Status of Residential Canal Benthic Habitats in the Florida Keys and the Effectiveness of Remediation Technologies Project Report

Prepared for the Water Quality Protection Program, Florida Keys National Marine Sanctuary & The Village of Islamorada, Monroe County, Florida

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Prepared for:
Canal Restoration Advisory Subcommittee,
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and

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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 FL 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 reengineered 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 2017 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 remediation 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 longterm effectiveness of remediation technologies. Further, the high-resolution benthic data presented here, compared to the ongoing and future data collected after the devastating 2017 Hurricane Irma, will offer a rare opportunity to evaluative how nearshore environmental heath and remediation respond to an intense storm event.

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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 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, undertaken by researchers at Florida International University.

1.1 Understanding Canals with Poor Water Quality

There are over 500 man-made canals in Monroe County spanning all of the Florida Keys, many of which exhibit signs of poor water quality and environmental conditions. These man-made canals vary widely in the length, location, use, and environmental context but 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.

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

This organic 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 gas, hydrogen sulfide.

Seagrass wrack and other organic material is not completely decomposed, and the material remaining 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.

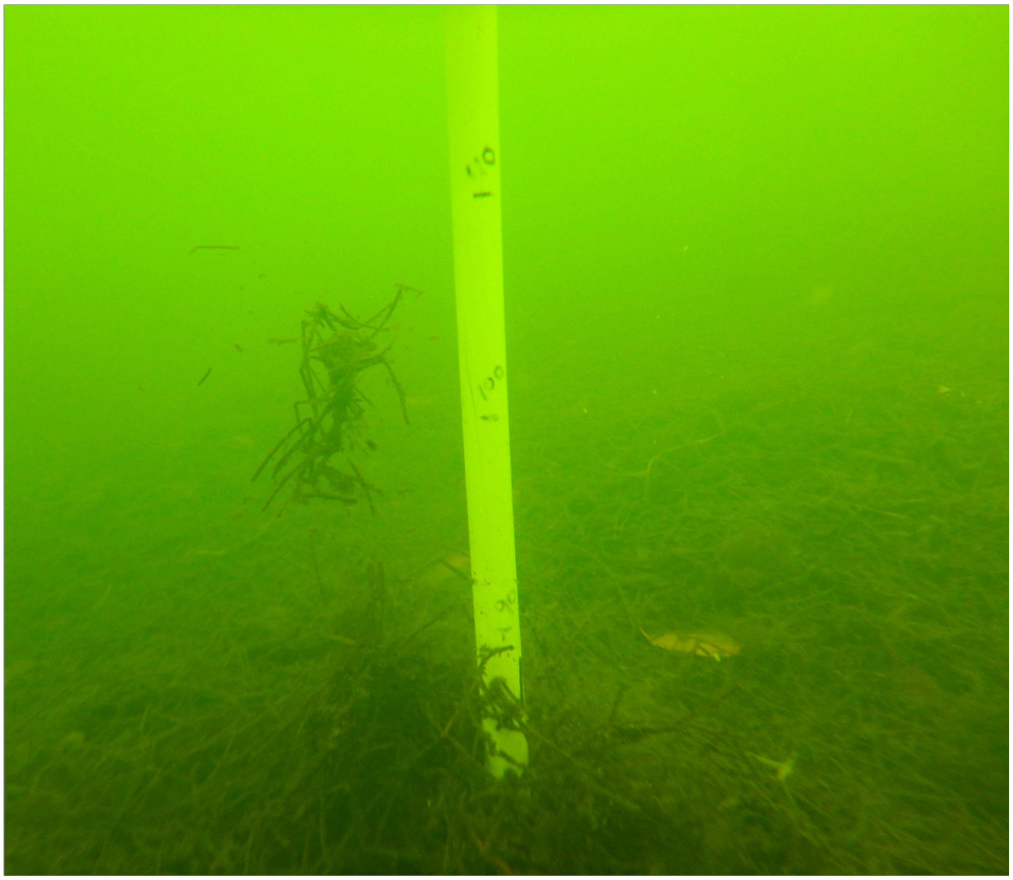

Figure 1.2: Seagrass wrack and impaired water accumulating inside a canal. Over 80 cm of lightweight organic material has settled within this canal on eastern Big Pine Key. The sediment surface consists of dead plant material rather than sand, making it unsuitable for plant growth and as a habitat for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

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.

Concurrent Monitoring Program in Islamorada

The canal demonstration projects approved by the County is not the only efforts underway to improve the nearshore and backyard waters of the Florida Keys. The city of Islamorada is interested in how the ongoing change from residential on-site wastewater management to municipal sewage will influence water quality in canals and nearshore waters. Beginning in Fall 2015, canals in Islamorada scheduled or undergoing changes in wastewater management were monitored using indictors and methods already used in the demonstration canals. By winter 2016, a total of six canals were added to monitoring efforts as part of a separate, but concurrent monitoring program (Table 1.3). 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.

1.2 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, though 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 1.1) where matched to the 10 canals, either alone (one technology in a single canal) or in combination (multiple technologies installed in a single canal) using preliminary knowledge of canal construction and causes of water quality problems. Of the 10 canals selected for demonstration projects, only 8 projects were ultimately implemented.

Table 1.1: 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 bottom	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 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.

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 ft, 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 ft. 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. 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 inappropriate 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.

Table 1.2: 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	-80356543	Plantation Key	Control for 137
137	24.95358	-80.57216	Plantation Key	Air curtain
147	24.87021	-80.70166	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	-81.6547	Geiger Key	Culvert
476	24.57641	-81.65692	Geiger Key	Control for 472

1.3 Project Canals

The demonstration projects were intended to showcase these available technologies that, if deemed effective and suitable, could be installed in additional in other 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 1.2). Control canals are thought to receive similar quantities of organic material, to have been created with similar lengths and depths, and be subjected to similar human influence as their adjacent remediated canals, thus 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.

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 ft deep, though depth increased to a maximum of 32 ft deep in 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 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, had a similar depth profile ranging from 6 ft at the mouth to 34 ft in the rear causing similar issues with water quality. With similar construction and context, canal 28 served as an experiential control for the demonstration canal.

The demonstrated technology was to backfill the canal to a consistent, 6-7 ft depth using low nutrient, carbonate fill material (similar to that found naturally in the area) to encourage flushing and light penetration throughout the water column. Backfilling began spring 2015 and was completed June 2015.

Figure 1.3: Map of Canal 29 and its experimental control. 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 ft at its widest point. After a narrow, 94 ft-long portion, the canal opens up 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 homeowner'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, thus this canal was designated to receive an air curtain to prevent the entry of wrack into the canal and six additional aerators within the canal's basin. All technologies were installed in November 2014. The neighboring canal to the northeast, Canal 132, was considered the experimental control. Its similar size, shape, exposure to the ocean, and existence of preliminary aerators made it an appropriate reference for the demonstration canal.

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

Canal 148 - Air curtain

Canal 148 is located on Lower Matacumbe 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 ft . 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 light-weight, 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.

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

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

Canal 266 - Organic Removal and Air Curtain

Canal 266 is located on 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 ft 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 has 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 an experimental control. While the length and design of this canal is notably different than 266, the location and orientation was thought to be similar enough to designate its use as a reference.

Canal 277 - Culvert

Canal 277 is located on 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 ft inland, the canal takes a sharp 90 degree 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 of similar shape and environmental context.

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

Figure 1.8: Map of Canal 287 and its experimental control. 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 distinguishable sea life. To address the inputs of organic wrack, an air curtain was installed (completed June 2016) to prevent the entry of additional material. The design is similar to that in Canal 137; a wall of small bubbles created at the mouth of the canal to block the entry of lightweight organics while allowing boat passage. Canal 288, located south of the demonstration canal, was used as an experimental control.

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 inspired residents to install two physical weed gates (one at the mouth and one at the half-way point) in the canal. These gates consisted of large, floating PVC rods that span the canal to block floating material, which are then moved for boat passage. These physical barriers were insufficient to improve water quality thus organic removal was completed in March 2016, 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. 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 ft 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, both mangrove and seagrass leaves are suspected to cause poor water quality through their accumulation and decomposition inside the canal. The proposed solution was a culvert that connects the canal's rear to an adjacent canal that is better exposed to ocean water, intended to increase the flushing of impaired waters and organic debris. Unfortunately this portion of the demonstration project was never completed, though Canal 459 and its control, Canal 458, continued to be visited as part of the monitoring program.

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

Canal 472 - Culvert

Canal 472 is a 325 ft-long canal located on Geiger Key with a consistent width of approximately 40 ft (Fig 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 ft and no mechanism to encourage mixing, thus poor water quality and organic-rich sediment have developed. This canal was the designated recipient of a culvert, connecting the canal's rear to a neighboring water body and creating a passage for water to flush through the canal. Enhanced circulation was also though to flush out lightweight sediments that have accumulated in stagnant waters. Canal 476 was designated the experimental reference.

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

1.4 Islamorada Canals

Six additional canals were monitored as part of a concurrent program in Islamorada (Table 1.3). Of these, Canal 145 was the only that appeared to have significant wrack accumulation like those in the Demonstration project. This canal was located on Lower Matacumbe, adjacent to two demonstration canals, 147 and 148, suffering from wrack loading and accumulation from the coastal Atlantic Ocean. Canal 114 shares a similar length and shape as Canal 147, though its location within Tavernier Creek blocks the influx of material. However, its location near the Overseas Highway, industry and residential homes along with poor circulation cause 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 densely constructed residential properties and businesses. Water quality issues here stem from nutrient influx, septic effluent and poor circulation more than the influx of nearshore organic material.

Table 1.3: Canals part of the concurrent monitoring project in Islamorada

Canal	Latitude (°)	longitude (°)	Location	Comments
114	25.00055	-80.533311	Tavernier Creek	Small network with primarily houses
118	25.000929	-80.538874	Near Cross Bank	Contains fueling & repair stations
120	24.989457	-80.547082	Near Cross Bank	Small network with primarily houses
145	24.874402	-80.699891	Eastern Lower Matacumbe	Wrack influence, faces ocean
150	24.859265	-80.726134	Western Lower Matacumbe	Half lined with natural vegetation
152	24.857479	-80.731729	Western Lower Matacumbe	Small network with primarily houses

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 tissue and surface sediments for chemical composition in the laboratory. Researchers on SCUBA conducted monitoring, though excessively poor water quality occasionally prevented entry into the water. Under these circumstances, sediments and vegetation were sampled from the boat using a small box grab.

2.1 Monitoring Overview and Rationale

Quantifying the abundance, type, and chemical composition of marine plants is a low-cost, reliable method of assessing water quality and benthic health (Fourqurean et al. 2001; Fourqurean et al. 1995; 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 plants community composition (Fourqurean et al. 2001; Fourqurean et al. 1995). 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 lobsters 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 and resulting 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 depth. Successful demonstration project technologies are expected to reduce the amount 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. These sampling sites were re-visited during each sampling campaign throughout the monitoring program (3 times per year). 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 (appendix 1) and a sediment depth measurement . Density of seagrass, algae, and benthic animal species (see Appendix 3 for list) were measured using a modified Braun-Blanquet scale: 0 = absent; 0.1 = one individual and < 5 %; 0.5 = few individuals and < 5 %; 1 = many individuals and < 5 %; 2 = 5 - 25 %; 3 = 25 - 50 %; 4 = 50 - 75 %; and 5 = 75 - 100 % (appendix 2); Fourqurean et al. 2002). Monitoring continued outside each canal where densities of benthic species and sediment type were monitored at 10 m, 50 m, 100 m, 250 m outside the canal mouth using similar methods.

Organisms on the sea wall were quantified using smaller, 10 x 10 cm quadrats randomly placed on the seawall at the canal mouth and rear. Organisms within 15 categories (appendix 4) were enumerated in three quadrats at both the mouth and rear using the modified Braun-Blanquet scoring scale.

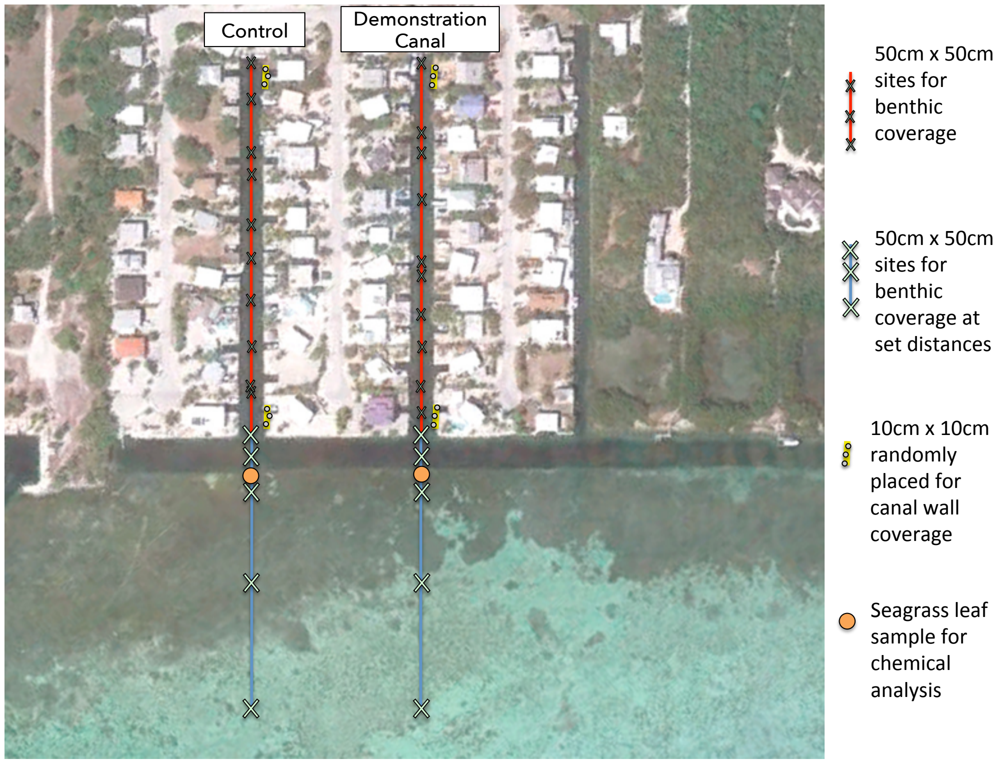

Figure 2.1: Depiction of sampling design for benthic surveys, seawall and seagrass tissue sampling.

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 encountered. For encounters of over 50 individuals 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, 10 - 20 leaves of *Thalassia testudinum* where collected the mouth of a canal, or the sampling site outside of the canal closest to the mouth which contained the species. Only sites with *Thalassia testudinum* found within the first 100 m were included in analysis, as tissue chemistry of grasses found further are less likely to be influenced by the canals. Leaf tissue samples were analyzed for C and N content using a Flash 1110 elemental analyzer (Fourqurean et al. 2001), P content was measured using a dry-oxidation, acid hydrolysis extraction followed by colorimetric analysis (Solórzano et al. 1980), and stable isotope ratio values δ^{13}C and δ^{15}N were measured with an elemental analyzer coupled to an isotope ratio mass spectrometer (EA-IRMS) using standard procedures (Fourqurean et al. 2005).

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

3 Results

3.1 Baseline Values

The 10 demonstration canals and 9 control canals were selected based on their poor water quality and high potential for improvement, along with proven support by the community. Our sampling of these canals for benthic vegetation, sediment chemical characteristics and seawall biodiversity began in May 2014 to collect baseline data, and was continued triannually until at least May 2017 to measure any environmental changes related to the installed technologies. Technologies were scheduled to be installed early during the monitoring (in 2014 - 2015) though delays in permitting pushed installation as far back as April 2017. The following baseline data represent mean values collected over the first three sampling campaigns (Spring 2014, Fall 2014, and Winter 2015), encompassing a year of data collection prior to any demonstrated technology. These data are compared to baseline values from Islamorada canals collected in winter, spring, and summer 2016.

Seagrass meadows and macroalgae are important ecosystem engineers in coastal South Florida but are markedly absent from the sampled canals (Fig 3.1). Out of the 19 demonstration project canals sampled, only three contained benthic vegetation within the canal during the first year of monitoring. Of those three, only two supported vegetation in the rear half, the portion of canals with typically the worst water quality. Benthic vegetation was present outside the mouths of canals, starting typically at the mouth or 10 m outside. It is important to note that canals 458 and 459 have mangroves outside the mouth of the canal, an unsuitable habitat for seagrasses and macroalgae regardless of water quality.

Canals monitored in Islamorada showed similar trends, with 2/3 of canals with benthic vegetation inside the canal, and only two canals with vegetation is the rear half. Canal 150, had benthic vegetation throughout almost the entire canal.

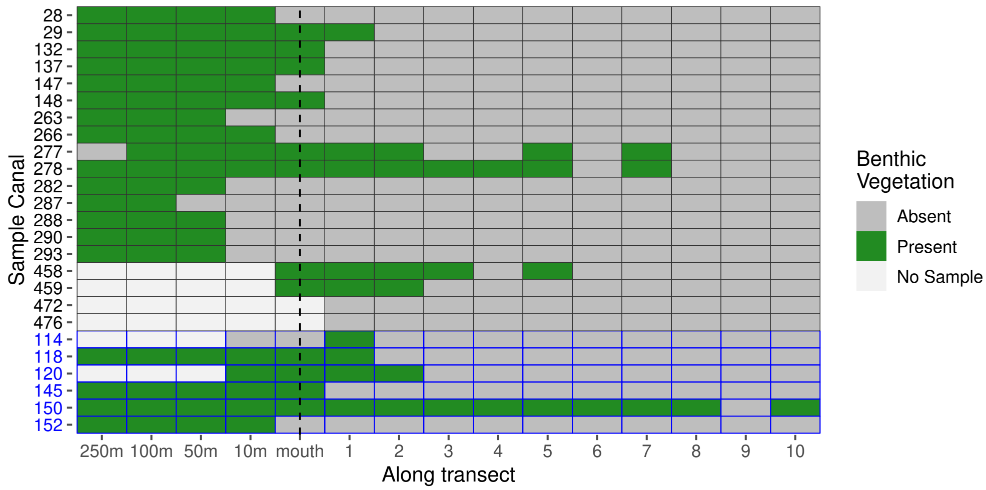

Figure 3.1: Presence of benthic vegetation along canal transects from 250 m outside monitored canals until the 10th monitoring site at the canal rear. Canals highlighted in blue are part of the concurrent monitoring program in Islamorada and data represent observations from the first year of project monitoring. Sites 1 - 10 are equally spaced from mouth to rear, and canal mouth is highlighted with a dotted line.

Turtle grass, *Thalassia testudinum*, was found in the greatest densities between 50 m and 250 m outside canals, though it was found in low densities within canals 150, 277, 458, and 459 during the first year of monitoring (Fig 3.2).

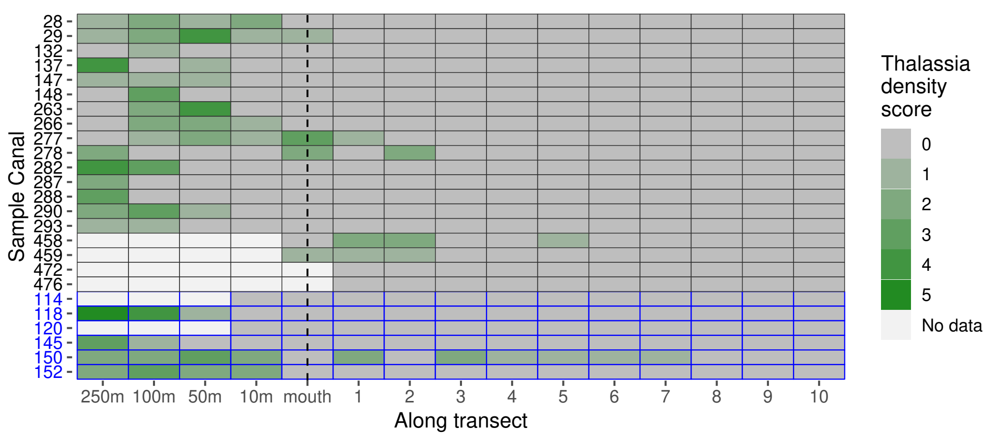

Figure 3.2: Presence of *Thalassia testudinum* along canal transects from 250 m outside monitored canals until the 10th monitoring site at the canal rear. Canals highlighted in blue are part of the concurrent monitoring program in Islamorada and data represent average scores for first year of monitoring. Sites 1 - 10 are equally spaced from mouth to rear, and canal mouth is highlighted with a dotted line.

The seagrass *Halodule wrightii* was found at a subset of monitored canals, where it more commonly inhabited sampling sites closer to the shore (mouth - 50 m). *Halodule* was found outside 14 of the 25 canals monitored, though two canals (278 and 150) hosted noteworthy abundances within (Fig 3.3).

Manatee grass, *Syringodium filiforme*, was found infrequently during initial monitoring efforts, only being observed at 7 of 25 canals. Only the interiors two of the canals, 278 and 277, both on Big Pine Key were inhabited by the species, each with only a single site inhabited near the mouth. Manatee grass was most frequently at 50 - 100 m outside the mouth (Fig 3.4).

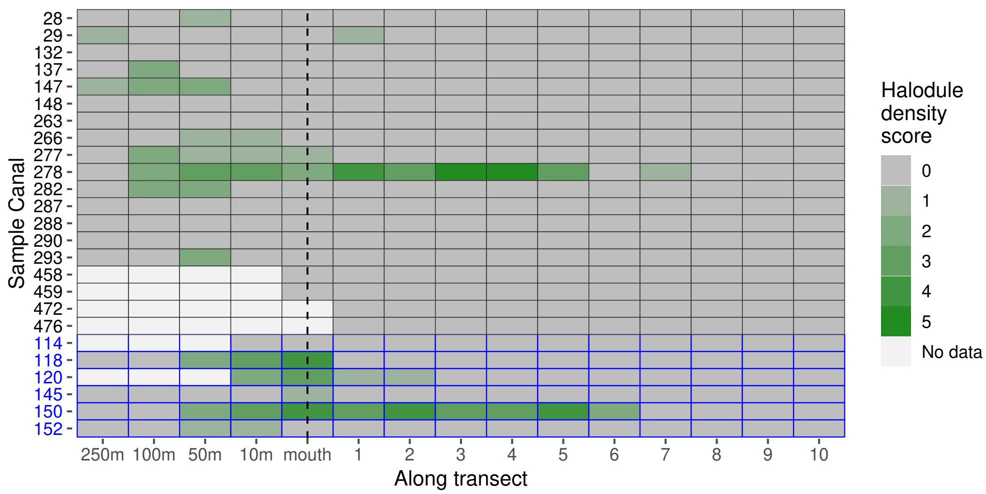

Figure 3.3: Presence of *Halodule wrightii* along canal transects from 250 m outside monitored canals until the 10th monitoring site at the canal rear. Canals highlighted in blue are part of the concurrent monitoring program in Islamorada and data represent average scores for first year of monitoring. Sites 1 - 10 are equally spaced from mouth to rear, and canal mouth is highlighted with a dotted line.

Calcifying macroalgae (genera *Halimeda*, *Penicillus*, *Acetabularia*, *et cetera*) was found outside 20 of the 25 canals, though only within 6 (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.

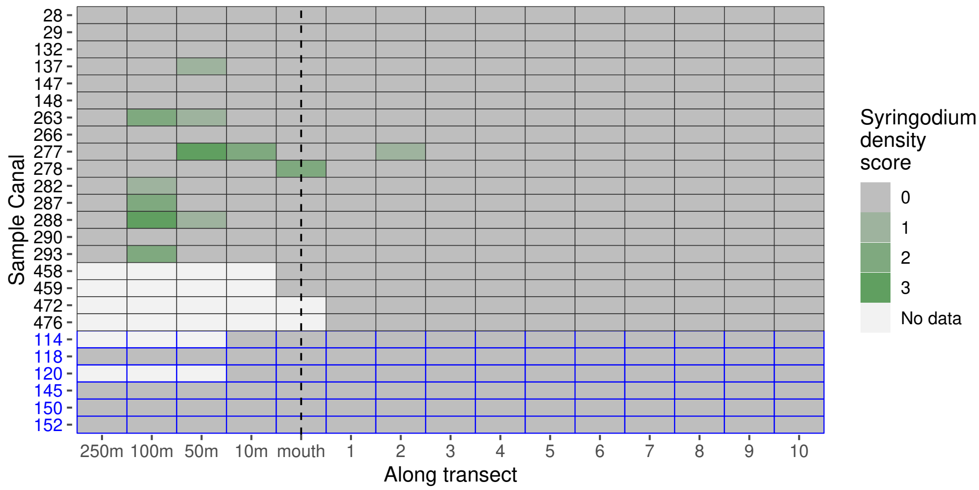

Figure 3.4: Presence of *Syringodium filiforme* along canal transects from 250 m outside monitored canals until the 10th monitoring site at the canal rear. Canals highlighted in blue are part of the concurrent monitoring program in Islamorada and data represent average scores for first year of monitoring. Sites 1 - 10 are equally spaced from mouth to rear, and canal mouth is highlighted with a dotted line.

