed in all the Islamorada canals except Canal 120 (Figs. 3.13 and 3.14). Mangrove snapper, unidentifiable juvenile fish, and mullet were the most commonly encountered, while an eagle ray observed in Canal 145 and Sergeant major observed in Canal 150 were singular events.

3.3 Effects of Demonstrated Technologies

3.3.1 Canal 29 – Backfilling

The backfilling of Canal 29 with carbonate sand was completed June 2015, leveling the canal depth to a consistent 6-7 feet from mouth the rear. The adjacent, untreated Canal 28 served as an experimental control for reference. Sediment densities and organic content were similar between Canal 28 and 29 prior to the implementation of demonstration technology, however P content was notably higher in Canal 28 than in Canal 29 (Fig. 3.31). After the backfilling in Canal 29 there were drastic differences in sediment characteristics between the two canals (Fig 3.31). After backfilling, sediment density in Canal 29 was greater, averaging 0.9 ± 0.2 g cm^{-3}, compared to the control Canal 28, which averaged 0.3 ± 0.1 g cm^{-3}. After backfilling, sediment density in Canal 29 was similar to the reported regional averages of 1.0 ± 0.1 g cm^{-3} for Florida Bay (Fourqurean et al. 2012a) and 0.73 ± 0.04 for the Florida Keys (Howard 2018). The new sediment of Canal 29 was denser and more commonly described as sand or muddy sand, compared to the control sediments exclusively categorized as mud or unconsolidated organic material. Percent organic material decreased in the backfilled canal relative to the control, 22.0 ± 2.9 % compared to 5.7 ± 3.1 % dry wt. Similar to organic material, the newly backfilled sediment was ~5 - fold lower in C_{org} on average compared to the control canal (2.4 ± 1.4 % compared to 10.2 ± 1.2 % dry wt.). There was no difference in average sediment P between the backfilled and control canal.

Sediment characteristics in Canal 29 improved immediately after backfilling in 2015, though it is important to note that changes were not consistent nor stable. Post-backfilling sediment was higher in organic material (along with C_{org}, N, and P) and lower in density near the canal mouth and has fluctuated, particularly near the mouth, over time (Fig 3.32).

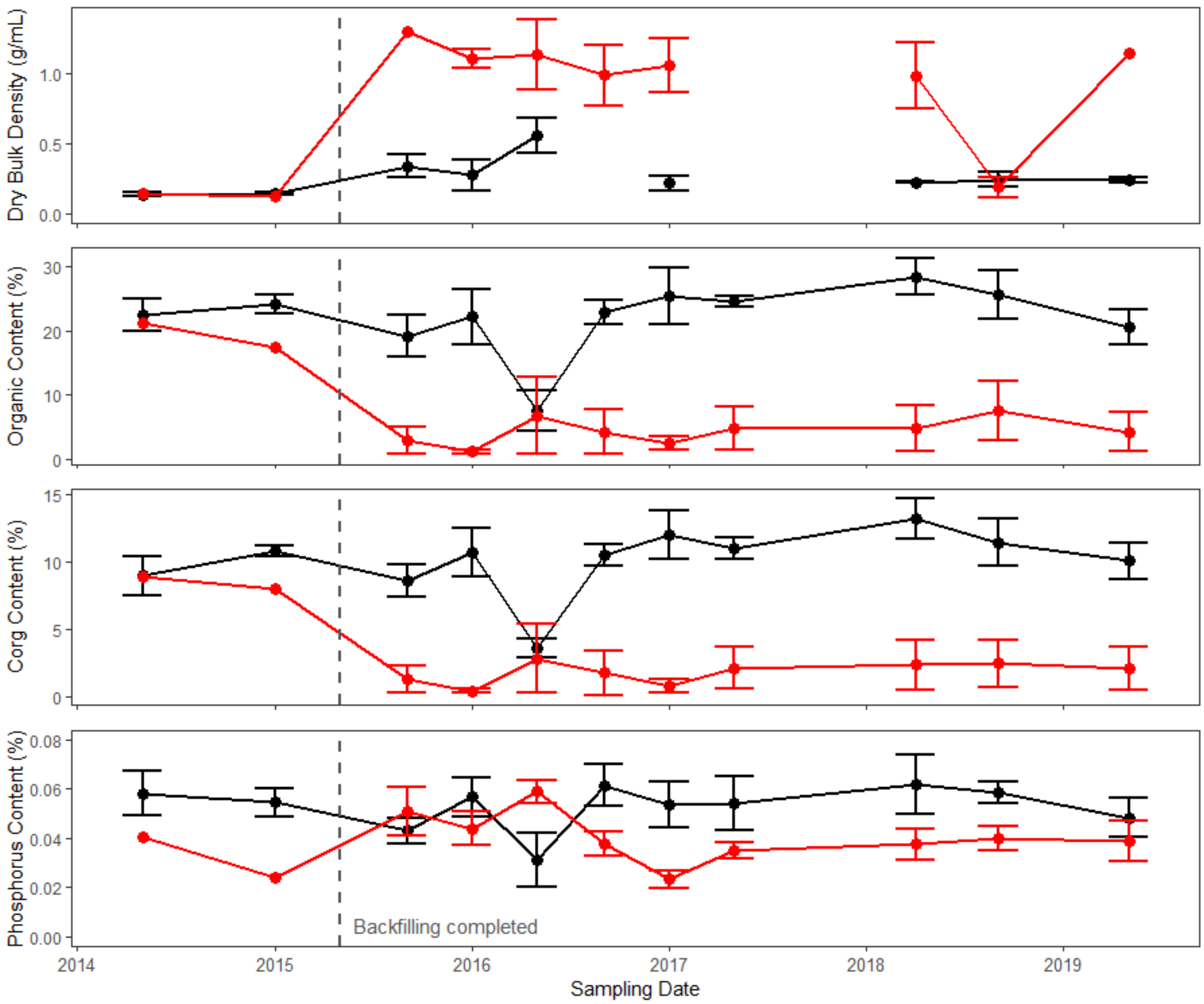

Figure 3.31: Changes in sediment characteristics over time in the backfilled Canal 29 (red) compared to the adjacent reference, Canal 28 (black). Points represent mean ± SE.

During baseline monitoring, the only vegetation observed in the canal pair was a small patch of the seagrass *Halodule wrightii* found near the mouth of Canal 29 in 2014 (Fig 3.3). Benthic vegetation was otherwise absent from the canals during baseline, pre-backfilling monitoring. Within one year of the backfilling, SAV (particularly species of *Penicillus* and *Halimeda*) began to colonize the benthos of the Canal 29, forming dense patches in the rear half of the canal (Fig 3.33). During the fall 2015 campaign and again in fall 2016, the seagrass *Halodule wrightii* was found inhabiting the canal, approximately halfway between the canal mouth and rear. The increasing total SAV trend persisted through 2017 however in 2018 we observe a drop in cover, likely associated to disturbances from Hurricane Irma. Interestingly, by the 2019 campaign the SAV cover had rebounded to levels closer to those observed in 2016, though didn't yet reach pre-hurricane, 2017 densities.

The communities of seawall-inhabiting organisms in Canal 29 shifted after the backfilling as well (Fig. 3.15a-b). In the rear, *Caulerpa sertularioides*, which was absent prior to backfilling, increased to 75% - 100% coverage of the seawall. Turf green algae and *Penicillus* also appeared on the rear seawall after treatment. Fish diversity and abundance both increased after the backfilling in Canal 29. Fish abundance slightly decreased while fish species diversity increased

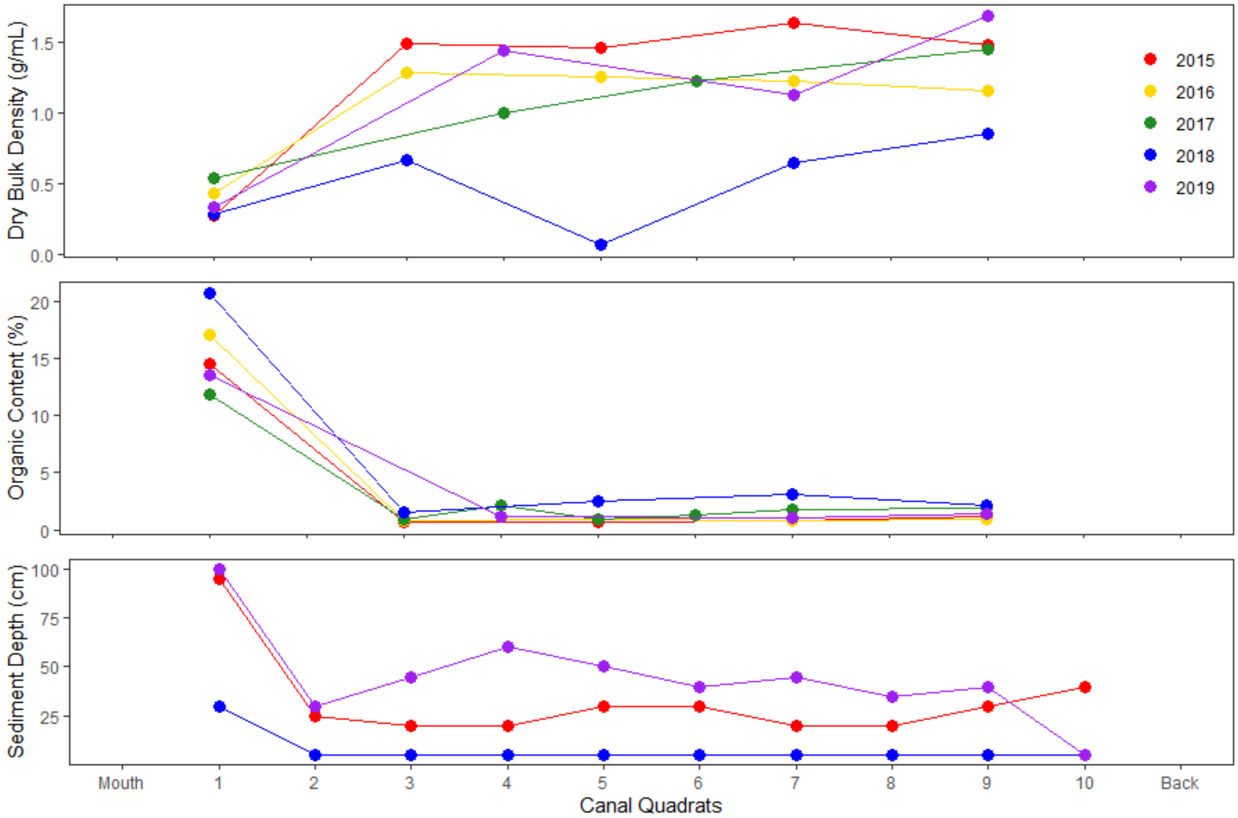

Figure 3.32: Changes in sediment dry bulk density (top), organic content (middle) and sediment depth (bottom) throughout backfilled Canal 29 over time.

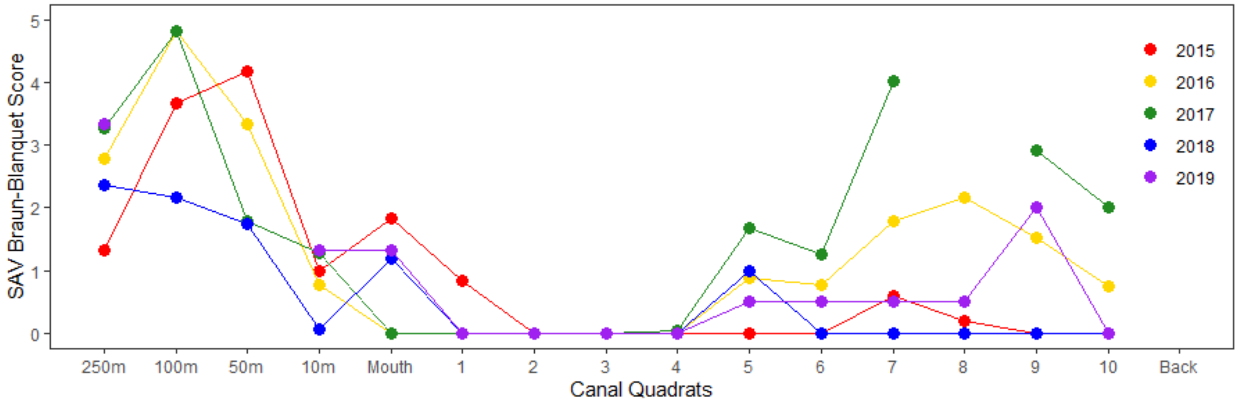

Figure 3.33: Changes in total submerged aquatic vegetation (SAV) outside of and throughout backfilled Canal 29 over time.

in Canal 28 after the backfilling in Canal 29. Therefore, conclusions regarding fish communities are unable to be reached as 1) data is likely to be biased as the improved water clarity resulting from the backfilling may have increased post-treatment fish counts, and 2) fish species diversity increased in both the demonstration and control, so we cannot conclude that backfilling was the reason behind the increase.

Seagrass leaf nutrient values varied considerably though there was no clear difference between those for the backfilled canal versus the adjacent (Fig 3.34). In fact, the directional trends for leaf tissue measurements are nearly identical for the two canals. Seagrass leaf C:P and N:P molar ratios increased through time ($p < 0.01$ and $p = 0.01$, respectively; Fig. 3.34), potentially indicating decreases in P availability. Average C:P was 1062.8 ± 83.3 and average N:P was 59.6 ± 2.6 (Fig. 3.34). Inside the canals, however, P content in the sediments displayed variability and divergence between canals (Fig. 3.31). There was fluctuation between increases and decreases in seagrass $\delta^{13}C$ and $\delta^{15}N$ throughout our monitoring, with $\delta^{13}C$ signatures ranging from –15.7 to –10.2 ‰ and $\delta^{15}N$ signatures ranging from 2.7 to 7.2 ‰ (Fig. 3.34).

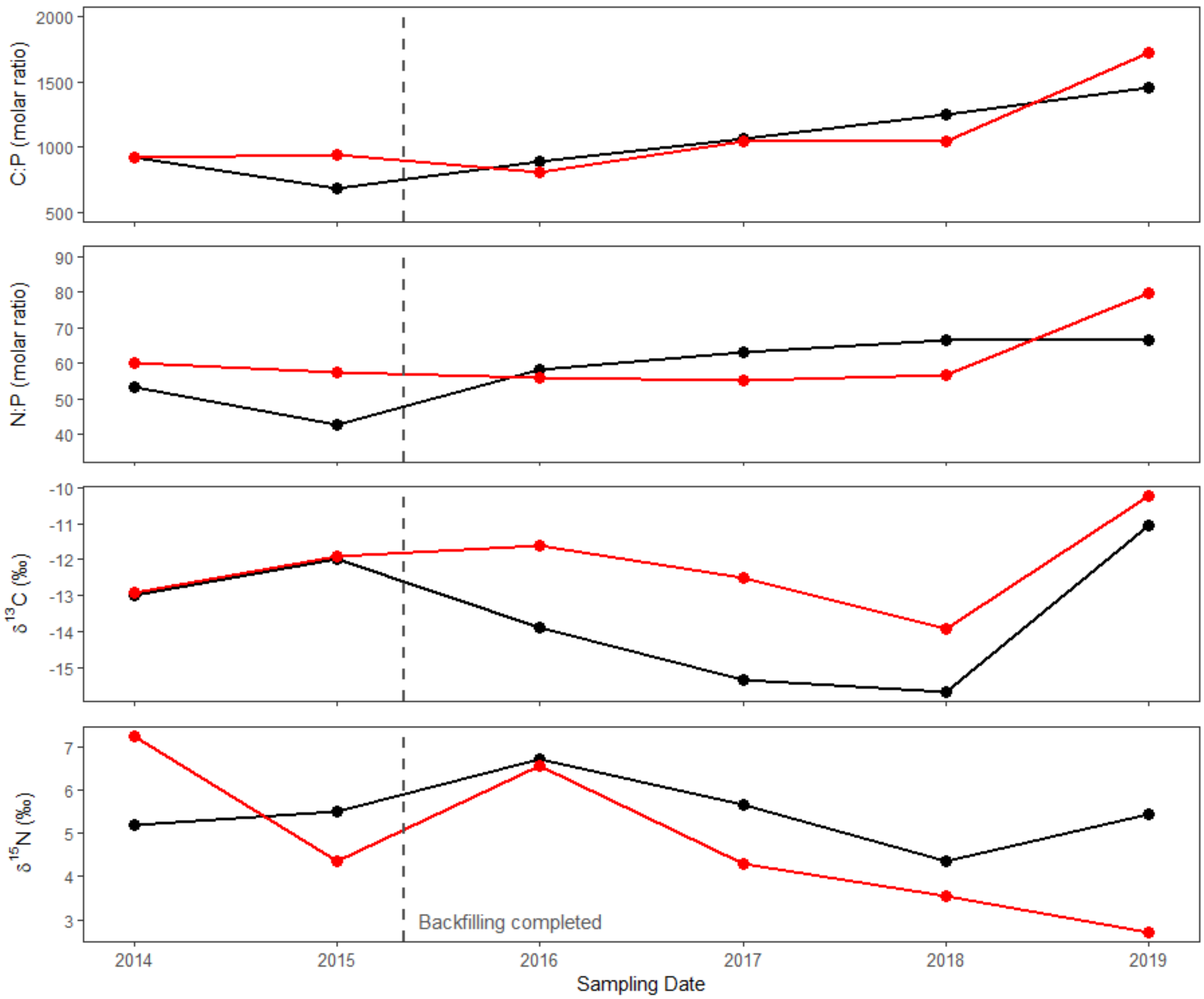

Figure 3.34: Changes in *Thalassia testudinum* leaf tissue nutrient content and stable isotope values of backfilled Canal 28 (red) and its reference, Canal 29 (black). Leaf samples were collected at the point closest to the canal mouth with seagrass, 10m – 250m outside canal.

3.3.2 Canal 137 – Air Curtain & Aerators

Canal 137 received an air curtain in November 2014 to prevent the entry of wrack into the canal along with 6 aerators in addition to the 6 already in existence. The adjacent Canal 132 served as an experimental control. Unfortunately, there were no demonstrable effects of the air curtain on canal sediment characteristics (Fig 3.35). Both canals had primarily muddy, low-density sediments both averaging 0.28 ± 0.07 g cm^{-3} with percent organic material averaging 12.6 ± 2.5 % and C_{org} content averaging 5.0 ± 0.9 %. Sediment phosphorus content remained relatively consistent through monitoring except for two points in Canal 132, with two high concentration samples influencing the mean. Over two years after the installation of the air curtain and additional aerators, the only detectible difference in sediment characteristics was slightly lowered P levels in compared to the control, although this could be unduly influenced by the presence of two anomalously high samples from Canal 132. Importantly, even though Canal 137 and 132 showed differences in sediment P content through time, Canal 137 did not show changes in sediment P between pre- and

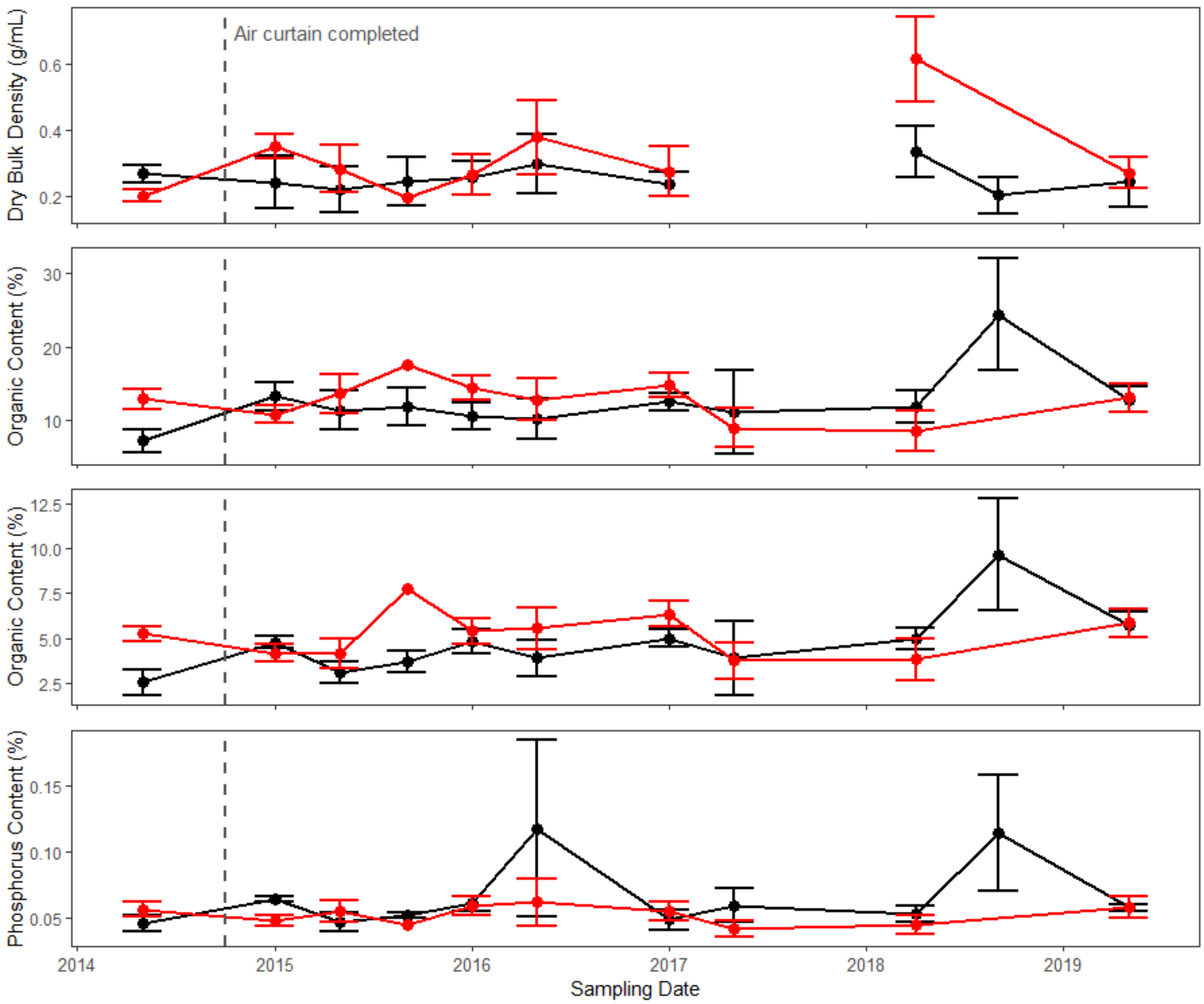

Figure 3.35: Changes in sediment characteristics over time in Canal 137 (red) compared to the adjacent, reference, Canal 132 (black). Data represent mean ± SE, and the vertical grey line indicates when the installation of air curtain and additional aerators was finished.

post-demonstration technology installation. There was variability in sediments characteristics over time though no trend or clear effect of the installed technologies for all other parameters. Sediment density, organic content, and depth also did not show consistent trends throughout monitoring for Canal 137 (Fig. 3.36).

