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Temporal changes in the larval Placopecten magellanicus population in a small-scale fishery closure area in coastal Maine, USA

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ABSTRACT

The Midcoast Maine Collaborative Scallop Project was established in 2013 by fishers, scientists, and policy makers to determine if a small-scale closure area could restore the local Atlantic sea scallop (*Placopecten magellanicus*) population to an area in coastal Maine that previously supported high scallop densities. These stakeholders established a three by one mile closure area in the Lower Muscle Ridge Channel to assess the response of the adult and larval scallop populations. Understanding the larval dynamics in a closure area is key to evaluating the recovery potential of the population and for future population stock levels. This study seeks to determine if larval abundance 1) has changed over the three-year closure period and 2) varies inside the closure area as compared to adjacent fished areas. To gauge larval abundance, 36 spat bags were deployed to collect scallop larvae over the three-year study. A before-after-control-impact (BACI) design was used to determine if recruitment increased within the closure using 2013 data for a baseline before the closure was implemented and to control for initial differences from different areas. In 2014 and 2015, higher abundance of larval scallops were recorded both inside and outside of the closure area as compared to 2013 abundance ($p=0.010$ and $p=0.011$). There was no significant difference in abundance inside compared to outside the closure ($p=0.30$), suggesting that scallop spat is increasing to the system as whole, not just within the closure area. This increase is a potential first sign of recovery for the resident scallop population, and indicative of increased adult populations and larger size class scallops. Early data analysis of adult populations shows increased frequency of juvenile size-class scallops in 2016, suggesting that the increased spat abundance seen in 2014 survived to juvenile age, an additional early sign of recovery showing success of the closure area to rebuild adult populations in the area.

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LITERATURE REVIEW

Importance of the Atlantic Sea Scallop

Placopecten magellanicus, the Atlantic sea scallop, is a bivalve mollusk found in waters along the Atlantic Coast as far south as Cape Hatteras, North Carolina, and north to the Gulf of St. Lawrence (Posgay 1957). The Atlantic sea scallop is an economically important species, with the United States having the most valuable wild scallop fishery in the world (Stokesbury 2002, NEFSC 2004). In 2015, the Atlantic sea scallop fishery had a landings value of 440 million dollars in 2015 (NOAA 2017). However, due to overfishing, population declines starting in the late 1980s and early 1990s prompted regulatory change in the fishery. The implementation of closed areas was used to help scallop populations recover first in the federal fishery, and later in the Maine state fishery (Murawski *et al.* 2000, Stokesbury 2002, Gell and Roberts 2003).

Placopecten magellanicus Life History

General

Atlantic sea scallops are typically found at depths between 20m-100m in beds in areas of suitable substrate (Serchuk *et al.* 1982, Naidu and Anderson 1984, Thouzeau *et al.* 1991a, b, Tremblay and Sinclair 1992). Juveniles tend to prefer a habitat of gravel, small rocks, sand and silt, while adults are more commonly found on firm sand, gravel, shells, and rocks (MacKenzie *et al.* 1978, Langton and Robinson 1990, Thouzeau *et al.* 1991a,b, Parsons *et al.* 1992a, Stewart and Arnold 1994).

Scallops have distinct sexes and reproduce through broadcast spawning. In areas of higher scallop density, the fertilization rate is greater because of the higher density of eggs and sperm in the water column during the spawning period (Singer 2011). The primary spawning event occurs in late summer, and could be triggered by a temperature change to a summer maximum temperature (Parsons *et al.* 1992b, Bonardelli *et al.* 1996). There is some evidence that an early spring spawning event might take place within some populations, especially those in the Mid-Atlantic region (Almeida 1994, DiBacco *et al.* 1995, NEFSC 2004). The importance of the two spawning events to population growth is

somewhat contested. Although the late summer spawning event produces more larvae, there is lower survivorship because of higher temperature-dependent mortality in the larvae throughout the fall, indicating that a smaller, spring spawning could be more important for the total larval production (Davies *et al.* 2014, Thompson *et al.* 2014). The greater magnitude of the late summer spawning event is likely due to more suitable temperature and food conditions than in the early spring. Scallops have greater reproductive output in warmer water and when there is higher food availability, both of which occur in the late summer (MacDonald and Thompson 1985).