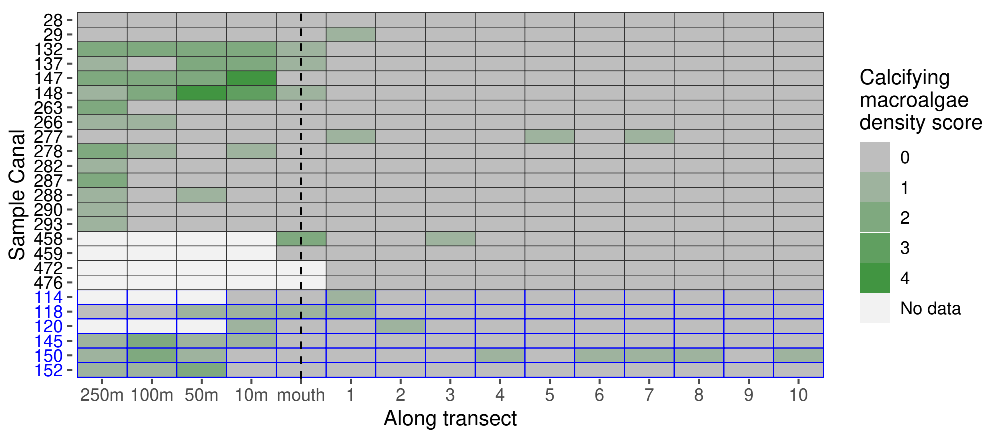

Figure 3.5: Presence of calcifying macroalgae along canal transects from 250 m outside monitored canals until the 10th monitoring site at the canal rear. Canals highlighted in blue are part of the concurrent monitoring program in Islamorada and data represent average scores for first year of monitoring. Sites 1 - 10 are equally spaced from mouth to rear, and canal mouth is highlighted with a dotted line.

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, as well as C:N and C:P molar ratios from seagrasses adjacent to canal mouths are considerably higher than average values for natural waters in the FL Keys (Table 3.1). Both N and P content of leaf tissue are high outside canals, though average N:P ratios suggest an abundance of P relative to N 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 δ^{15}N between monitoring projects. Average tissue δ^{15}N during the baseline measurements were indistinguishable from the average value for the natural waters of the FL Keys (2.3 $\pm$ 0.8 ‰ compared to 2.0 $\pm$ 0.2 ‰; Campbell et al. 2009). Values of leaf tissue δ^{13}C were lower on average for samples collected outside canals compared to values for the FL Keys more broadly (-8.6 $\pm$ 0.2 ‰; Campbell et al. 2009). There was also a difference in baseline δ^{13}C values between monitoring projects; Demonstration canals had lower values than samples from Islamorada canals (-10.7 $\pm$ 0.5 compared to -9.4 $\pm$ 0.4 ‰).

Table 3.1: Baseline *Thalassia* seagrass tissue analysis. Data represent Mean $\pm$ SE (min - max) for first year of project sampling. Regional values for the Florida Keys through the FKNMS monitoring program as reported in Campbell et al. 2009

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	Unit	Demonstration project canals	Islamorada canals	Regional values for FL Keys
C	% dry wt.	37.2 $\pm$ 0.5 (32.5 - 40.6)	37.1 $\pm$ 0.7 (32.5 - 40.9)	43.4 $\pm$ 0.3 (35 - 46.3)
C:N	molar ratio	14.4 $\pm$ 0.3 (12 - 17.6)	13.5 $\pm$ 0.5 (11.3 - 17.7)	24.1 $\pm$ 0.3 (17.1 - 33.9)
C:P	molar ratio	277.5 $\pm$ 12.8 (184.1 - 382.1)	286.1 $\pm$ 27.4 (179.2 - 469.9)	870.8 $\pm$ 26.3 (500.3 - 1902.3)
δ^{13}C	‰	-10.7 $\pm$ 0.5 (-15.8 - -8.2)	-9.4 $\pm$ 0.4 (-12.6 - -5.9)	-8.6 $\pm$ 0.2 (-13 - -5.3)
δ^{15}N	‰	2.3 $\pm$ 0.4 (-0.9 - 7.2)	2.8 $\pm$ 0.5 (-2 - 6.7)	2 $\pm$ 0.2 (-2.2 - 5.4)
N	% dry wt.	2.6 $\pm$ 0.1 (2 - 3.2)	2.8 $\pm$ 0.1 (2 - 3.4)	1.9 $\pm$ 0 (1.4 - 2.6)
N:P	molar ratio	19.3 $\pm$ 0.8 (14.5 - 27.2)	21.2 $\pm$ 1.7 (13 - 31.5)	36.5 $\pm$ 1.1 (17.1 - 76.5)
P	% dry wt.	0.1 $\pm$ 0 (0.1 - 0.2)	0.1 $\pm$ 0 (0.1 - 0.2)	0.1 $\pm$ 0 (0.1 - 0.2)

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 ± 0.03 g cm^{-3} in Canal 266 (Big Pine Key) to 0.70 ± 0.05 g cm^{-3} (similar to the FL Keys regional average; Howard 2018) in Canal 150 in Islamorada (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 (0.44 ± 0.03 g cm^{-3} compared to 0.18 ± 0.01 g cm^{-3}).

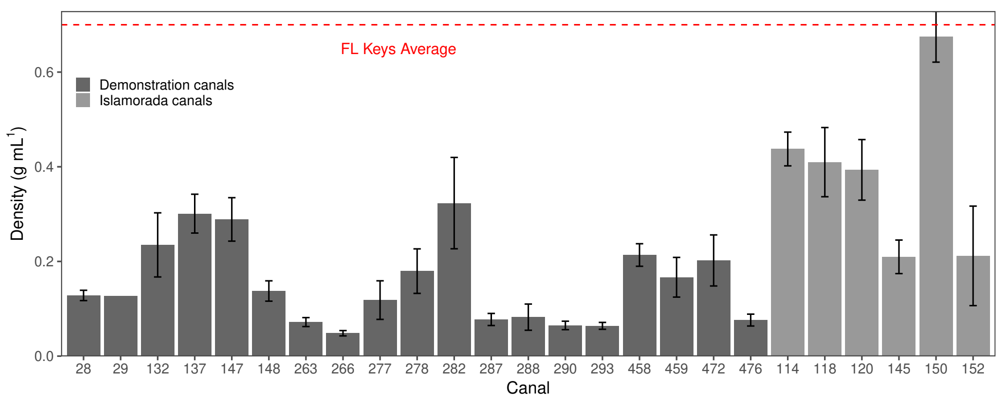

Figure 3.6: Values of sediment density (measured as dry bulk density) during the first year of monitoring, prior to demonstration technologies. Values represent mean ± SE compared to the average (red line) for natural waters in the FL Keys from Howard, 2018.

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.

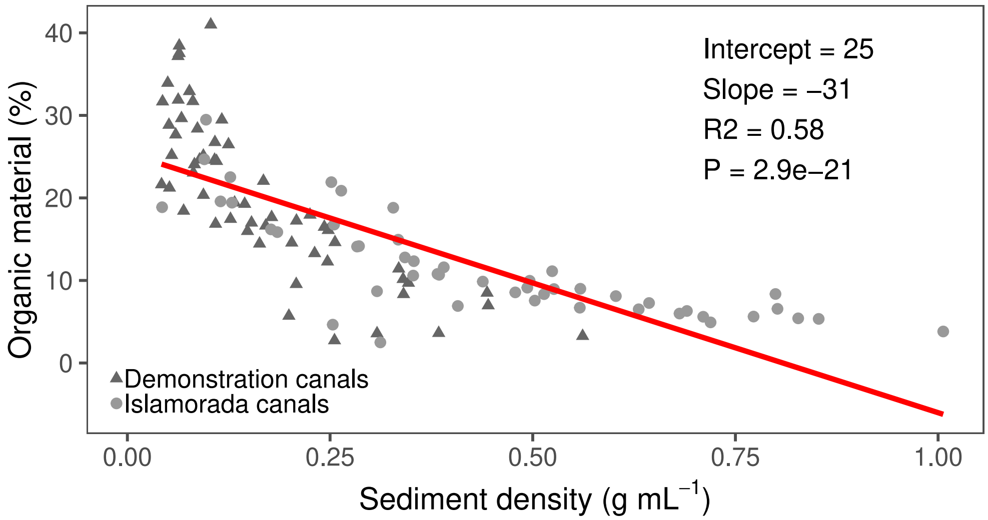

Figure 3.7: Correlation between sediment density and percent organic material of sediments. The negative slope indicates denser sediments contain less organic material.

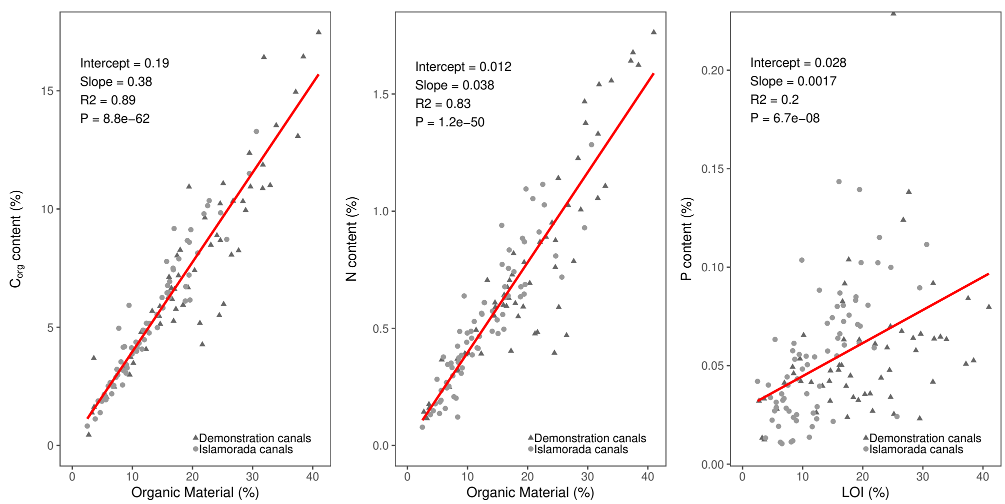

Figure 3.8: Correlations between percent organic material and C_{org}, N, and P content of sediments. There is a significant, positive relationship between all of the presented variables.

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, 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. Patterns of Organic material and C_{org} are similar across canals (Fig 3.10), though P varies independently, with Canal

148 having the highest average P content at 0.135 ± 0.032 % and a more modest variance 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).

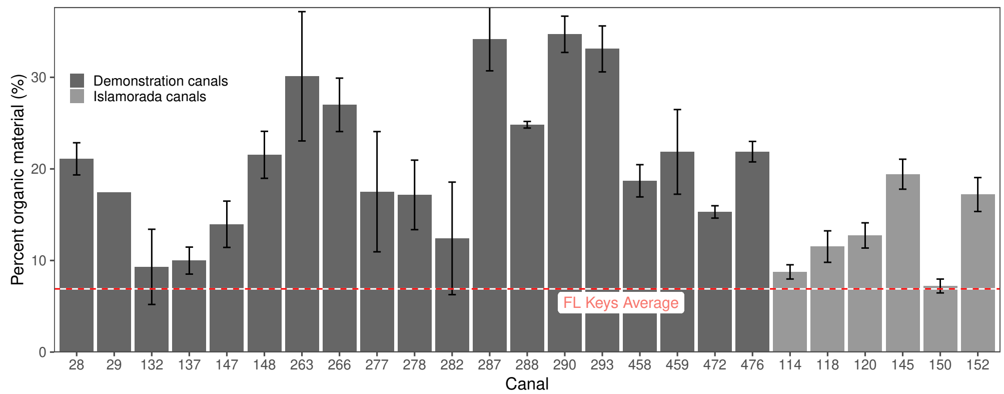

Figure 3.9: Values of sediment percent organic material (measured as LOI) during the first year of monitoring, prior to demonstration technologies. Values represent mean ± SE compared to the average (red line) for natural waters in the FL Keys from Howard, 2018.

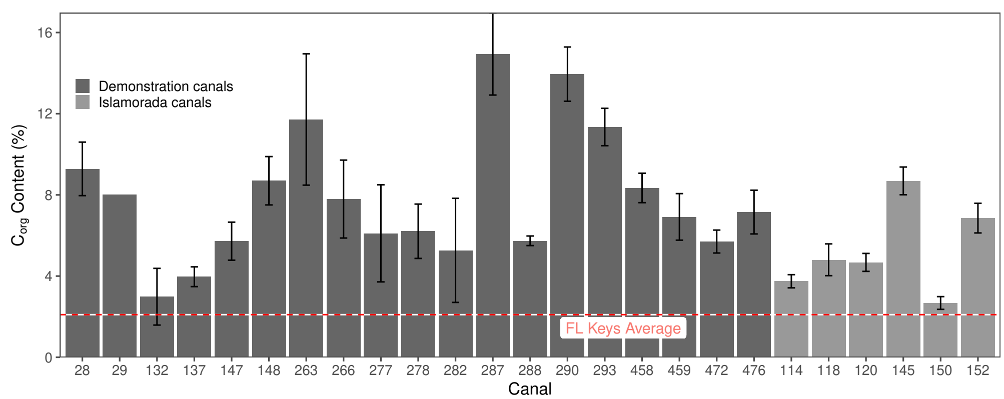

Figure 3.10: Values of sediment C_{org} content during the first year of monitoring, prior to demonstration technologies. Values represent mean ± SE compared to the average (red line) for natural waters in the FL Keys from Howard, 2018.

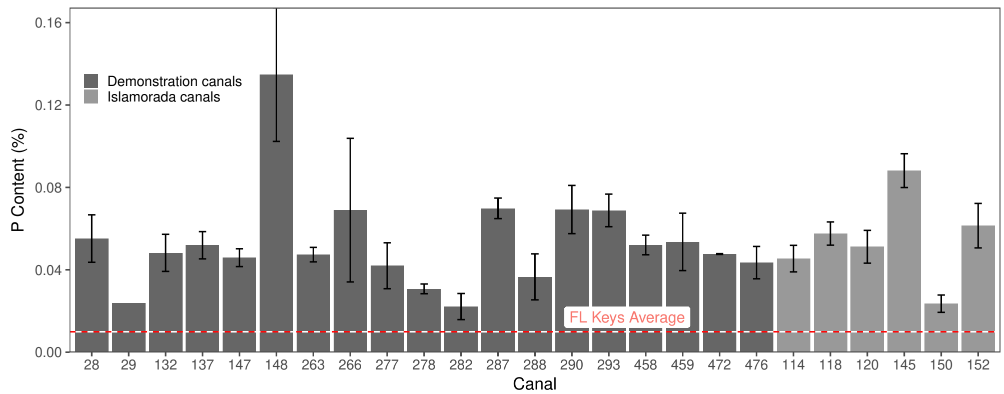

Figure 3.11: Values of sediment phosphorus content during the first year of monitoring, prior to demonstration technologies. Values represent mean ± SE compared to the average (red line) for natural waters in the FL Keys from Howard, 2018.

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 ± 18 cm measured in Canal 132 to an average of 249 ± 16 cm in Canal 293. The baseline average sediment depth across in monitored canals was 105 ± 15. 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).

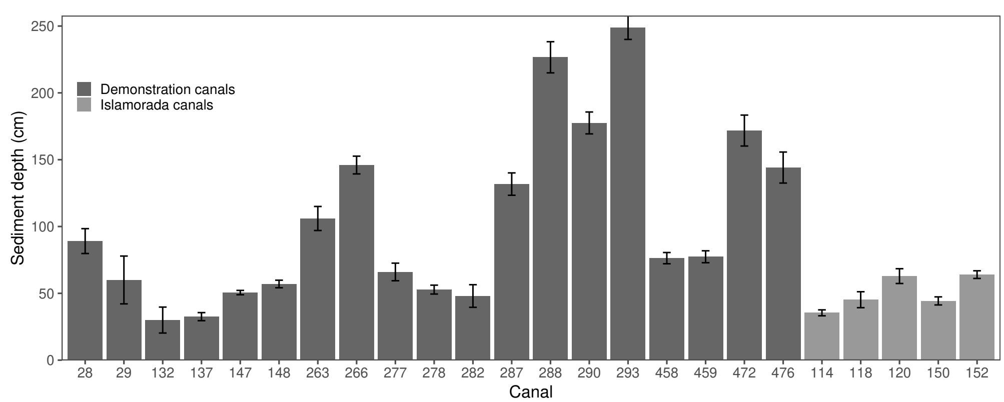

Figure 3.12: Sediment depth during the first year of monitoring, prior to demonstration technologies. Values represent mean ± SE.

Baseline Fish Observations

During the first three sampling events (Spring 2014, Fall 2014, and Winter 2015) of the Demonstration project, there were a total of 61 fish encounters, ranging from 1 to 500 individual fish per encounter. There were 12 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*). Other species were rare, being observed only once or twice. Only six of the monitored canals had more than one species of fish 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, it's likely that varying turbidity may influence the successful fish observation. Nevertheless, the pair of canals in Geiger Key (canals 458 and 459) had the highest average fish count during baseline monitoring due to schools of juvenile fish present, followed by Canal 137 on Plantation Key and the pair of canals on Key Largo (28 and 29). Three of these canals (137, 458, 459) also reported the highest number of fish species as well (Fig 3.14).

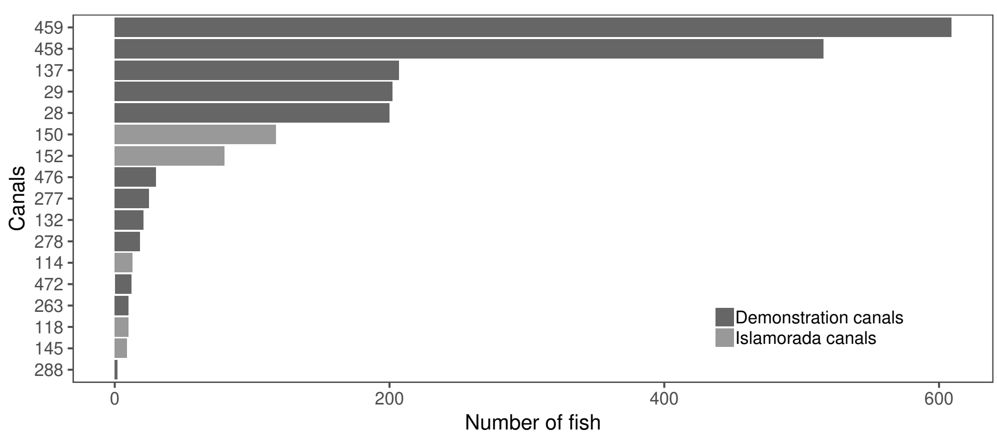

Figure 3.13: Average number of fish observed during each campaign during the first year of monitoring. Counts were estimated for encounters of over 20 individuals.

In the initial year of the Islamorada canal monitoring program, unidentifiable juveniles were the most abundant category of fish and Mangrove snapper, mullet (*Mugil cephalus*), and needle fish were the identifiable fish in highest abundance. Fish were observed in five out of six (83 %) of the Islamorada canals during the first year, compared to the 12 out of 19 (63 %) for the demonstration project canals. Canal 144 hosted the highest average number of species observed per campaign during the first year. The types of fish and the number of species were comparable between Demonstration project and Islamorada canals.

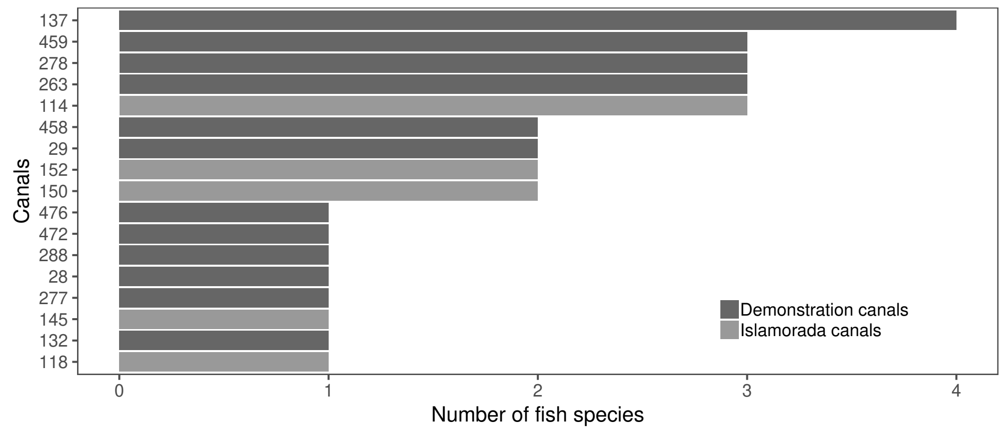

Figure 3.14: Average number of fish species observed during each campaign during the first year of monitoring.

Seawall Inhabiting Organisms

The walls of the canals were assessed for biodiversity at the canal mouth and rear. Organisms inhabiting the seawall were categorized into 15 taxonomic groups (appendix 4) and measured for density using the 5-point, modified Braun-Blanquet scale (appendix 2). There was a clear difference in the organism inhabiting the seawall of the canal mouth compared to that of the canal rear (Fig 3.15).

Of the 19 canals monitored as part of the Demonstration project, 14 had more types of organisms present at the mouth whereas only two had more types inhabiting the seawall in the rear. Turf green algae was by far the most common seawall-inhabiting organism group on average, followed by *Caulerpa sertularioides* and barnacles (Fig 3.16). The green algae *Caulerpa racemosa* was the only organism with higher average density in the canal rear compared to the mouth.

Only four of the six canals in Islamorada that had seawalls that could be sampled. Of those four, three had higher abundances of organisms in the canal rear, primarily turf green algae, barnacles and a sponges there were present in the canal rear but the the mouth. The Canal mouth of Islamorada canals had species of *Udotea* and *Halimeda* that were absent from the rear.

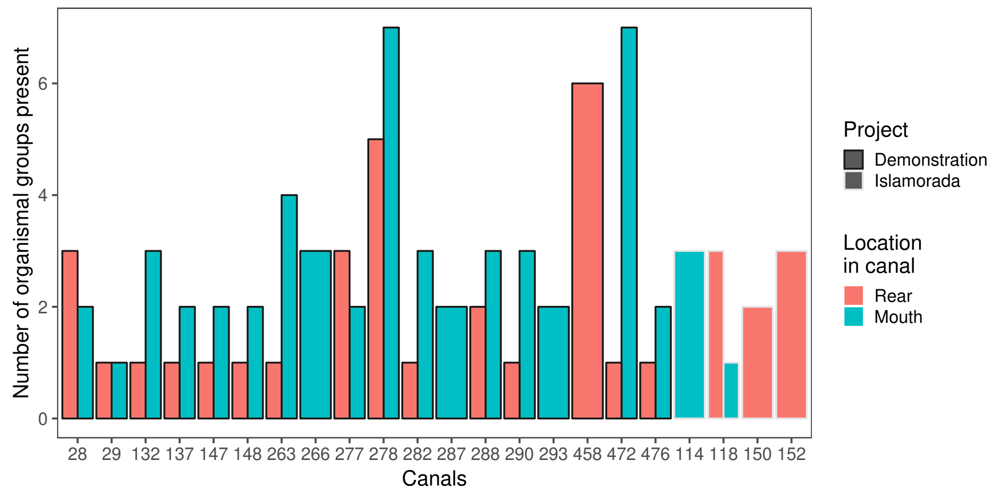

Figure 3.15: Average number of organismal groups (of 15 categories) observed on the seawall during the first year of monitoring. Seawall mouth and back refer to monitoring location within the canal, regardless of canal length. A list of organisms and abbreviations can be found in Appendix 4.