While fish were observed in both canals during baseline monitoring, fish abundance increased in Canal 132 but decreased in Canal 137 after installation of the demonstration technologies, despite the increased oxygen availability (Fig. 3.13). Additionally, the seawalls at the mouth and rear of Canal 137 showed decreases in the number of organism species present after the installation of air curtains and aerators (Fig. 3.15a-b).

After the air curtain and aerator installations, benthic vegetation was only observed outside of Canal 137, SAV being completely absent from the interior (Fig 3.37). *Thalassia testudinum* from adjacent areas outside of the canal was only present during four monitoring campaigns after demonstration technology installation, so results must be interpreted with caution. Directly following air curtain and aerator installation, no changes were observed in C:P molar ratios, but there were decreases in N:P molar ratios and $\delta^{15}N$ values, and an increase in $\delta^{13}C$ values (Fig 3.38). There have been marked increases in all four parameters since the first post-technology monitoring campaign and the most recent campaign, possibly suggesting less P availability (Fig. 3.38). However, sediment P content did not show a consistent trend over time (Fig. 3.36), so this trend may be emerging from the low number of samples and may not be indicative of an overall change in nutrient exports to adjacent areas.

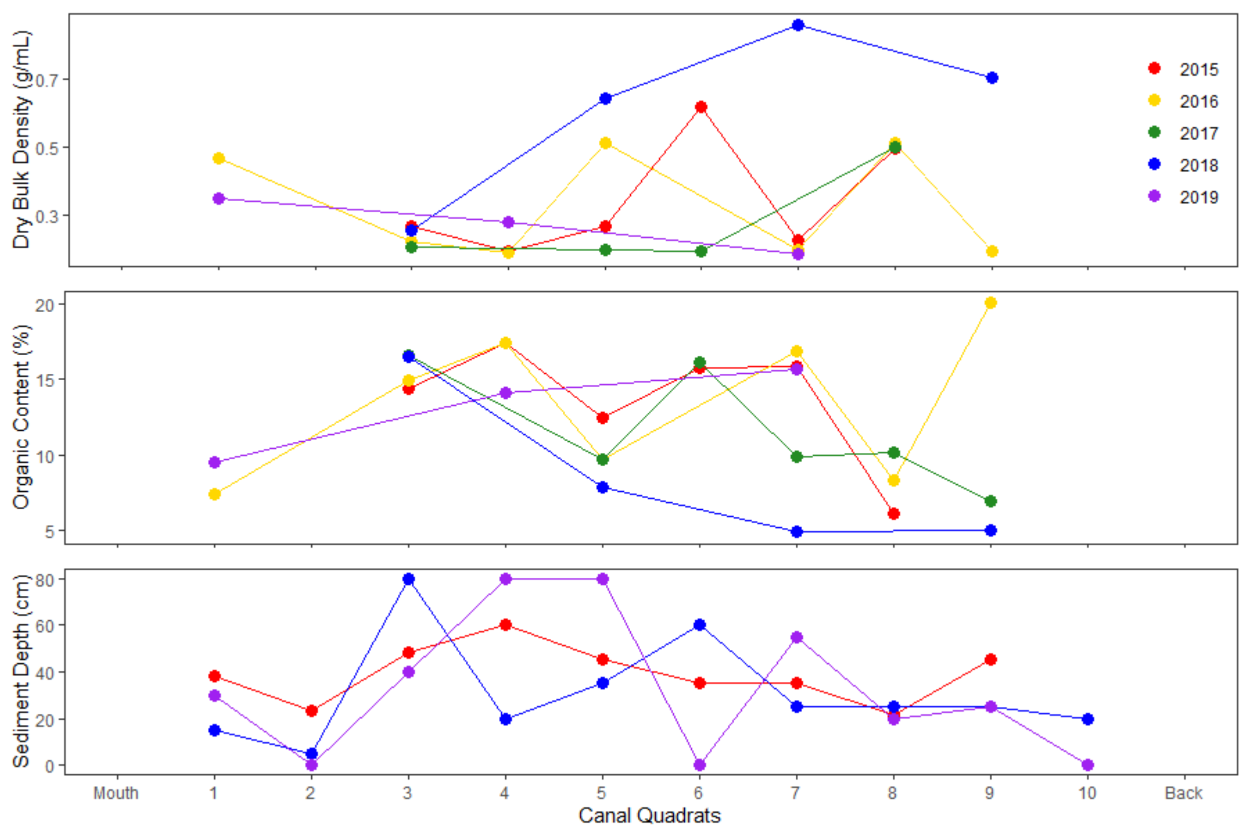

Figure 3.36: Changes in sediment dry bulk density (top), organic content (middle) and sediment depth (bottom) throughout Canal 137 over time.

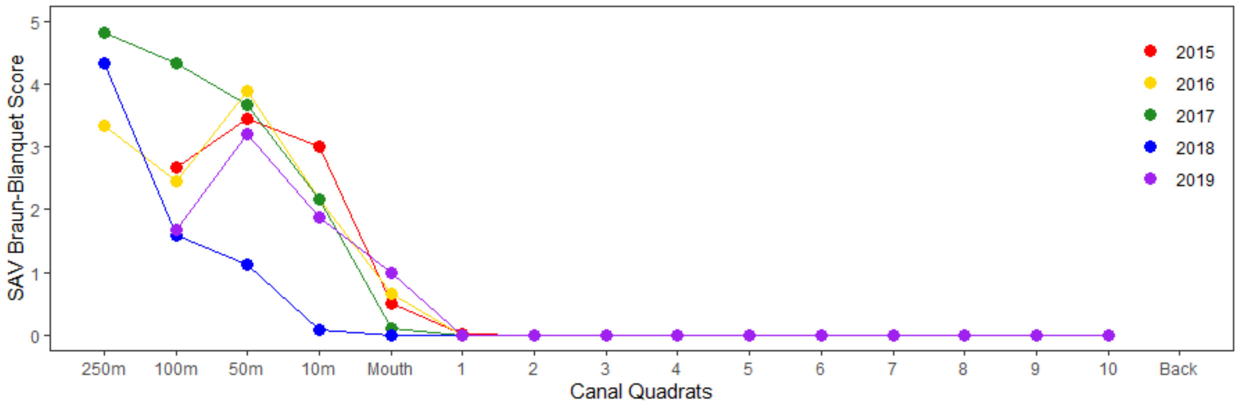

Figure 3.37: Changes in total submerged aquatic vegetation (SAV) outside of and throughout Canal 137 over time.

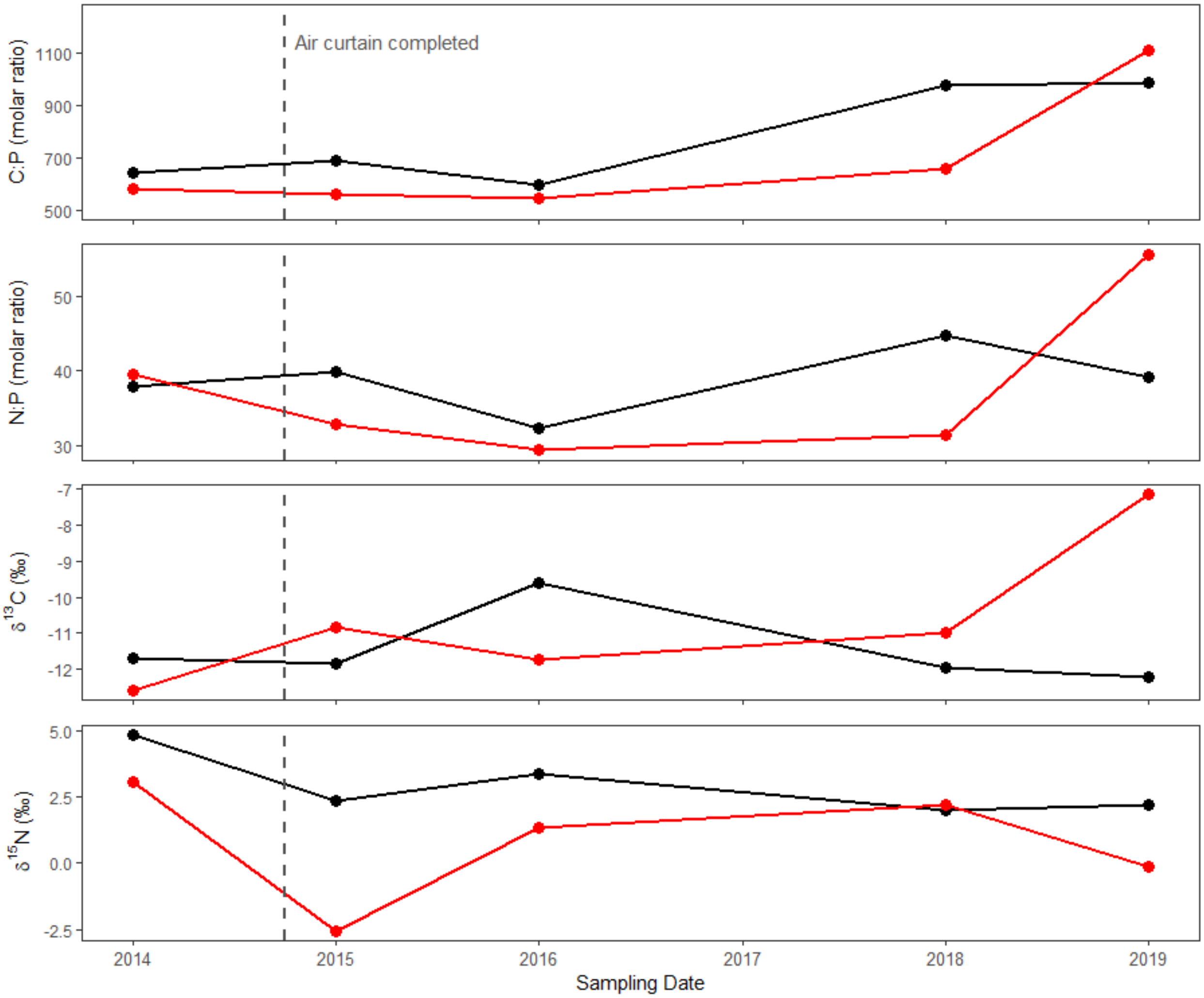

Figure 3.38: Changes in *Thalassia testudinum* leaf tissue nutrient content and stable isotope values in backfilled Canal 137 (red) and its reference, Canal 132 (black). Leaf samples were collected at the point closest to the canal mouth with seagrass, 10m – 250m outside canal.

3.3.3 Canal 148 – Air Curtain

Canal 148 was slated to receive a weed gate in 2015, though permitting obstacles postponed the installation until April 2017. Monitoring in this report is from 2014 through September 2018, thus the effectiveness of the installed air curtain cannot be accurately assessed here. In both Canal 148 and its control, Canal 147, water quality was periodically impaired enough to prevent sampling on SCUBA, thus sediment sampling was done using a box grab operated from the boat. This method unfortunately impedes accurate depth measurements as well as dry bulk density measurements, which are not included.

Sediment organic content is indistinguishable between Canals 147 and 148 but varies greatly over time (Fig 3.39) with a max of 19.9 % and a minimum of 11.8 %, averaging 17.6 ± 2.8 %. Corg content ranged greatly during the period from 4.0 % to 10.1 % averaging 7.3 ± 1.3 %. Sediments in both canals were consistently described as unconsolidated organic material and mud, containing high quantities of identifiable seagrass detritus. Trends in sediment density, organic

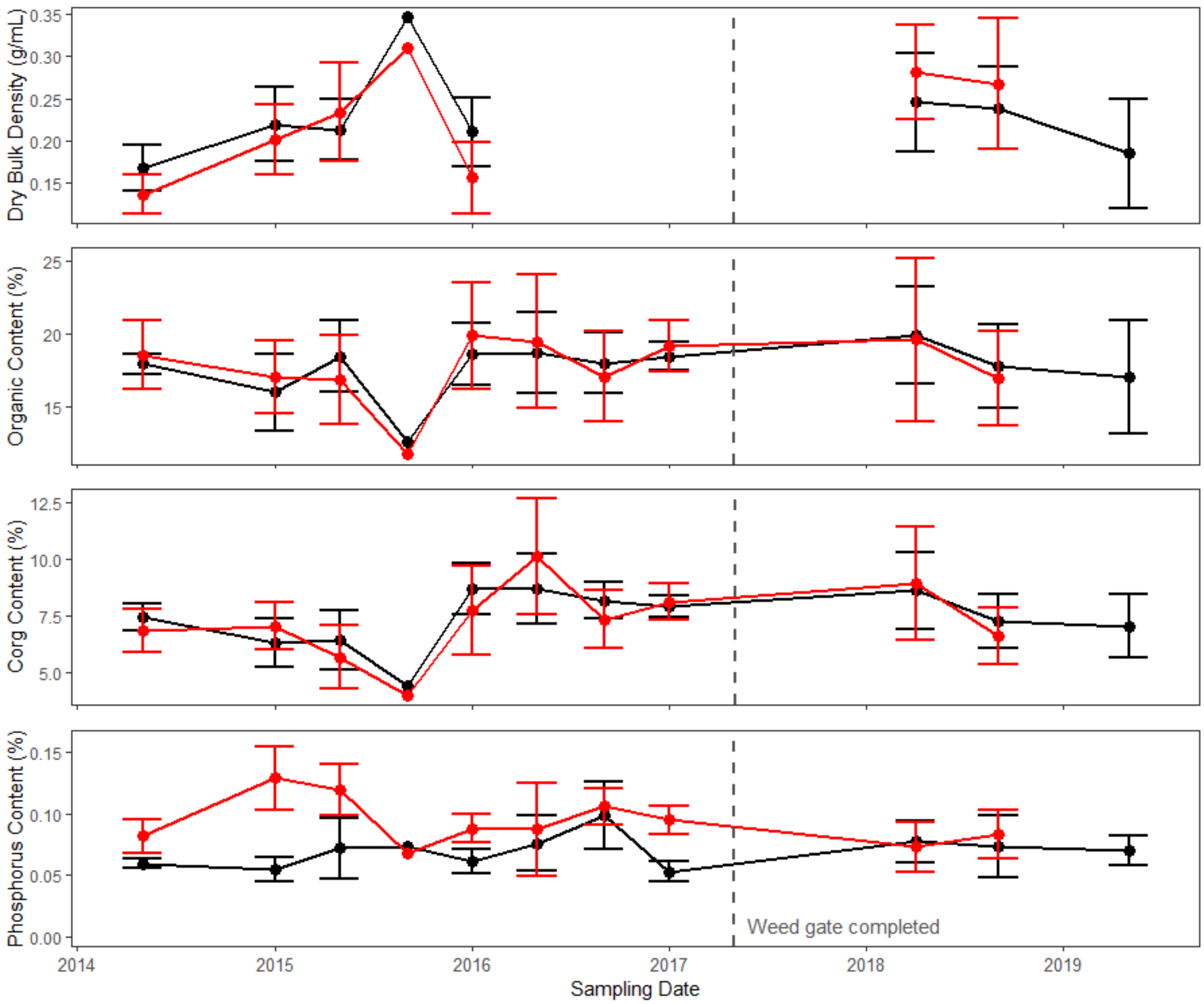

Figure 3.39: Changes in sediment characteristics over time in Canal 148 (red) compared to the adjacent reference, Canal 147 (black). Data represent mean ± SE, and the vertical grey line indicates when the installation of the weed gate was finished.

and Corg content track similarly between Canals 147 and 148, though phosphorus does not share such similar fluctuations (Fig 3.39). There was no measurable effect of demonstrated technology on sediment characteristics, though this is not a surprise given the short period after the installation. After the air curtain installation, sediment density was greater and organic content was lower for Canal 148 compared to pre-installation levels (Fig. 3.40). Dry bulk density decreases and organic content increases moving from mouth to rear of Canal 148, a trend which held both before and after the air curtain installation (Fig. 3.40). Sediment depth varied greatly throughout the canal during 2015 monitoring but has not yet been assessed after demonstration technology installation (Fig. 3.40).

Seagrass detritus was a common occurrence in canals, but living benthic vegetation was completely absent from both canals throughout the monitoring (Fig. 3.41). Observations of benthic vegetation begin outside the canal mouth, reaching the highest density 50 m - 100 m outside the canal where *Thalassia testudinum*, *Halodule wrightii*, and calcifying macroalgae where regularly found (Fig 3.41). *Thalassia* leaf tissue C:P and N:P were typically similar over time outside of Canals 147 and 148, though an abrupt decrease from 41.3 to 21.3 in N:P molar ratios was observed outside of Canal 148 just after demonstration technology installation (Fig. 3.42). δ^{13}C values were usually lower and δ^{15}N values were usually higher for seagrasses outside of Canal 148 compared to Canal 147 but marked changes to grasses outside of Canal 148 were not observed after the air curtain installation (Fig. 3.42). δ^{13}C signatures ranged from –10.1 to –7.6 ‰ and from –10.5 to –8.8 ‰ and averaged -8.8 ‰ and –9.7 ‰ for Canals 147 and 148, respectively (Fig. 3.42). δ^{15}N

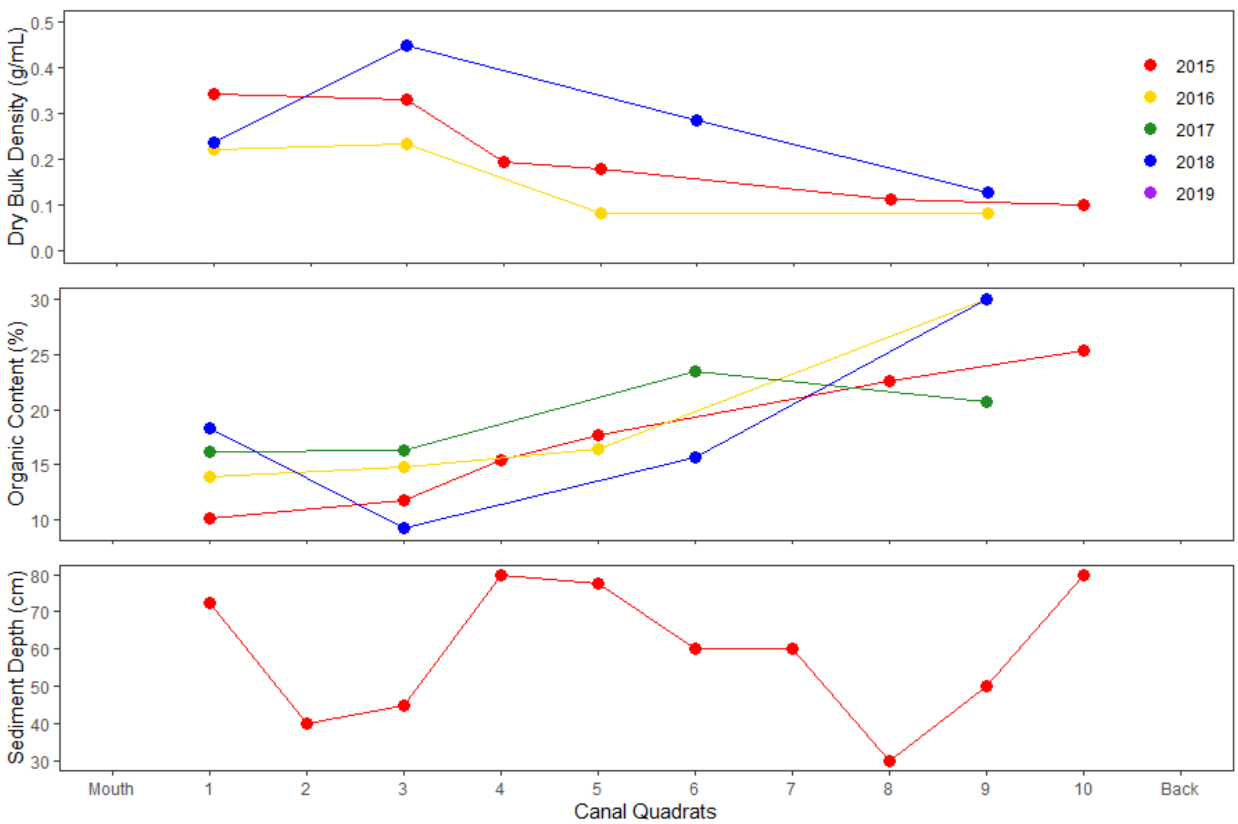

Figure 3.40: Changes in sediment dry bulk density (top), organic content (middle) and sediment depth (bottom) throughout Canal 148 over time.