Post spawning, scallop larvae remain in the water column in a planktonic form for approximately 4-7 weeks before settling on the bottom (Posgay 1957). The length of the larval stage is highly dependent on location due to temperature variations (Tremblay *et al*. 1994). On Georges Bank, the larval stage ranges from 40-60 days (Thouzeau *et al.* 1991a, Parsons *et al.* 1993). While in the planktonic life stage, the larvae remain in the water column and dispersal is caused by the presence and strength of different oceanic currents (NEFSC 2004). A longer planktonic life stage causes scallops to have higher larval dispersal than many other mollusks including the soft-shell clam and Asian mussel because of the longer time period that the larvae are in the water column and subject to current transport (NEFSC 2004, Shanks 2009). In addition to horizontal current movement, larvae have also shown vertical migration with a higher abundance of larvae found at the thermocline (Pearce *et al.* 2004). Once the larvae reach approximately 0.25mm in shell height, the larvae settle onto the substrate and transition into spat. Spat face high mortality rates because of specific requirements for suitable substrate. Sand bottoms are unsuitable habitats while hard surfaces offer a greater chance for survival (Merrill and Edwards 1976, Larsen and Lee 1978). The availability of suitable substrate is an important factor for scallop survival. In addition, spat settlement is greater as depth increases (Pearce *et al.* 1998).

Unlike other bivalve mollusks, scallops have the ability to swim, and while they initially require a hard substrate, at a shell height of 5-12mm, scallop spat detach themselves from their initial settlement location and are free moving thus transitioning into their juvenile life stage (Dow and Baird 1960). Scallops swim to escape predation

and have more active swimming patterns when they are smaller. Once they reach an approximate shell height of 80mm, this activity declines (Baird 1954).

The Atlantic sea scallop reaches sexual maturity at two to three years of age, which corresponds to an average shell height of 40-90mm. During the first few years of reproduction, egg production is lower and increases with shell height. On average, a four-year old scallop will release two million eggs while scallops younger than four years old do not significantly contribute to egg production (MacDonald and Thompson 1985, NEFSC 2004). Langton *et al.* (1987) found that egg production in the Atlantic sea scallop increased at the fastest rate until scallops reached age five, and then the rate of egg production slowed, but did not decline. Reproductive output is also higher in scallops living in shallower waters because of greater food availability and warmer temperatures (MacDonald and Thompson 1985).

Gulf of Maine

In the Gulf of Maine, Atlantic sea scallops are commonly found closer to shore at depths less than 40m and as shallow as 2m in estuaries and tidal ecosystems (Serchuk *et al.* 1982*,* Naidu and Anderson 1984). In addition to the shallow, coastal populations found in the Gulf of Maine, there are some populations found as deep as 180m (Barber *et al* 1988, Schick *et al* 1988).

In the Gulf of Maine, recent research has indicated a spring spawning event that is driven by climate-related variability in current patterns. This is in addition to the primary spawning event that takes place in late summer and indicates that scallops in the Gulf of Maine are bivoltine, rather than some univoltine populations in other parts of the Atlantic sea scallops range (Gilbert *et al*. 2010, Davies *et al*. 2014, Thompson *et al.* 2014).

Federal Scallop Fishery

The federal Atlantic sea scallop fishery has jurisdiction from three nautical miles offshore, where the Maine fishery ends, to 200 nautical miles offshore. The Atlantic sea scallop fishery is the most valuable federal fishery, with a landing value of $440 million in 2015 (NOAA 2017a). The primary method for scallop fishing is through the use of scallop dredges, which are towed underwater behind the vessel collecting scallops as they

scrape along the seafloor bottom, however some scallop vessels in the Mid-Atlantic region use trawl gear (NOAA 2017b). Fishers utilizing scallop dredges are considered draggers, and while they dominate the fishery, there are still a small number of fishers who harvest scallops through SCUBA diving in the state fisheries (Smith 2017).

Maine Scallop Fishery

The Maine scallop fishery includes all scallop harvesting within three nautical miles of the coast. Unlike the federal fishery in which vessels are out at sea for extended trips, the Maine scallop fleet is a day-boat fishery where scallops are brought back to the dock the same day they are harvested resulting in a fresher product (Schick and Feindel 2005). For most Maine scallop fishers, scallops are a secondary fishery during the winter months when the lobster fishery is at its slowest.