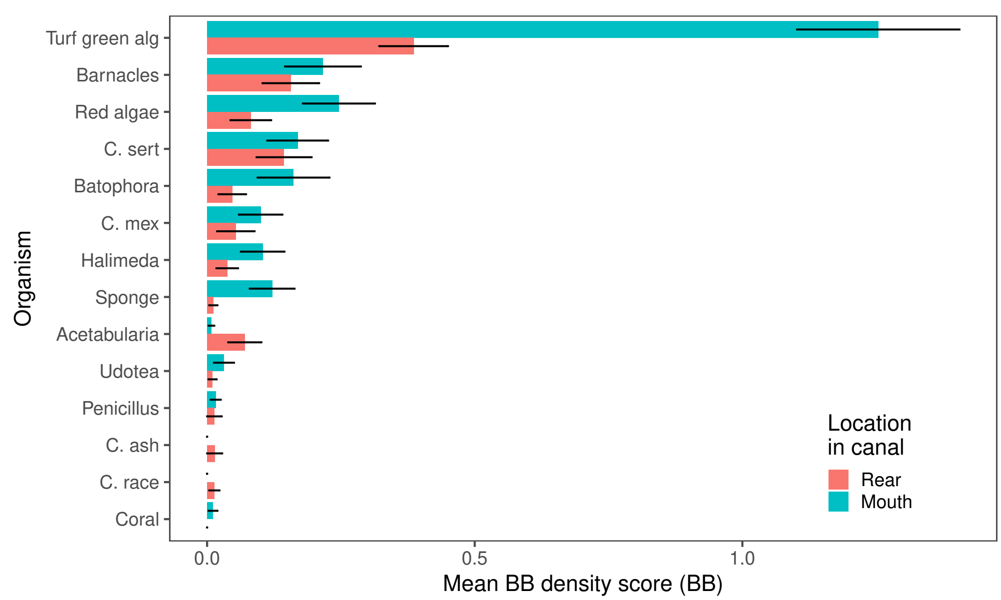

Figure 3.16: Density of organisms inhabiting canal seawalls during the first year of monitoring. Data is mean ± SE from all canals monitored (both Demonstration project and Islamorada canals). A list of organisms and abbreviations can be found in Appendix 4.

3.2 Effects of Demonstrated Technologies

3.2.1 Canal 29 - Backfilling

The backfilling of Canal 29 with carbonate sand was completed June 2015, leveling the canal depth to a consistent 6 - 7 ft from mouth the rear. The adjacent, untreated Canal 28 served as an experimental control for reference. Poor water quality conditions and depth prevented sediment measurements of Canal 29 prior to backfilling, though similar shape, depth (25 - 30 ft in rear) and orientation suggest similarities between canal conditions. 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 28 and 29 during baseline, pre-backfilling monitoring.

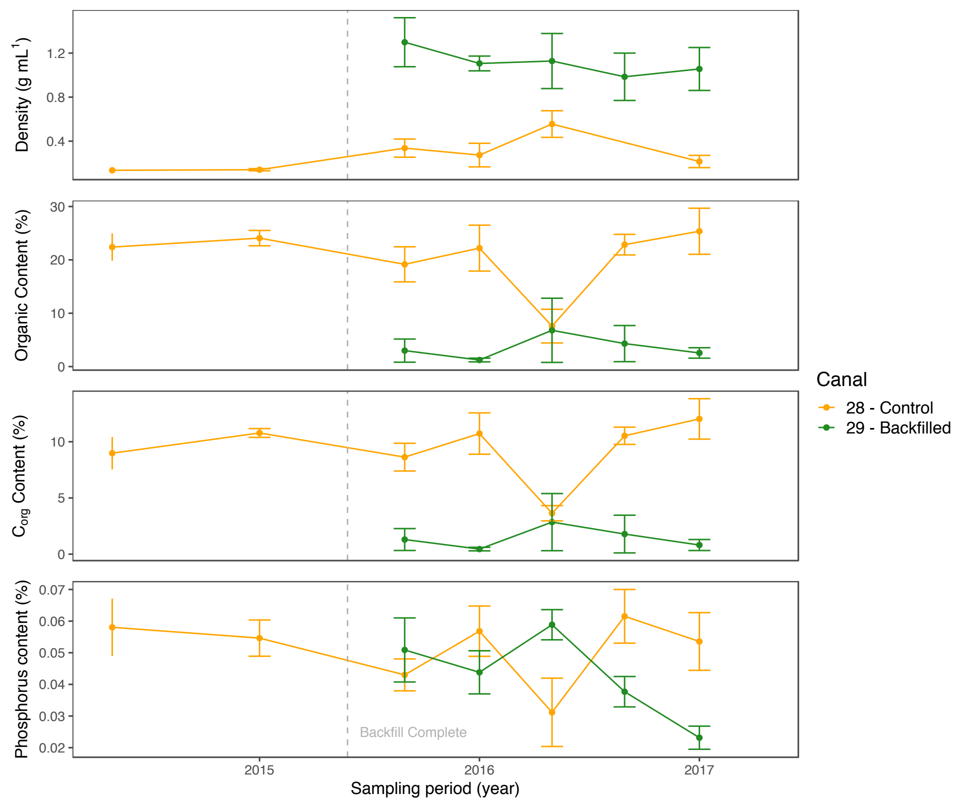

Figure 3.17: Changes in sediment characteristics over time in the backfilled canal 29 compared to the adjacent reference canal. Measurements in canal 29 prior to backfill were unable to be made. Points represent mean ± SE.

After backfilling there was a drastic difference in sediment characteristics between the two canals (Fig 3.17) . After treatment, sediment density in backfilled canal averaged 1.30

$\pm$ 0.22 g cm^{-3}, compared to the control canal of 0.34 $\pm$ 0.08 g cm^{-3} and the reported regional averages of 1.0 $\pm$ 0.1 g cm^{-3} for Florida Bay (Fourqurean et al. 2012a) and 0.73 $\pm$ 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, 19.2 $\pm$ 3.3 % compared to 3.0 $\pm$ 2.2 % dry wt.

Similar to organic material, the newly backfilled sediment was ~7 - fold lower in C_{org} on average compared to the control canal (1.2 $\pm$ 1.0 % compared to 8.6 $\pm$ 1.3 % dry wt.) and also lower in nitrogen (0.1 $\pm$ 0.1 vs 0.7 $\pm$ 0.1 % dry wt.). There was no difference in average sediment P between the backfilled and control canal.

Sediment characteristics 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 3.18)

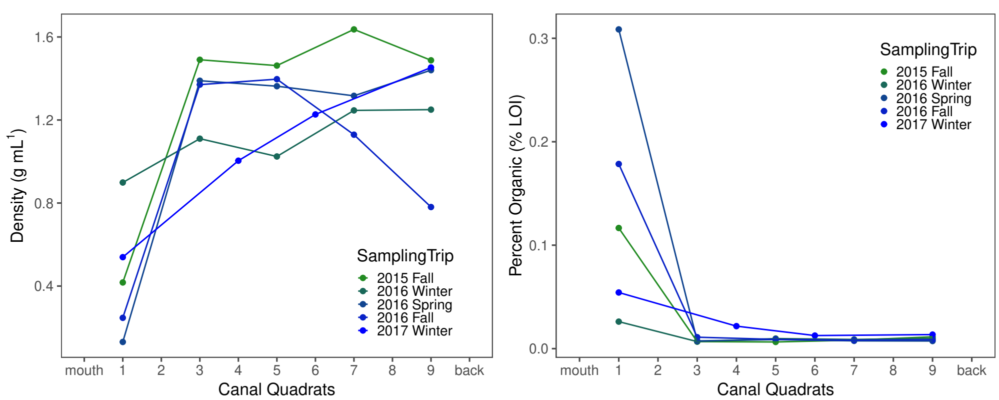

Figure 3.18: Changes in in sediment density and percent organic carbon throughout backfilled Canal 29 over time.

Within one year of the backfilling, macroalgae (particularly species of *Penicillus* and *Halimeda*) began to colonize the benthos of the backfilled canal, forming dense patches in the rear half (Fig 3.19). 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 communities of seawall-inhabiting organisms shifted after the backfilling as well; in the rear, *Caulerpa Sertularioides*, which was absent prior to backfilling, increased to 75 % - 100 % coverage of the seawall (Fig 3.20). Turf green algae and Penicillus also appeared on the rear seawall after treatment.

Fish diversity and abundance both increased after the backfilling, though fish encounters were rare throughout the monitoring. Prior to backfilling, fish encounters only oc-

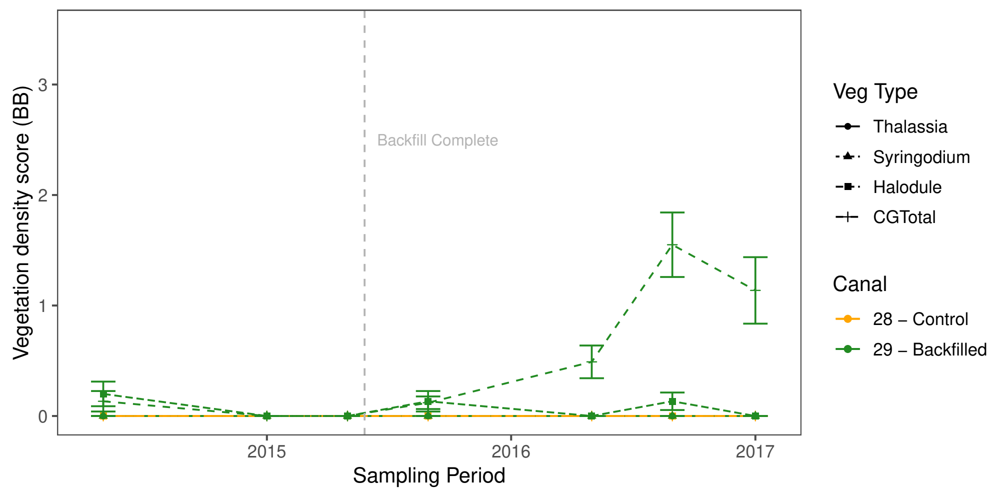

Figure 3.19: Increases in benthic vegetation in Canal 29 after backfilling. Points represent mean ± SE of quadrats sampled.

curred once (in winter 2015) with observations of 4 needlefish and approximately 200 juvenile fish. After the backfilling there were fish encounters only in fall 2015, including the observations of mangrove snapper and unidentifiable jacks along with hundreds of juvenile fish (Fig 3.21). While diversity and number of fish were higher after backfilling, conclusions regarding fish communities are unable to be reached as 1) encounters were low overall, and 2) data is likely to be biased as the improved water clarity resulting from the backfilling may have increased post-treatment fish counts.

Seagrass leaf nutrient concentrations, as well as stable isotope ratios are indicative of water quality and nutrient abundance and source. Leaves of *Thalassia testudinum* were collected outside canals 28 and 29 at 50 - 100m at the closest point containing *Thalassia* and analyzed. Nutrient and stable isotope values varied considerably though there was no clear difference between those for the backfilled canal versus the adjacent (Fig 3.22). In fact the directional trends for leaf tissue measurements are nearly identical for the two canals. There was a peak in N and P content as well as δ^{15}N during winter 2016.

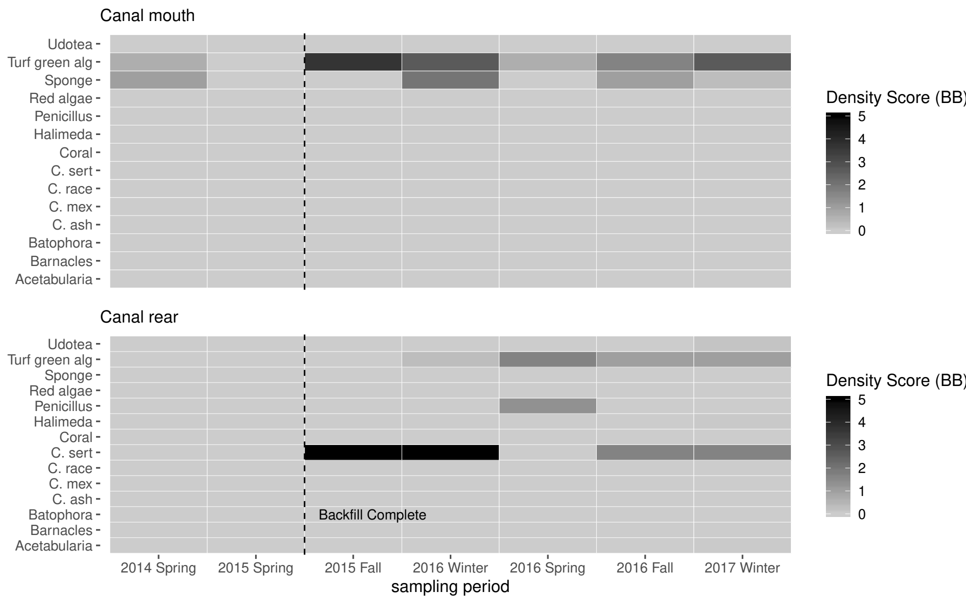

Figure 3.20: Changes in seawall-inhabiting organism in backfilled Canal 29 at the canal mouth and rear. Data represent mean values of three measurements. Organismal categories explained in Appendix 4.

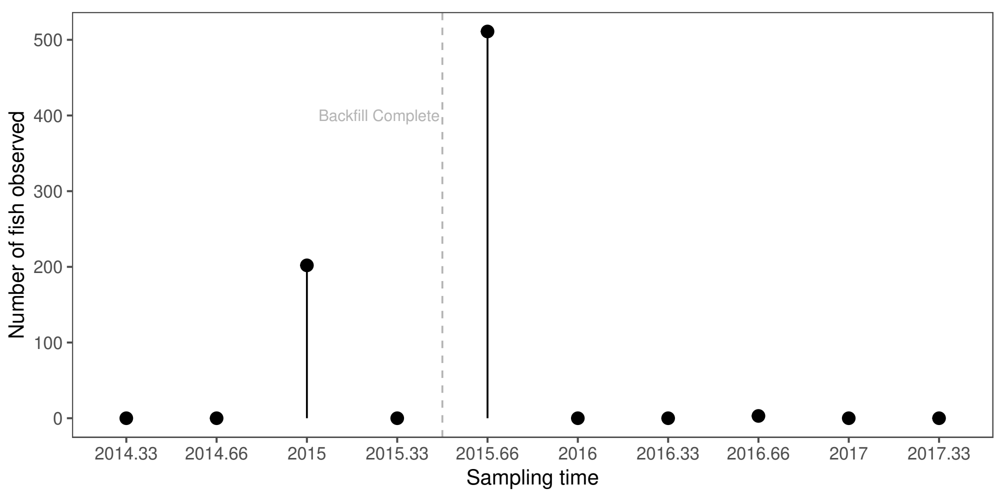

Figure 3.21: Number of fish observed in backfilled Canal 29 through project monitoring. Data represents sum of all fish encounters during a monitoring campaign.

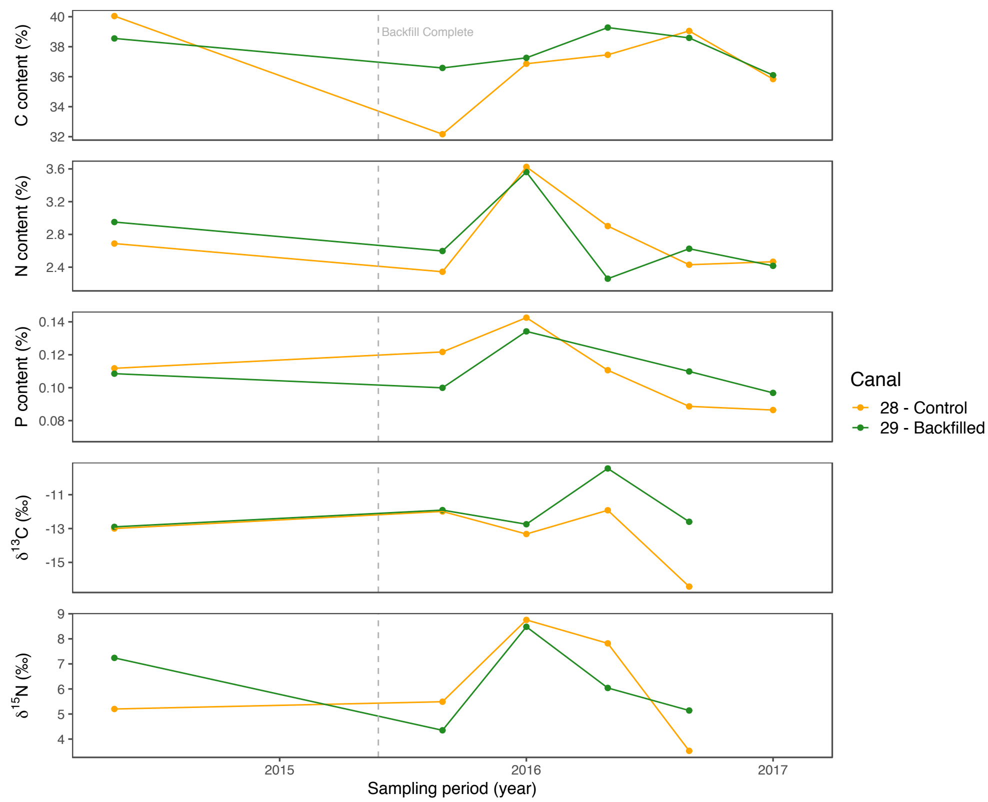

Figure 3.22: Thalassia leaf tissue nutrient content and stable isotope values in Canal 28 and 29. Leaf samples were collected at the point closest to the canal mouth with seagrass, 50m-100m outside canal.

3.2.2 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. Benthic vegetation was extremely rare in both the experimentally altered canal and the reference, with only three observations of benthic vegetation throughout the monitoring program (two occurrences in Canal 137 and one in 132) all with low densities of calcifying green algae 3.23).

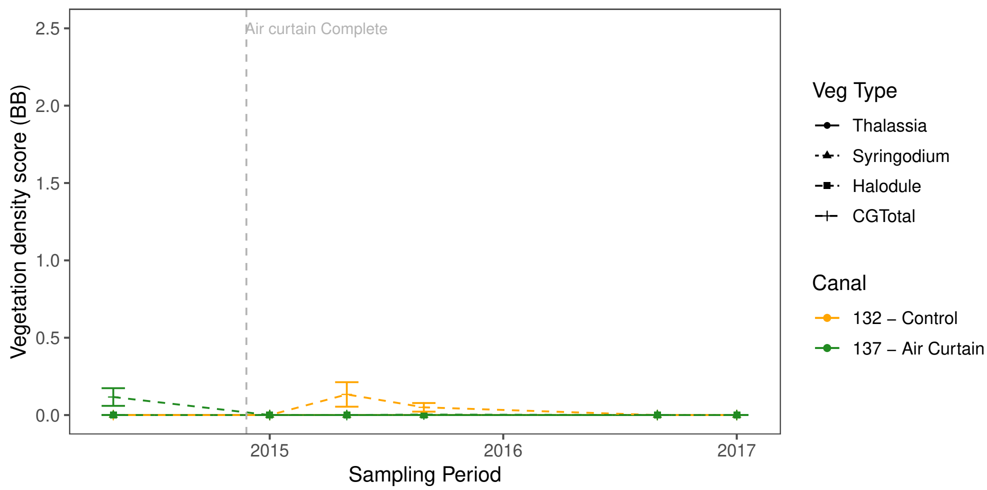

Figure 3.23: Changes in benthic vegetation density in Canal 137 compared to reference, Canal 132 over time. Data represent mean ± SE, and the vertical grey line indicts when air curtain and aerator installation was finished.

The only observations of benthic vegetation after the air curtain installation occurred in the reference canal, though the scarcity of observations suggest findings are inconclusive. After over two years of the installed technologies, there was only benthic vegetation outside the canal, being completely absent from the interior (Fig 3.24).

There was no consistent difference in sediment depth between the Canal 137 with air curtain and additional aerators and its reference. In fact, average sediment depth was higher in the demonstration canal at three of five, post-installation monitoring periods (Fig 3.25).

Just as there was no measurable effect of installed technologies on sediment depth, there were no effects on sediment characteristics (Fig 3.26). Both canals had primarily muddy, low-density sediments averaging 0.3 ± 0.2 g cm^{-3} (canal sediment characteristics were statistically indistinguishable from one another; repeated measures ANOVA, $p > 0.05$) with percent organic material averaging 24.5 ± 3.1 % and C_{org} content ranging from 1.3 to 6.7 %, averaging 4.1 ± 0.3 %. Sediment phosphorus content remained relatively consistent through monitoring except for one point in Canal 132 that averaged

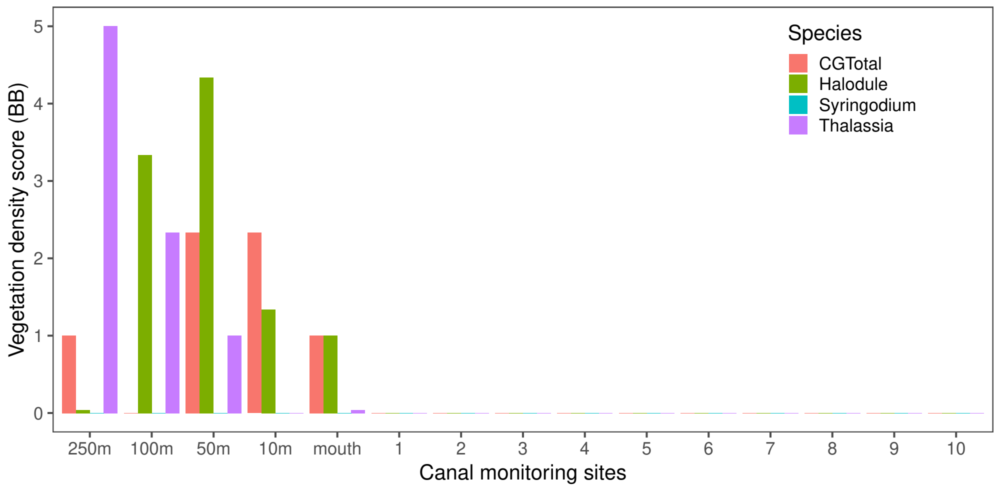

Figure 3.24: Benthic vegetation from 250m outside experimentally altered Canal 137 to site 10 at the canal rear during the final monitoring campaign in winter 2017. Data represent average score of three measurements at each site.

0.12 ± 0.07 % dry wt, due to a single, high concentration sample influencing the mean. Over two years after the installation of the air curtain and additional aerators, there was still no detectible difference in sediment characteristics compared to the control. There was variability in sediments characteristics over time though no trend or clear effect of the installed technologies.

While fish were observed during baseline monitoring (2 individuals in Canal 132, 4 individuals in Canal 137), there were not any documented in the demonstration canal or the control after the installation of the air curtain. Throughout monitoring, seawalls of Canal 137 hosted almost exclusively turf green algae, while much higher densities at the mouth compared to the rear and no measureable effect of the air curtain (Fig 3.27).

Leaves of *Thalassia testudinum* were analyzed for chemical composition (nutrient ratios and stable isotope values) though due to an irregular occurrence of plants within the first 100 m from the mouth, samples were collected during only four campaigns (Fig 3.28). This was inadequate to judge any influence of installed technologies. There may be a trend forming for seasonality; measurements of N and P during the fall campaigns were higher than those during the spring campaigns, though there is insufficient data to support conclusions.

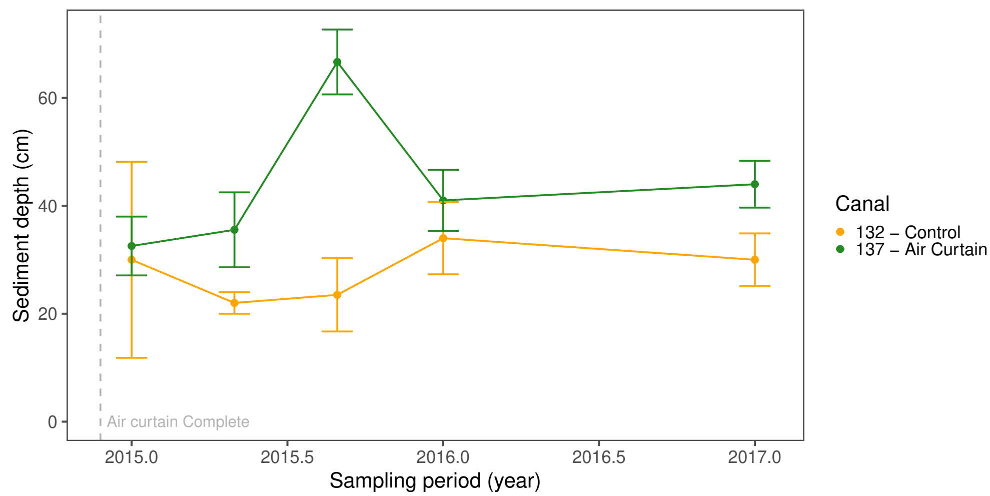

Figure 3.25: Sediment Depth in Canal 137 compared to its reference, Canal 132 over time. Data represent mean ± SE, and the vertical grey line indicts when the installation of air curtain and additional aerators was finished.