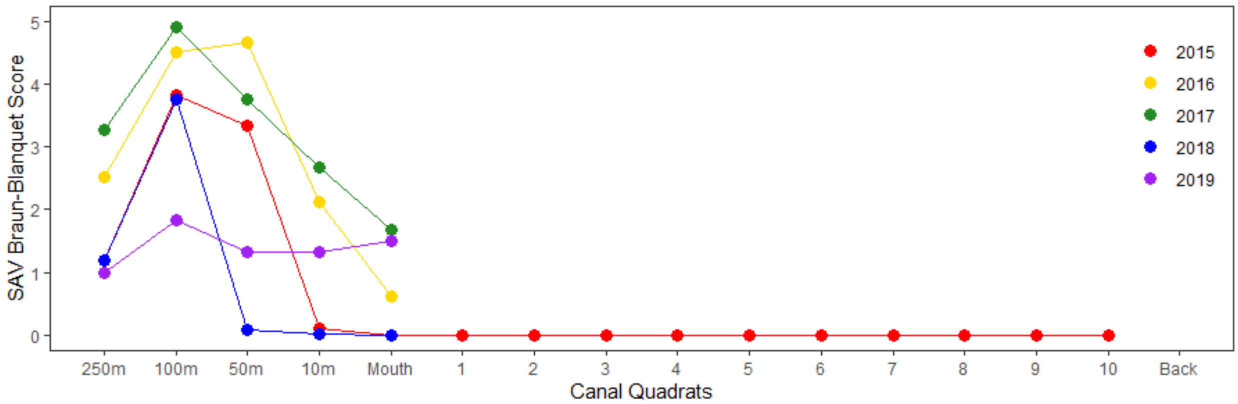

Figure 3.41: Changes in total submerged aquatic vegetation (SAV) outside of and throughout Canal 148 over time.

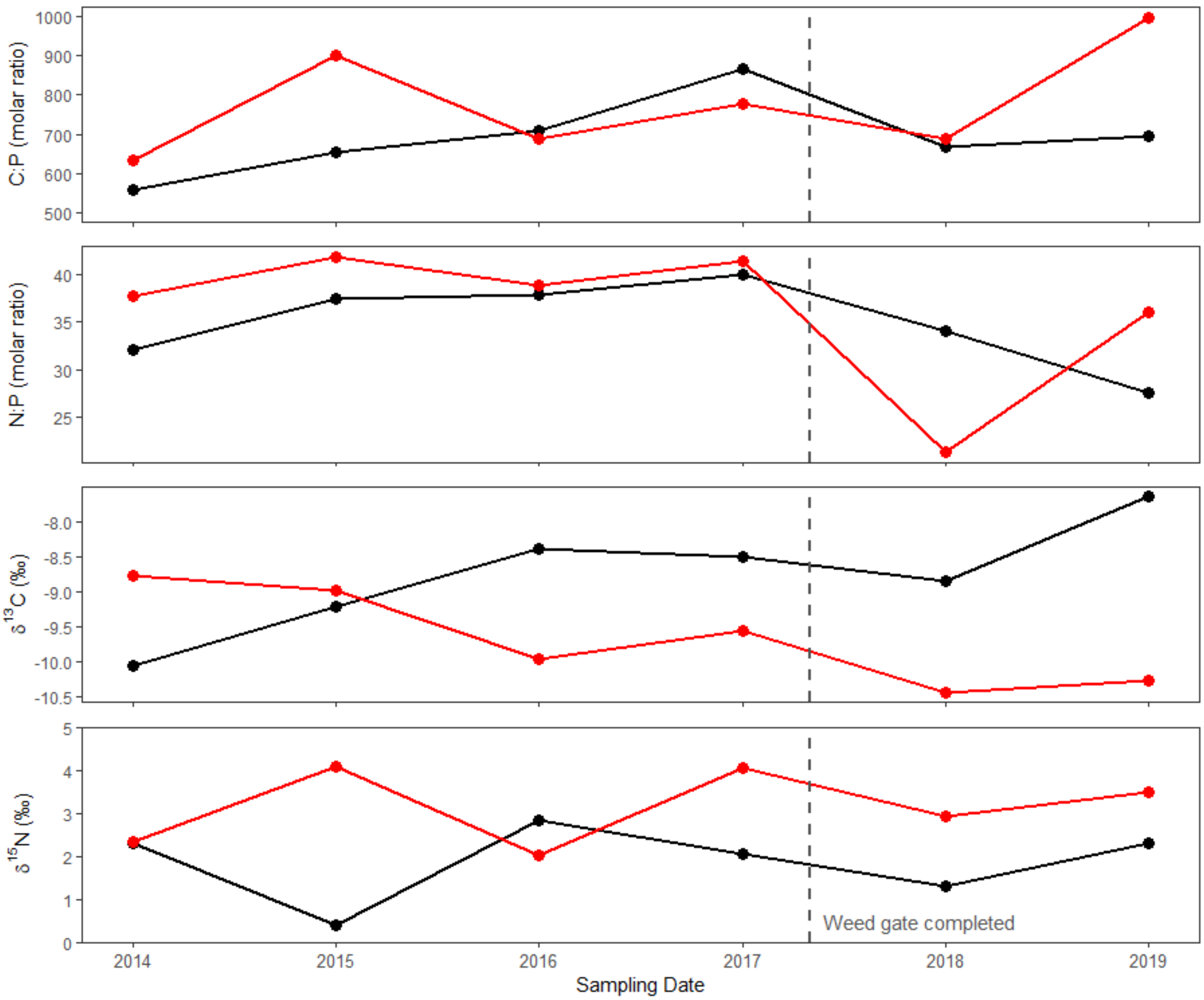

Figure 3.42: Changes in *Thalassia testudinum* leaf tissue nutrient content and stable isotope values in Canal 148 (red) and its reference, Canal 147 (black). Leaf samples were collected at the point closest to the canal mouth with seagrass, 10m – 250m outside canal.

signatures ranged from 0.4 to 2.8 ‰ and from 2.0 to 4.1 ‰ and averaged 1.9 ‰ and 3.1 ‰ for Canals 147 and 148, respectively (Fig. 3.42).

The seawalls of Canal 148, at both the mouth and canal rear, had high densities of barnacles in 2014 and 2015 with some turf green algae at the mouth. The seawalls of Canal 147 and 148 followed the same temporal trends, with the number of organismal groups on seawalls at the mouths decreasing over time, but the number of organismal groups on seawalls at the rears increasing over time (Fig. 3.15a-b). Fish were never observed in Canal 148, and both fish abundance and species number increased in Canal 147 after baseline monitoring (Figs. 3.13 and 3.14).

3.3.4 Canal 266 – Organic Removal

Canal 266 was dredged (completed in May 2016) of accumulated organic material and covered with ~5 cm of sand. Prior to the organic removal, Canal 266 and its control Canal 263 had similar sediment density, organic content, and Corg and P concentrations (Fig. 3.43). As anticipated, after organic removal Canal 266 bulk density increased (from 0.6 ± 0 g to 1.2 ± 0 g cm^{-3}), and organic content and Corg content abruptly decreased (from 31.9 ± 1.0 % to 1.0 ± 0.1 % and from 11.4 ± 1.2 % to 1.8 ± 0.1 %, respectively; Fig. 3.43). These immediate impacts lasted about a year, and in 2017 sediment density decreased and organic material and Corg content began to increase (Fig. 3.43). By 2018, two years after organic removal, sediment parameters from Canal 266 were again nearly identical to those of Canal 263 (Fig. 3.43). Sediment P content did not show any changes after organic removal or throughout the subsequent years (Fig. 3.43). The effects of the organic removal are reinforced when sediment characteristics from Canal 266 are compared to its control, Canal 263. Sediment characteristics (density, organic material, Corg) in Canal 263 stayed relatively constant during Canal 266's drastic response to organic removal.

Prior to the organic removal in 2016, organic-rich sediment reached almost 6 feet in depth at points near the canal mouth as well as the rear, making water depth less than three feet at times (Fig. 3.44). Organic removal decreased the average sediment depth of Canal 266 from 154 ± 12 cm to 40 ± 5 cm (Fig 3.44). Dry bulk density increased and organic content decreased after the organic removal as well (Fig. 3.44). However, despite these changes, it appears that for all three parameters, 2018 levels have begun to depart from the lower 2016-2017 levels and shift closer towards the baseline measurements from 2015 (Fig. 3.44).

Benthic vegetation was absent from inside both Canals 266 and 263 throughout our monitoring, until 50 m outside the mouths where *Thalassia* and *Syringodium* seagrasses were observed (Fig 3.45). The sites at the mouth and 10 m outside the canal both contained thick mats of wrack instead of sandy sediments typical of the open waters in the area. Seagrass leaves from areas adjacent to Canals 263 and 266 were strikingly different in their tissue nutrient and isotopic parameters, making comparisons between control and treatment difficult (Fig. 3.46). $\delta^{13}C$ signatures ranged from –11.0 to –9.6 ‰ and from –10.4 to –8.9 ‰, and averaged –10.5 ‰ and –9.8 ‰ for Canals 263 and 266, respectively (Fig. 3.46). $\delta^{15}N$ signatures ranged from 0.7 to 3.1 ‰ and from 1.7 to 3.2 ‰ and averaged 1.7 ‰ and 2.2 ‰ for Canals 263 and 266, respectively (Fig. 3.46). Fluctuations in C:P and N:P molar ratios were evident between seagrasses outside of Canals 263 and 266, and within each canal through time (Fig. 3.46). Examining Canal 266 pre- and post-

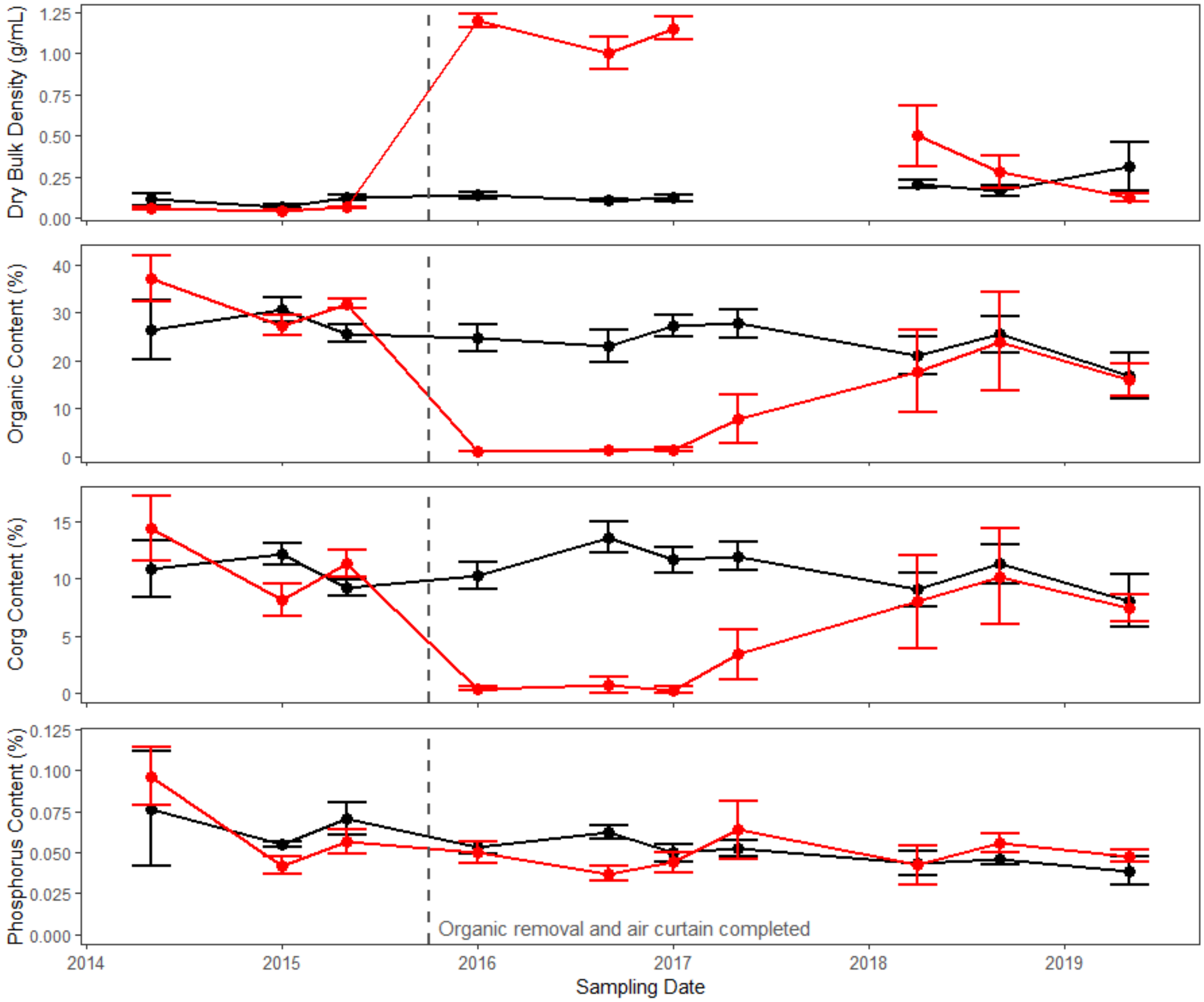

Figure 3.43: Changes in sediment characteristics over time in Canal 266 (red) compared to the adjacent reference, Canal 263 (black). Data represent mean ± SE, and the vertical grey line indicates when the installation of the organic removal and air curtain installation was finished.

demonstration technology, we see large fluctuations in most parameters throughout the course of our monitoring, but no clear directional trends between any parameter pre- and post-organic removal (Fig. 3.46).

Canals 263 and 266 had significantly different number of species as well as abundance of fish (Figs. 3.13 and 3.14). The relationship between the two canals did not change, however there was a marginal increase in both metrics for Canal 263 for the duration of the monitoring project. Canal 263 also displayed significant differences from Canal 266 in seawall organisms at both the mouth and the rear of the canal. There was a decrease in the number of organismal groups at the mouth between the first year and through the end of the monitoring at both canals, however Canal 266 showed a greater decrease (Fig. 3.15).

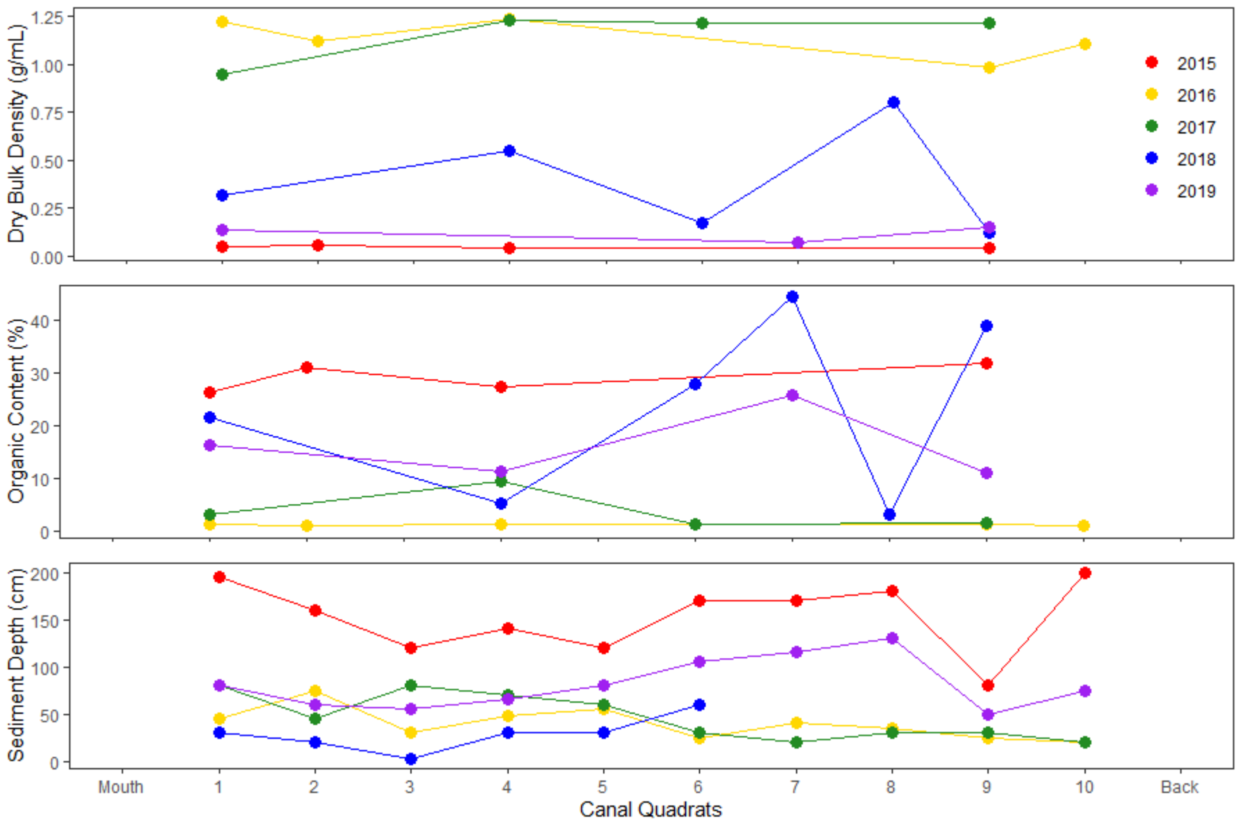

Figure 3.44: Changes in sediment dry bulk density (top), organic content (middle) and sediment depth (bottom) throughout Canal 266 over time.

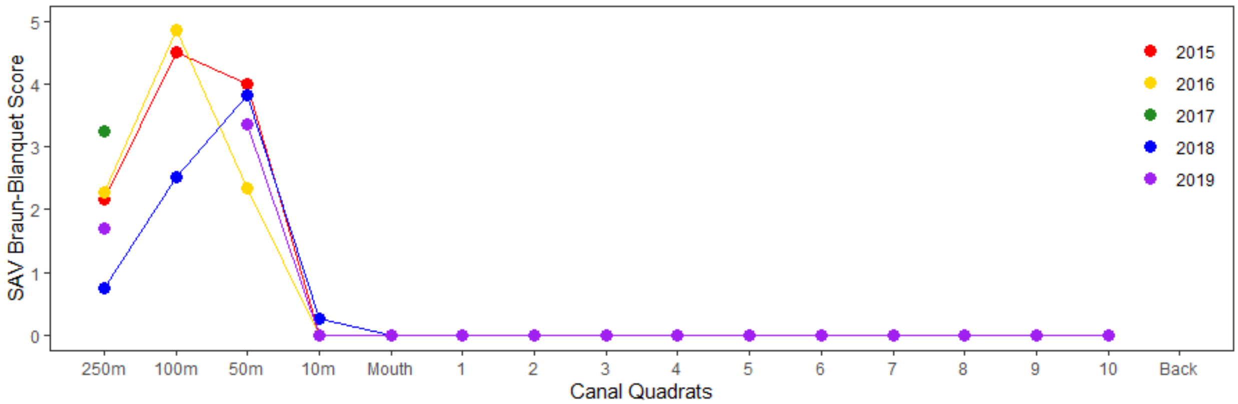

Figure 3.45: Changes in total submerged aquatic vegetation (SAV) outside of and throughout Canal 266 over time.

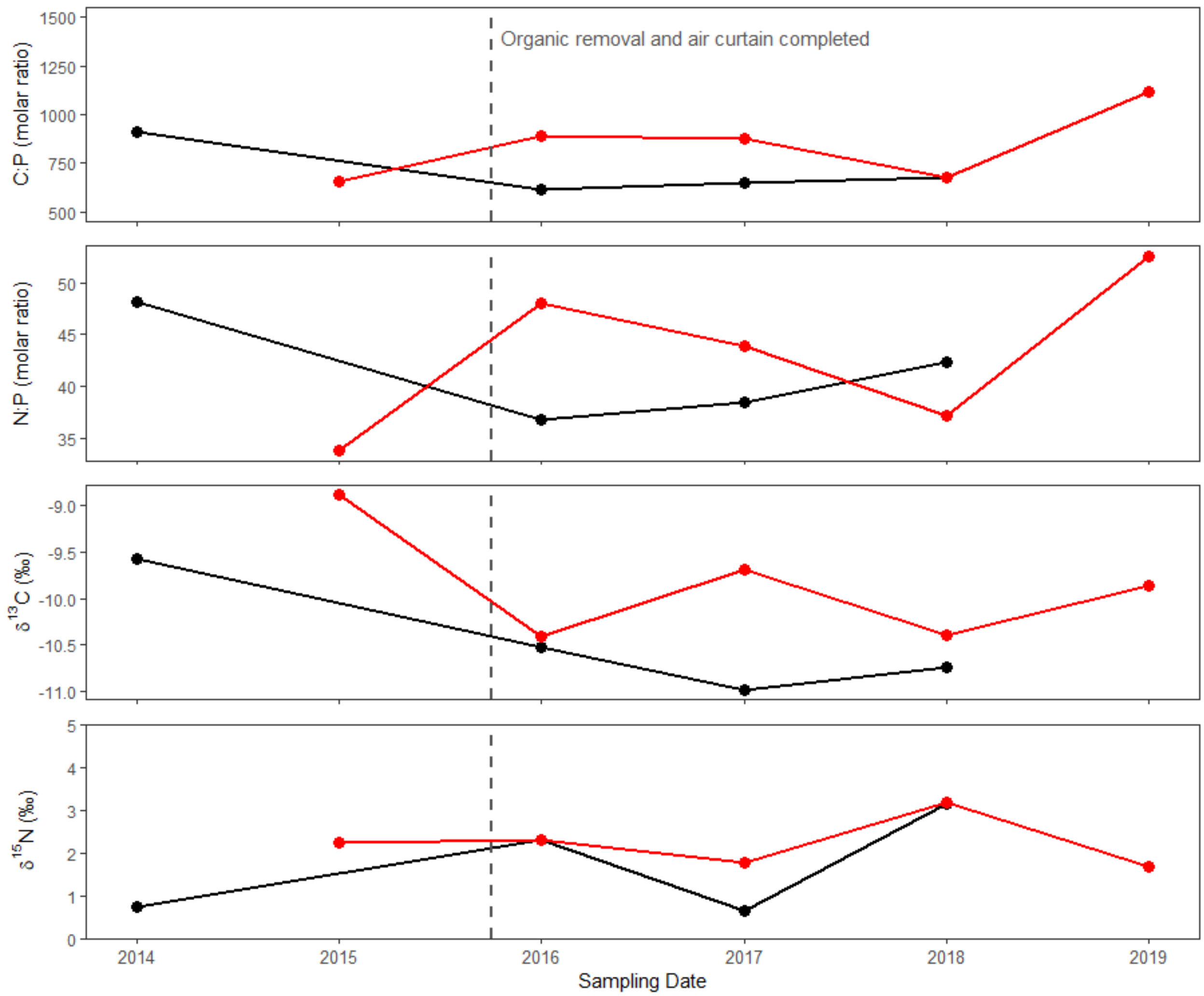

Figure 3.46: Changes in *Thalassia testudinum* leaf tissue nutrient content and stable isotope values in Canal 266 (red) and its reference, Canal 263 (black). Leaf samples were collected at the point closest to the canal mouth with seagrass, 10m – 250m outside canal.