The Maine scallop fishery has been a small but important fishery for the state since the late 1800s (Schick and Feindel 2005). Early regulations for the Maine state scallop fishery in the mid 1990's were limited, but mandated a minimum three-inch shell height for harvest. In addition, the fishery was closed every year from April 16 to October 31 (DMR 1981). This seasonal closure falls during the spawning season, but the timing of the closed season was not likely created with the conservation of the spawning season as a consideration, but rather due to the timing of peak harvest for the lobster fishery (DMR 1981). The scallop fishery is a secondary fishery for most fishers, with the lobster fishery being their primary focus. As the lobster fishery is more profitable in the summer, fishers switch their efforts from scalloping to lobstering, leaving a period of low effort that allowed for a closed season with minimal impact on the fishers (DMR 1981).

Incomplete and underestimated landing data from early and mid-20th century shows strong harvest years in ten-year cycles, with especially notable years occurring in 1910, 1933, 1953 and 1961. In these years, landings ranged from under 100,000 pounds to over 2,700,000 pounds (DMR 1981). Since landing data has been consistently tracked since 1950, cyclical patterns of increased and decreased landings have been common (Figure 1). A record number of landings occurred in 1981 of 3.81 million meat pounds. The industry saw a collapse in landings starting in the late 1980s through the 1990s (DMR 2017). By 1999, landings were less than half of the catch in 1990 (GPCEL 2001). In 2005, record low landings were recorded of only 33,141 meat pounds (DMR 2017).

The continued decline in landings pushed the Maine Department of Marine Resources (DMR) to institute new regulations in 2008 in hopes of rebuilding the scallop fishery. In 2015, 373 dragging licenses and 52 diver licenses were issued for the fishery (Cheney 2016). In 2016, 537,790 meat pounds were landed and the fishery was valued at $6.87 million (DMR 2017).

Although significantly smaller than the lobster fishery in number of licenses, pounds landed and economic value, at times the scallop fishery has ranked as the second-highest value fishery in the state (Schick and Feindel 2005). In 2016, Maine scallop fishery landings were valued at $6.87 million (DMR 2017). This provides fishers a small amount of diversification and additional income during the winter. In 2002, 831 dragging licenses and 369 diver licenses were issued, but after limited entry was established in 2008, only fishers who were active in the previous year could obtain a license for the following year, which caused a decline in the number of licenses for both divers and draggers (Singer 2011).