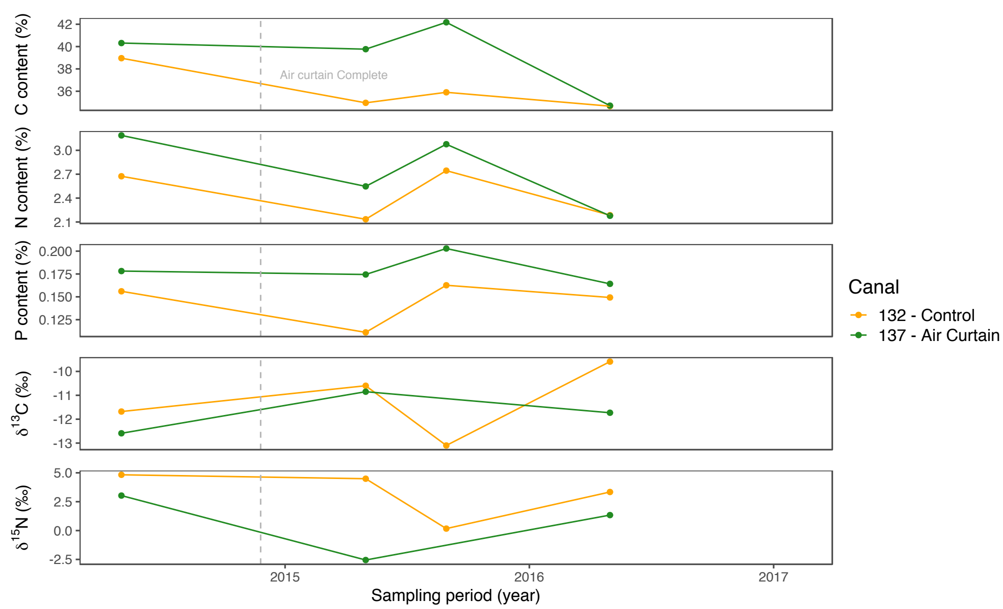

Figure 3.28: Thalassia leaf tissue nutrient content and stable isotope values in Canal 132 and 137. Leaf samples were collected at the point closest to the canal mouth with seagrass, 10m-50m outside canal. the vertical grey line indicts when the installation of air curtain and additional aerators was finished.

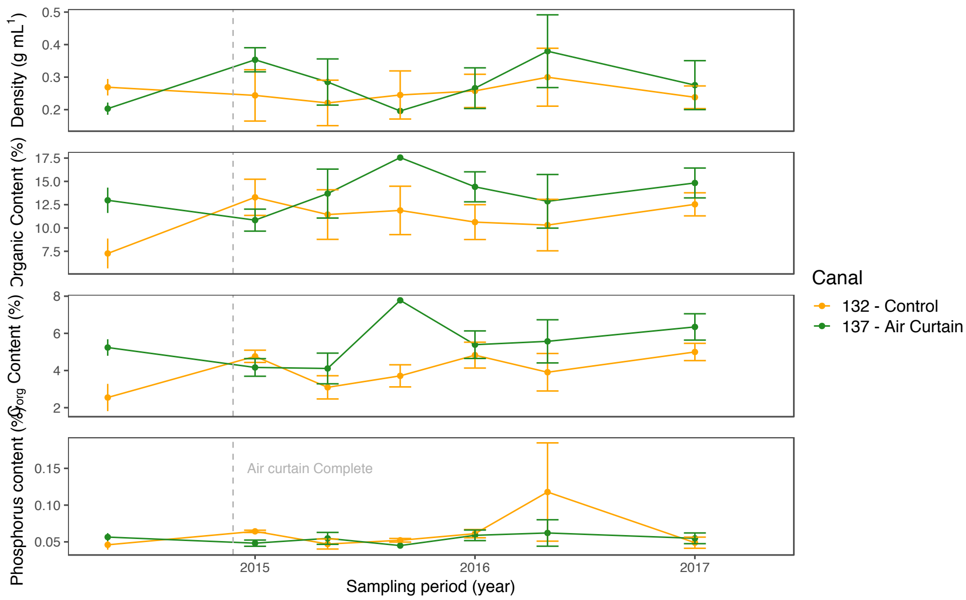

Figure 3.26: Changes in sediment characteristics over time in the Canal 137 compared to the adjacent, reference canal. Data represent mean ± SE, and the vertical grey line indicts when the installation of air curtain and additional aerators was finished.

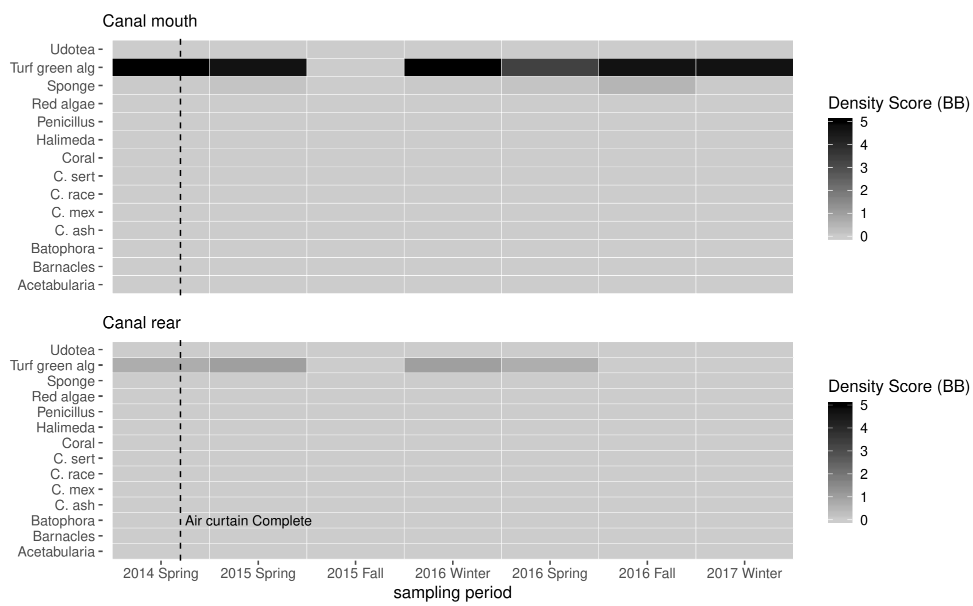

Figure 3.27: Changes in seawall-inhabiting organism in Canal 137 at the canal mouth and rear. Data represent mean values of three measurements, and the vertical grey line indicts when the installation of air curtain and additional aerators was finished. Organismal categories explained in Appendix 4.

3.2.3 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 spring 2017, thus the effectiveness of the installed air curtain cannot be accurately assessed here. In both Canal 148 and its control, Canal 147, water quality is impaired enough 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.

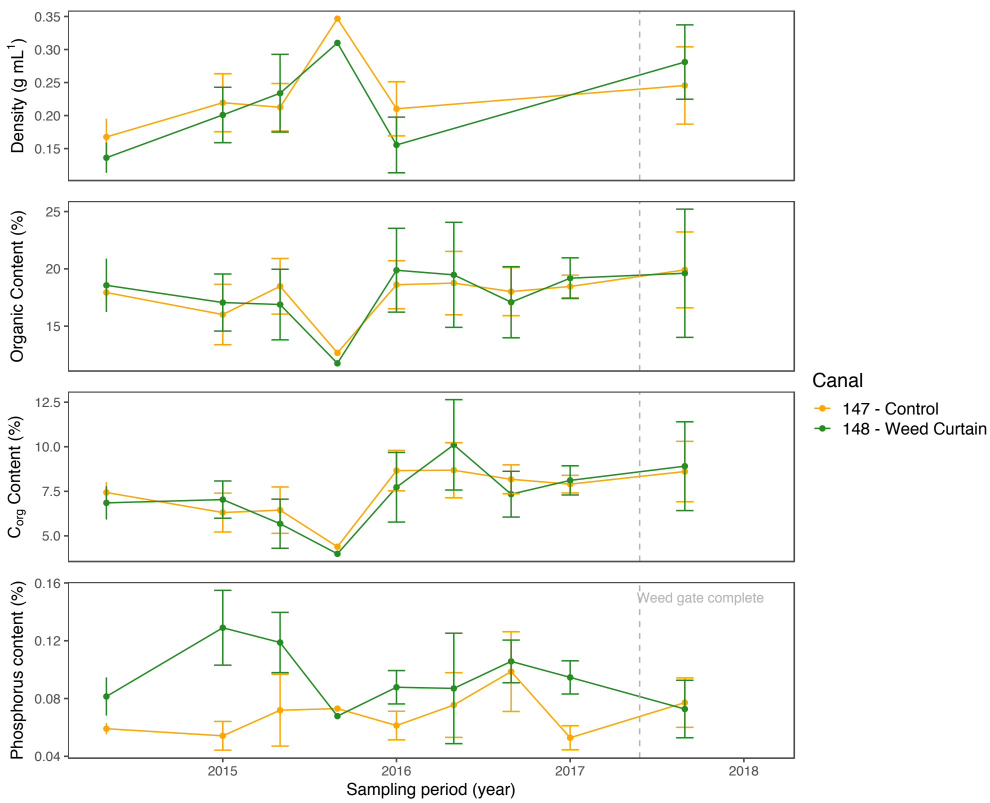

Figure 3.29: Changes in sediment characteristics over time in the Canal 148 compared to the adjacent reference canal. Data represent mean ± SE, and the vertical grey line indicts when the installation of air curtain was finished.

Sediment organic content is indistinguishable between canals 147 and 148, but varies greatly over time (Fig 3.29) with a max of 19.9 % and a minimum of 11.8 %, averaging 17.6 ± 0.5 %. C_{org} content ranged greatly during the period from 4.0 % to 10.1 % averaging 7.6 ± 0.4 %. 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, C_{org}, and N content track similarly between canals 147 and

148, though phosphorus does not share such similar fluctuations (Fig 3.29). There was no measurable effect of demonstrated technology on sediment characteristics, though this is not a surprise given the short period after the installation.

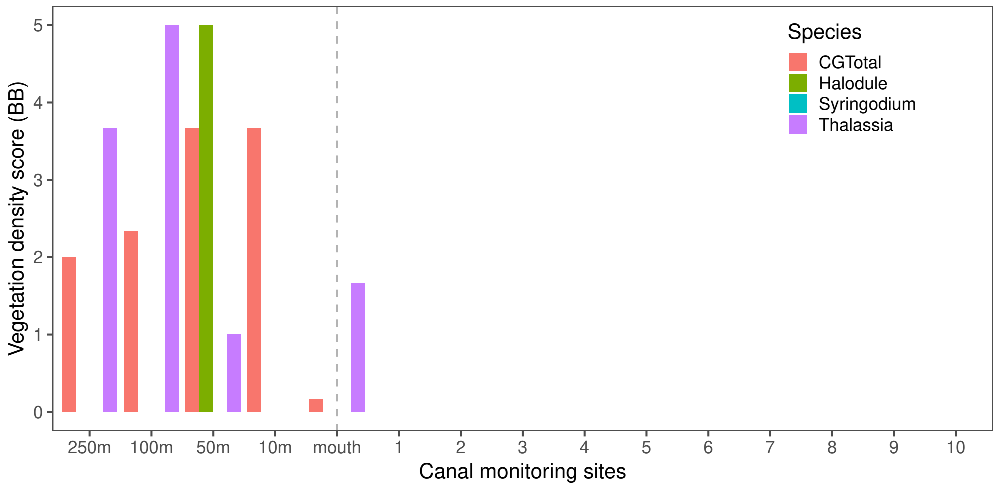

Figure 3.30: Average benthic vegetation from 250m outside Canal 148 to site 10 at the canal rear during the final year of monitoring (Spring 2016 through Winter 2017). Data represent average score of three measurements at each site for three consecutive sampling campaigns.

Seagrass detritus was a common occurrence in canals, but living benthic vegetation was completely absent from both canals throughout the monitoring. 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 3.30).

Fish observations were conducted in both canals, though only a total of seven individuals were recorded during the monitoring from 2014 to 2017, all found in the control, Canal 147. 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 (Fig 3.31). Seawalls of Canal 148 were barren of living biomass after fall 2015.

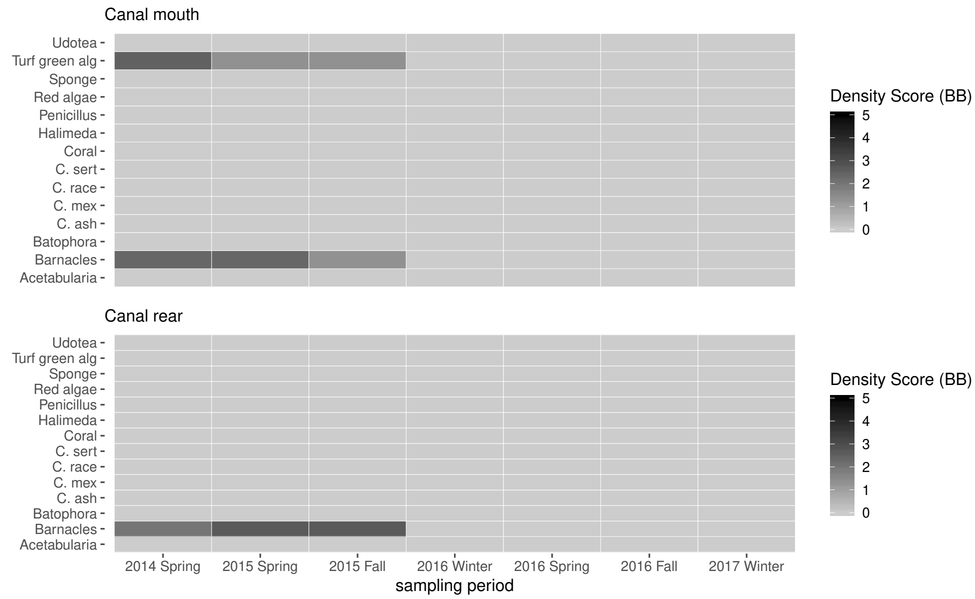

Figure 3.31: Changes in seawall-inhabiting organism in Canal 148 at the canal mouth and rear. Data represent mean values of three measurements. Organismal categories explained in Appendix 4.

3.2.4 Canal 266 - Organic Removal

In Fall 2015 and corrected in May 2016, Canal 266 was dredged of accumulated organic material and covered with ~5 cm of sand. Prior to the dredging, organic-rich sediment reached almost 6 ft in height at points near the canal mouth as well as the rear (Fig 3.32), making water depth less than three feet at times.

Organic removal decreased the average sediment depth of Canal 266 from 215 $\pm$ 5 cm to 38 $\pm$ 8 cm (Fig 3.33). Though sediment depth was considerably lower after dredging, it was not consistent through the length of the canal. The average sediment depth after dredging in the front half of the canal was greater compared the back portion of the canal (67.5 $\pm$ 4.79 cm and 30 $\pm$ 0 cm, respectively) during the winter 2016 sampling campaign. Differences in sediment depth caused by organic removal persisted through the remainder of monitoring.

Accompanying this change was a reduction in organic material (31.9 $\pm$ 1.0 to 1.0 $\pm$ 0.1 %) and C_{org} content (11.4 $\pm$ 1.2 to 0.4 $\pm$ 0.1 % dry wt) in surface sediments, as the organic-rich sediment was replaced with a layer of sand. Sediment N content similarly decreased (0.97 $\pm$ 0.23 % to below detection) though there was no clear reduction in sediment P content (Fig 3.34).

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, C_{org}) in Canal 263 stayed relatively constant during Canal 266's drastic

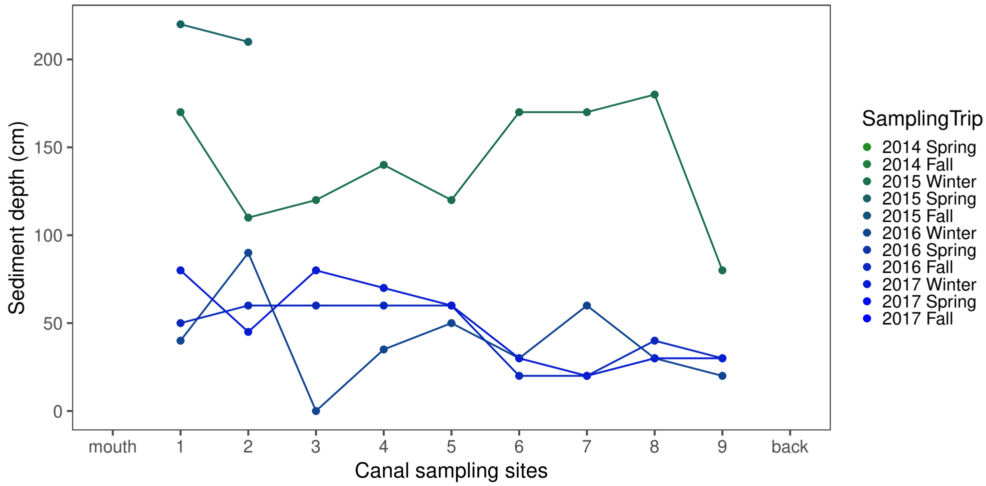

Figure 3.32: Changes in sediment depth at sites within Canal 266 over time. Organic removal occurred before the winter 2016 sampling campaign. Points represent the mean of three quadrats.

response to dredging. However, since the completion of dredging in May 2016, average organic and C_{org} content in Canal 266 has increased. By the final sampling in Fall 2017, there were no longer differences in surface sediment organic or C_{org} content between the dredged and control canals. Although the interior of canal was thoroughly dredged, the area directly outside the canal mouth continues to have over 1.5 m of accumulated seagrass and algae wrack (Fig 3.35).

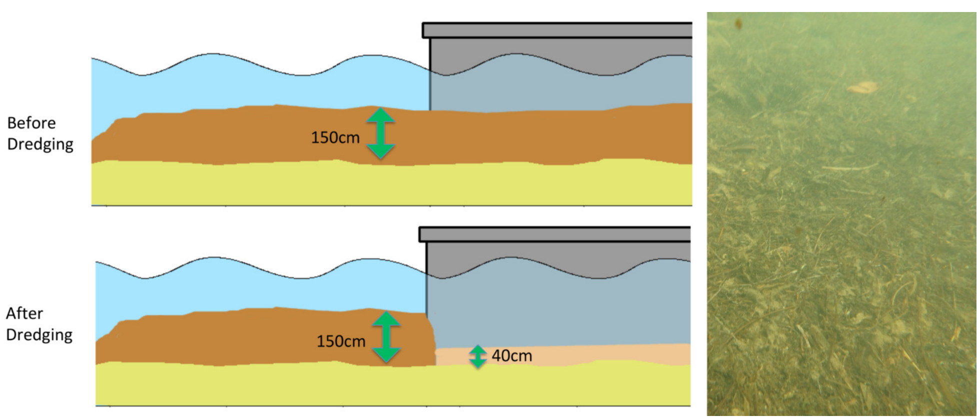

Figure 3.35: Left - Diagram depicting excess of wrack remaining outside Canal 266 after interior was dredged. Right - Photo of seagrass wrack accumulated outside canal mouth.

Depth measurements outside the monitored canals were not part of our sampling procedure, though may be important to understand post-dredging changes in Canal 266.

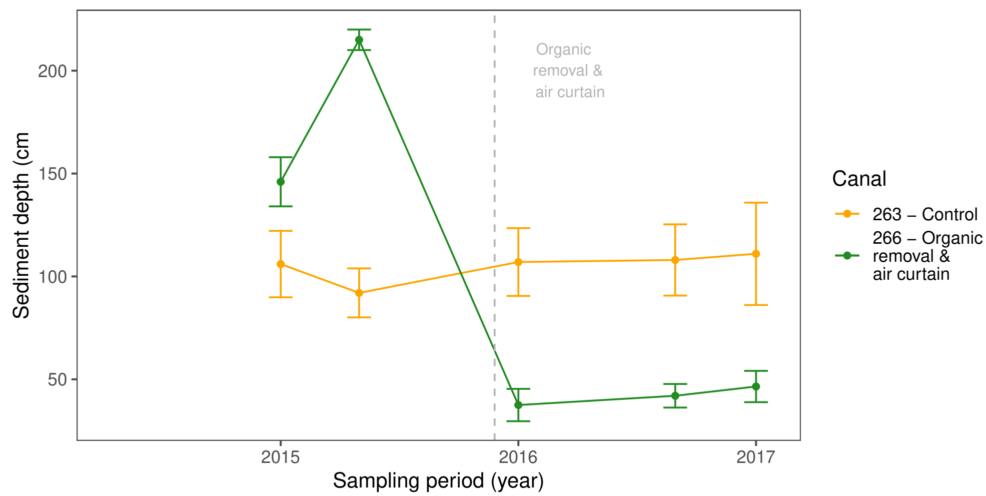

Figure 3.33: Sediment Depth in Canal 266 compared to its reference, Canal 263 over time. Data represent mean ± SE, and the vertical grey line indicts when the organic removal and air curtain installation was finished.

The difference in sediment depth between the inside and outside of the canal represent an ongoing threat, as exterior wrack could influx into the canal. During sampling, the installed air curtain seemed to keep much of that material at bay (personal observation).

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 3.36). 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.

No fish were observed within Canal 266 during our monitoring efforts and there were only four types of organisms observed on the sea wall at the canal mouth of 266. No organisms were observed inhabiting the seawall of the rear. There was no measurable effect of dredging on communities inhabiting the seawall.

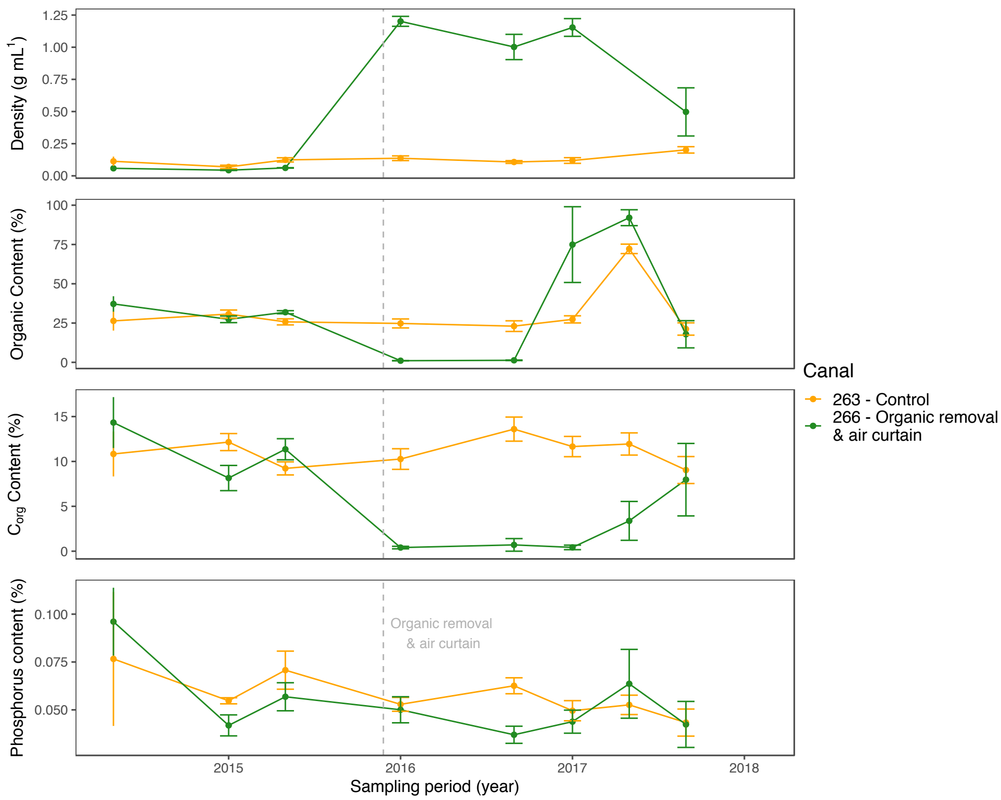

Figure 3.34: Changes in sediment characteristics over time in the Canal 266 compared to the adjacent reference, Canal 263. Data represent mean ± SE, and the vertical grey line indicts when the organic removal and air curtain installation was finished.