3.3.5 Canal 277 – Culverts

Two culverts were installed in Canal 277 in May 2016 allowing water from the final quarter of the canal to mix with water bodies adjacent to the canal. Sediments in Canal 277 and its control, Canal 282, were most commonly described as unconsolidated organic material, with similar densities (Fig. 3.47). No changes in sediment density or P content were observed after culvert installation in Canal 277 (Fig. 3.47). Organic content and Corg content were similar in Canals 277 and 282 throughout the monitoring period, though abrupt declines were notable in Canal 277 directly following culvert installation (from 25.8 ± 4.8 % to 13.3 ± 2.6 % and from 10.9 ± 1.5 % to 5.0 ± 1.3 %, respectively; Figs. 3.47 and 3.48). These declines both increased during the next monitoring period, and 2018 organic content and Corg content levels are not notably different from pre-culvert levels (Figs. 3.47 and 3.48). Sediment depth, density and organic content were drastically different throughout the length of Canal 277 (Fig. 3.48).

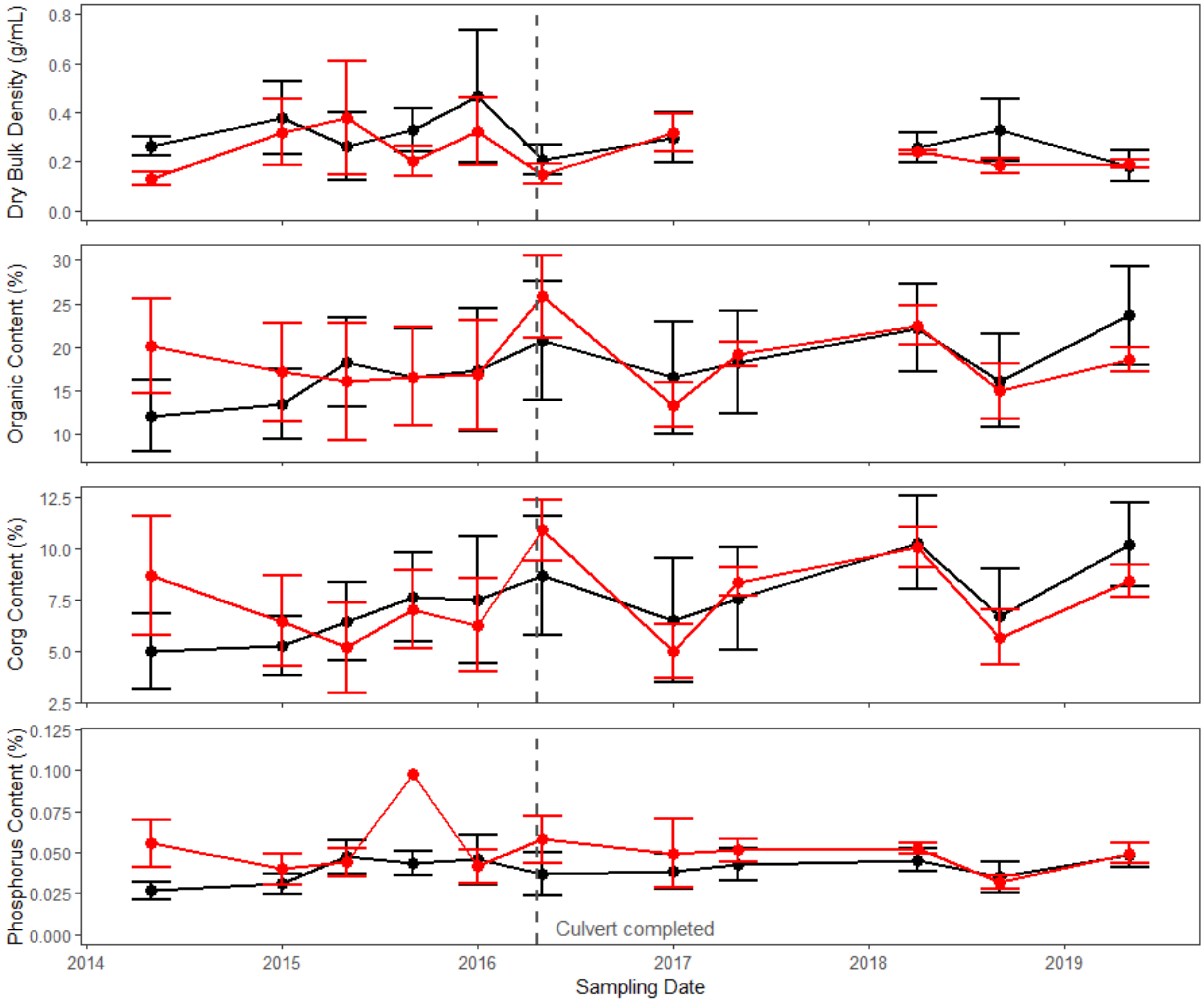

Figure 3.47: Changes in sediment characteristics over time in Canal 277 (red) compared to the adjacent reference, Canal 282 (black). Data represent mean ± SE, and the vertical grey line indicates when the culvert installation was finished.

Benthic vegetation was observed periodically in the first 3 sites within Canal 277, including the seagrass *Thalassia*, *Syringodium*, and *Halodule*, as well as species of calcifying macroalgae (Fig. 3.49). These first three sites within Canal 277 differed from the others in that they had sediments occasionally described as sand, rubble, and rock; very different than the muddy and unconsolidated sediments in the remainder of the canal. There was no discernible effect of culvert installation on benthic plants (Fig. 3.49).

On the sea walls of Canal 277, turf green algae was regularly observed in the canal front and rear. *Caulerpa Mexicana* and *Caulerpa sertularioides* were observed in both locations in varying densities. Additionally, *Batophora* sp. and red algae present on the walls of the canal's mouth were absent in the rear. The number of organismal groups on seawalls decreased at both the mouth and rear locations in Canal 277 throughout our monitoring compared to baseline values (Fig. 3.15a-b). The number of organismal groups on Canal 282 mouth seawalls decreased through time compared to baseline values as well, while the number of organismal groups on the back seawall during baseline monitoring and all monitoring years remained the same (Fig. 3.15a-b).

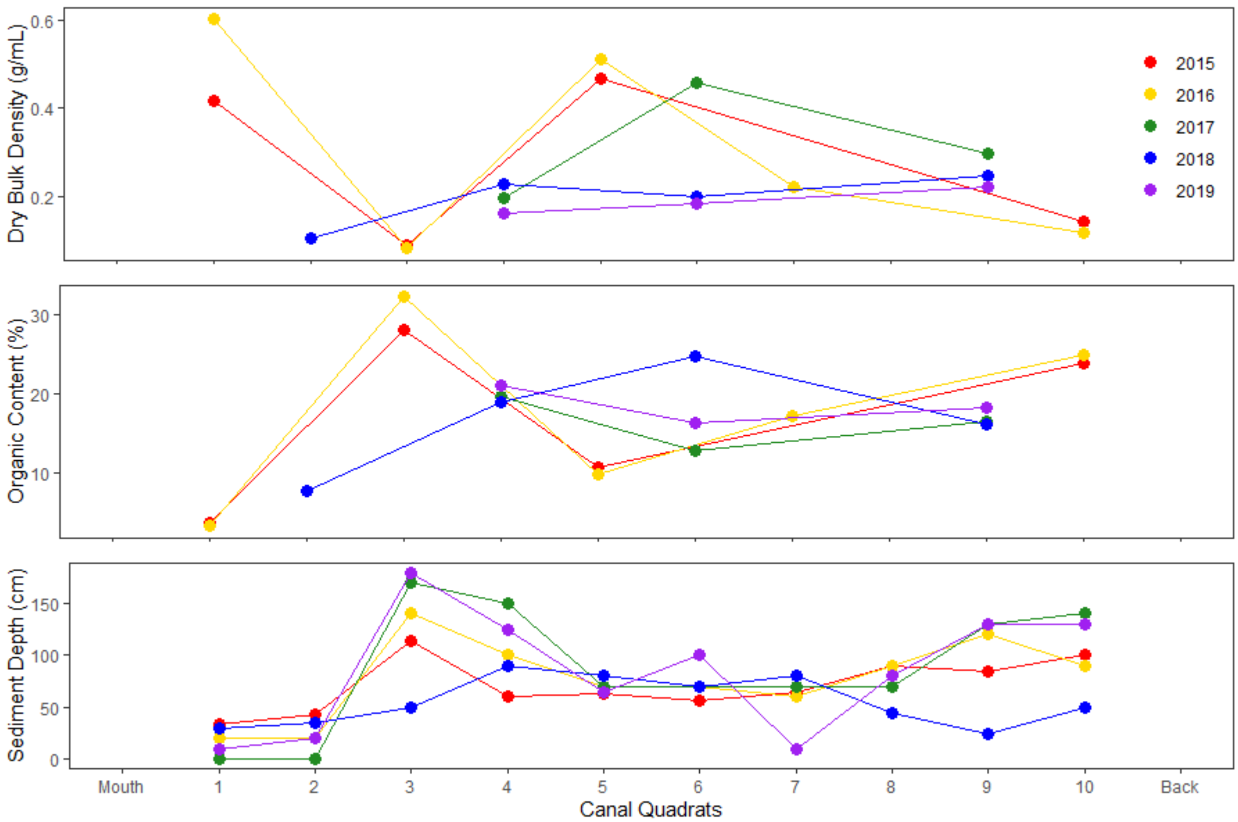

Figure 3.48: Changes in sediment dry bulk density (top), organic content (middle) and sediment depth (bottom) throughout Canal 277 over time.

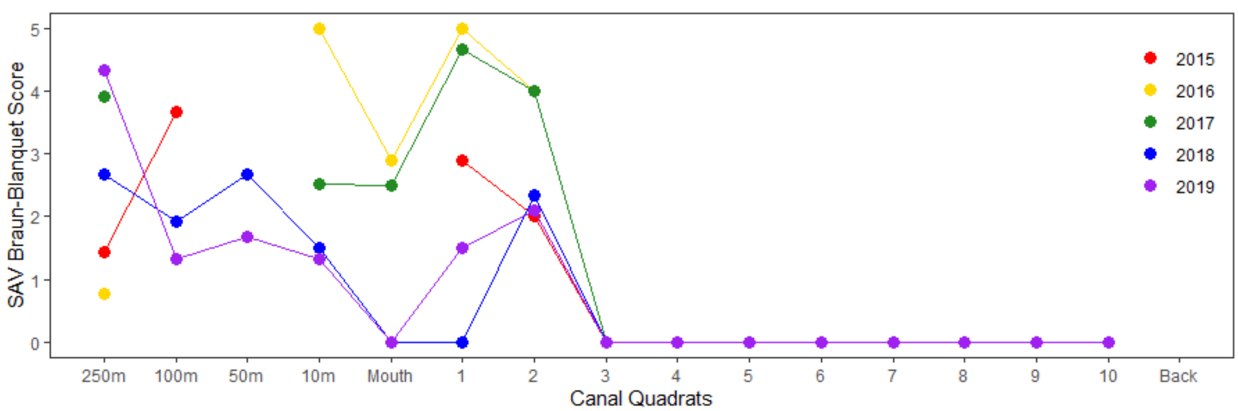

Figure 3.49: Changes in total submerged aquatic vegetation (SAV) outside of and throughout Canal 277 over time.

Fish abundance remained the same in Canal 277 from baseline monitoring compared to all years of monitoring, though the number of species increased (Figs. 3.13 and Fig. 3.14). In Canal 282, there were increases in both fish abundance and the number of fish species from baseline values to values compiled across all monitoring years (Figs. 3.13 and 3.14).

Seagrass tissue chemistry was analyzed from outside of Canal 277 and its reference, though only once prior to culvert installation was *Thalassia* found outside of Canal 282 (Fig. 3.50). Although $\delta^{15}N$ values were similar between Canals 277 and 282 prior to culvert installation, tissue C:P, N:P molar ratios and $\delta^{13}C$ values were markedly different, making comparisons between control and reference challenging (Fig. 3.50). After culvert installation, there were increases in C:P and N:P molar ratios in seagrasses outside of Canal 277, possibly indicating lower P availability (Fig. 3.50), despite no trends in P content noted within Canal 277 pre- and post-culvert (Fig. 3.47). There was no trend in seagrass $\delta^{13}C$ signatures after culvert installation, with average values of –16.0 ‰ and –10.2 ‰ for Canals 277 and 282, respectively (Fig. 3.50). The $\delta^{15}N$ signatures showed average values of 2.8 ‰ and 2.0 ‰ for Canals 277 and 282, respectively, with a slight decrease in the $\delta^{15}N$ signature observed just after culvert installation, though that trend had reversed by the next monitoring timepoint in 2018 (Fig. 3.50).

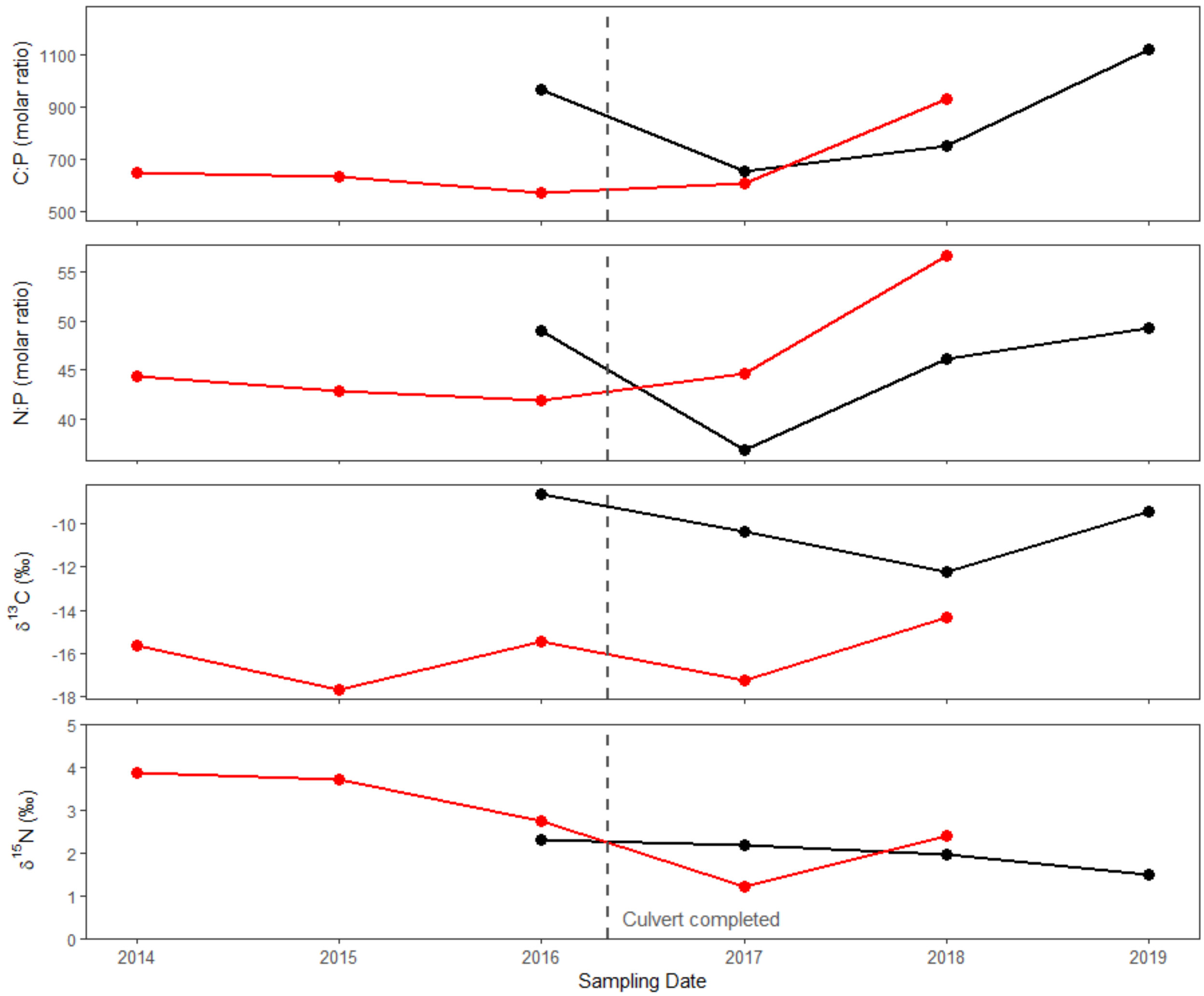

Figure 3.50: Changes in *Thalassia testudinum* leaf tissue nutrient content and stable isotope values in Canal 277 (red) and its reference, Canal 282 (black). Leaf samples were collected at the point closest to the canal mouth with seagrass, 10m – 250m outside canal.

3.3.6 Canal 278 – Pumping (Installation Pending)

Canal 278 was slated to receive a pumping system to flush stagnant water through the rear of the long canal network. This work was never completed, though monitoring continued as scheduled. This canal was unique in that it was the only one to consistently have dense seagrasses growing inside. Canal 278 was also the only canal in its area, particularly of its size and shape, thus there was not an appropriate control for comparison.

Sediment density in Canal 278 ranged from 0.2 to 0.5 g mL^{-1}, averaging 0.3 ± 0.1 g cm^{-3} (Fig. 3.51). Sediment organic content and Corg content ranged from 9.0 to 18.2 % and 2.9 to 7.6 %, averaging 15.4 ± 3.3 % and 5.9 ± 1.4 %, respectively (Fig. 3.51). Sediment P content was relatively constant throughout our monitoring, ranging from 0.03 to 0.04 % and averaging 0.03 ± 0.01 % (Fig. 3.51). There were no discernable temporal trends in sediment density, organic content, or sediment depth within Canal 278 (Fig. 3.52). Average sediment depth was variable throughout the length of Canal 278 and was also variable through time, averaging 50 ± 3 cm across all monitoring sites and all years, with a minimum of 0 cm and a maximum of 100 cm (Fig. 3.52).

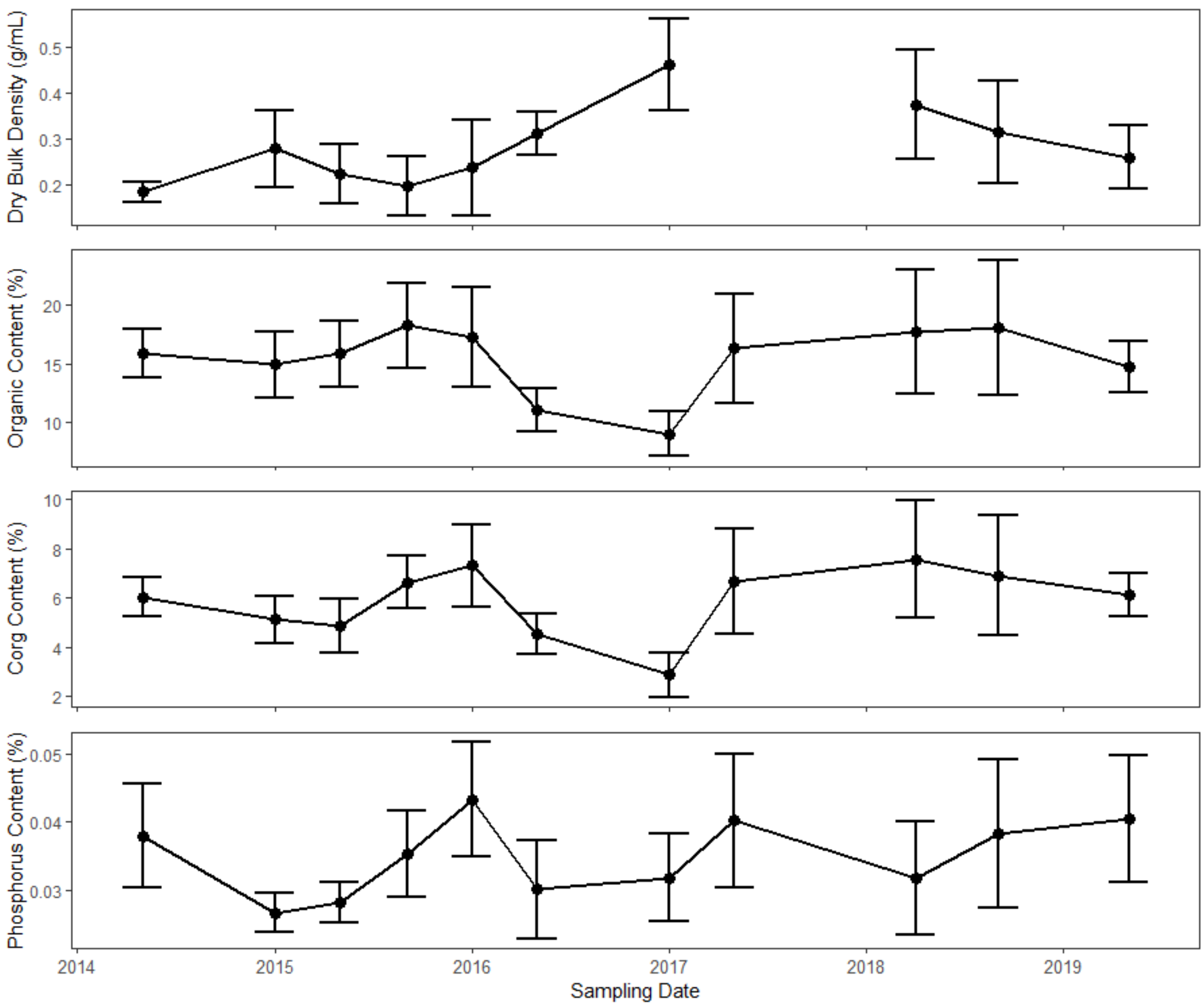

Figure 3.51: Changes in sediment characteristics over time in Canal 278. Data represent mean ± SE.