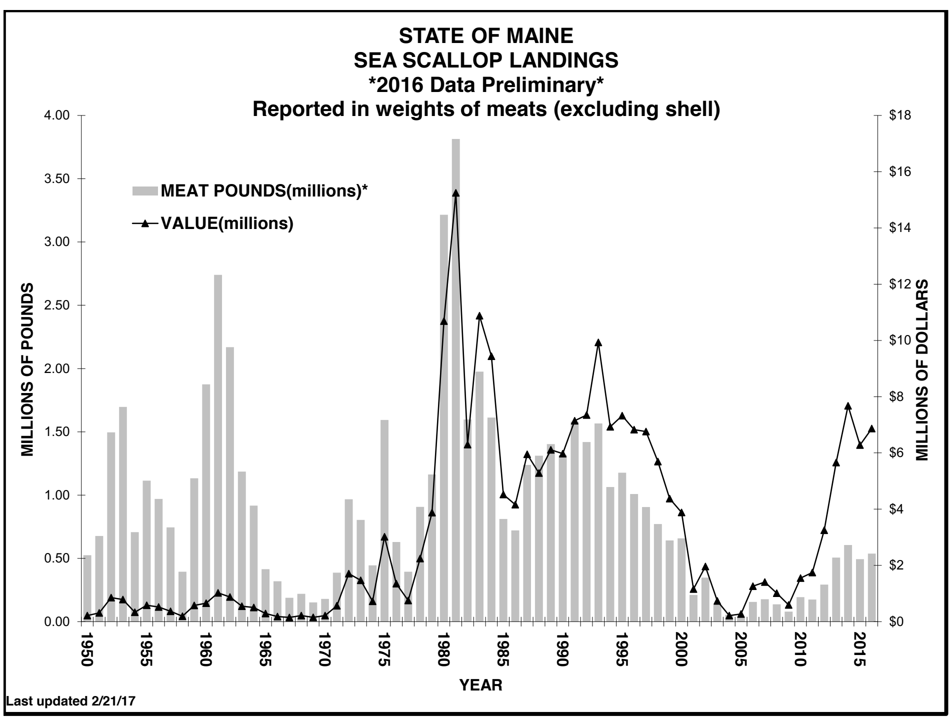

Figure 1. Sea scallop landings for the state of Maine in meat pounds (millions) and value (millions) from 1950 to 2016 (from DMR 2017).

Fishery Closures

Closure areas are a popular management strategy for many types of fisheries in order to build biomass by giving the population time free from fishing pressure (Gell and Roberts 2003, Fogarty and Botsford 2007, McCook *et al.* 2010). Closures are not all homogeneous; some may be temporary on a yearly or seasonal basis, while others exist as extended permanent closures or large scale area protection in the form of Marine Protected Areas (Lauck *et al*. 1998). Additionally, some closures target a single species, or are managed for multi-species and ecosystem recovery. The success of closures is dependent factors unique to each location, such as the design structure of the closure, local spatial characteristics, life history traits of the target species, the degree of depletion when the closure is implemented, ecosystem and anthropogenic impacts (Hiborn *et al.* 2005). Closures have been more successful for managing target species that have limited mobility rather than highly migratory fish stocks (Lauck *et al.* 1998, Hilborn *et al.* 2005).

Marine Protected Areas have shown considerable success in recovering species at an ecosystem based level and helping habitat recover (Gell *et al.* 2002). A permanent closure allows species a spatial area in which there is no fishing pressure, nor a threat from potential bycatch and disturbance. In Kenya marine reserves, tropical coral reef fish biomass recovered by a factor of 10 after 10 years of a closure, but it took 37 years for the ecosystem to recover to full diversity, biomass and ecological states after heavy fishing (McClanahan *et al.* 2007). For fisheries management, temporary closures allow the population time to recover, but also balance the economic demands of the industry (Dinmore *et al.* 2003, Caddy and Agnew 2004).

Temporary closure areas were successfully used in the Iceland herring fishery to manage the recovery of a depleted population (Caddy and Agnew 2004). In the late 1960s, the herring fishery collapsed following increased fishing pressure and poor environmental conditions. In 1971, a five-year closure was enacted to rebuild the spawning biomass. After the fishery reopened in 1975, seasonal spawning biomass had increased and restrictions were kept in place to protect areas of overwintering (Jakobsson and Stefánsson 1999). The quick recovery in the spawning biomass of the Icelandic herring population is linked to their early age of maturity, fast growth and high fecundity

rates, allowing for high natural factors of recovery when removing fishing mortality (Jakobsson and Stefánsson 1999, Jennings 2001, Caddy and Agnew 2004).

Seasonal area closures can be less effective because without additional management strategies, seasonal closures concentrate fishing effort directly outside the closure area and on either end of the closure period (Dinmore *et al.* 2003). Seasonal closures on Georges Bank for haddock and off Nantucket Island for yellowtail flounder were implemented to give protection during the spawning season, but increased fishing pressure immediately prior to and following the seasonal closure exploited the large aggregations of these species that remained in the area, negating any impact of the closure (Halliday 1988, Murawski *et al* 2000).

Benthic species of limited mobility are better suited for closure management because areas can be better targeted for protection and recovery (Lauck *et al.* 1998, Gell and Roberts 2003, Caddy and Agnew 2004, Hilborn *et al.* 2005, Hart and Rago 2006). In British Columbia, spatial closures for the Dungeness crab fishery in Queen Charlotte Sound resulted in increased body size and catch per unit effort after one year of restricted fishing. In areas outside of the closures, fishing continued through the year, showing that for a species with little migratory patterns, spatial closures can be an effective management strategy (Frid *et al.* 2016). Seasonal closures have been successfully used in the Japanese sea cucumber fishery to reduce fishing effort and increase sea cucumber densities. The seasonal closure of the Japanese sea cucumber fishery lasts for 10 months of the year, allowing for a two-month fishing season which has successfully kept the population from being overfished (Purcell and Vasconcellos 2010).