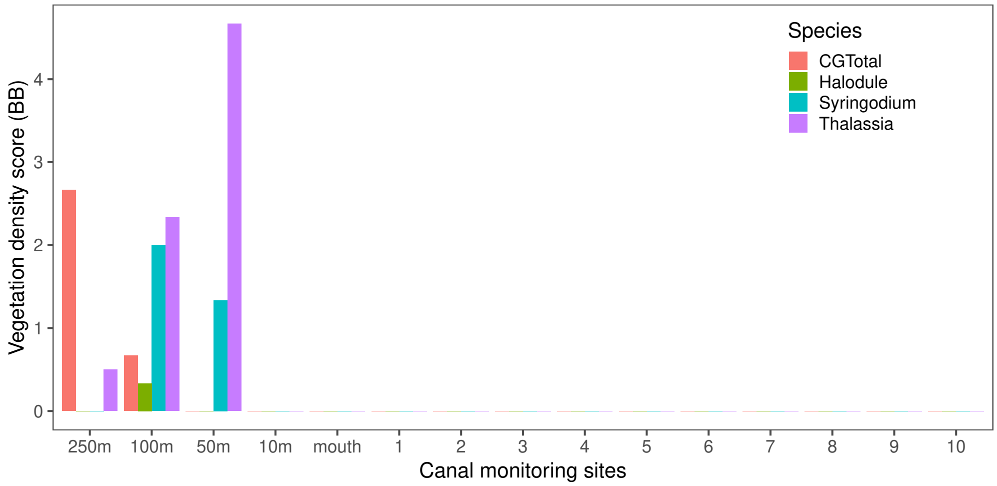

Figure 3.36: Average benthic vegetation from 250m outside Canal 266 to site 10 at the canal rear during the final year of monitoring (Spring 2016 through Winter 2017). Data represent average score of three measurements at each site for three consecutive sampling campaigns.

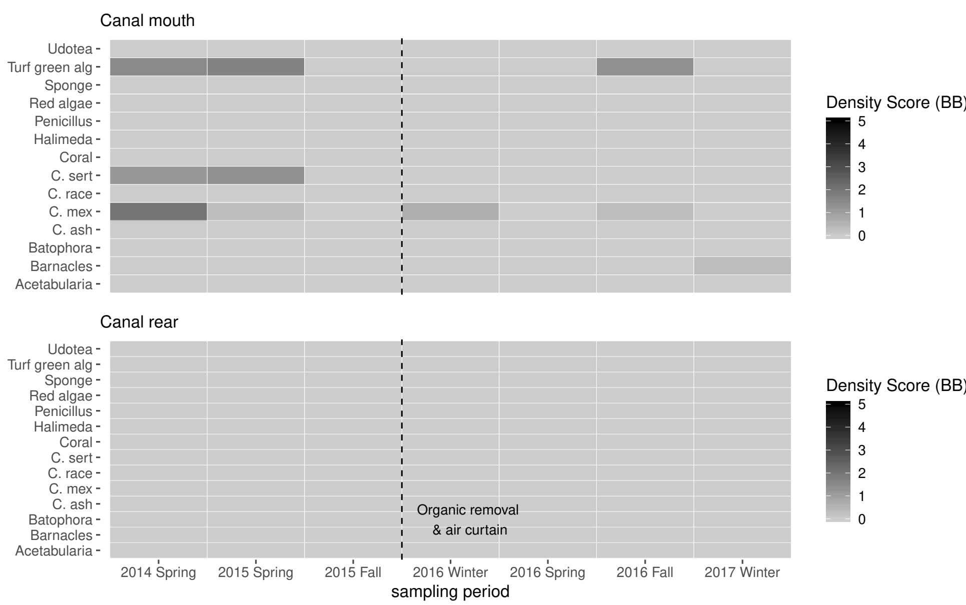

Figure 3.37: Changes in seawall-inhabiting organism in Canal 266 at the canal mouth and rear. Data represent mean values of three measurements. Organismal categories explained in Appendix 4.

3.2.5 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. Sediment depth in Canal 277 during baseline monitoring averaged 66 ± 12 cm with a maximum of 140 cm and minimum of 20 cm, compared to control canal 282 with a depth of 48 ± 15 cm. While average baseline values of sediment depth were indistinguishable between canals, depth measurements diverged over time until Canal 277 had a deeper sediment depth (Fig 3.38). The difference in depth between experimental and control canals occurred prior to the installation of culverts, thus was not a result of demonstration technology.

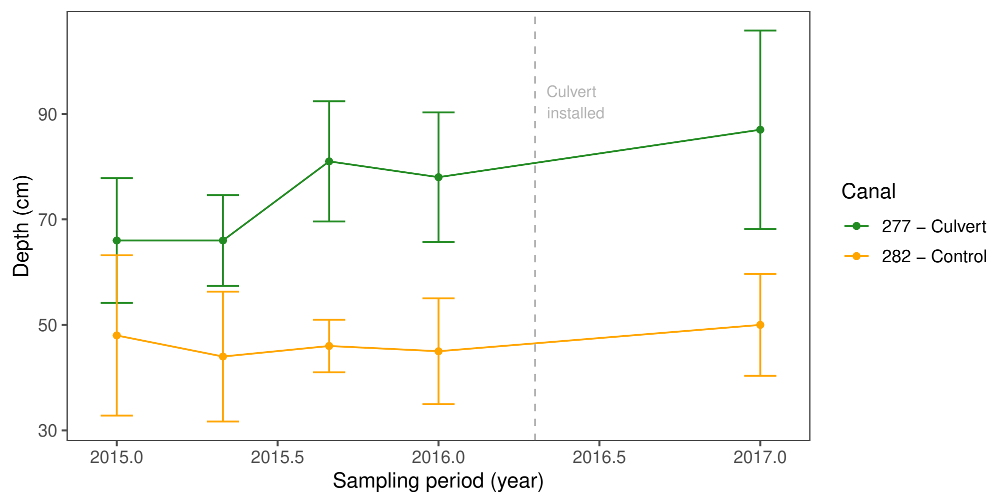

Figure 3.38: Sediment depth in Canal 277 compared to its reference, Canal 282 over time. Data represent mean ± SE, and the vertical grey line indicts when the culvert installation was finished.

Sediments in both canals were most commonly described as unconsolidated organic material, with Canal 277 having a baseline organic material content averaging 9.5 ± 4.5 %, comparable to that of the control, Canal 282, at 12.5 ± 5.1 %. Measurements of percent organic material remained similar between canals until 2017. Sediment density, C_{org}, N content, and P content were also indistinguishable between canals through the duration of monitoring (repeated measures ANOVA. $p > 0.05$), suggesting that the effects of the culvert installation on sediment characteristics were undetectable in the span of our monitoring.

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. 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 were also cal-

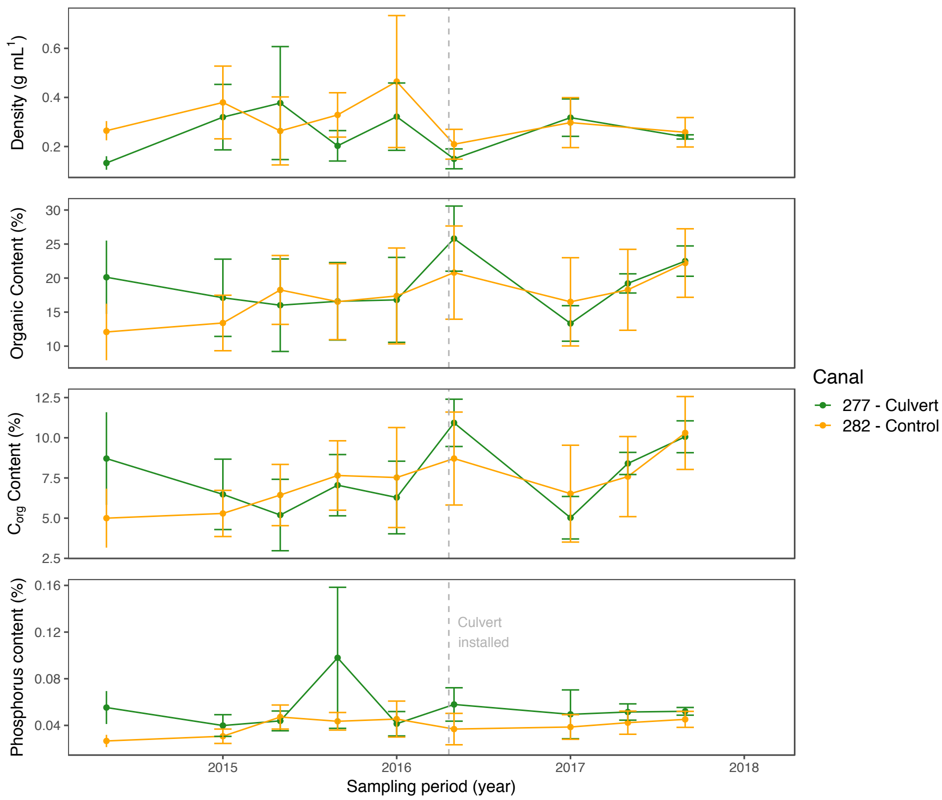

Figure 3.39: Changes in sediment characteristics over time in the Canal 277 compared to the adjacent reference, Canal 282. Data represent mean ± SE, and the vertical grey line indicts when the culvert installation was finished.

cifying macroalgae was found at sites 7 and 8 towards the rear of the canal, though only in 2014. There was no discernible effect of culvert installation on benthic plants (ANOVA. $p > 0.05$).

Similarly, there was no measurable effect of culvert installation on fish type or quantity. Only 6 individual fish were observed within Canal 277 during sampling; 4 in 2014, 1 in 2014 and 1 in 2016. All observed fish were Mangrove snapper. 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.

Seagrass tissue chemistry was analyzed from Canal 277 and its reference, though only once was *Thalassia* found outside Canal 282. Seagrass tissue chemistry indicated a decrease in δ^{15}N shortly after the installation of the culvert though this is inconclusive as there was only one post-culvert measurement and only one measurement from the reference (Fig 3.42).

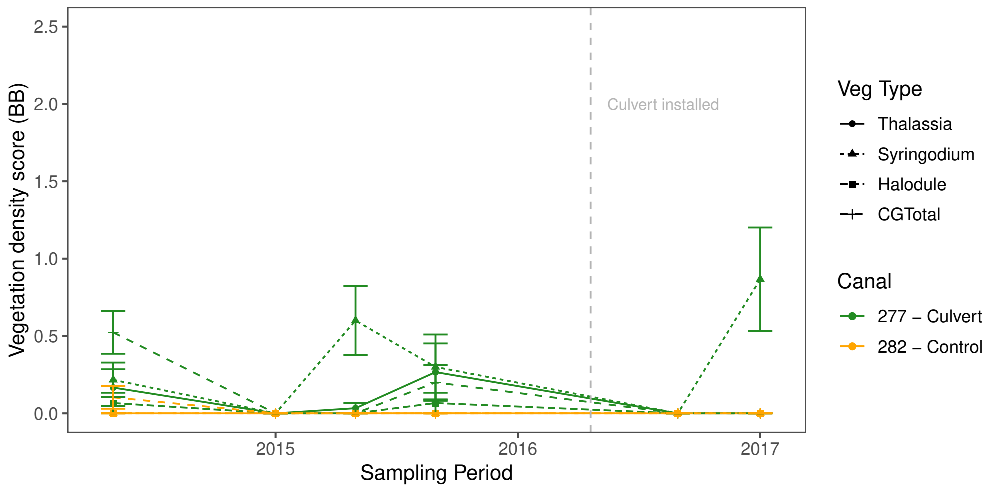

Figure 3.40: Changes in benthic vegetation density in Canal 277 compared to reference, Canal 282 over time. Data represent mean ± SE, and the vertical grey line indicts when the culvert installation was finished.

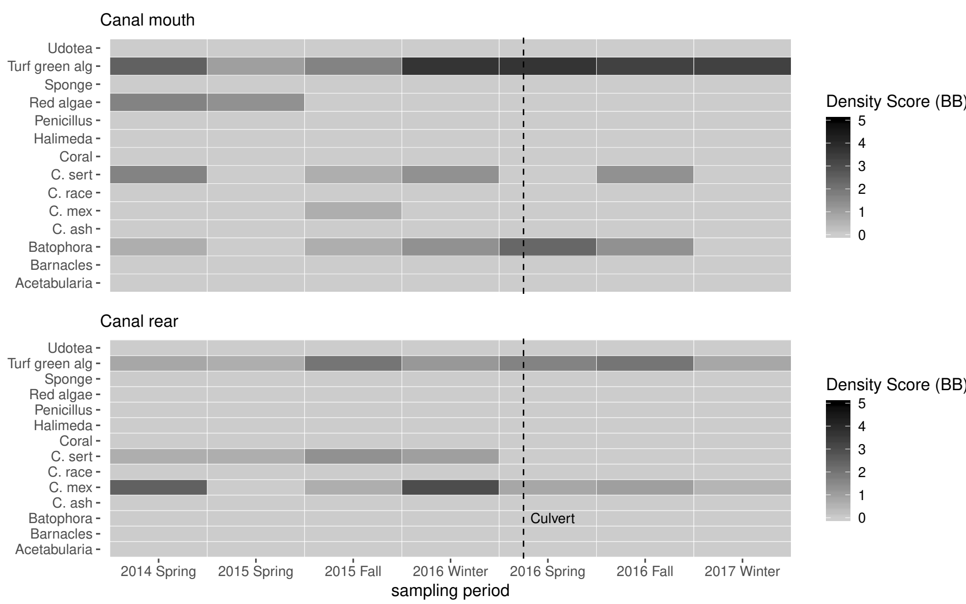

Figure 3.41: Changes in seawall-inhabiting organism in Canal 277 at the canal mouth and rear. Data represent mean values of three measurements, and the vertical grey line indicts when the culvert installation was finished. Organismal categories explained in Appendix 4.

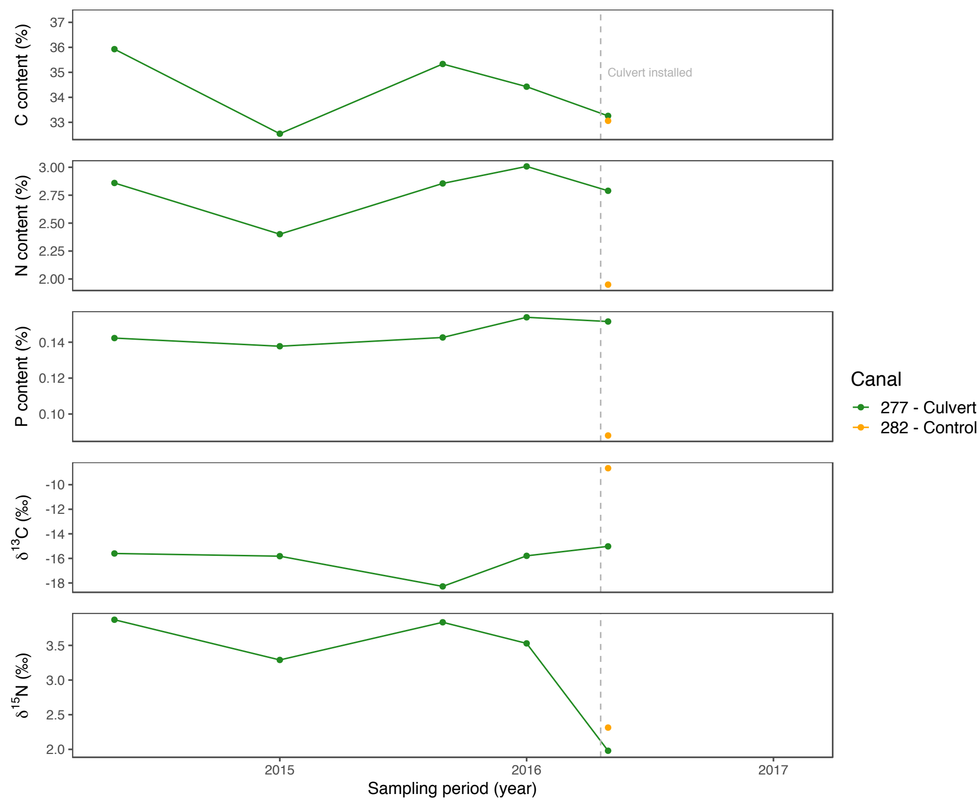

Figure 3.42: Thalassia leaf tissue nutrient content and stable isotope values outside canals 277 and 282. Leaf samples were collected at the point closest to the canal mouth with seagrass, 10m-50m outside canal. Plants were only found within the first 100m of Canal 282 once in Spring 2016.

3.2.6 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.

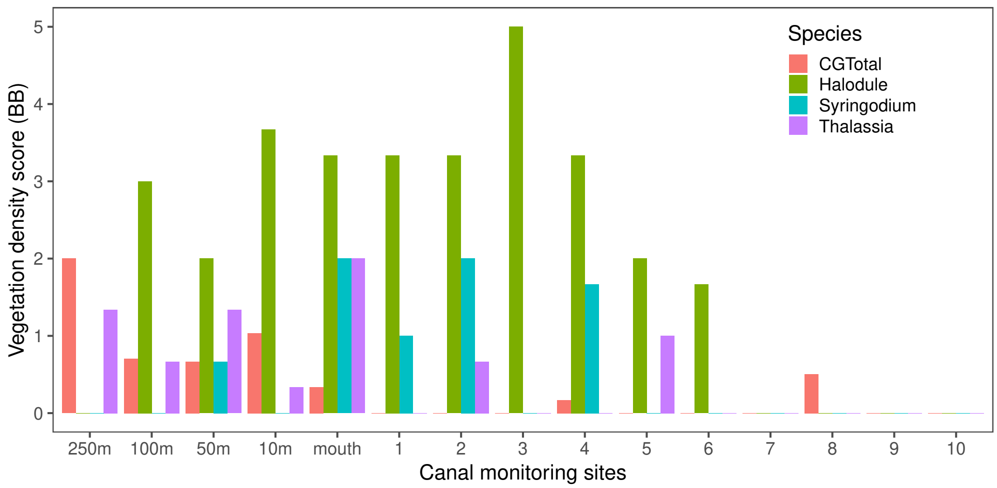

Figure 3.43: Average benthic vegetation from 250m outside Canal 278 to site 10 at the canal rear during the final year of monitoring (Spring 2016 through Winter 2017). Data represent average score of three measurements at each site for three consecutive sampling campaigns.

Fig 3.43 shows average BB scores in canal 278 during the last year of sampling. Over 50 % of sites within the canal had at least 5 % seagrass coverage (BB score ≥ 2). Seagrass was observed until site 6 (located approximately halfway into the canal) and many sites within the canal had a higher density of benthic vegetation than the adjacent open waters. The seawall of Canal 278's mouth hosted the highest diversity of organisms of all monitored canals, regularly inhabited by corals and sponges. The seawall in the rear had considerably fewer types of organisms, typically only 1 - 2 types per monitoring expedition.

Sediment depth in Canal 278 was highly variable between locations within the canal as well as over time, averaging 50 $\pm$ 2 cm over the course of the project with a min of 0 cm and max of 100 cm. Similarly organic material content is highly variable averaging 14.8 $\pm$ 1.1 % with a min of 2.8 and max of 31.8 %.

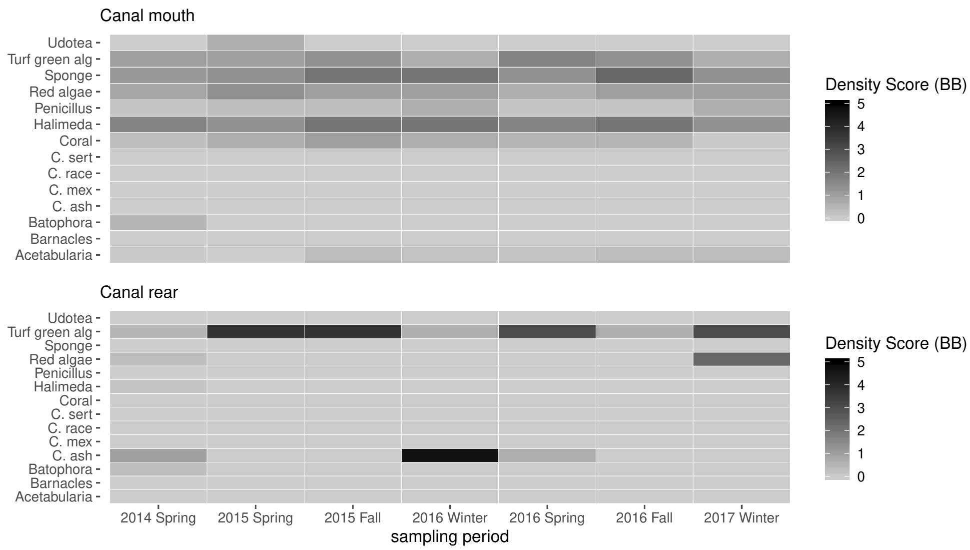

Figure 3.44: Changes in seawall-inhabiting organism in Canal 278 at the canal mouth and rear. Data represent mean values of three measurements. Organismal categories explained in Appendix 4.

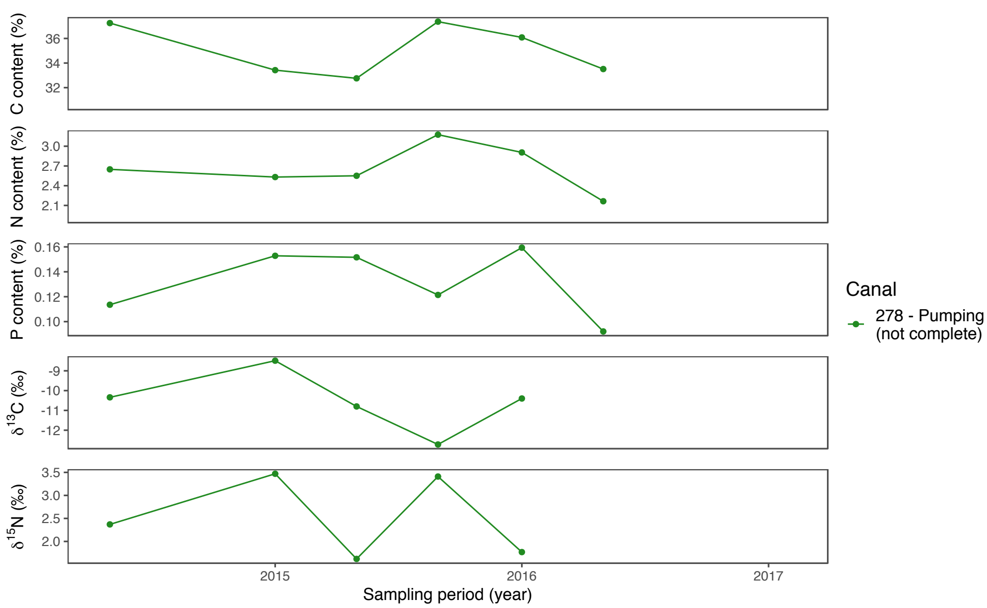

Figure 3.45: Changes in sediment characteristics over time in Canal 278. Data represent mean ± SE. The planned installation of a water pump to increase circulation was never completed.

3.2.7 Canal 287 - Air Curtain

A weed gate was installed in canal 287 in June 2016 to prevent further entry of seagrass wrack and sea-born organic material into the canal. Canal 288, located approximately 125 m to the south was used as a control. There were no observations of seagrass or macroalgae within either canal, nor was there benthic vegetation until the 50 m site outside the canal mouth (Fig 3.46).