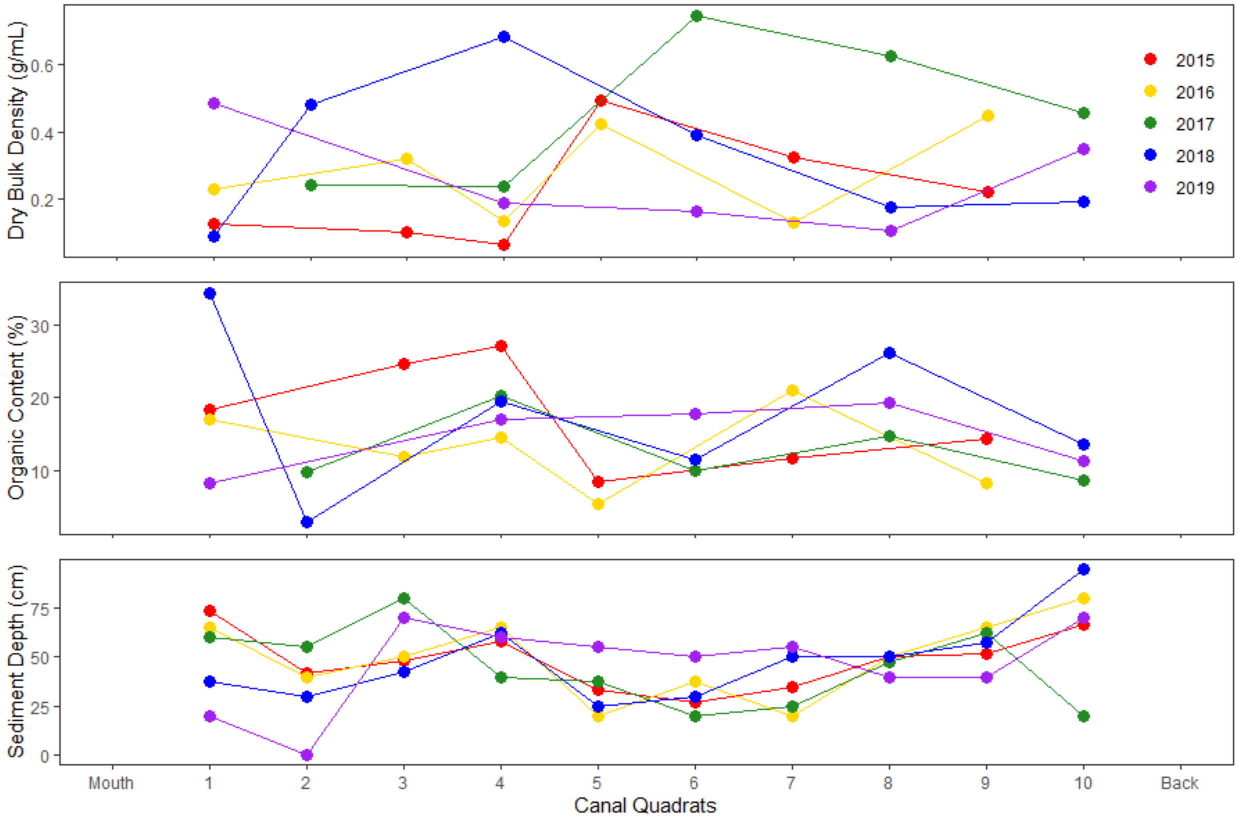

Figure 3.52: Changes in sediment dry bulk density (top), organic content (middle) and sediment depth (bottom) throughout Canal 278 over time.

Similary, organic material content was highly variable averaging 14.8 ± 1.1 % with a min of 2.8 and max of 31.8 % (Fig. 3.52).

Moderately-dense to dense SAV coverage was observed outside of Canal 278, and the canal also supported SAV inside the mouth through at least monitoring station 5 across all years (Fig. 3.53). Monitoring stations 6-8 also contained SAV during some monitoring years, but no

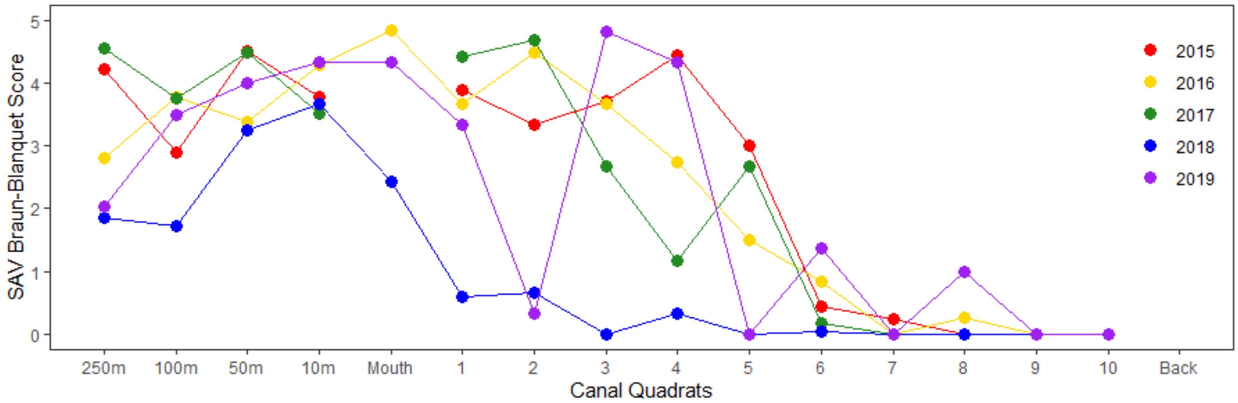

Figure 3.53: Changes in total submerged aquatic vegetation (SAV) outside of and throughout Canal 278 over time.

SAV was ever observed at the rear of the canal at monitoring station 10 (Fig. 3.53). The seawall at the mouth of Canal 278 hosted the highest diversity of organisms of all monitored canals across all years and was regularly inhabited by corals and sponges (Fig. 3.15a). The seawall in the rear, however, had considerably fewer types of organisms (Fig. 3.15b). Canal 278 usually had one of the highest numbers of fish species observed compared to all monitored canals (Fig. 3.13). Nonetheless, fish abundance was typically very low in most monitoring years, with the exception of 2017 when one school of an estimated 10,000 minnows was observed, greatly increasing the average abundance across all monitoring years (Fig. 3.14).

Thalassia testudinum collected outside of Canal 278 had C:P and N:P molar ratios that tracked relatively well through time, with C:P remaining stable ($p > 0.05$) and N:P decreasing ($p < 0.05$) from 2014 through 2018 (Fig. 3.54). Both values sharply spiked in 2019, likely indicative of a large decrease in P availability (Fig. 3.54). Seagrass leaf $\delta^{13}C$ and $\delta^{15}N$ signatures from 2014 through 2018 remained stable, averaging –10.5 ‰ and 2.6 ‰, respectively (Fig. 3.54). Both isotopic signatures underwent dramatic deviations from previous values in 2019, with $\delta^{13}C$ signatures increasing to –9.0 ‰ and $\delta^{15}N$ signatures decreasing to –0.8 ‰ (Fig. 3.54).

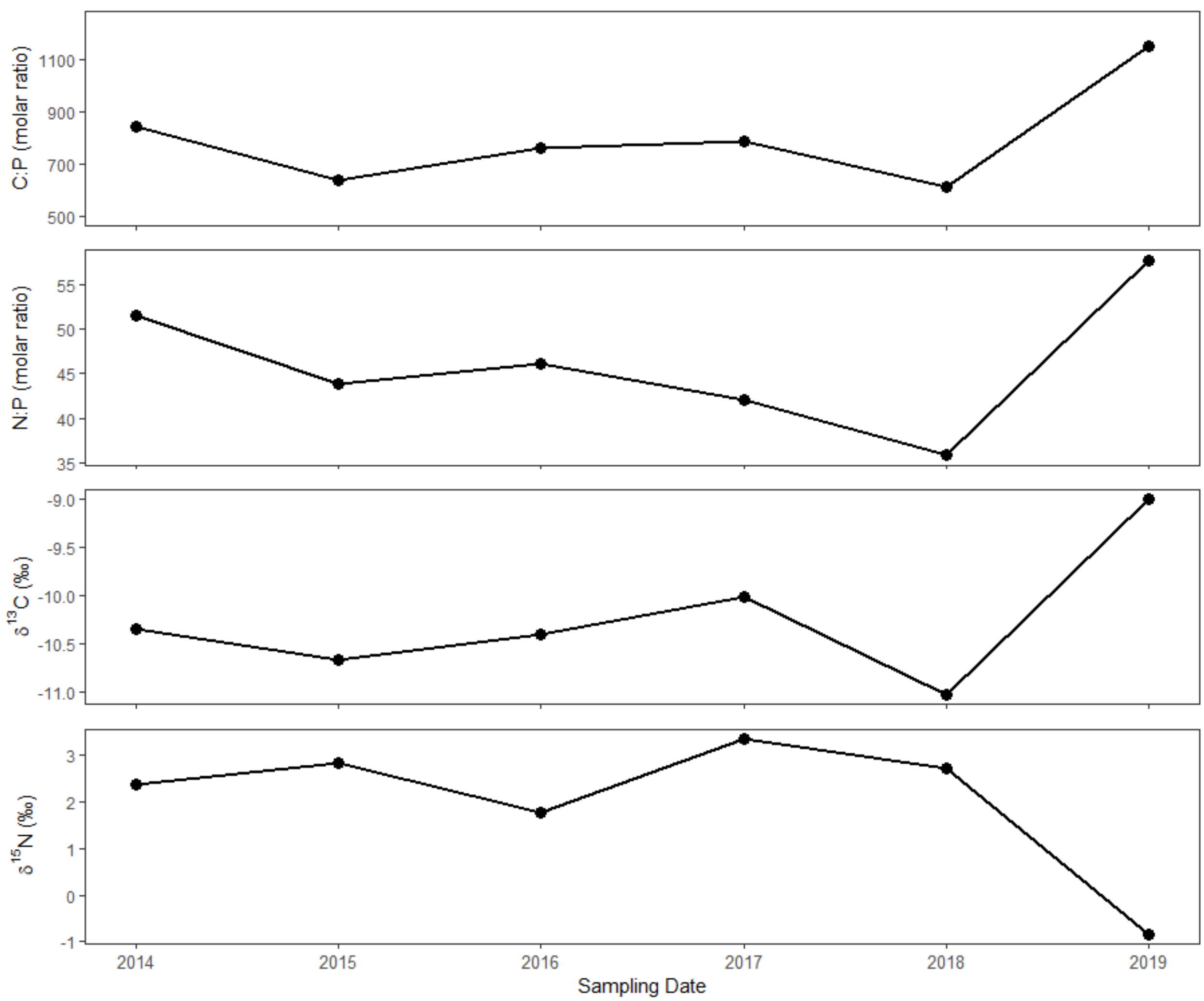

Figure 3.54: Changes in *Thalassia testudinum* leaf tissue nutrient content and stable isotope values in Canal 278. Leaf samples were collected at the point closest to the canal mouth with seagrass, 10m – 250m outside canal.

3.3.7 Canal 287 – Air Curtain

An air curtain weed gate was installed in Canal 287 in June 2016 to prevent further entry of seagrass wrack and organic material into the canal. Canal 288, located approximately 125 m to the south, was used as a control. Sediment density and sediment organic, Corg and P content were all similar between experimental and control canals (Fig. 3.55). Parameters changed little through time, and the similarity between control and experimental canals indicates that the installed air curtain had little impact on organic matter influxes (Fig. 3.55). The average sediment density was extremely low, averaging 0.08 ± 0.01 g cm^{-3} (compared to a South Florida average of 0.73 ± 0.04 g cm^{-3}; Howard, 2018). Sediments were consistently unconsolidated organic material, appearing to consist more of decomposing seagrass than the expected granular, sediment-like material (personal observation). Organic content between both canals averaged 34.5 ± 2.8 %, with a maximum of 43.3 % and a minimum of 26.8 % (Fig 3.56). Organic carbon content averaged 13.2 ± 1.6 %, and P content averaged 0.06 ± 0.01 % (Fig. 3.56).

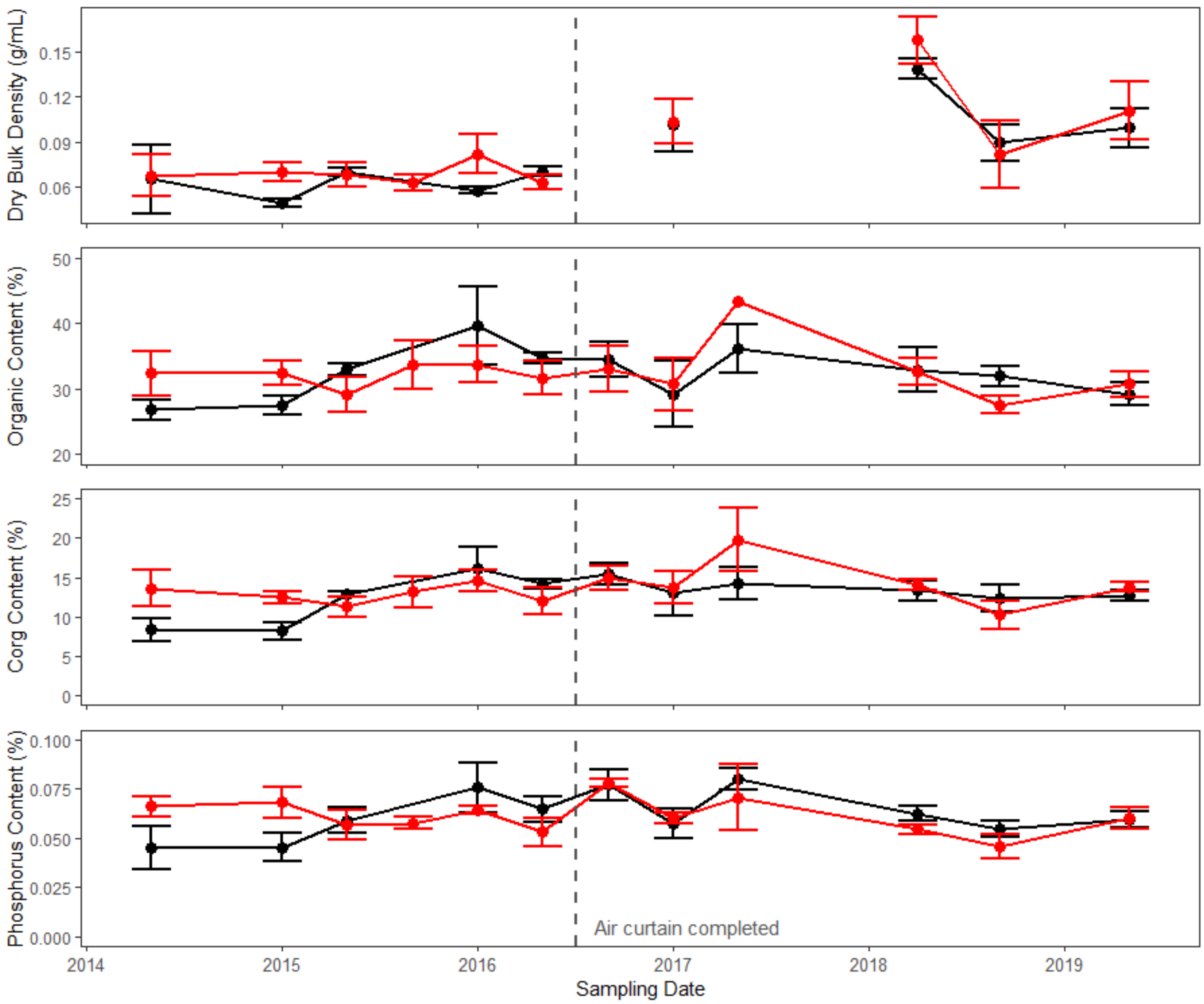

Figure 3.55: Changes in sediment characteristics over time in Canal 287 (red) compared to the adjacent reference, Canal 288 (black). Data represent mean ± SE, and the vertical grey line indicates when the air curtain installation was finished.

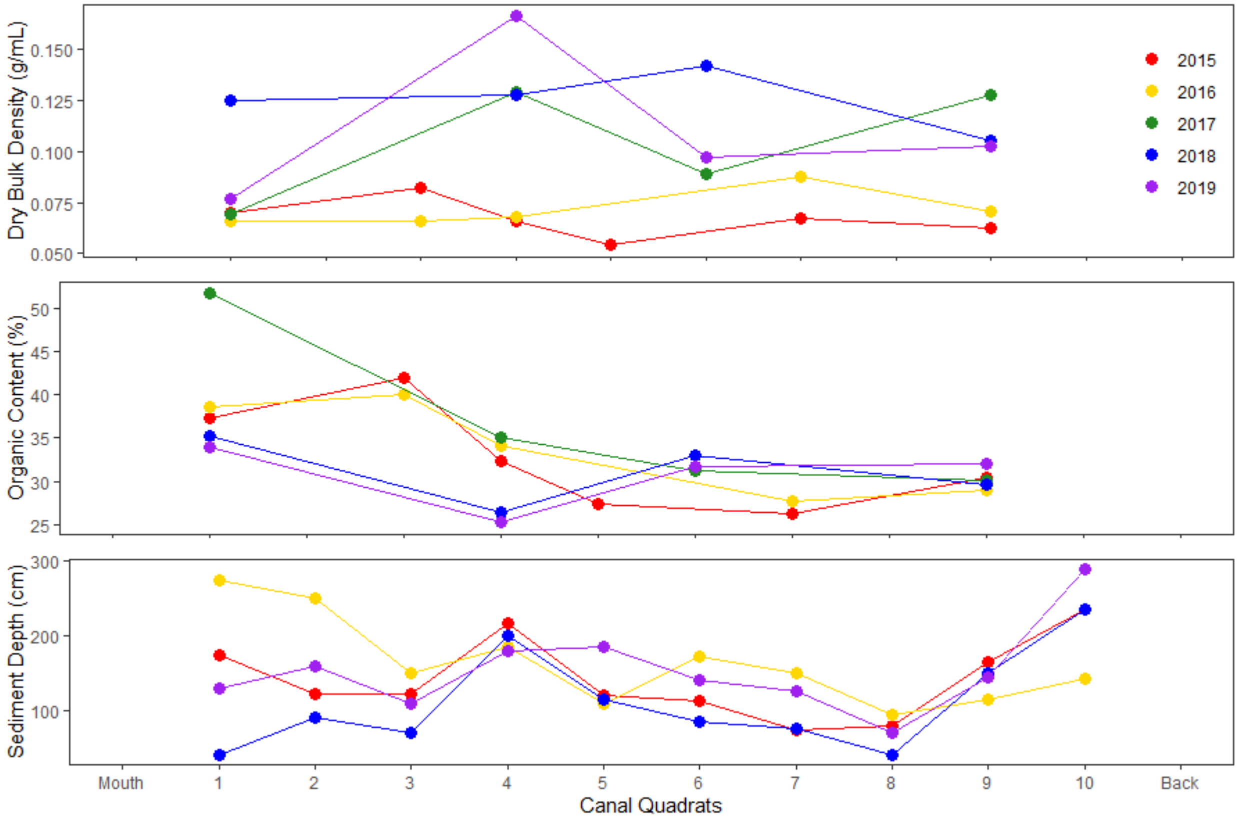

Figure 3.56: Changes in sediment dry bulk density (top), organic content (middle) and sediment depth (bottom) throughout Canal 287 over time.

The sediment density of Canal 287 was greater after air curtain installation in 2017, 2018 and 2019 compared to pre-treatment in 2015 and 2016 (Fig. 3.56). However, the temporal trends in sediment density were identical for Canal 288 (Fig. 3.55), which did not receive an air curtain, and thus are unfortunately not indicative that the air curtain increased sediment density in Canal 287. Organic content was temporally variable and also varied throughout the length of the canal, ranging from a minimum value of 24.1 % at monitoring station 4 in 2019 and a maximum value of 51.8 % at monitoring station 1 in 2017 (Fig. 3.56). Sediment depth was highly variable throughout years and along the length of Canal 287, ranging from 0 cm at monitoring stations 1 and 8 in 2018, to 290 cm at the rear of the canal at monitoring station 10 in 2019 (Fig. 3.56).

There were no observations of seagrass or macroalgae within either canal, nor was SAV observed until at least 50 m outside the mouth of Canal 287 (Fig 3.57). Fish were observed once in 2017 and once in 2019 (Figs. 3.13 and 3.14). No other living organisms were observed in the canals throughout the monitoring program, including on seawall at the canal rear (Fig. 3.15b). Seawalls at the mouth of 287 were inhabited by high densities of barnacles with turf green algae, red algae and *Caulerpa sertularioides* all being observed once (Fig. 3.15a).

There was no difference in *Thalassia testudinum* found outside of Canals 287 and 288 in C:P and N:P molar ratios, nor in $\delta^{13}C$ and $\delta^{15}N$ signatures both prior to after the air curtain installation ($p > 0.05$ for all; Fig. 3.58). No changes were observed after air curtain installation in Canal 287 for any parameter ($p > 0.05$ for all; Fig. 3.58). Average values for both canals were 900.1 ± 60.6 for C:P, 49.0 ± 1.7 for N:P, -10.6 ± 0.5 ‰ for $\delta^{13}C$, and 1.3 ± 0.3 ‰ for $\delta^{15}N$ (Fig. 3.58).