To make a fishery closure economically viable, the cost of closing an area to fishing pressure has to be justified by gains to the fishery (Jaini and Paredes 2008). In order for a fishery closure to increase fishery yields, the yields from the increase of biomass in the closure or from spillover, increases in species biomass outside of the closure area, have to be greater than the loss of catch from closing the area to fishing (Gell and Roberts 2003, Hart 2006, Lorenzo *et al.* 2016). Closures can cause short-term economic loss, but in a successful closure, this will be balanced out by long-term gains to the fishery (Hart and Rago 2006). This requires careful selection of closure areas in order to ensure that the areas closed have a stock population that will allow for population

growth. Protecting metapopulations - separate populations that have some interaction usually thought reproduction - that are important sources of larval production can have a positive impact on other areas and metapopulations even while they remain open to fishing by increasing the larval stock for the entire system (Hart 2006). Closures have also successfully restored habitat by preventing damage and disturbance caused by fishing gear (Lauck *et al.* 1998). Increases in biodiversity and ecological benefits to species other than the target specie can also make a closure economically viable through a multi-species, rather than a single-species, approach (Armstrong 2007).

Scallop Fishery Closures

Global Scallop Closures

In 1994, following a collapse of many groundfish species including cod, haddock, and flounder, three large-scale closure areas were implemented on Georges Bank with the hope of recovering groundfish stocks (Murawski *et al.* 2000, Stokesbury 2002). Although these closures had some positive impact in increased abundance of groundfish species, the greatest increase was seen in the Atlantic sea scallop due to its benthic nature and limited mobility (Gell and Roberts 2003, Hart and Rago 2006). Between 1998 and 2011, scallop landings from Georges Bank increased by 46 million pounds (Stokesbury 2002). Four years after the closure, the total harvestable biomass had increased by a factor of 15 and by 2004, close to 80% of the federal fishery scallop biomass on George's Bank was located in areas closed to ground fishing (Murawski *et al.* 2000, Hart and Rago 2006). During a ten-year period after the start of the closure, the biomass of scallops in small, medium and large size classes increased both inside and outside the closure (Davies *et al.* 2015). By reducing the harvest of legal-size scallops, scallops grew into larger size-class scallops, contributing to more egg production (DiBacco *et al.* 1995). Growth of scallops and increased egg production from areas outside of the closure indicates a positive spillover effect from the closure, and the closures on Georges Bank were seen as a successful management option for the recovery of the scallop populations (Lubchecno *et al*. 2003, Davies *et al.* 2015).

Closures were also a successful management tool for *Pecten maximus* populations, the great scallop, off the Isle of Man in the Irish Sea, where a 14-year study

showed increased density of scallops above the legal landing size to be seven times higher in the closed area than the open fishing area (Beukers-Stewart *et al.* 2005). A fishery closure duration greater than 10 years is unusual. Rotational closures longer than three years have shown to be successful with six years as the optimal time period (Smith and Rago 2004, Beukers-Stewart *et al.* 2005). Unlike haddock and yellowtail flounder, which did not respond positively to closure areas, life history traits of scallops including low natural mortality, fast growth rates and limited mobility allowed a quick recovery when fishing pressure was removed (Murawski *et al.* 2000, Stokesbury 2002, Davies *et al.* 2015).

Closures in the Maine State Scallop Fishery

The Maine scallop fishery is regulated by the DMR, which has divided the coast into three zones. Zone 1 includes the area from the Maine and New Hampshire border to Penobscot Bay, Zone 2 stretches from Penobscot Bay to Lubec, while Zone 3 covers Cobscook Bay and the St. Croix River (DMR 2016a, Figure 2). DMR adopted closures as a management technique after seeing the success of closures in federal scallop fishery (Murawski *et al.* 2000, Stokesbury 2002, Davies *et al.* 2015, DMR 2016b). In Zone 2, a ten-year plan rotational management plan was implemented in the 2012-2013 season which closes 2/3 of the coast in Zone 2 for two consecutive years, while rotating the open 1/3 every year to allow for spat rebuilding and population growth (DMR 2016b). In addition to rotational closures, DMR also uses a system of limited entry, season length, daily limits, limited access areas, targeted closures, rotational closures and minimum harvest size to help rebuild the fishery (DMR 2016b)