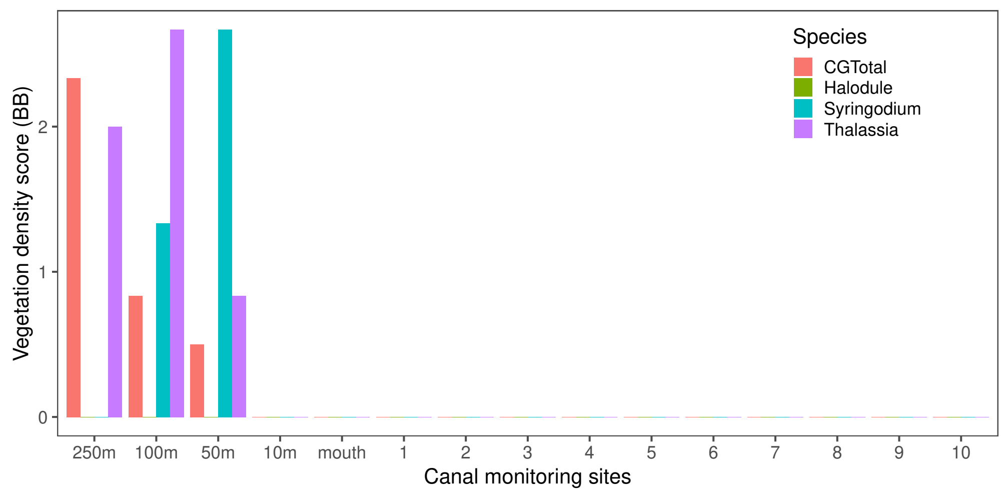

Figure 3.46: Average benthic vegetation from 250m outside Canal 287 to site 10 at the canal rear during the final year of monitoring (Spring 2016 through Winter 2017). Data represent average score of three measurements at each site for three consecutive sampling campaigns.

The poor water quality prevented entry of researchers on SCUBA, preventing a complete record of depth measurements; those data will be not be analyzed or included. Other sediment characteristics like sediment density, organic material, C_{org}, N, and P content remained similar between experimental and control controls and there was no change over time or in response to the installed air curtain (Fig 3.47). The average sediment density was extremely low, averaging 0.08 ± 0.02 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). Percent organic material averaged 31.7 ± 0.7 % with a high of 42.4 % and a minimum of 20.4 % dry wt.

Fish were observed only once, during Spring 2017. Three unidentifiable juvenile fish were swimming near the canal surface. No other living organisms were observed in the canals throughout the monitoring program.

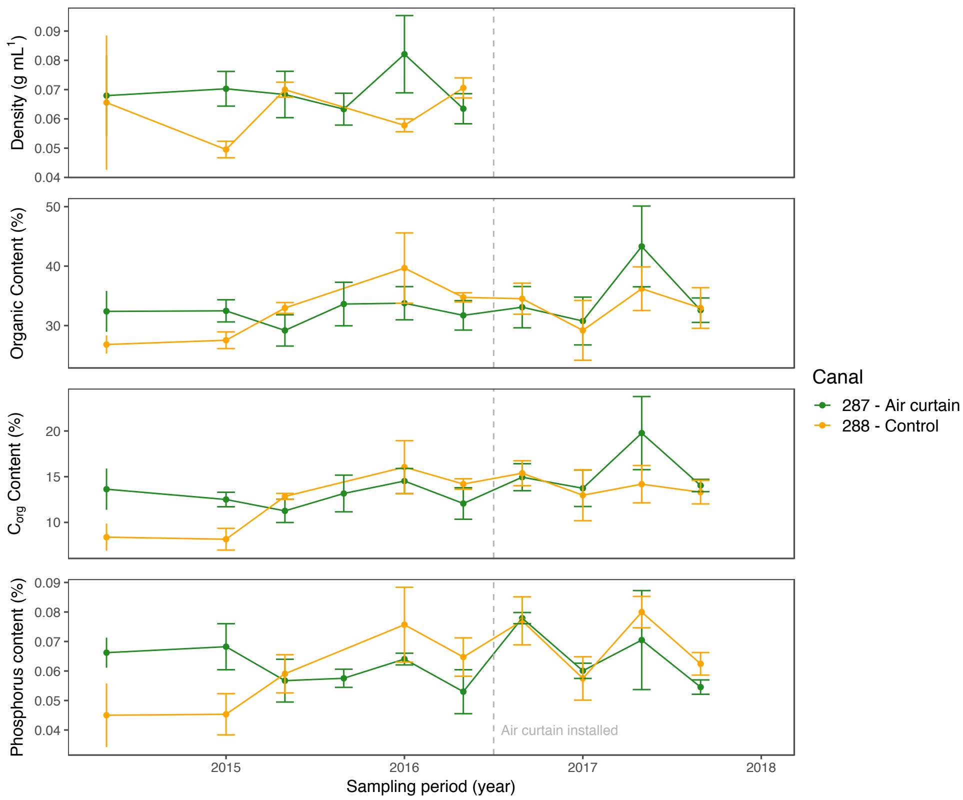

Figure 3.47: Changes in sediment characteristics over time in Canal 287 compared to the adjacent reference, Canal 288. Data represent mean ± SE, and the vertical grey line indicts when the air curtain installation was finished.

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. The sea wall of the canal rear lacked living organisms entirely (Fig 3.48).

Thalassia testudinum was only found within 100 m outside the canal mouths on three occasions, thus results for leaf tissue chemistry were not robust enough to make conclusions (Fig 3.49).

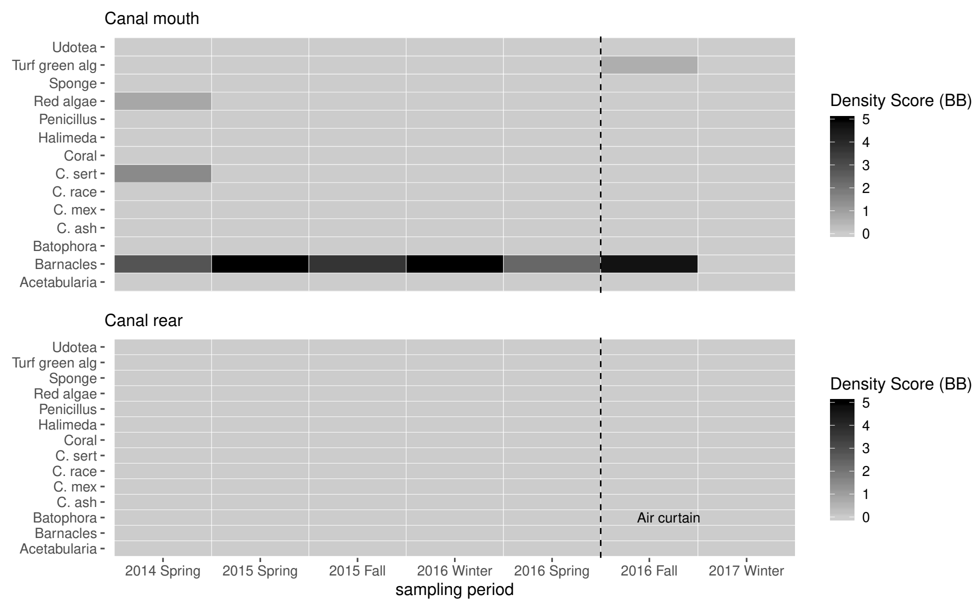

Figure 3.48: Changes in seawall-inhabiting organism in Canal 287 at the canal mouth and rear. Data represent mean values of three measurements. The vertical grey line indicts when installation of the air curtain finished. Organismal categories explained in Appendix 4.

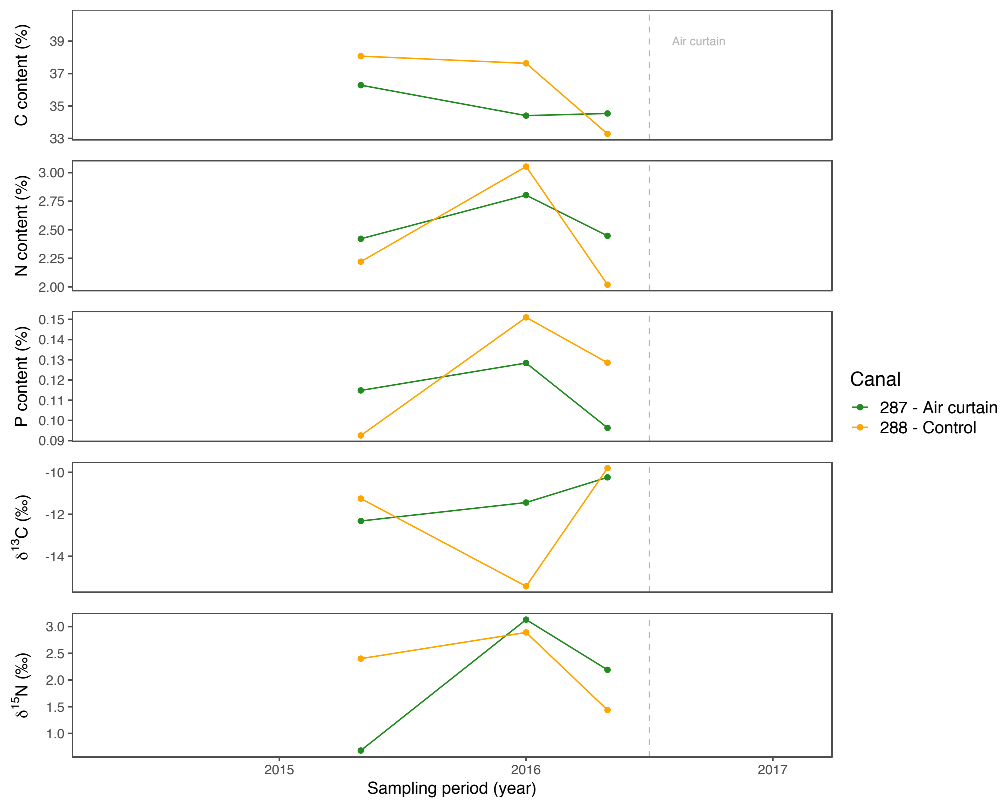

Figure 3.49: Thalassia leaf tissue nutrient content and stable isotope values outside canals 287 and 288. Leaf samples were collected at the point closest to the canal mouth with seagrass, 10m-50m outside canal. Plants were rarely found outside canal mouths, thus data is limited.

3.2.8 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. This layer of wrack extended from the canal to 50 m outside the mouth, where the wrack subsided and benthic vegetation was first observed (Fig 3.50).

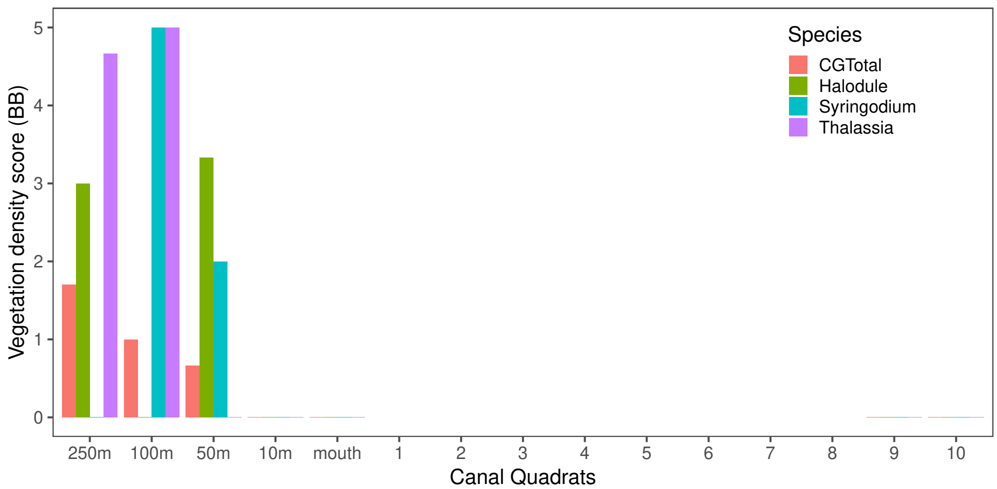

Figure 3.50: Average benthic vegetation from 250m outside Canal 290 to site 10 at the canal rear during the final year of monitoring (Spring 2016 through Winter 2017). Data represent average score of three measurements at each site for three consecutive sampling campaigns.

During 2015, prior to organic removal, sediment depth for Canal 290 averaged 168 $\pm$ 5 cm with a maximum depth of 270 cm (Fig 3.51). Average sediment depth decreased to 45 $\pm$ 2.24 cm after dredging. The control canal had a greater sediment depth on average (248 $\pm$ 7 during 2015), though showed no significant decrease during the dredging period. Unfortunately poor water quality prevented depth measurements after Spring 2016 though sediment composition continued to be measured throughout the monitoring program.

Average sediment density in Canal 290 increased dramatically from 0.1 $\pm$ 0.0 g cm^{-3} prior to organic removal to 0.7 $\pm$ 0.3 g cm^{-3} shortly after. During the same period, percent organic material decreased from 32.23 $\pm$ 1.02 to 12.24 $\pm$ 6.30 and C_{org}, N, and P content all showed significant decreases in concentration (Fig 3.52). Throughout the next several sampling campaigns, sediment characteristics in Canal 290 remained significantly different from the control canal as well as pre-dredging conditions. However, there was a return to baseline values during 2017, leaving average post-dredging values for sed-

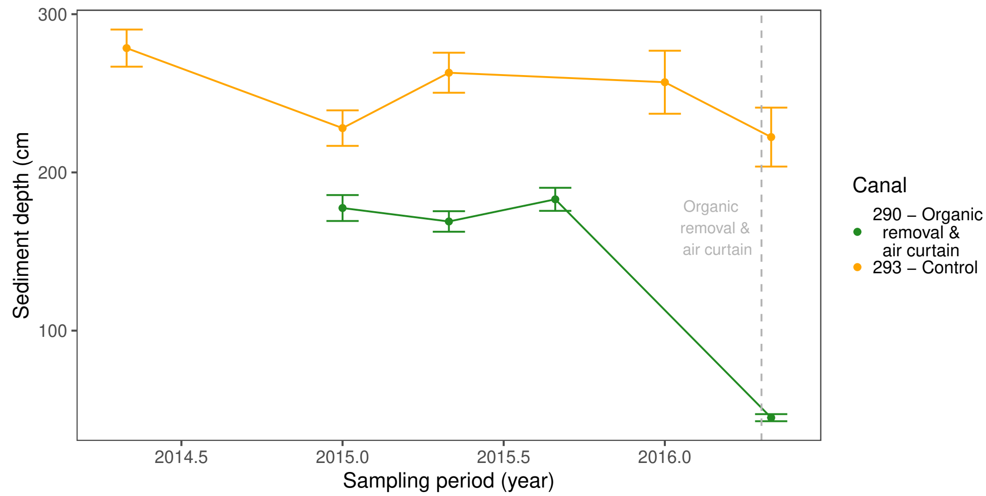

Figure 3.51: Changes in sediment depth over time in Canal 290 compared to its reference, Canal 293. Data represent mean ± SE, and the vertical grey line indicts when the organic removal and air curtain installation was finished.

iment density, organic material, C_{org}, and Phosphorus content indistinguishable from pre-dredging conditions. The demonstrated technology has a clear and quick effect on sediment conditions, though we observed a full reversal of these conditions less than two years later.

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 (Fig 3.53). Other organisms were noted but only during 2014. After dredging, there were no identifiable organisms inhabiting the mouth or rear seawalls.

No fish were observed in canal 290 before or after the installation of demonstrated technologies. A total of 24 fish were observed in the control canal from 2014 - 2017, including 15 tarpon (*Megalops atlanticus*) and 9 mullet (*Mugil cephalus*). While fish observed may be indicative of inherent differences between canals, any conclusions based on so few data would be premature.

Similarly, *Thalassia* seagrasses close enough the canal mouth to be sampled for nutrients were too scarce to draw conclusions. There were only four tissue samples analyzed for each Canal 290 and 293, all within the range of C:N:P ratios, δ^{13}C and δ^{15}N values measured throughout South Florida (Fig 3.54).

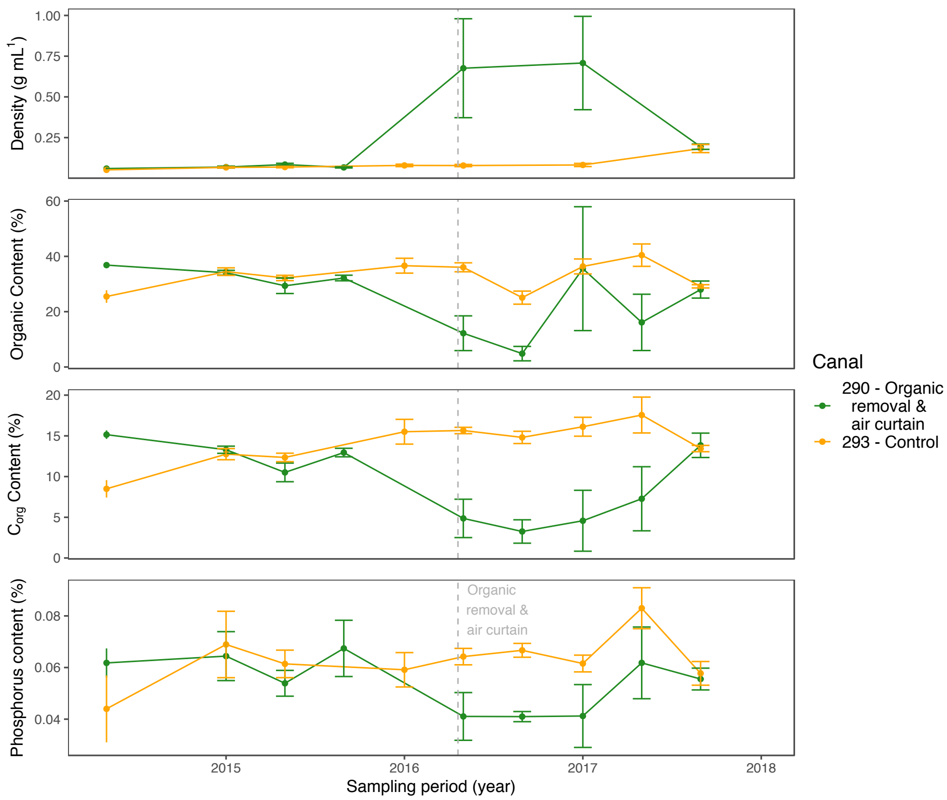

Figure 3.52: Changes in sediment characteristics over time in Canal 290 compared to its reference, Canal 293. Data represent mean ± SE, and the vertical grey line indicts when the organic removal and air curtain installation was finished.

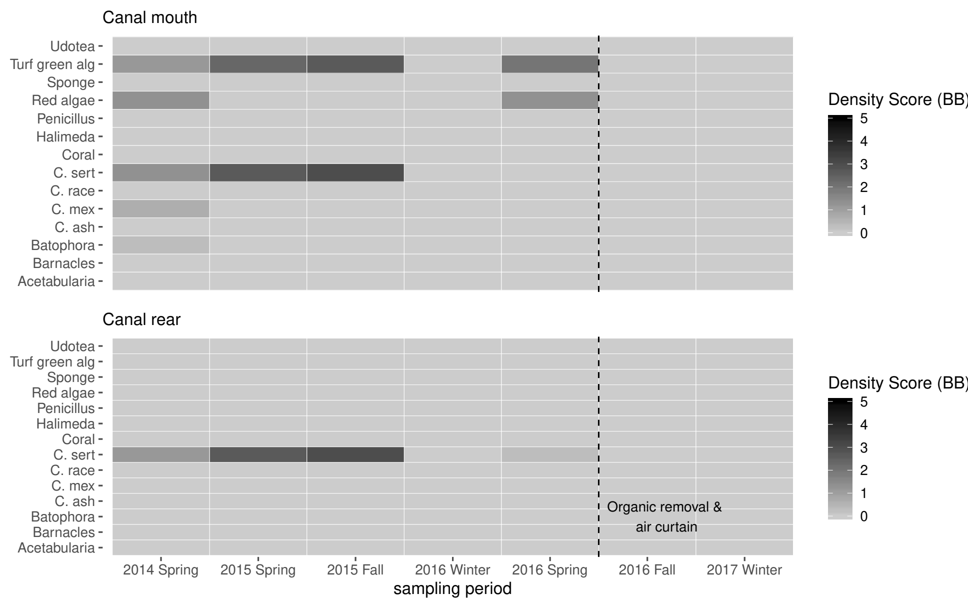

Figure 3.53: Changes in seawall-inhabiting organism in Canal 290 at the canal mouth and rear. Data represent mean values of three measurements. Organismal categories explained in Appendix 4.

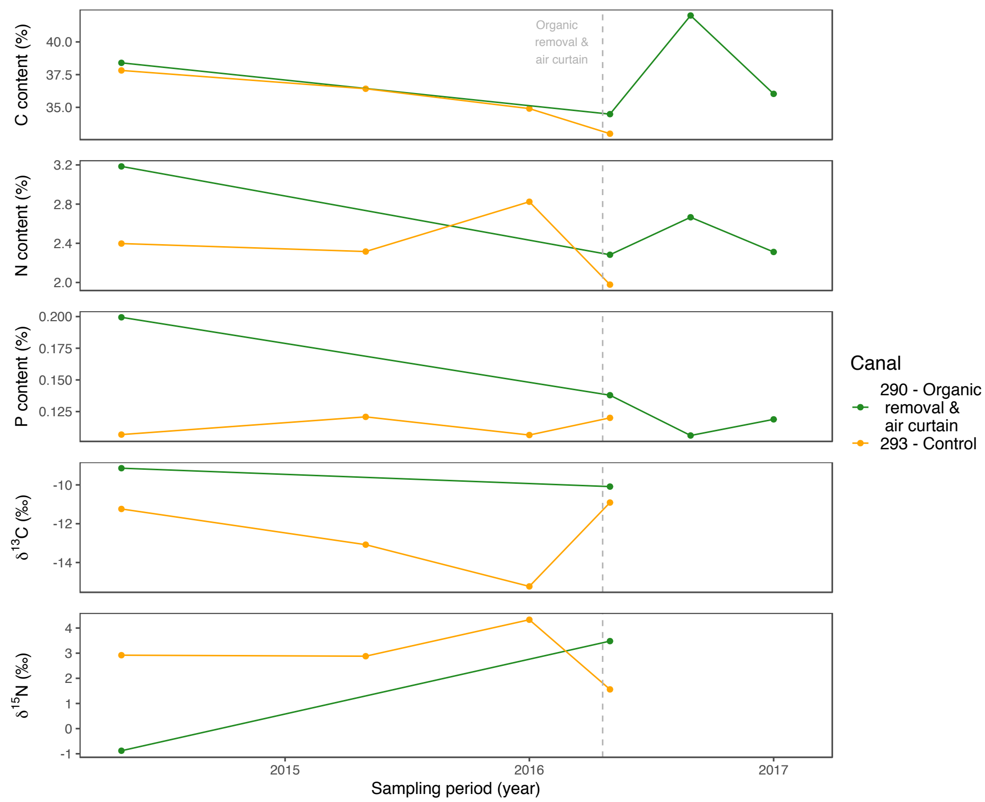

Figure 3.54: Thalassia leaf tissue nutrient content and stable isotope values outside canals 290 and 293. Leaf samples were collected at the point closest to the canal mouth with seagrass, within 100m of canal mouth. Plants were rarely found outside in this area, thus data is limited.

3.2.9 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 250m outside. Canal 459 was scheduled to receive a culvert to connect the back 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.

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 3.55; Fig 3.56).

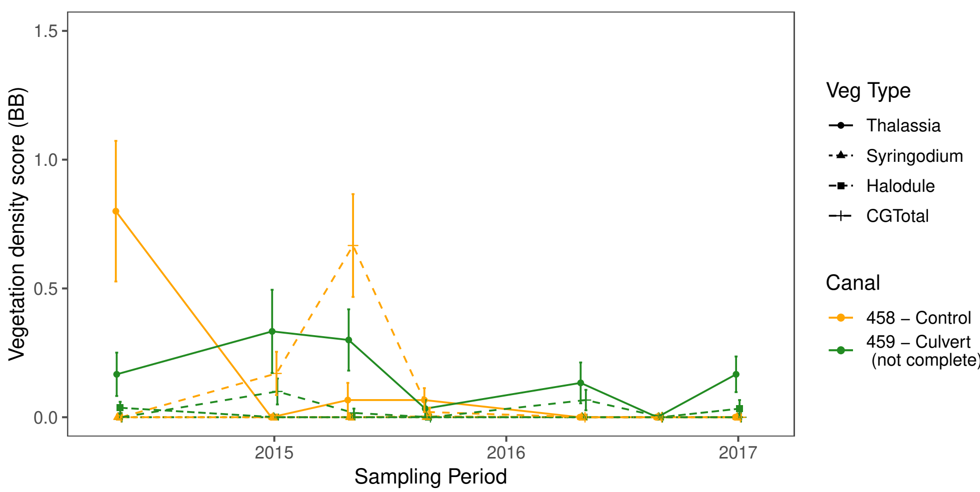

Figure 3.55: Changes in benthic vegetation density in Canal 459 compared to reference, Canal 458 over time. Data represent mean ± SE.