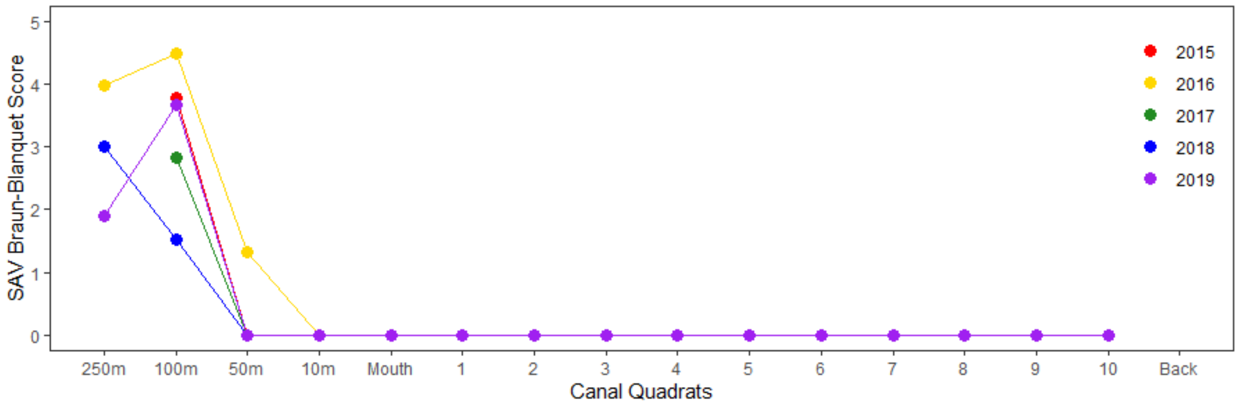

Figure 3.57: Changes in total submerged aquatic vegetation (SAV) outside of and throughout Canal 287 over time.

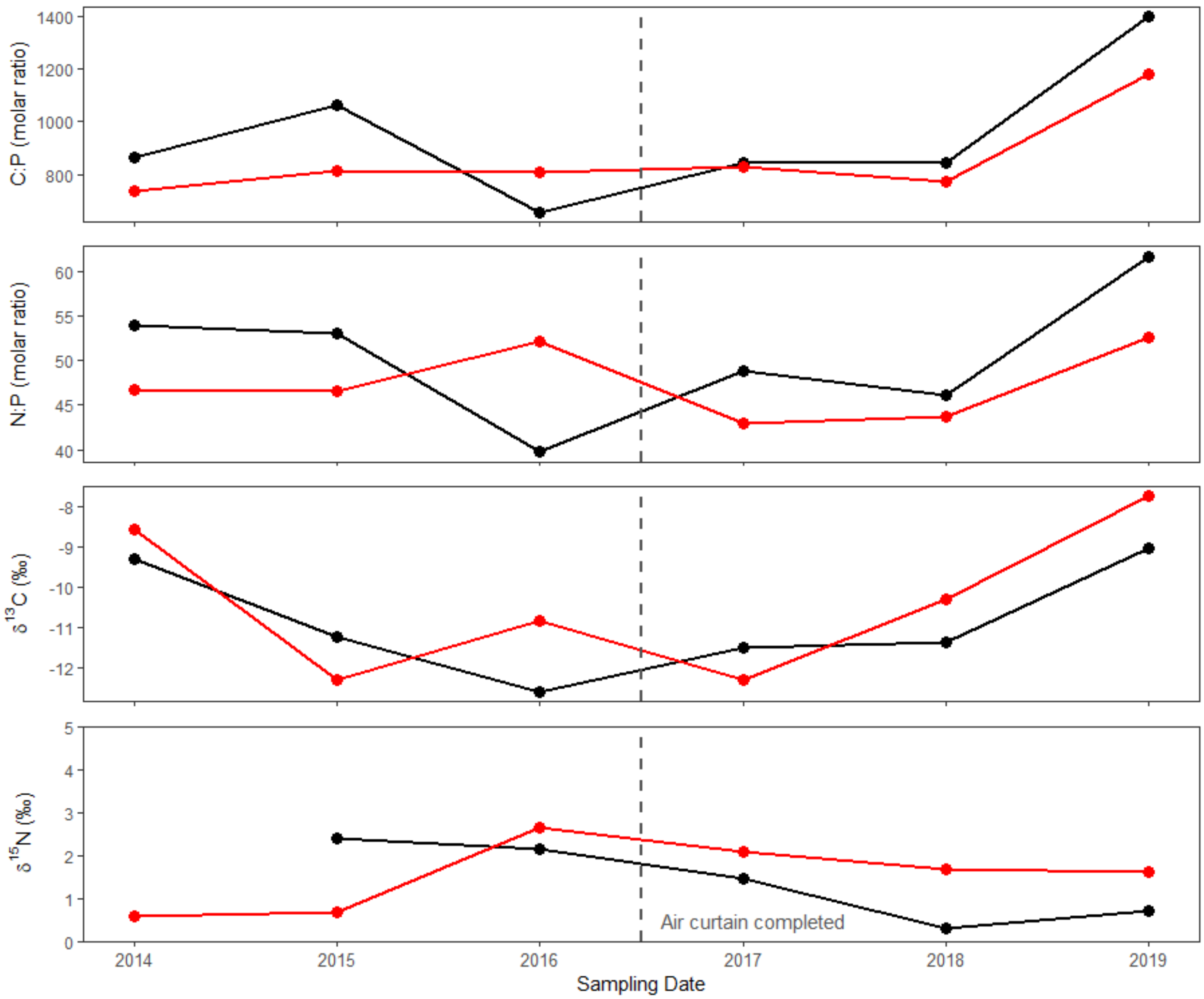

Figure 3.58: Changes in *Thalassia testudinum* leaf tissue nutrient content and stable isotope values in Canal 287 (red) and its reference, Canal 288 (black). Leaf samples were collected at the point closest to the canal mouth with seagrass, 10m – 250m outside canal.

3.3.8 Canal 290 – Organic Removal

Canal 290 was dredged of organic material in March 2016 followed by the installation of an air curtain in June 2017. Like other canals on the eastern side of Big Pine Key, unconsolidated, organic-rich sediment comprised mostly of partially decomposed seagrass wrack was found through Canal 290 as well as its control, Canal 293. Although measurements of sediment density could not be completed during every monitoring campaign, it was apparent that sediment density in Canal 290 increased dramatically from 0.1 ± 0.0 g cm^{-3} prior to organic removal to 0.7 ± 0.3 g cm^{-3} shortly after in summer 2016 (Fig. 3.59). Sediment density was still elevated in January 2017 (0.7 ± 0.3 g cm^{-3}) but had dropped sharply to 0.2 ± 0.0 cm^{-3} by May 2018 (Fig. 3.59). During the same period, organic content decreased from 32.2 ± 1.0 % to 12.2 ± 6.3 %, organic carbon content decreased from 13.0 ± 0.5 % to 4.9 ± 2.4 %, and P content decreased from 0.07 ± 0.01 % to 0.04 ± 0.01 % (Fig 3.59). Throughout the next several sampling campaigns, sediment characteristics in Canal 290 remained significantly different from the control canal as well as pre-dredging condi-

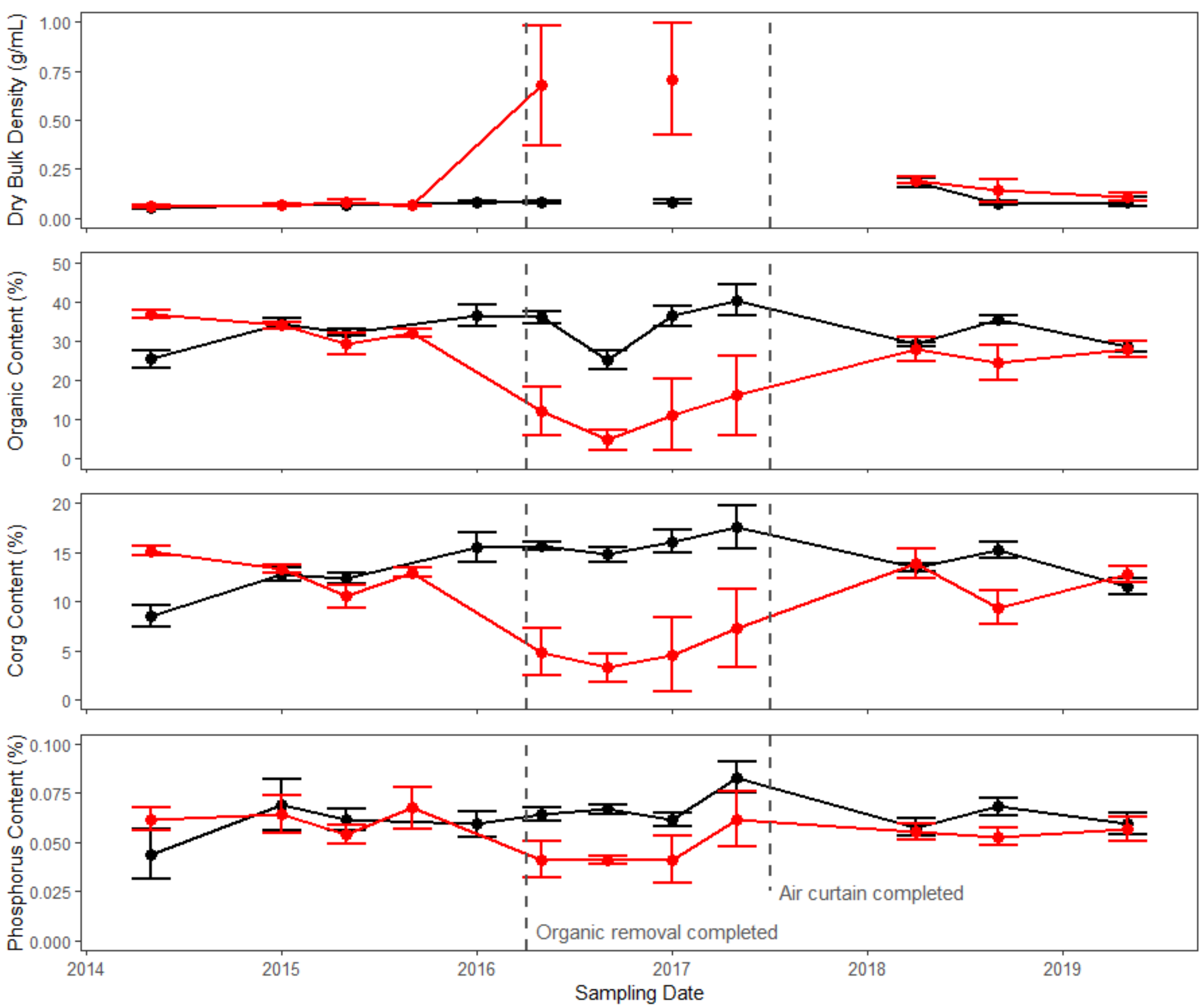

Figure 3.59: Changes in sediment characteristics over time in Canal 290 (red) compared to the adjacent reference, Canal 293 (black). Data represent mean ± SE, and the vertical grey line indicates when the organic removal and air curtain installation was finished.

-tions. However, there was a return to baseline values during 2017, so that by 2019 the sediment characteristics of Canal 290 are indistinguishable from pre-dredging conditions (Fig. 3.59). The demonstrated technology of organic removal via dredging had a clear and quick effect on sediment conditions, though we observed a full reversal of these conditions less than two years later in surface sediments (Fig. 3.59). It is difficult to assess efficacy of the air curtain since it was installed one year after the organic removal; it is possible that it may have been more effective if installed directly after the dredging was completed (Fig. 3.59).

During 2015, prior to organic removal, sediment depth for Canal 290 averaged 177 ± 12 cm with a maximum depth of 243 cm (Fig 3.60). Only two monitoring stations were accessible to collect sediment depth measurements in 2016, which had an average post-dredging depth of 50 ± 5, and monitoring stations could not be accessed for sediment depth in 2017 (Fig. 3.60). After this, the average sediment depth continued to stay lower than pre-dredging conditions but increased from 110 ± 9 cm in 2018 to 160 ± 11 cm in 2019 (Fig. 3.60). In 2015 (pre-dredging), sediment density was 0.07 ± 0.00 g cm-^{3} and organic content was 32.0 ± 1.1 % (Fig. 3.60). Both parameters showed clear deviations from pre-dredging conditions at monitoring stations 3 through 10 through our 2016 and 2017 monitoring campaigns, where sediment density notably increased to 0.7 ± 0.2 g cm-^{3} and sediment organic content notably decreased to 10.6 ± 4.0 % (Fig. 3.60). However, during the 2018 and 2019 monitoring campaigns, sediment density and organic content levels had essentially returned to pre-dredging, 2015 values (0.14 ± 0.02 g cm^{-3} for sediment density and 27.2 ± 1.2 % for organic content; Fig. 3.60).

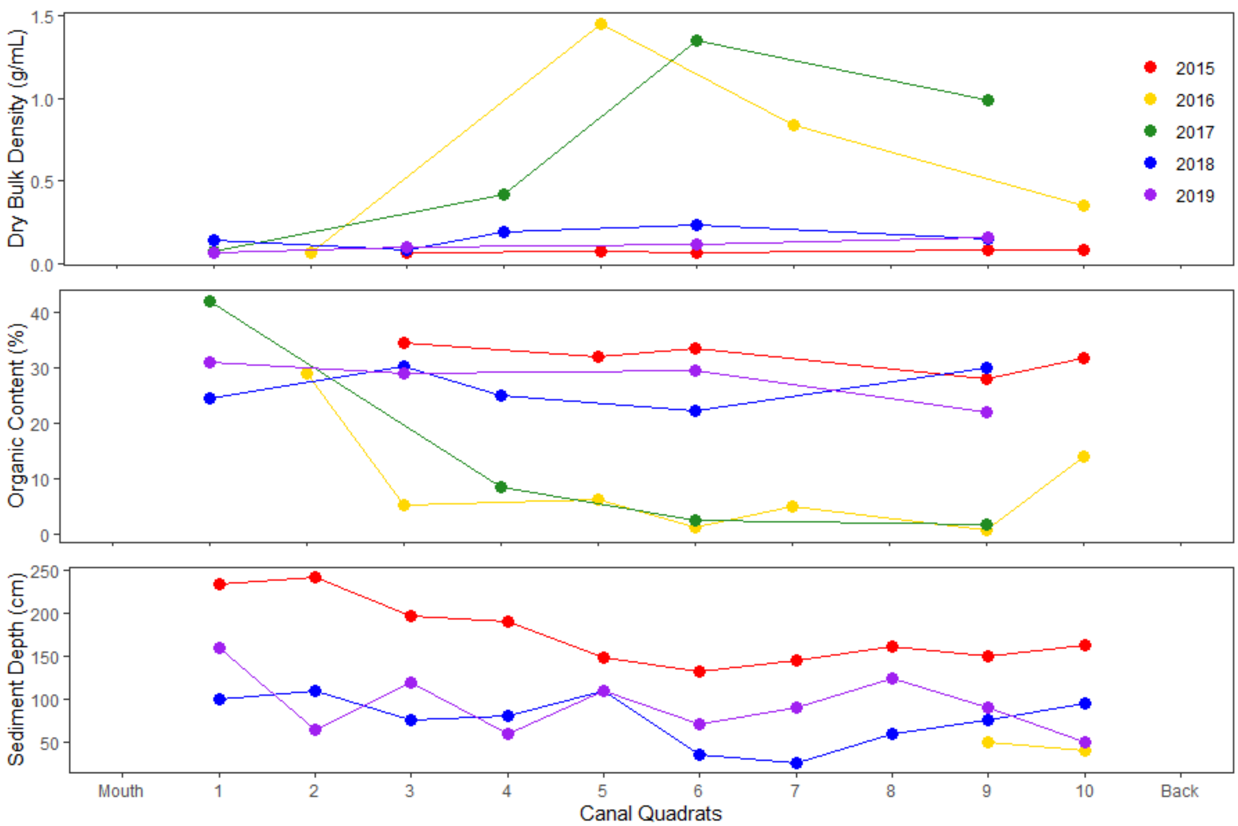

Figure 3.60: Changes in sediment dry bulk density (top), organic content (middle) and sediment depth (bottom) throughout Canal 290 over time.

Turf green algae and *Caulerpa sertularioides* were found in greatest abundance along with red algae on the seawall of Canal 290 prior to organic removal in 2016. The number of organisms inhabiting seawalls at the mouths and rears of Canals 290 and 293 observed during baseline monitoring were conserved and reflected in monitoring results across all years combined (Fig. 3.15a-b). No fish were observed in Canal 290 before the installation of demonstrated technologies, and very few were observed afterwards (Fig. 3.13). Fish abundance in Canal 293 was also low (Fig. 3.13), as was fish species diversity across both canals (Fig. 3.14).

Prior to dredging, the layer of wrack extended 50 m outward from the mouth of Canal 290, where the wrack subsided, and benthic vegetation was first observed (Fig 3.61). Samples from *Thalassia testudinum* outside of Canals 290 and 293 were drastically different for all parameters in 2014 but were closer in tissue elemental composition by our 2016 monitoring just prior to organic removal, with the exception of $\delta^{13}C$ values (Fig. 3.62). The C:P and N:P molar ratios in seagrasses outside Canal 290 both decreased following the organic removal in our 2017 monitoring to 781.7 and 43.0, respectively (Fig. 3.62). However, both parameters increased in value through 2018 and 2019, averaging 1,029.9 and 52.8, respectively (Fig. 3.62). The $\delta^{13}C$ and $\delta^{15}N$ signatures varied greatly through time, making it difficult to responsibly draw conclusions related to post-treatment effects (Fig. 3.62). The $\delta^{13}C$ signatures ranged from –13.5 to –9.1 ‰ for Canal 290 and from –13.1 to –9.2 ‰ for Canal 293, and $\delta^{15}N$ signatures ranged from –0.9 to 3.7 ‰ for Canal 290 and from 1.1 to 3.0 ‰ for Canal 293 (Fig. 3.62).

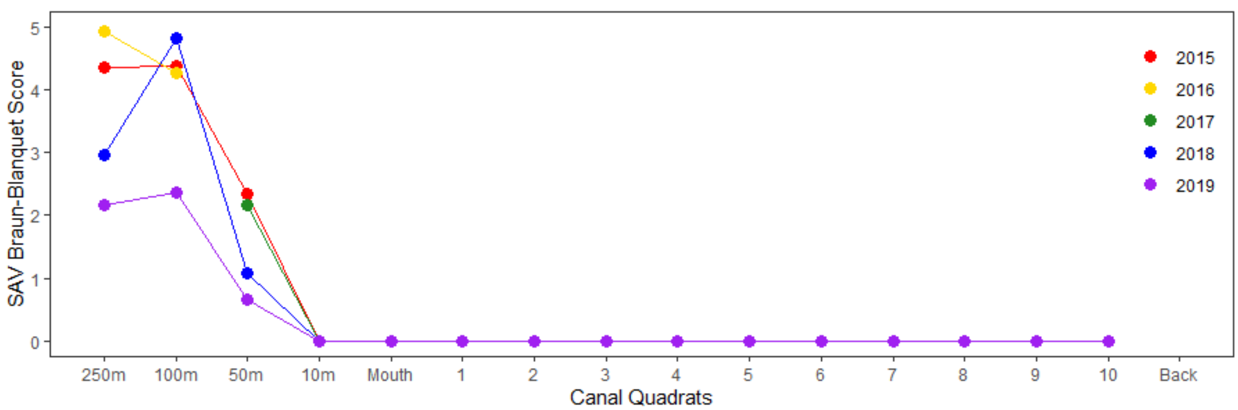

Figure 3.61: Changes in total submerged aquatic vegetation (SAV) outside of and throughout Canal 290 over time.

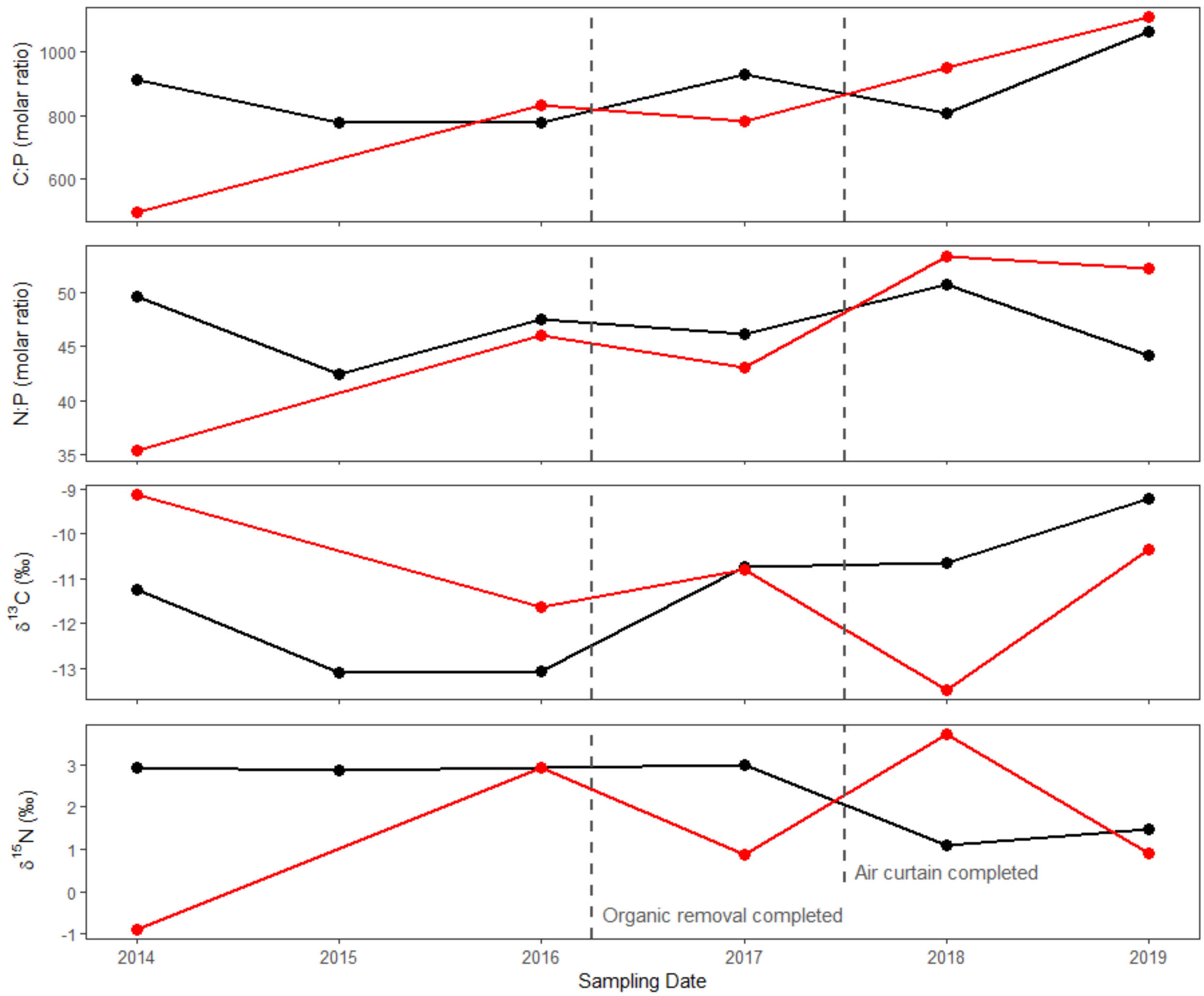

Figure 3.62: Changes in *Thalassia testudinum* leaf tissue nutrient content and stable isotope values in Canal 290 (red) and its reference, Canal 293 (black). Leaf samples were collected at the point closest to the canal mouth with seagrass, 10m – 250m outside canal.