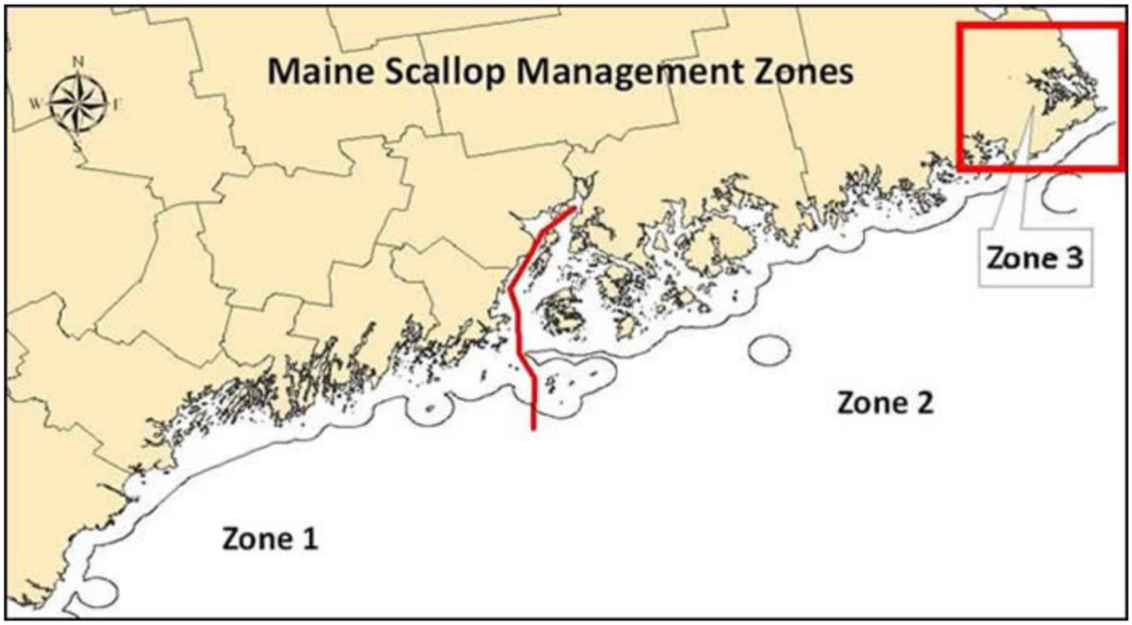

Figure 2. Geographical boundaries of the Maine scallop management zones (from DMR 2016a).

Jaini and Paredes (2008) recommended that the most successful closure areas for the Maine state fishery are in areas of historically productive scallop grounds that still contain high scallop densities, and areas that have evidence of recruitment in and out of the area. Because closures established in the Maine state fishery in 2008 were not selected at ideal locations for population rebuilding, spat-producing scallops, or allowing the growth of sublegal scallops, the closures may have caused more economic loss from the closure of fishing grounds than the benefit to the scallop population (Hart 2006, Jaini and Paredes 2008, DMR 2016b).

Source/Sink Population Dynamics

General

Due to current patterns and a long planktonic life stage allowing for higher larval dispersal, scallop larvae do not necessarily settle in the same area as their source (Roughgarden *et al.* 1985, Murawski *et al.* 2000, Stokesbury 2002, Gell and Roberts 2003, Beukers-Stewart *et al.* 2005). Current patterns play a large role in scallop larval dispersal and therefore are extremely important for rebuilding scallop populations. The source and sink dynamics of metapopulations are important factors that drive closure

success. In areas where a population has low recruitment retention, that population becomes a larval source for other metapopulations (Pulliam 1988, Beukers-Stewart 2005). On Georges Bank, sea scallop populations are thought to be self-sustaining because they have persisted for such long periods of time (Sinclair *et al.* 1985, Tremblay and Sinclair 1988, Smith and Rago 2004).

On Georges Bank, genetic research has shown high differentiation between the US and Canadian sides of the scallop beds, suggesting that these beds could be two different self-seeding populations (Kenchington *et al.* 2006). In addition, the current patterns on Georges Bank have well-established gyres and eddies which recirculate the larvae rather than transporting them elsewhere (Brand 2006). However, at offshore scallop beds, there are low genetic differences between offshore populations, indicating that those populations are open to different larval sources (Kenchington *et al.* 2006).