Unlike other canals within this monitoring program, Canal 459 did not have seawalls to monitor for sessile organisms. The canal mouth was flanked by mangroves rather than manmade seawalls. Towards the rear of the canal, sediments and organic rack accumulated to the water surface covering the seawalls, preventing an assessment of any resident taxa.

Fish were encountered in Canal 459 during seven of 10 sampling campaigns Fig 3.57), with juvenile fish and Mangrove snappers most commonly encountered.

Sediment depth was indistinguishable between canals 458 and 459 and remained consistent from 2015 to 2017 (Fig 3.58). Depth averaged 69 ± 0 cm ranging from 0 to 220 cm. The rear of canal 459 has the thickest sediment layer, averaging over 80cm for site 7, 8, and 9 (Fig 3.59).

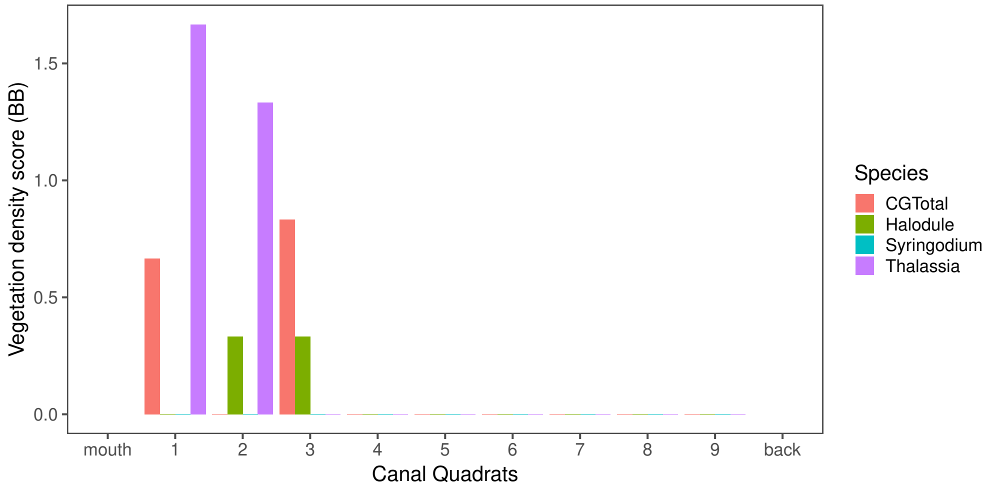

Figure 3.56: Average benthic vegetation from 250m outside Canal 459 to site 10 at the canal rear during the final year of monitoring (Spring 2016 through Winter 2017). Data represent average score of three measurements at each site for three consecutive sampling campaigns.

Sediment composition (density, organic material, C_{org}, N and P) is indistinguishable between canals and shows no change over time (Fig 3.60).

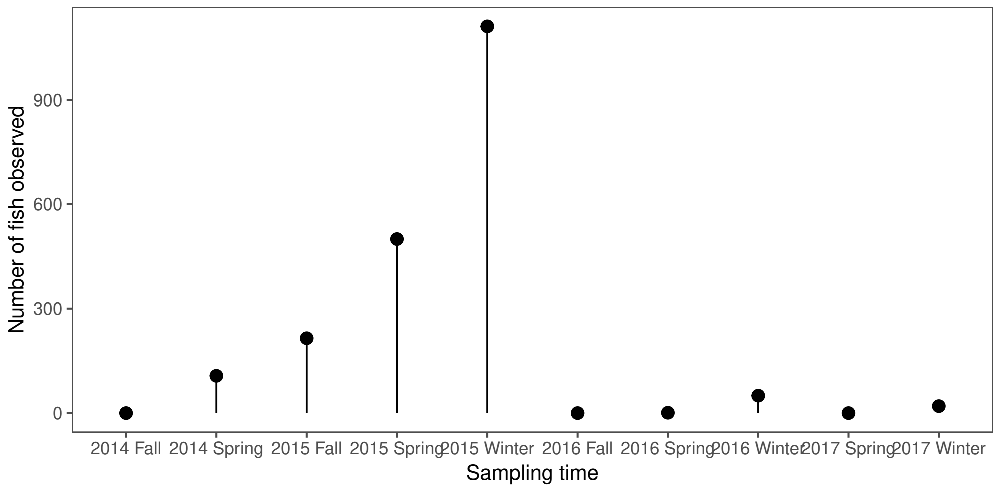

Figure 3.57: Fish counts in Canal 459 over time

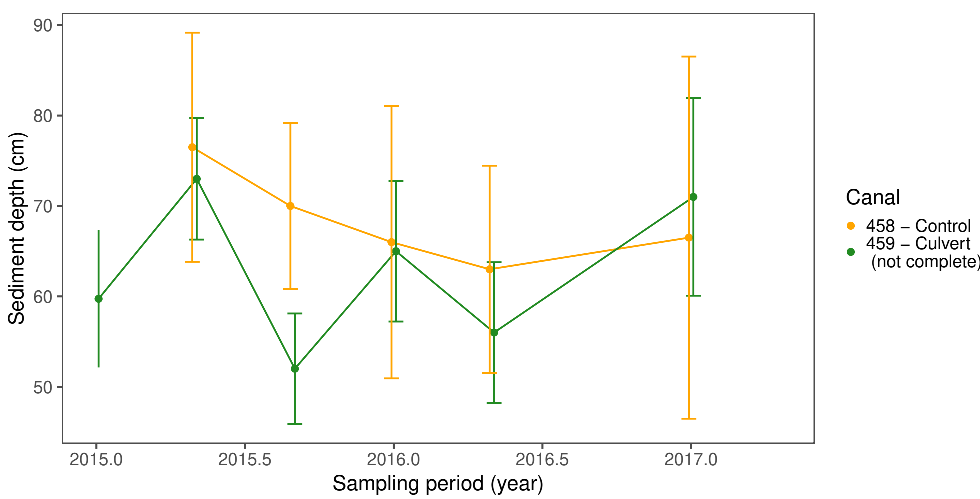

Figure 3.58: Changes in sediment depth in Canal 459 compared to reference, Canal 458 over time. Data represent mean ± SE, and the planned culvert for Canal 459 was never completed.

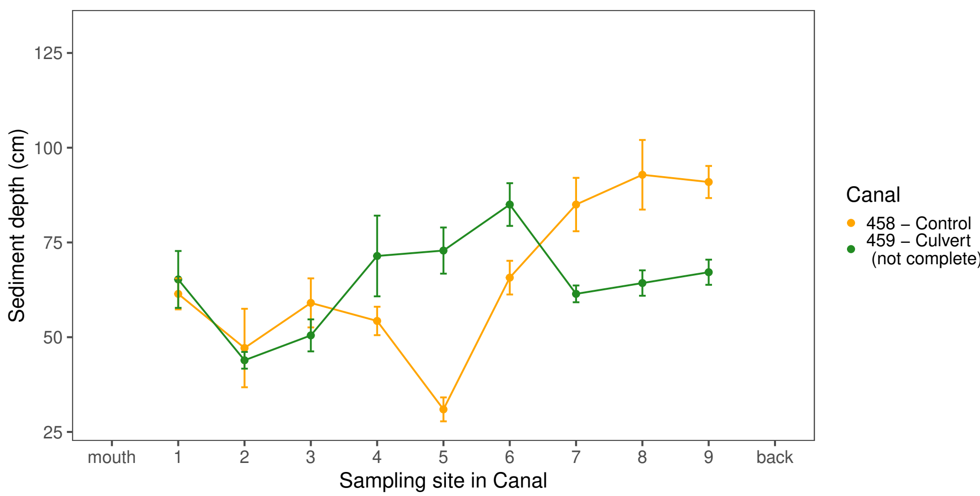

Figure 3.59: Variation in sediment depth from canal mouth to rear in Canal 459 compared to reference, Canal 458. Data represent mean ± SE, of measurements at each site from 2014-2017.

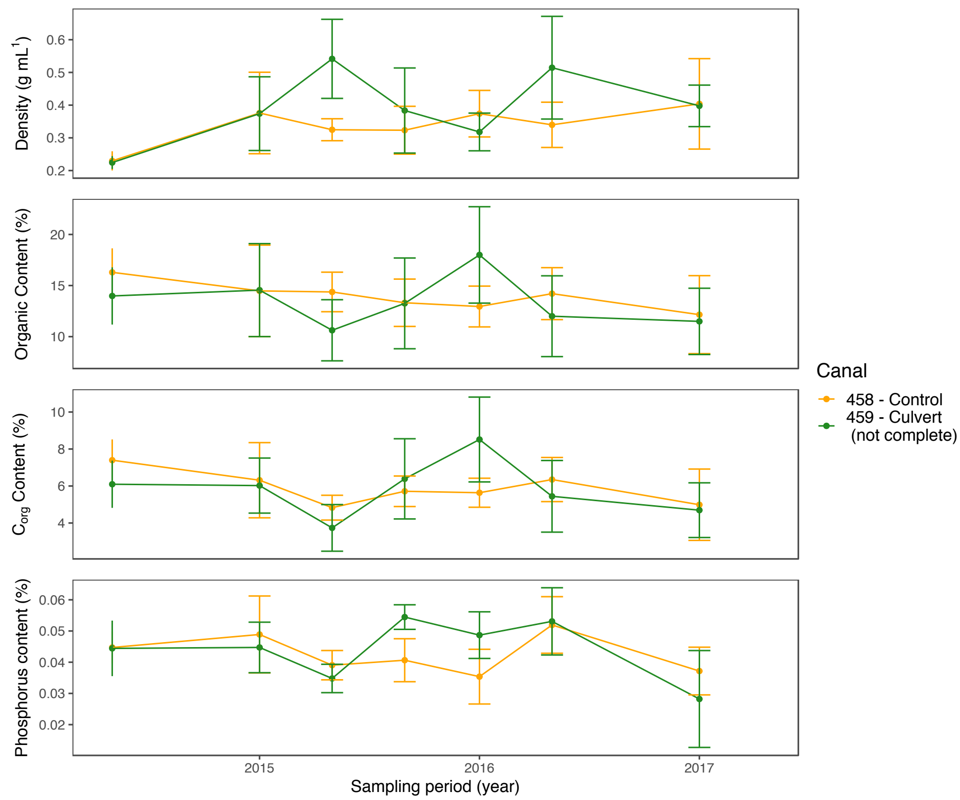

Figure 3.60: Changes in sediment characteristics over time in Canal 459 compared to its reference, Canal 458. Data represent mean ± SE. The culvert planned for 459 was never completed.

3.2.10 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.

Benthic vegetation was completely absent in the control, Canal 476, though there were two observations in canal 472. In winter 2015, calcifying macroalgae was observed in low abundances towards the mouth of the canal. Then in 2016, after the completion of the culvert, calcifying macroalgae was again observed in low abundances at the mouth as well as the seagrass, *Halodule wrightii* in multiple sites, sparsely present as individual shoots, growing at site 10 towards to back of the canal (Fig 3.61).

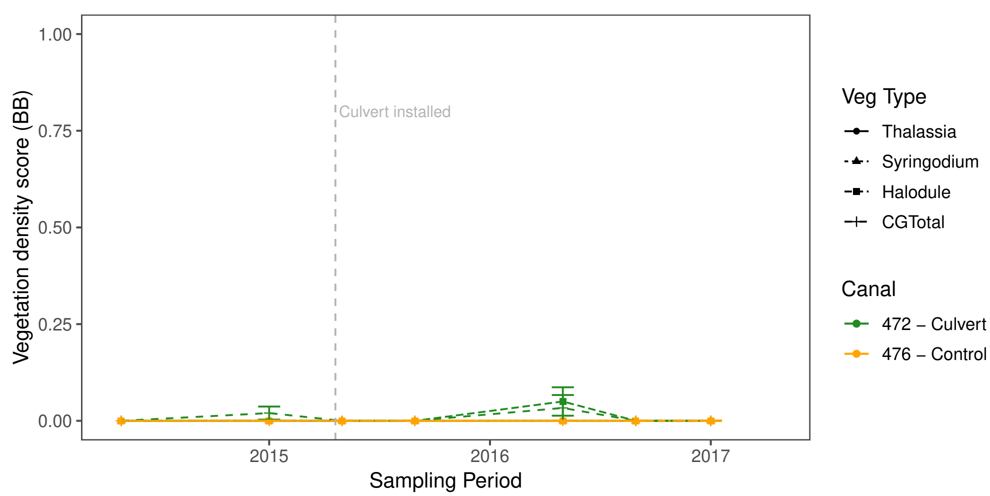

Figure 3.61: Changes in benthic vegetation density in Canal 472 compared to reference, Canal 476 over time. Data represent mean ± SE, and vertical grey line indicates when the installation of the culvert finished.

The seawalls of Canal 472 contained primarily turf green algae as well as *Caulerpa Mexicana*, species of *Halimeda* and *Batophora*, and on two occasions, sponges (Fig 3.62). There were higher abundances and densities of organism after the culvert was installed, however there was only one set of pre-culvert data for comparison. *Batophora* at the canal mouth and turf green algae in the rear increased in density at points following the culvert's installation. Sponges were observed on the rear seawall in 2016, a first for this canal and uncommon for canals within this monitoring program. For comparison, only turf green algae was present in the control canal, and it was only present in the rear when the floating mat of wrack was absent, allowing light to reach the water and seawalls.

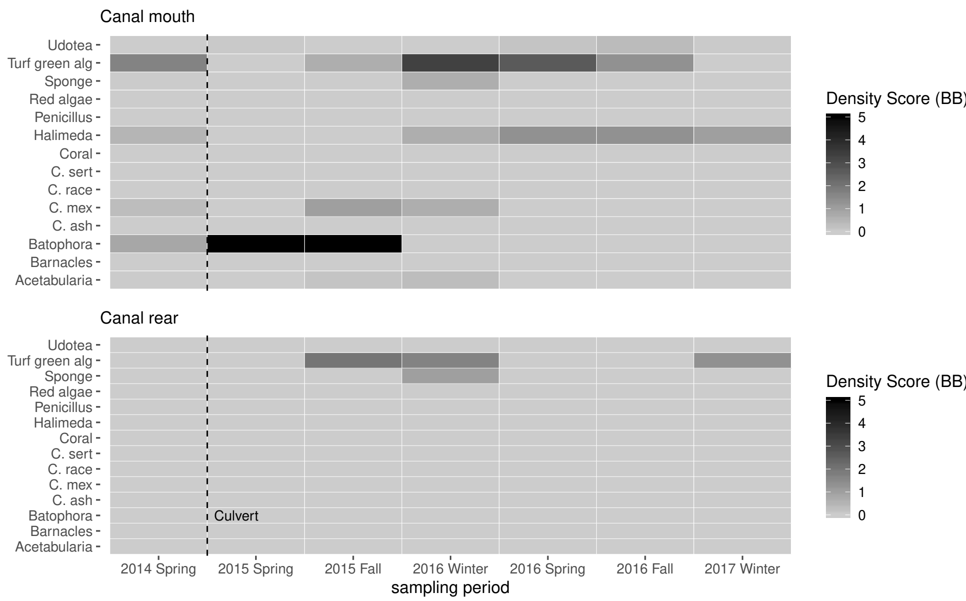

Figure 3.62: Changes in seawall-inhabiting organism in Canal 476 at the canal mouth and rear. Data represent mean values of three measurements. Organismal categories explained in Appendix 4.

Fish were observed sporadically throughout the monitoring of this canal, with a clear increase after the installation of the culvert (Fig 3.63). After installation, Mangrove snapper (size 10 - 20 cm) began to be observed in the rear of the canal, where no fish had been previously encountered. 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. Either case signifies an improvement in water quality. Fish counts decreased in late 2015 and 2016 though increased in 2017 after the culvert was reopened. Juvenile fish and Mangrove snapper were the most abundant though needle and parrot fish (family: Scaridae) were also observed.

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 sed-

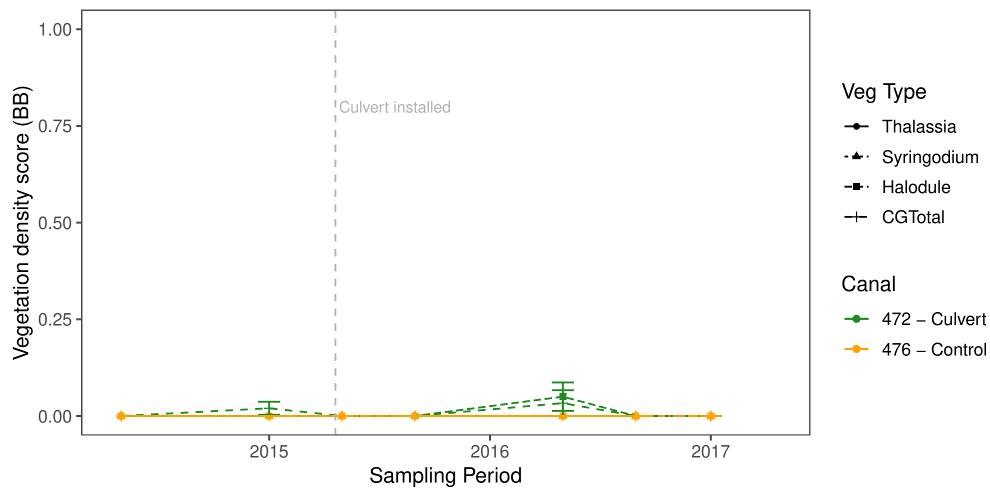

Figure 3.63: Total number of fish observed in Canal 476 over time.

iments. Sediment depth in the control canal remained consistent around 200 cm through our monitoring (Fig 3.64). Canal 472 showed an average depth of over 200 cm during initial sampling in spring 2014 but maintained average depths under 180 cm during all subsequent campaigns (Fig 3.64).

From Spring 2014 to Winter 2015 sediment depth decreased from an average of 246 $\pm$ 17 cm to 97 $\pm$ 14 cm, and has been increasing overall from winter 2015 to winter 2017 (Fig 3.64). The drastic decrease in sediment depth occurred before the final completion of the culvert (April 2015) with the most extreme decreases in sediment depth occurring within the latter half of the canal (Fig 3.65).

Sediment characteristics varied over time for both the control and culvert-recipient. The control canal showed an increase in organic content from 2014 to 2015 that remained increased for the remained of the monitoring program (Fig 3.66). The control canal also exhibited a small average increase in sediment C_{org} content from 2014 to 2017. Neither of these patterns were documented in Canal 472. There was an increase in sediment density shortly before and after the official opening of the culvert in April 2015, increasing from an average of 0.20 $\pm$ 0.03 g cm^{-3} in 2014 to 0.30 $\pm$ 0.06 g cm^{-3} in 2015 after culvert opening (Fig 3.66). Again, the most extreme changes in sediment density occurred at the canal rear (sites 9 and 10), where the minimum measurement during monitoring was 0.08 g cm^{-3} and a maximum was 0.46 g cm^{-3}. Sediment C_{org} and P content also decreased from 2014 to after the culvert opened 2015. Change in sediment composition was short-lived; values at during the final sampling in 2017 were indistinguishable from those in 2014, with the exception of P content.

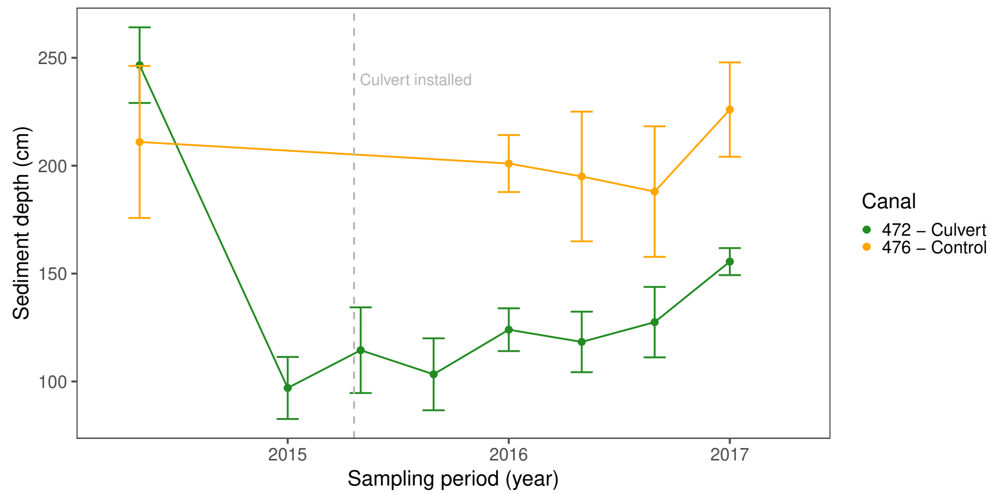

Figure 3.64: Changes in sediment depth in Canal 472 compared to reference, Canal 476 over time. Data represent mean ± SE, and the vertical grey line indicates when the culvert installation was finished.

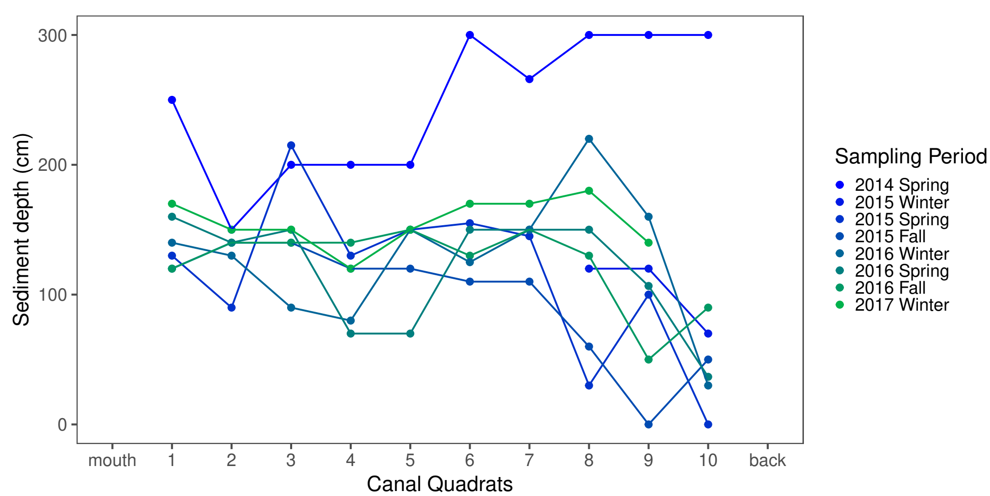

Figure 3.65: Changes in sediment depth at sites within Canal 472 over time. Culvert installation was finished prior to the Spring 2015 sampling campaign.