3.3.9 Canal 459 – Culvert (Installation Pending)

Canal 459 on Geiger Key and its control canal to the north, Canal 458, are surrounded by a mixture of residential properties and mangrove stands. Mangroves also inhabit the area outside the mouths of both canals, nullifying the benthic monitoring typically conducted from the mouth to 250 m outside (however, *Thalassia testudinum* samples were collected at the canal mouth for both canals). Canal 459 was scheduled to receive a culvert to connect the rear canal wall to an abutting body of water, intended to increase flow through the entirety of the canal. However, the culvert was never installed due to project restraints. Nevertheless, monitoring of both Canal 458 and 459 continued as scheduled.

Sediment composition (density, organic material, Corg, and P) is indistinguishable between canals ($p > 0.05$ for all) and neither canal showed significant changes over time for any parameter ($p > 0.05$ for all; Fig. 3.63). Sediment density across both canals averaged 0.35 ± 0.07

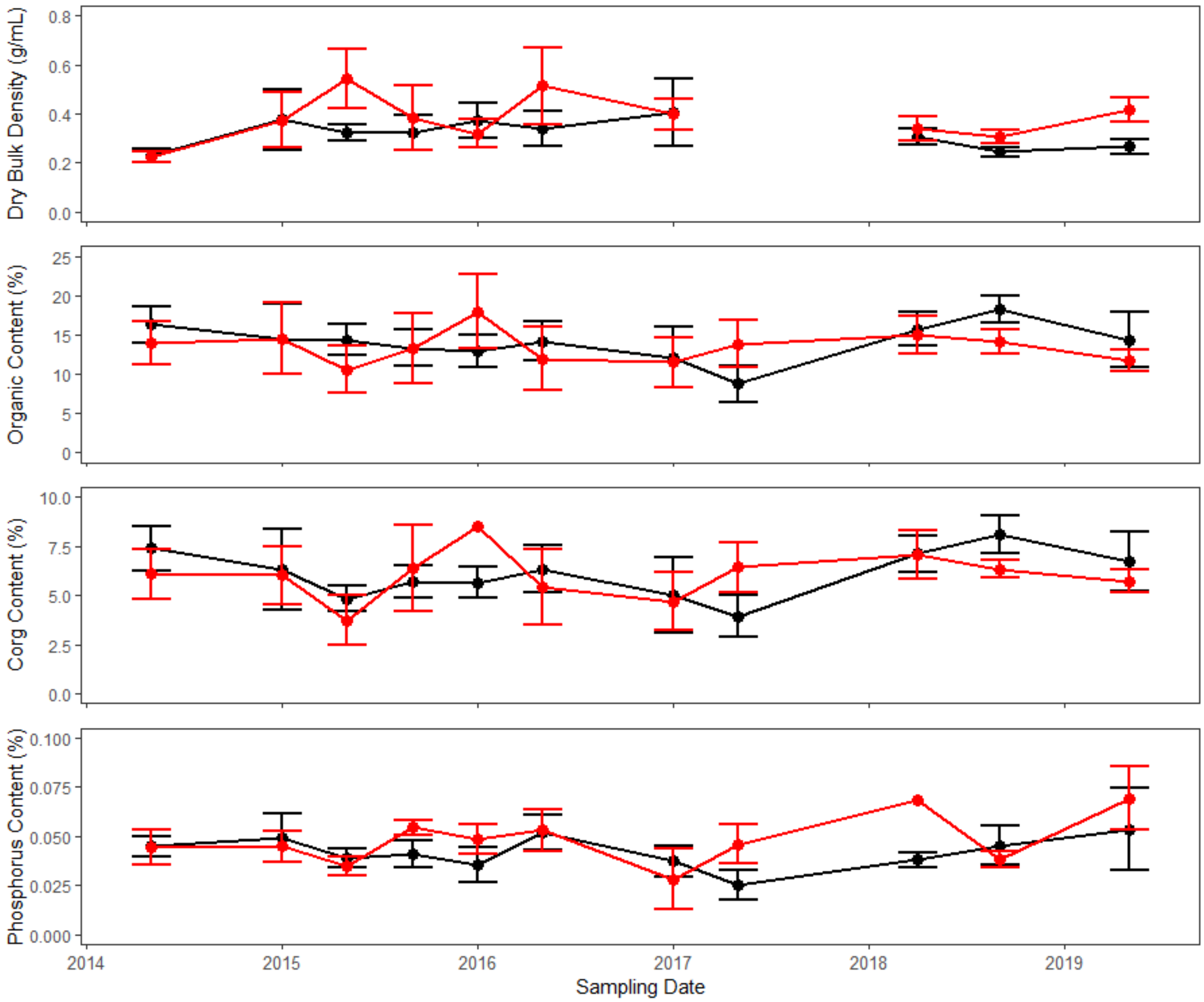

Figure 3.63: Changes in sediment characteristics over time in Canal 459 (red) compared to the adjacent reference, Canal 458 (black). Data represent mean ± SE. The culvert planned for 459 was never completed.

g cm^{-3}, organic content averaged 13.8 ± 2.9 %, organic carbon content averaged 6.1 ± 1.3 %, and phosphorus content averaged 0.04 ± 0.01 % (Fig. 3.63).

Across all years, sediment density generally decreased and organic content generally increased from the mouth of the canal moving toward the rear (Fig. 3.64). Across all years, sediment density ranged from 0.18 to 0.71 g cm^{-3}, averaging 0.36 ± 0.03 g cm^{-3}, organic content ranged from 6.4 to 31.2 %, averaging 14.0 ± 1.2 %, and sediment depth had a large range from 20 to 165 cm, averaging 79 ± 4 cm (Fig. 3.64). Benthic vegetation was observed near the mouth of 459 at the first three sites, with densities of *Thalassia*, *Halodule* and calcifying macroalgae varying over time (Fig 3.65). Throughout 2015 and 2019, SAV was occasionally observed further inside the canal at low abundances (Fig 3.65).

There were no differences in seagrass tissue parameters for the seagrasses observed outside the mouths of Canals 458 and 459 throughout our monitoring ($p > 0.05$ for all), and we did not observe any changes over time ($p > 0.05$ for all; Fig. 3.66). The C:P molar ratios ranged from 474.6 to 889.2, averaging 680.3 ± 35.1, N:P molar ratios ranged from 32.0 to 52.4, averaging 38.7 ± 2.0,

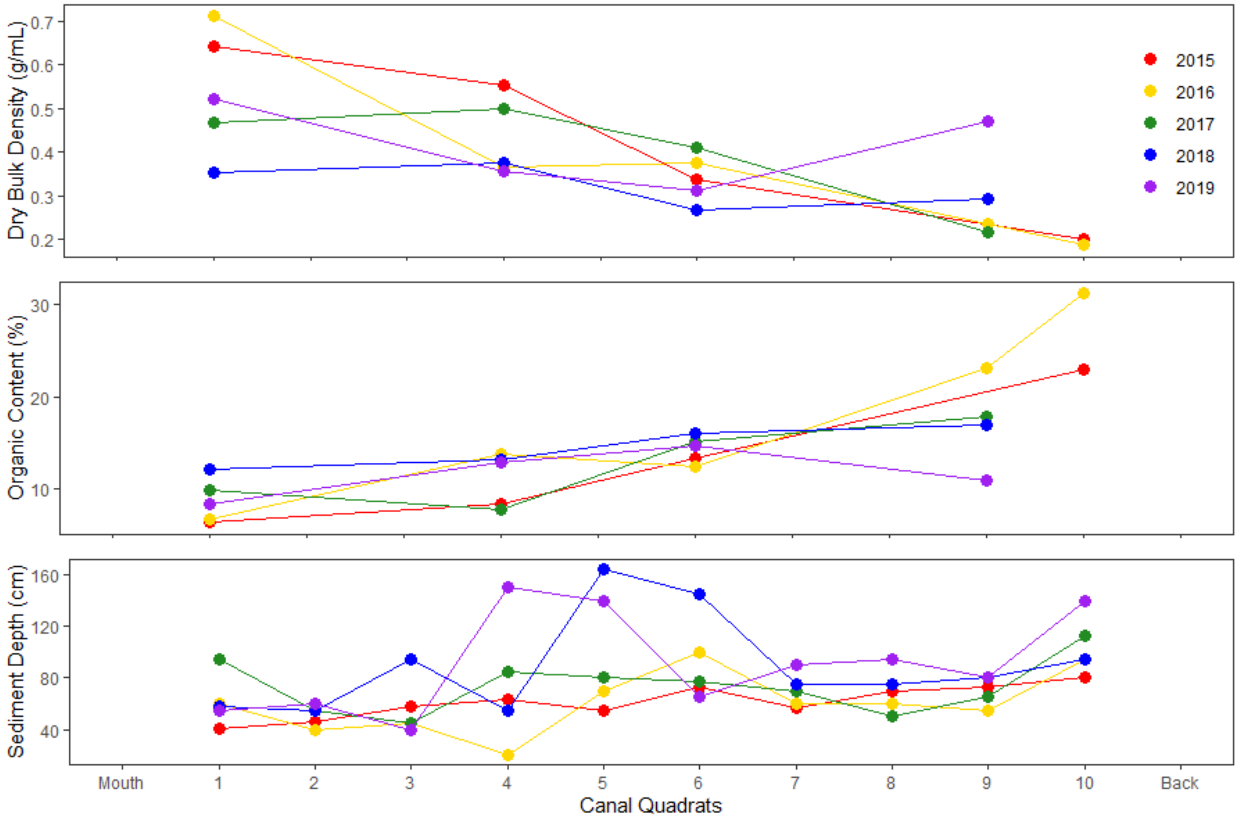

Figure 3.64: Changes in sediment dry bulk density (top), organic content (middle) and sediment depth (bottom) throughout Canal 459 over time.

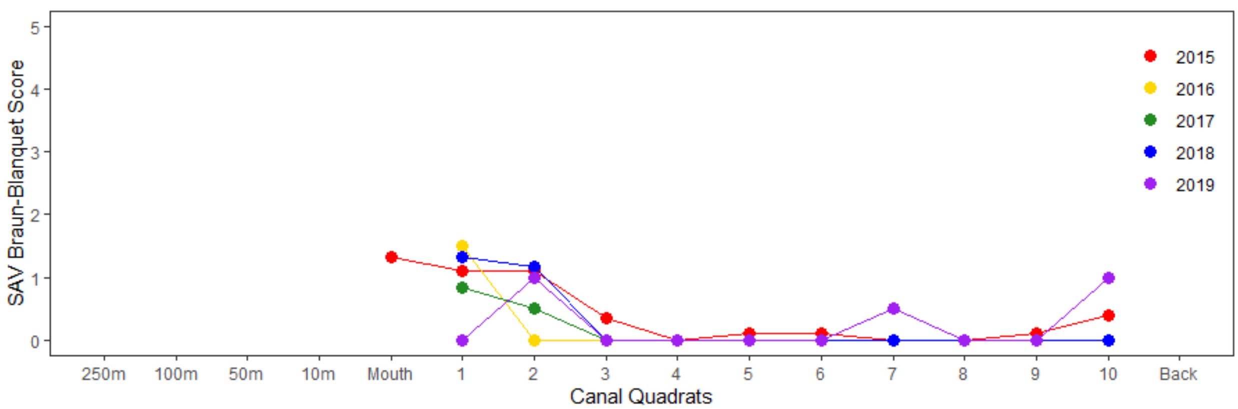

Figure 3.65: Changes in total submerged aquatic vegetation (SAV) throughout Canal 459 over time. Note that because of mangrove stands at the mouth of the canal, collections of seagrasses outside the canal were not completed.

$\delta^{13}C$ signatures ranged from –10.9 to –7.7 ‰, averaging –9.7 ± 0.3 ‰, and $\delta^{15}N$ signatures ranged from –1.1 to 1.4 ‰, averaging 0.2 ± 0.3 ‰ (Fig. 3.66).

Unlike other canals within this monitoring program, Canal 459 did not have seawalls to monitor for sessile organisms (Fig. 3.15a). The canal mouth was flanked by mangroves rather than

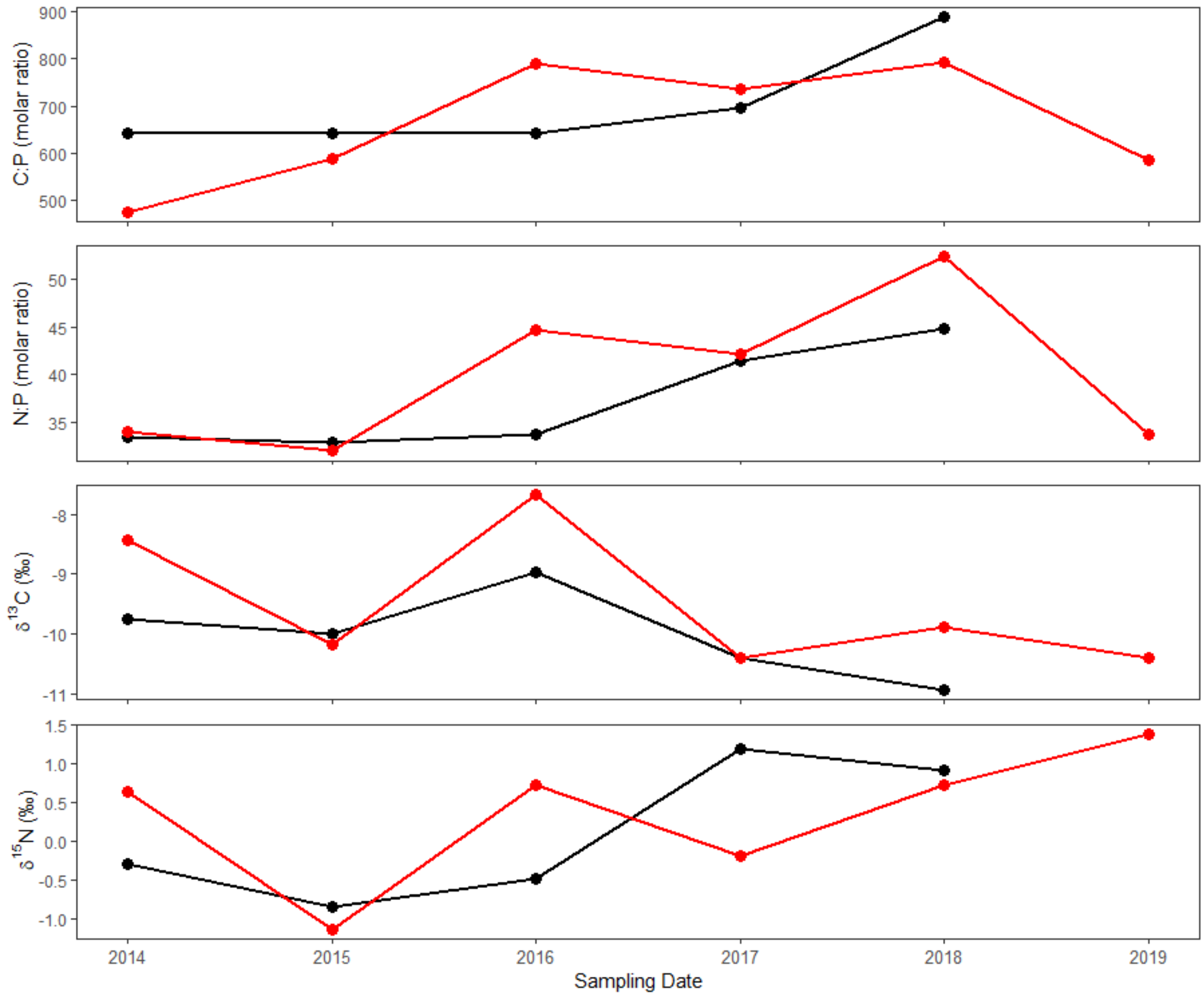

Figure 3.66: Changes in *Thalassia testudinum* leaf tissue nutrient content and stable isotope values in Canal 459 (red) and its reference, Canal 458 (black). Leaf samples were collected at the point closest to the canal mouth with seagrass, 10m – 250m outside canal.

manmade seawalls. Towards the rear of Canal 459, sediments and organic rack accumulated to the water surface covering the seawalls, preventing an assessment of any resident taxa (Fig. 3.15b). However, Canal 458 showed a large diversity of organisms during both baseline monitoring and throughout all years of monitoring (Fig. 3.15b). Fish were encountered in moderate abundances in both Canals 458 and 459 during baseline monitoring, as well as across the other monitoring years (Fig. 3.13). The number of fish species observed during baseline monitoring increased across all years of monitoring in both canals (Fig. 3.14).

3.3.10 Canal 472 – Culvert

The installation of a culvert in the rear seawall of Canal 472 was finished in May 2015, connecting its waters to an abutting canal. The installed culvert was intended to allow water to flow through the canal from mouth to rear and flush out impaired waters and low-density particulates concentrated in stagnant waters. Though the original culvert was installed in April 2015, it was closed from summer 2015 until spring 2016 due to a complaint from a local resident. The culvert was reopened in 2016 and remains a passage for flowing water. The control canal shared a similar location and orientation, though the control canal often had a thick layer of seagrass wrack spanning the entire rear half that prevented data collection on SCUBA. The area outside the canals was shallow (< 1 m) and environmentally isolated from the shore, thus the monitoring of sites from the mouth to 250 m outside was not completed, and seagrass tissues were not collected.

Sediment characteristics varied over time for both the control Canal 476 and culvert-recipient Canal 472. Sediment density was not different between Canals 472 and 476 prior to culvert completion ($p > 0.05$ for all), but after the culvert was re-opened, Canal 472 had greater sediment density (0.23 ± 0.2 g cm^{-3}) than Canal 476 (0.12 ± 0.01 g cm^{-3}; $p < 0.01$; Fig. 3.67). There were no differences in organic content prior to culvert completion ($p > 0.05$), but after the culvert was re-opened, Canal 472 had lower organic content (17.3 ± 1.1 %) than Canal 476 (21.0 ± 1.9 %; $p < 0.05$; Fig. 3.67). The same trend was observed for organic carbon content, with no difference

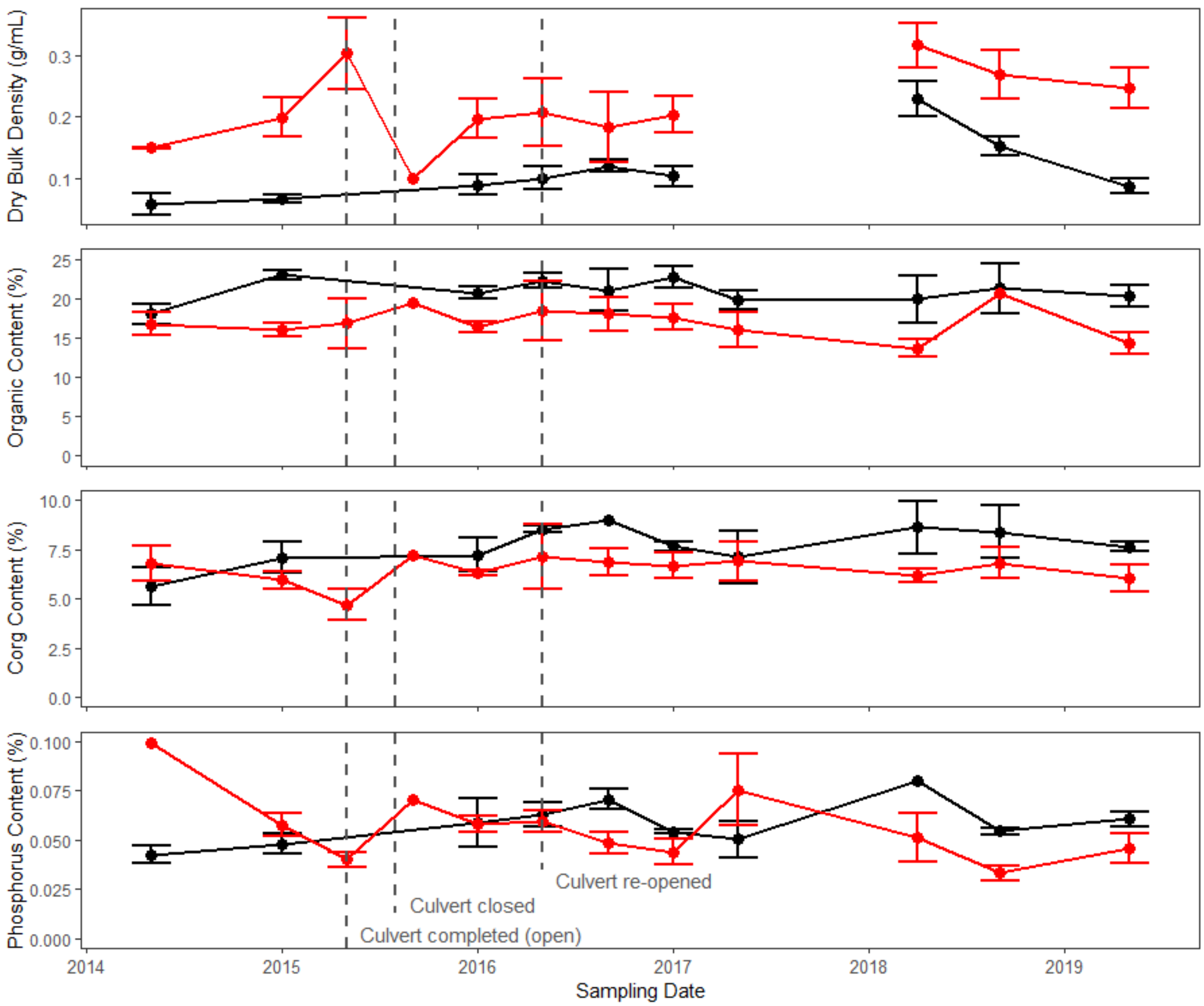

Figure 3.67: Changes in sediment characteristics over time in Canal 472 (red) compared to the adjacent reference, Canal 476 (black). Data represent mean ± SE, and vertical grey line indicates when the installation of the culvert was finished.

between canals prior to culvert completion ($p > 0.05$), followed by lower organic carbon content in Canal 476 (8.0 ± 0.9 %) than Canal 472 (6.7 ± 0.8 %; $p < 0.05$; Fig. 3.67). There were no differences in P content between Canals 476 and 472 before culvert completion or after culvert re-opening ($p > 0.05$ for both), with P content averaging 0.06 ± 0.00 % in Canal 476 and averaging 0.05 ± 0.01 in Canal 472 (Fig. 3.67).

Sediment density and organic content in Canal 472 varied little across time, but density generally decreased toward the rear of the canal and organic content generally increased (Fig. 3.68). Sediment depth in Canal 472 had a very large range from 0 to 215 cm, with greater depths generally found from the mouth up until monitoring station 9 (Fig. 3.68). One note-worthy finding was that sediment in both canals consisted of low-density, high-organic material covered by a thin biofilm that kept sediment intact. This "skin" was easily penetrated during depth measurements and coring, though penetration of sediments often resulted in the release of bubbles. The gas contained in the bubbles proved to partially consist of methane (gas chromatography; standard methods; Schonhoff 2015). This finding requires further investigation and may be important to understanding the health and functions of canal sediments.

Benthic vegetation was almost completely absent in Canal 472, except occasional observations of SAV at monitoring stations 4, 9 and 10, all prior to 2018 (Fig. 3.69). The seawalls of Canal 472 contained primarily turf green algae as well as *Caulerpa mexicana*, species of *Halimeda* and *Batophora*, and more organisms were observed on seawalls at the mouth than at the rear (Fig 3.15a-b). There were higher abundances and densities of organism after the culvert was

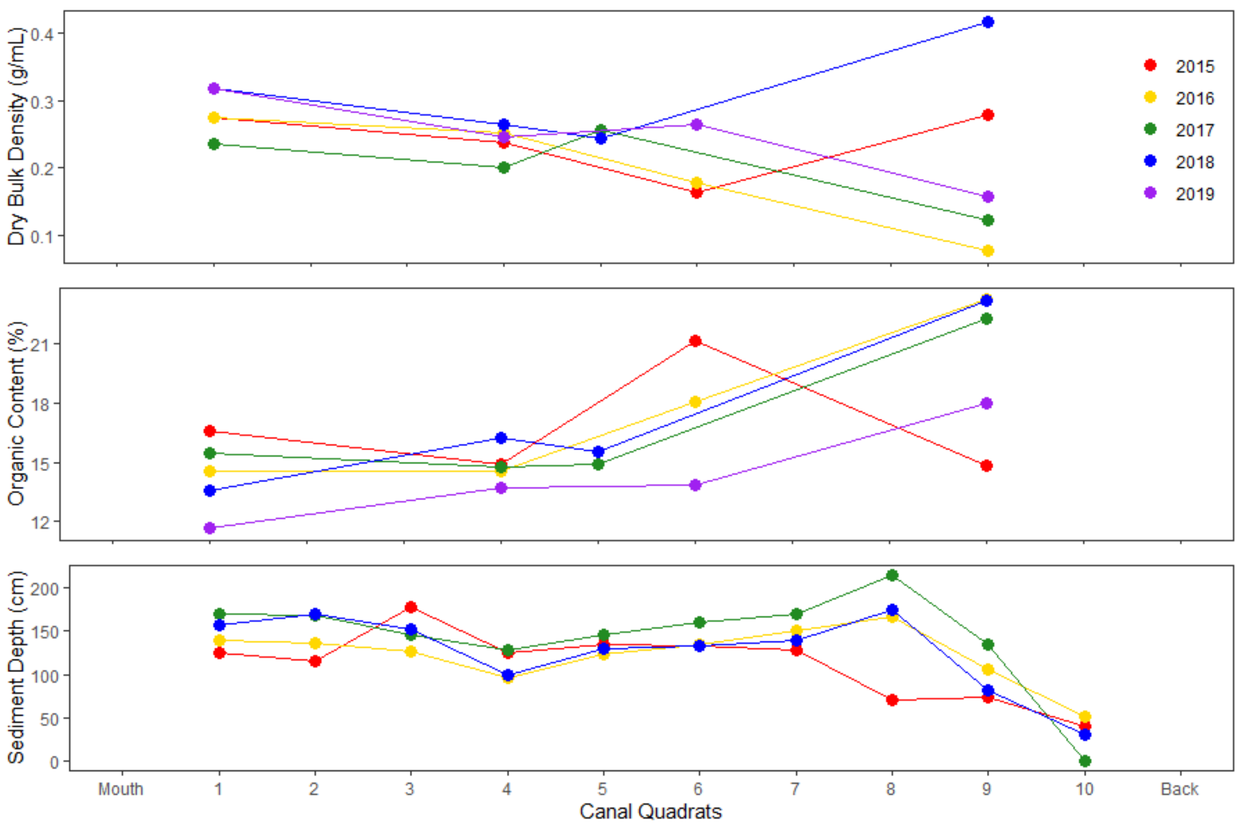

Figure 3.68: Changes in sediment dry bulk density (top), organic content (middle) and sediment depth (bottom) throughout Canal 472 over time.

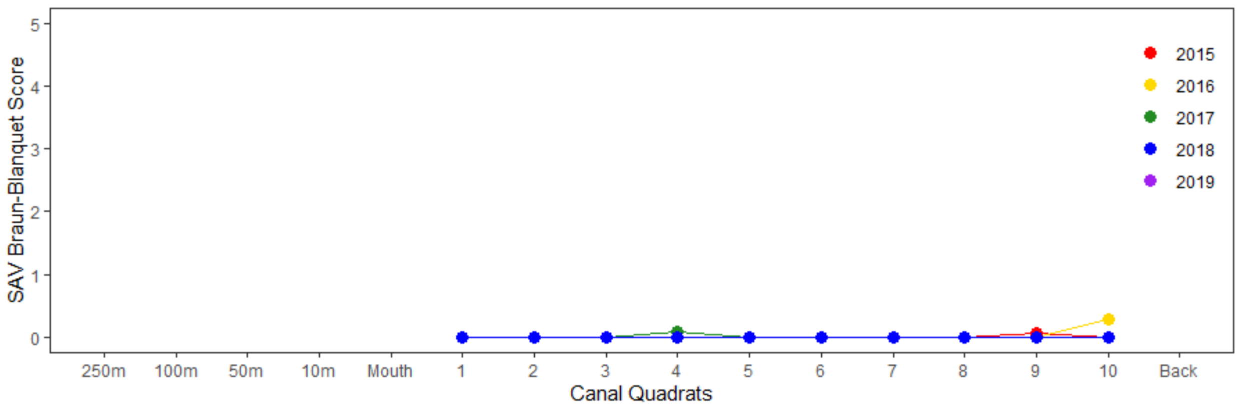

Figure 3.69: Changes in total submerged aquatic vegetation (SAV) outside of and throughout Canal 472 over time.

installed, however there was only one set of pre-culvert data for comparison (Fig. 3.15a-b). Fish were observed sporadically throughout the monitoring of this canal, with a clear increase after the installation of the culvert (Figs. 3.13 and 3.14). The installation of the culvert drastically improved water clarity (personal observation) so there is a possibility that increased fish counts in the canal rear could have been due to increased visibility rather than fish presence, though either case signifies an improvement in water quality.

4 Conclusions

Seagrasses are a vital component of healthy, functioning nearshore ecosystems in South Florida and, through their community composition and chemistry, are excellent indicators of long-term water quality. Their absence in the demonstration canals is a result of poor water quality and environmental health, as well as a contributing factor to the lack of fish and benthic life. The impaired canals included in the monitoring program have a number of negative conditions that preclude seagrass growth, animal diversity and healthy water.

High Nutrients

Seagrasses thrive in low to moderate nutrient concentrations but are outcompeted by fast-growing phytoplankton when concentrations become high. Measuring C, N, and P content in seagrasses is an established, commonly used method to infer nutrient availability in the water column (Ferdie et al. 2004; Fourqurean et al. 2001). Seagrass nutrient content (both N and P) measured during this monitoring program was higher on average and had a greater range than that reported for the entire Florida Keys (Campbell et al. 2009). Similarly, baseline sediment nutrient concentrations were consistently higher that those reported for Florida Bay and the Florida Keys (Fourqurean et al. 2012a; Howard 2018). The result of high nutrient availability can be seen in canal surface waters where a greenish, translucent hue indicates high concentrations of algae. Living algae block light that would otherwise reach plants on the bottom, and dead algae quickly decompose, consuming oxygen and producing nutrients. High nutrients in the canals likely result from nearby communities (waste, excess fertilizer) as well as decomposing organic material washing in from adjacent waters.

Low Light

Seagrasses and other benthic vegetation require high light to grow. Monitored canals are visibly turbid with phytoplankton and organic material, sometimes with floating wrack blocking light entirely. The lack of seagrass and algae within the benthos and seawalls suggest insufficient light. Further, seagrass tissue $\delta^{13}C$ was consistently lower than the average values for natural waters in the Florida Keys, suggesting a low photosynthetic rate (due to a lack of light) relative to the abundance of CO_2 in the environment (Fry et al. 1989).

Figure 4.1: Researchers are required to use underwater lights in some canals due to low light penetration. The cloudy, yellow water indicates sulfur metabolism and hydrogen sulfide resulting from a lack of oxygen.

Unsuitable Sediments

Benthic plants and animals require firm, stable sediments in which to take root. Average baseline measurements of sediment density in monitored canals were lower than those within South Florida seagrass meadows, and likely too low for anchorage of any seagrass species (Fourqurean et al. 2012a; Fourqurean et al. 2012b). Low-density sediments like those found in the canals are not compacted/firm enough to support plants and can easily be overturned, stirred up, or moved. Furthermore, the high organic content and the recognition of partially decayed wrack within canal sediments suggest that these sediments are actively decomposing. Decomposition in sediments consumes oxygen (required by benthic plants and animals) and produces hydrogen sulfide (a toxic gas) after oxygen is depleted.

Figure 4.2: Unstable, low-density sediments of impaired canals can easily be disturbed. Note the dead leaves and plant detritus that dominate surface sediments rather than expected sand grains. The pictured device was used to remove cores of surface sediment for laboratory analysis.

Low Oxygen

Plants, fish and many surveyed animals require oxygen, though the smell of hydrogen sulfide and layer of yellow, cloudy water (indicative of anaerobic sulfur chemistry) present in many canals suggest that bottom waters are depleted of oxygen. The amount of decomposing wrack and the lack of animals and benthic vegetation further support this theory. For seagrass, fish, and healthy waters to return to canals, these issues must be addressed. The technologies demonstrated through this project address one or more of these issues and have mixed success over the timespan of this monitoring program.

4.1 Canal Monitoring in Islamorada

The six canals monitored in Islamorada as part of a concurrent monitoring project varied greatly in characteristics and water quality. These canals were selected to understand changes in wastewater management rather the based on their level of impairment. The period of monitoring data presented here is relatively short and may be inadequate to show effects of water management changes due to the short time frame, when changes to water quality stemming from these types of changes may be gradual. Canal 145 was the only Islamorada canal with water quality and environmental conditions comparable to the demonstration canals. The canal, adjacent to two demonstration canals, received wrack loading from the coastal ocean that accumulates. Water quality was impaired enough to prevent research divers from entering the water. Sediment collections from benthic grabs indicated organic-rich, low-density material incapable of plant growth. Turbid waters prevent plant and algae growth beyond the surfaces.

On the other end of the spectrum was Canal 150, that hosted seagrasses from mouth the rear. The first half of Canal 150 contained *Thalassia* and *Halodule* with environmentally sensitive sponges. The rear of the canal contained benthic macroalgae and *Halophila*, suggesting a low-light environment but light and sediment conditions that are still adequate for benthic vegetation. This canal is lined on one side by residential housing though maintains natural vegetation and shoreline on the other potential contributing to overall canal health. The canal is also 90 ft wide at its most narrow, allowing for better dilution and circulation compared to other canals.

The other canals monitored as part of the current Islamorada program (Canals 114, 118, 120, and 152) share similar conditions. These are medium to long canals surrounded by businesses and residential properties. Sediment density and composition in these canals are comparable to the least impaired demonstration project canals, but still below average compared to values for the South Florida region more broadly. Unlike many demonstration canals, Islamorada canals contain

Figure 4.5: Sponge found in dense meadows of *Halodule wrightii* approximately a third into Canal 150. Benthic conditions in Canal 150 were consistently better compared to demonstration canals and other Islamorada project canals.

sediments without recognizable seagrass wrack and waters that are turbid with phytoplankton rather than detritus and tannins that turn water brown. Seagrasses and benthic macroalgae are sporadically found within canals, near the mouth, but environmental health is not high enough for plants to permanently establish or colonize sites further into the canal.

The monitoring of benthic vegetation, fish and sessile organisms is a standard method for assessing water quality and environmental health in nearshore waters of South Florida. Depending on the relative abundance of some species compared to others, and the chemical composition of plant tissue, conclusions about environmental conditions can be inferred. Unfortunately, baseline conditions of impaired canals were extreme enough to inhibit these organisms almost entirely, preventing standard methods of assessment to be useful. Improvements in sediment conditions and have already been observed in some of the demonstration canals, and over time these sediment conditions can translate to improvements in fish, grasses, and other animals. Not all demonstrated remediation technologies can be expected to show environmental improvements in the short period of time covered in this report, thus continued monitoring efforts are key to understanding the long-term effectiveness of remediation technologies.

4.2 Demonstrated Technologies

Improvements in water quality and environmental health were not clear in all demonstration canals, though this is not a surprise. Backfilling and organic removal were expected to induce rapid changes in canal conditions; this is generally supported by results from sediment, vegetation and fish observations. These remediation methods address current conditions, but they leave canals vulnerable to continued wrack influx. The coupling of air curtains with these methods may be effective to prevent the re-entry of wrack into improved canals. However, air curtains, aerators and culverts do not directly address the causes of impaired waters, thus their effectiveness is likely to be measurable as time scales beyond the years monitored during this program. Continued or periodic monitoring is recommended if improvements are to be measurable.

Backfilling

The backfilling of Canal 29 resulted in immediate improvements in sediment conditions and benthic vegetation. Sediment density was increased beyond the average value for the Florida Keys, making it suitable for plants to take root. Decomposing, organic-rich sediment was buried by the added carbonate fill, preventing it from further affecting water column oxygen and nutrient levels. The decreased water depth allowed light to penetrate to the sediment. As a result, there were measurable increases in benthic vegetation, fish diversity and abundance and inhabitants of the sea walls.

The backfilling quickly addressed many of the original causes of impaired water quality, though the influx of organic-rich sediments from outside the canals are beginning to affect sediment characteristics towards the canal mouth. Over time, continued influx of organic material may turn the newly formed sandy bottoms back into muddy, organic sediments. For the improvements to water and sediment quality resulting from backfilling to persist, organic matter and wrack inputs to Canal 29 must be addressed.

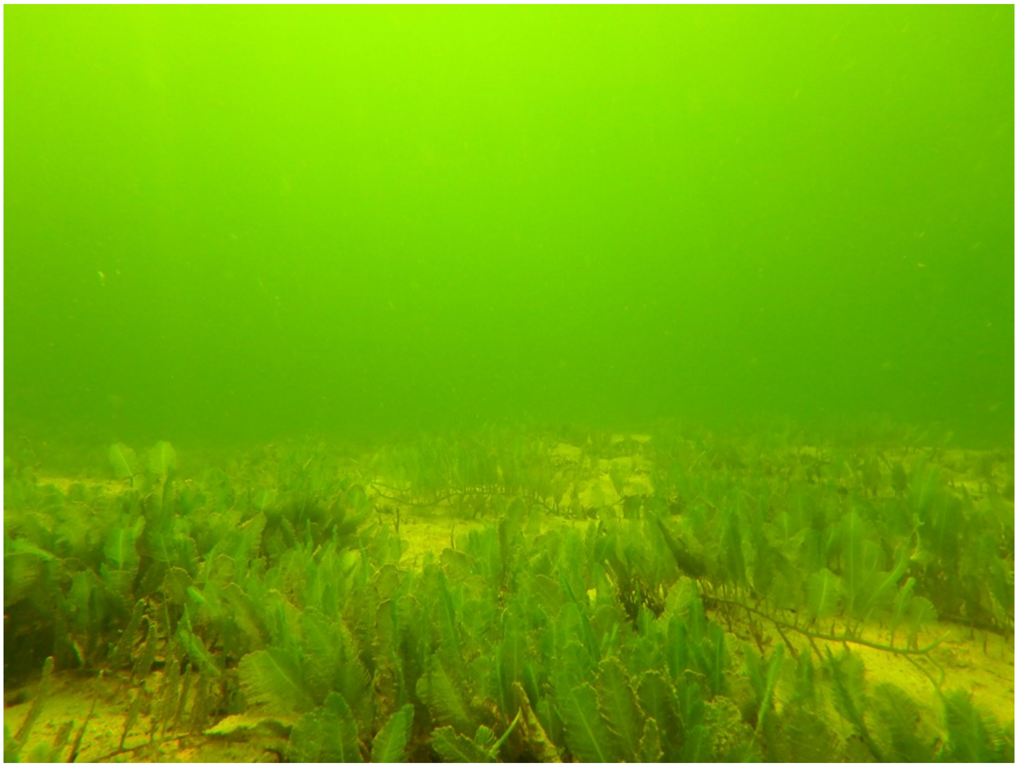

Figure 4.3: Benthic algae taking root in newly backfilled sediment in Canal 29. Prior to backfilling, light did not penetrate more than 10 ft into the water.

Air Curtains

The air curtains had no measurable effect on sediment, fish, or seawall characteristics in either Canal 137, 148, or 287 where they were installed. Air curtains block the influx of additional wrack from entering a canal, though they do not address problems related to the organic material already contained in the sediment. In this way, air curtains help prevent impaired waters in the future rather than directly addressing current problems, thus improvements in water quality or environmental conditions were not expected to be measurable in the short time frame of this monitoring. Continued, long-term surveys would address the long-term effectiveness of the installed air curtains.

Air curtains were also installed in Canals 266 and 290, though their effect was likely masked by organic removal that was expected to have more immediate effects. The short-term (1-2 years) reversal of sediment conditions in Canals 266 and 290 after dredging stress the importance of keeping out organic material after it has been removed.

Aerators

Six additional aerators were added to Canal 137 in addition the air curtain. There was no measurable difference in sediment, seawall or fish community characteristics between the canal and its control or the canal before and after the aerators were installed. Aerators are expected to rapidly address water column conditions through the introduction of oxygen, though any effect on the benthos would require a longer period of time than our monitoring could measure. Introduced oxygen would likely spur the decomposition of organics in the sediment, and while continued decomposition could change sediment depth and content enough to be suitable for benthic vegetation, it would require a prolonged period. Continued, long-term surveys would address the long-term effectiveness of the installed aerators.

Organic Removal

The removal of organic material accumulated within canals proved to be a method for immediately, drastically improving environmental conditions. Prior to organic removal, Canals 266 and 290 both contained portions where sediment depth reached over 2 m, interfering with boat propellers and effecting the navigation within the waterways. The sediment depth decreased drastically after organic removal to an average of less than 50 cm in both canals, removing the navigation hazard and decreasing the amount of material contributing to low oxygen and high nutrients. Sediment density increased in both dredged canals to values within the range of seagrass growth in South Florida. Organic content along with the related Corg, N and P content decreased in the surface sediments of dredged canals, lessening the amount of material that could potentially decompose. Water clarity and floating wrack was not quantified, though there were perceived improvements in the dredged canals by crew and residents in the area. Organic removal is an effective method for remediating canal water quality as measured in this report.

There were not changes in benthic vegetation, fish, or seawall communities related to the organic removal. Sediment and water column conditions may have improved enough to meet requirements of marine plants, though there may be a delay in plant recruitment and animal use, especially considering the first 50 m outside canal mouths are also heavily impaired. This impaired area outside the canals may serve as a geographic barrier for plants and animals. This area, rich in organic sediment, also acts as a continued threat to the dredged canals. Without air curtains, this material accumulated outside canal mouths could easily be blown into the canals where it would effectively reverse all improvements generated from the dredging.

Culverts

Culverts had mixed effects on measured variables. In Canal 277, there was no measurable effect of the culvert on sediment characteristics, fish abundance or seawall diversity compared to the control or pre-treatment conditions. The increased circulation provided by culvert insulation was intended to primarily address water column conditions, thus the subsequent effects on sediment and vegetation may require additional time in order to be identified. During surveys, it was also noted that the adjacent water bodies to which the culvert connects are also impaired with anoxic benthos (cloudy, yellow water indicating sulfur metabolism) and accumulated, unconsolidated organic sediments. The culvert installed in Canal 472 resulted in improvements in sediment conditions, fish abundances and seawall inhabiting communities. Fish counts, seawall communities and benthic vegetation were improved compared to pre-culvert conditions and control, but conclusions must be approached carefully as positive observations are scarce and pre-culvert culvert data in general is lacking.

Figure 4.4: Dozens of mangrove snapper observed in the rear of Canal 472 after the opening of the culvert.

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