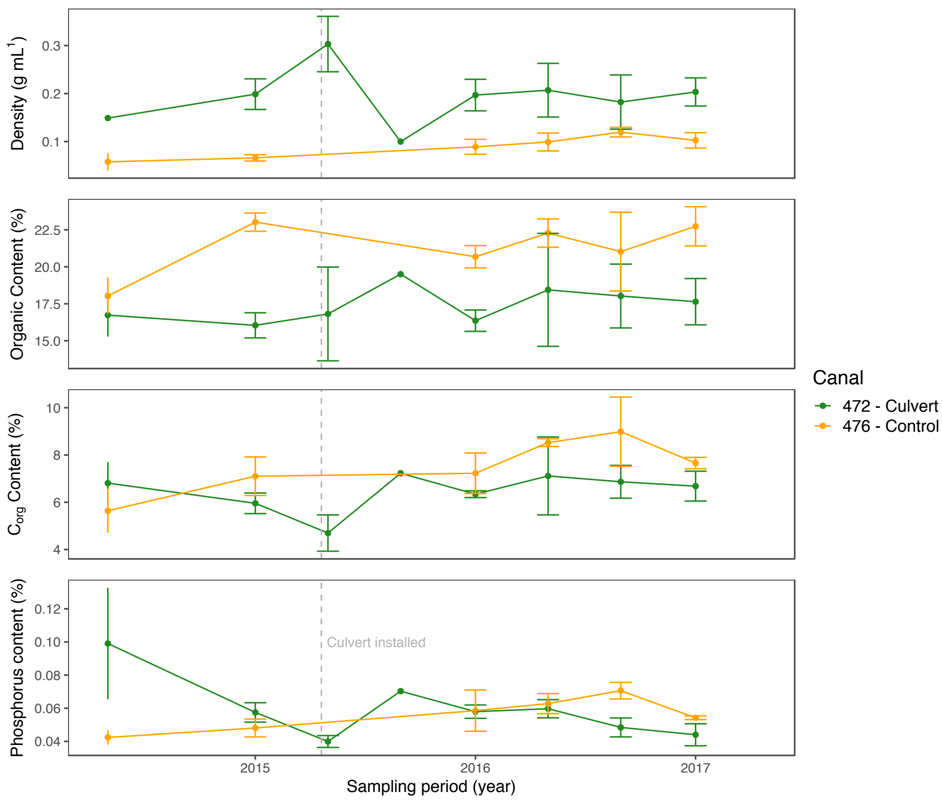

Figure 3.66: Changes in sediment characteristics in Canal 472 compared to reference, Canal 476 over time. Data represent mean ± SE, and vertical grey line indicates when the installation of the culvert finished.

3.3 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). There are clear differences in sediments characteristics between Islamorada canals; Canal 145 (facing the Atlantic Ocean) has sediments with the highest organic, C_{org}, and phosphorus content, while Canal 150 consistently has the lowest values (Fig 3.67). Sediment characteristics have not changed over time in any canal between 2016 and 2017.

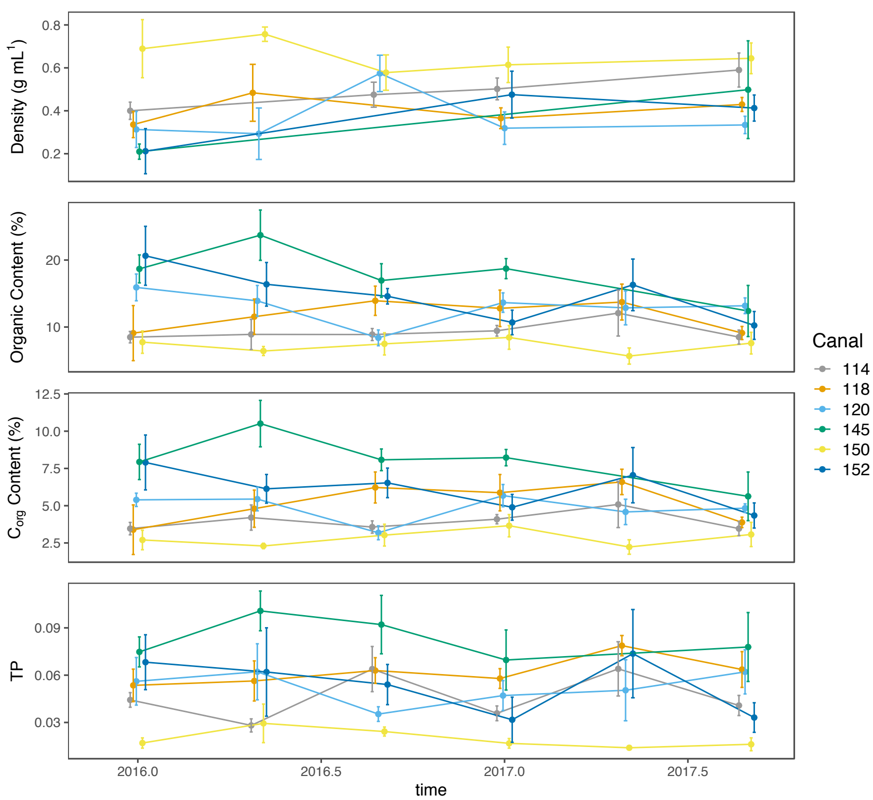

Figure 3.67: Changes in sediment characteristics over time in canals part of the Islamorada monitoring program. Data represent mean ± SE. Data points are slightly offset for time for better interpretation.

Table 3.2: Sediment characteristics compared between Demonstration project canals, Islamorada canals, and regional averagers. Data represent Mean ± SE (min - max). Regional values for the Florida Keys published in Fourqurean et al. 2012 and Howard 2018

	Unit	Demonstration project canals	Islamorada canals	Regional values
Sediment density	g cm^{-3}	0.18 ± 0.01 (0.03 - 1.04)	0.44 ± 0.03 (0.04 - 1.01)	0.7 ± 0 (0.2 - 1.5)
Depth	cm	113 ± 5 (0 - 300)	49 ± 4 (0 - 180)	NA
Organic material	% dry wt.	20.0 ± 0.7 (2.0 - 47.4)	12.7 ± 0.8 (2.5 - 30.6)	6.9 ± 0.6 (3.3 - 19.5)
C_{org}	% dry wt.	7.7 ± 0.3 (0.2 - 19.4)	5.2 ± 0.3 (0.8- 13.3)	2.4 ± 0.3 (1.7 - 8.6)
N	% dry wt.	0.8 ± 0.0 (0.1 - 1.9)	0.5 ± 0.0 (0.1 - 1.3)	NA
P	% dry wt.	0.056 ± 0.002 (0.005 - 0.229)	0.054 ± 0.004 (0.01 - 0.143)	0.1 ± 0.02 (0.004 - 0.344)

Sediment depths in the Islamorada canals varied between canals averaging 49 ± 2 cm. Canal 114 had lowest sediment depths, averaging 36 ± 2 cm while 120 had the highest at 64 ± 5 cm. Canals 118, 150, and 152 had intermediate depths but also varied over time. This may indicate fluctuations in sediments, or potentially a heterogeneity in the canals that is difficult to address in longer, branching canals like these.

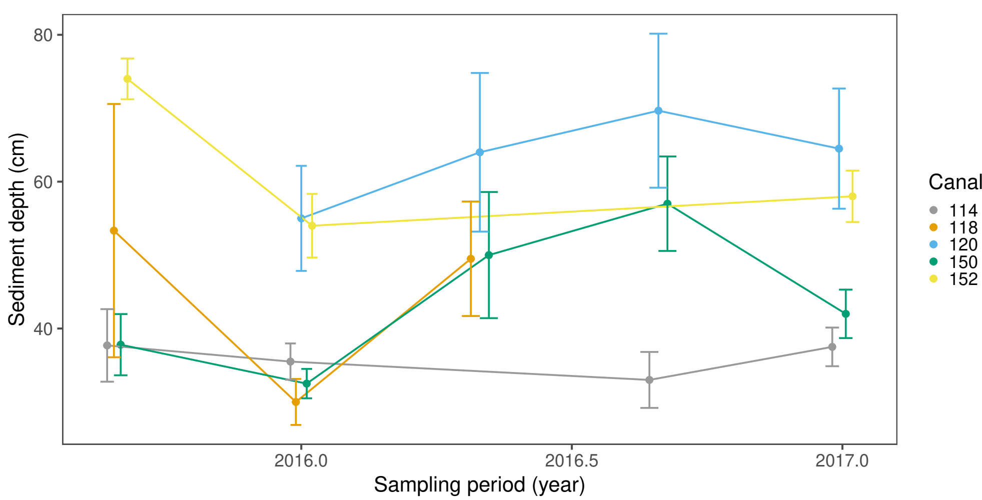

Figure 3.68: Changes in sediment depth over time in canals part of the Islamorada monitoring program. Data represent mean ± SE. Data points are slightly offset for time for better interpretation.

Five of the Islamorada canals supported benthic vegetation at some point during their monitoring from Fall 2015 to Winter 2017. Canal 145 lacked vegetation throughout the monitoring program (Fig 3.67). Canal 114 supported very small densities of calcifying macroalgae in Fall of 2015 and 2016. In Winter 2017, seagrasses *Thalassia* and *Halodule* made an appearance in Canal 152 for the first time during monitoring, thought observed plants were limited to the fist site within the canal mouth. Canal 114 had low densities of calcifying macroalgae at the first two sites within the canal mouth, though were only observed during Fall 2015 and Winter 2016. Similarly, canal 118 had ephemeral plots of calcifying macroalgae, observed only near the mouth in Spring 2016. Canal 120 had varying densities of calcifying macroalgae at sites 1 and 2 along with single observations of benthic vegetation at sites 5 and 7, along with *Halodule wrightii* in the first three sites inside the canal. Canal 150 consistently contained seagrasses in over half its length. *Thalassia* was found in varying densities from site 1 at the mouth until site 7, with density scores reaching 4 in the four sites. *Halodule* was also observed from sites 1-7 with density scores occasionally reaching 5 in the first half of the canal. Canal 150 also contained the seagrass *Halophila dicipens* at sites 7, 8, and 10 in the fall 2016 (not included in figure). This is a small, ephemeral seagrass species adapted to low light conditions and typically found in deeper waters over 20 ft. This canal had a number of sponges interspersed between seagrasses at sites 2 through 5, identified as potentially *Haliclona magnifica*. It is unclear where these have been introduced by residents or are naturally occurring.

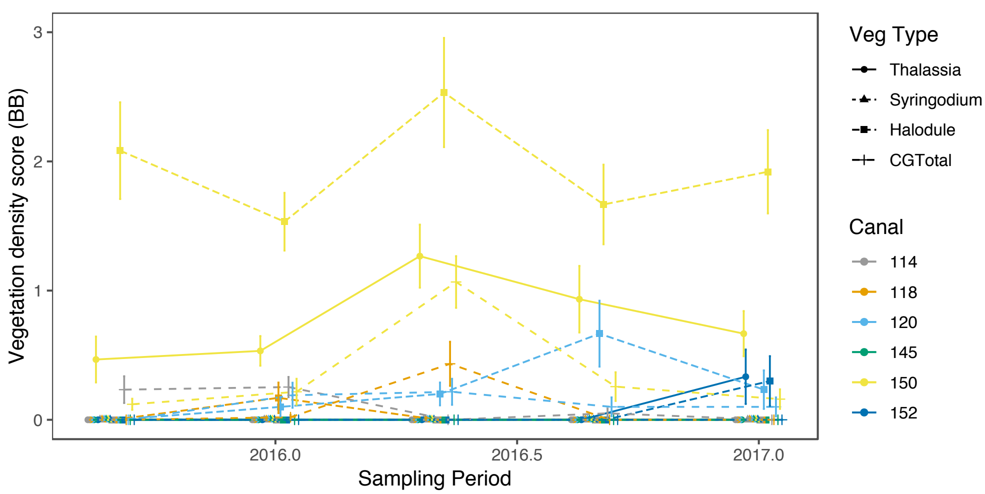

Figure 3.69: Changes in benthic vegetation density over time in canals part of the Islamorada monitoring program. Data represent mean ± SE. Data points are slightly offset for better interpretation.

Seawall inhabiting organisms were only observed and quantified in canal 118, where only barnacles and turf green algae was present. The Islamorada canals are heavily used and densely occupied by docked boats. Seawall space typically monitored for organism was shadowed by docked boats or cleaned of organisms in such a way to prevent fouling.

Fish were observed in Islamorada canals during fall and winter sampling campaigns only, with seven species identified and mangrove snapper being the most abundant. Fig 3.70 shows total number and identity of species observed in Islamorada canal. Mangrove snapper, unidentifiable juvenile fish, and mullet were the most commonly encountered, while the eagle ray observed in Canal 144 and Sergeant major observed in 150 were singular events. Canal 150 had over two hundred more observations than other canal in the

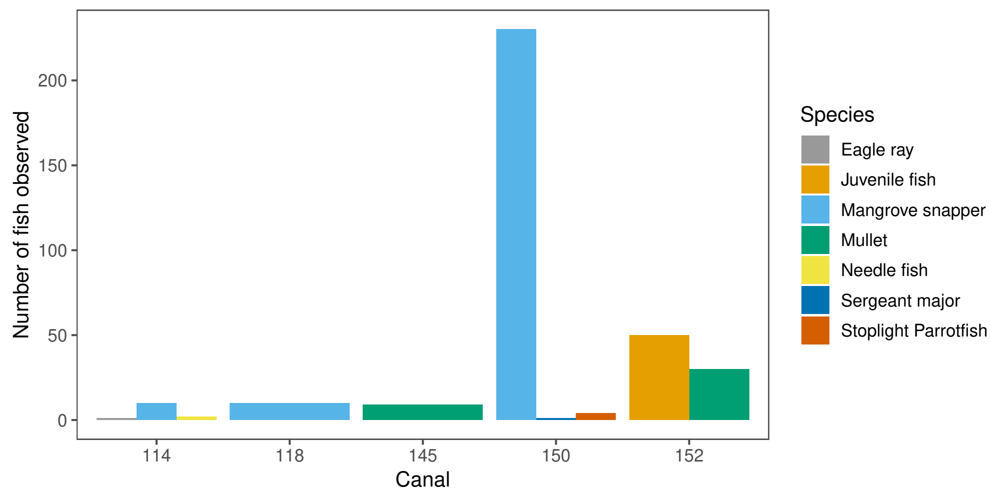

Figure 3.70: Total fish observed in Islamorada project canals from Fall 2015 until fall 2017.

monitoring program. Canal 145 is not included in the figure as there where no observations of fish from 2015 through 2017.

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 that the average values for natural waters in the FL 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 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 have to 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 Demonstrated Technologies

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 FL 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.

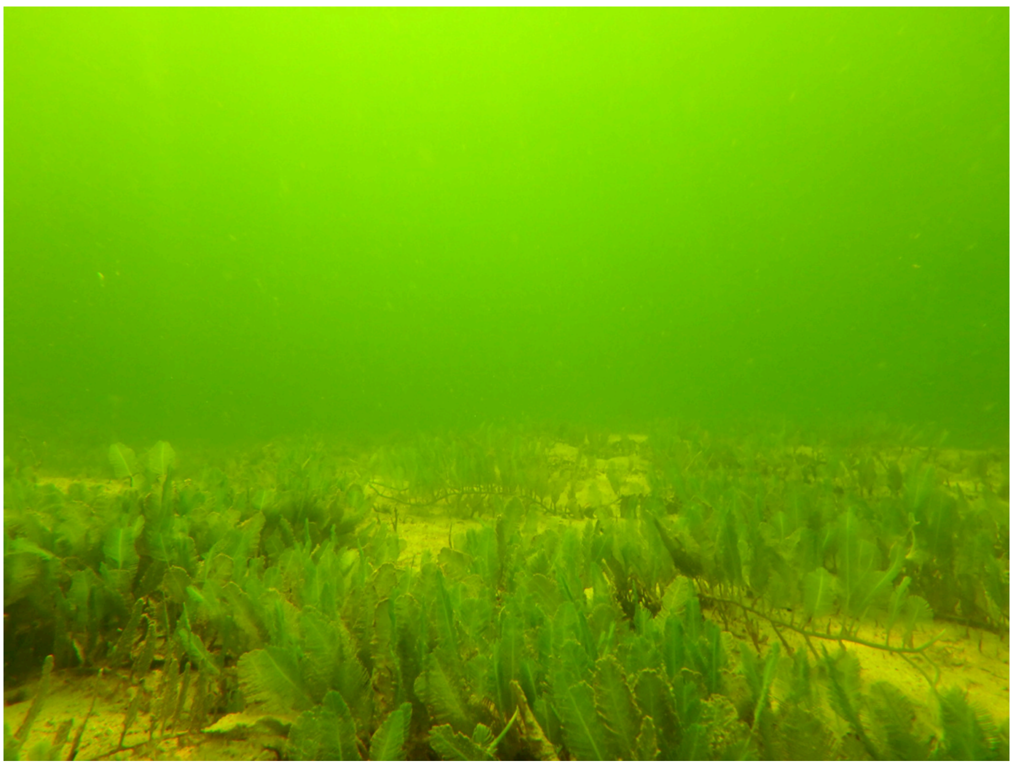

Figure 4.3: . Benthic algae taking root in newly backfilled sediment in Canal 29. Prior to backfilling, light did not penetrate more than 10 ft into the water.

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 sediments characteristics towards the canal mouth. Over time, continued influx of organic material may turn the newly formed sandy bottoms back into muddy, organic sediments.

Air Curtains

The air curtains had no measurable effect on sediment, fish, or seawall characteristics in either Canal 137, 138, or 287 where they were installed. Air curtains block the influx of additional wrack from entering a canal, 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 are not expected to be measurable in the short timeframe 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 high quantity of organic material outside Canal 266 and the partial reversal of sediment conditions in Canal 290 after dredging stress the importance of keeping out organic material with air curtains after it has been removed.

Aerators

Six additional aerators were added to Canal 137 in addition the air curtain. There were 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. 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 C_{org}, 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 affective 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. Sediment depth decreased over 50 % in Canal 472, though occurred prior to the official opening of the culvert. Construction in the canal and preliminary openings alone could have flushed out or compacted sediments in the canal rear. 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.

Improvements in water quality and environmental health were not clear in all demonstration canals, though this is not a surprise. Backfilling and organic removal are 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.

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 1 - 3 years monitored during this program. Continued or periodic monitoring is recommended if improvements are to be measurable.

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

4.2 Concurrent Canal Monitoring in Islamorada

The six canals monitored in Islamorada starting in Fall 2015 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 short period of monitoring data presented here is inadequate to show effects of water management changes. Data from this period better represent of state of the canals to which future monitoring results can be compared. 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* in densities thicker than adjacent open waters with environmentally sensitive sponges. The rear of the canal contained benthic macroalgae and seagrass $_{\text{Halophila}}$, 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.

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.

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 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 longterm effectiveness of remediation technologies. Further, the high-resolution benthic data presented here, compared to the ongoing and future data collected after the devastating 2017 Hurricane Irma, will offer a rare opportunity to evaluative nearshore environmental heath and remediation efforts in response to an intense storm event.

References

AMEC Environment & Infrastructure (2012). *Monroe County Canal Management Master Plan, Phase 1 Summary Report*. URL: http://www.monroecounty-fl.gov/598/Canal-Restoration.

– (2013). *Monroe County Canal Management Master Plan*. URL: http://www.monroecounty-fl.gov/598/Canal-Restoration.

Campbell, J. E. and J. W. Fourqurean (2009). "Interspecific variation in the elemental and stable isotope content of seagrasses in South Florida". In: *Marine Ecology Progress Series* 387, pp. 109–123.

Ferdie, M and J. W. Fourqurean (2004). "Responses of seagrass communities to fertilization along a gradient of relative availability of nitrogen and phosphorus in a carbonate environment". In: *Limnology and Oceanography*, pp. 2082–2094.

Fourqurean, J. W., A Willsie, C. D. Rose, and L. M. Rutten (2001). "Spatial and temporal pattern in seagrass community composition and productivity in south Florida". In: *Marine Biology* 138.2, pp. 341–354.

Fourqurean, J. W., G. V. Powell, W. J. Kenworthy, and J. C. Zieman (1995). "The effects of long-term manipulation of nutrient supply on competition between the seagrasses Thalassia testudinum and Halodule wrightii in Florida Bay". In: *Oikos* 72.3, pp. 349–358.

Fourqurean, J. W. and J. C. Zieman (2002). "Nutrient content of the seagrass Thalassia testudinum reveals regional patterns of relative availability of nitrogen and phosphorus in the Florida Keys USA". In: *Biogeochemistry* 61.3, pp. 229–245.

Fourqurean, J. W., S. P. Escorcia, W. T. Anderson, and J. C. Zieman (2005). "Spatial and seasonal variability in elemental content, δ13C, and δ15N ofThalassia testudinum from South Florida and its implications for ecosystem studies". In: *Estuaries* 28.3, pp. 447–461.

Fourqurean, J. W., G. A. Kendrick, L. S. Collins, R. M. Chambers, and M. A. Vanderklift (2012a). "Carbon, nitrogen and phosphorus storage in subtropical seagrass meadows: examples from Florida Bay and Shark Bay". In: *Marine and Freshwater Research* 63.11, p. 967.

Fourqurean, J. W., C. M. Duarte, H. Kennedy, N. Marbà, M. Holmer, M. A. Mateo, E. T. Apostolaki, G. A. Kendrick, D. Krause-Jensen, K. J. McGlathery, et al. (2012b). "Seagrass ecosystems as a globally significant carbon stock". In: *Nature geoscience* 5.7, p. 505.

Fry, B. and E. B. Sherr (1989). "δ^{13}C measurements as indicators of carbon flow in marine and freshwater ecosystems". In: *Stable isotopes in ecological research*. Springer, pp. 196–229.

Howard, J. (2018). "Patterns of carbon metabolism, storage, and remineralization in seagrass ecosystems". PhD thesis. Florida International University.

Lamb, J. B., J. A.J. M. van de Water, D. G. Bourne, C. Altier, M. Y. Hein, E. A. Fiorenza, N. Abu, J. Jompa, and C. D. Harvell (2017). "Seagrass ecosystems reduce exposure to bacterial pathogens of humans, fishes, and invertebrates". In: *Science* 355.6326, pp. 731–733.

Reidenbach, M. A. and E. L. Thomas (2018). "Influence of the Seagrass, Zostera marina, on Wave Attenuation and Bed Shear Stress Within a Shallow Coastal Bay". In: *Frontiers in Marine Science* 5, p. 397.

Schonhoff, B. (2015). "Gaseous Carbon Emissions (Methane and Carbon Dioxide) from Wetland Soils in a Re-created Everglades Landscape". PhD thesis. Florida International University.

Seitz, R. D., H. Wennhage, U. Bergström, R. N. Lipcius, and T. Ysebaert (2013). "Ecological value of coastal habitats for commercially and ecologically important species". In: *ICES Journal of Marine Science* 71.3, pp. 648–665.

Solórzano, L. and J. H. Sharp (1980). "Determination of total dissolved phosphorus and particulate phosphorus in natural waters". In: *Limnology and Oceanography* 25.4, pp. 754–758.

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Appendix

Table 1: Sediment categories and their assigned ranking of increasing coarseness

Sediment Category	Numerical Value	Description
Mud	1	Individual grains indistinguishable, easily compress in hand, sediment remains clumped after compression
Sandy Mud	2	Majority of grains indistinguishable but textured upon touch, easily compress 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 (approx. 5-10 mm in size)
Halimeda-Hash	6	Remains of carbonate segments from *Halimeda* detritus (approx. 5-10 mm in size)
Rubble	7	Medium size rock (approx. 10-25 mm in size)
Live Coral	8	Continuous living coral
Rock	9	Bedrock or solid biogenic catbonate formations

Table 2: 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 short 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

Table 3: Organisms identified and quantified during benthic surveys using modified Braun-Blanquet density scores

Seagrasses	Algae		Animal	
Thalassia testudinum	Calcifying Green Algae	Other Green Algae	Octocoral	Sea Star
Syringodium filiforme	*Halimeda* spp.	*Batophora* spp.	Stony Coral	Other Echinoderm
Halodule Wrightii	*Udotea* spp.	*Avrainvilla*	Sponges	Queen Conch
Halophila decipiens	*Penicillus* spp.	*Dasycladus*	Barnacles	Fighting Conch
	Rhipocephalus spp.	Other	*Diadema* spp.	Other Gastropod
	Acetabularia spp.		*Lytechinus* spp.	Pen Shell
	Neomeris spp.	Red Algae	Heart urchin	Other Bivalve
	Cymopolia spp.	*Laurencia* spp.	Other urchin	Spiny Lobster
		Other	Sea biscuit	Stone Crab
	Brown Algae		Sand Dollar	Other crustacean
	Dictyota spp.		Sea Cucumber	
	Sargassum spp.			
	Other			

Table 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
C. mex	green algae *Caulerpa mexicana*
C. sert	green algae *Caulerpa sertularioides*
C. ash	green algae *Caulerpa ashmeadii*
C. race	green algae *Caulerpa racemosa*
Halimeda	Includes all species of green algae within the genera *Halimeda*
Penicillus	Includes all species of green algae within the genera *Penicillus*
Acetabularia	Includes all species of green algae within the genera *Acetabularia*
Red algae	Includes all species of red algae
Batophora	Includes all species of green algae within the genera *Batophora*
Udotea	Includes all species of green algae within the genera *Udotea*