Gulf of Maine

The estuaries and bays of coastal Maine cause different patterns of larval circulation than what exists in the open ocean areas of Georges Bank (Jaini and Paredes 2008). While some metapopulations interact through larval transport, others have high larval retention. Larvae can be transported from their source population to a different metapopulation causing a spillover effect at either a regional or local level, or in closed populations, larvae will not circulate out of their source area (Jaini and Paredes 2008). For inshore beds in Cobscook, Gouldsboro, Penobscot and Casco Bays in the Gulf of Maine, genetic differences between populations are higher than what is found in the offshore populations (Kenchington *et al.* 2006, Owen and Rawson 2013). However, there is much higher genetic variation in the eastern Gulf of Maine sites (Gouldsboro and Cobscook) compared to the western sites (Penobscot and Casco) which showed genetic homogeneity (Owen and Rawson 2013). The difference in genetic structure between these locations is likely due to the impacts of localized circulating current systems in Gouldsboro and Cobscook Bay which cause high larval retention (Owen and Rawson 2013, Brooks 2004). In addition, the Eastern Maine Coastal Current (EMCC) facilitates larval dispersal in the western Gulf of Maine, but not in the eastern Gulf of Maine (Owen and Rawson 2013, Xue *et al.* 2008). In small near-shore areas and bays, local current

patterns play a larger role in larval retention and dispersal, which could cause smaller inshore populations to have different larval transport patterns than what is found at a regional scale (Owen and Rawson 2013).

Penobscot Bay Currents

Circulation patterns are impacted by wind-driven currents, tidal currents, bathymetry, fresh water inputs, temperature and salinity (Xue *et al.* 2000). The EMCC is the strongest circulation current in the Gulf of Maine and shows increased strength in the summer while scallop larvae are in their planktonic form in the water column (Pettigrew *et al.* 1998). The EMCC impacts Penobscot Bay as it flows by the mouth of Penobscot bay in a southwestward flow (Xue *et al*. 2000). The general water direction in Penobscot Bay is highly impacted by the influx of fresh water from the Penobscot River, which can push the EMCC offshore (Burgund 1995, Xue *et al.* 2000). The Princeton Ocean Model created by Xue *et al.* (2000), found that currents throughout the water column in outer western Penobscot Bay demonstrated a southward flow on the western side of the channel while surface currents flowed northeast on the western side of the channel and southeast on the eastern side. Both Normandeau (1975) and Xue *et al.* (2000) found a clockwise flow around Isleboro.

Even with current models, currents in Penobscot Bay are hard to localize at a fine scale due to changes at different depths, local variability in winds, tidal changes, and fresh water input which cause high variability especially in the western areas (Fidler 1979, Humphreys and Pearce 1981, Burgund 1995, Xue 2000). Temporal changes of currents are an additional consideration for larval transport because multiple spawning events in the spring and late summer cause the larvae to be in the water column during two different seasons, potentially subject to different current movements. Larval retention will be highest when the spawning period aligns with times of minimal current activity, when larvae are at a water column depth where current flow is slower, and the period of the planktonic phase is decreased (Byers and Pringle 2006). These factors, plus prevailing current direction, all add variability to where larvae will be carried and settle.

INTRODUCTION

Fishery Closures

Fishery closure areas are a management tool used to aid in the recovery of overfished populations. Without fishing pressure, species have time and space to grow in size and abundance, increasing biodiversity in the closed region (Babcock *et al*. 1999, Halpern and Warner 2002). In addition to population recovery, closure areas allow habitat recovery by limiting disturbance to an area (McCook *et al.* 2010, Lauck *et al.* 1998, Gell and Roberts 2003). Closures have been used to manage a wide range of species worldwide, and have been especially successful in tropical reef environments (Bohnsack 1998, McClanahan *et al.* 2007).

Closures are implemented in a variety of ways and are not all homogeneous. Closures tend to have less of an impact on highly migratory and mobile species, and are more effective for territorial and sessile species (Murawski *et al* 2000). The time period of a closure varies from seasonal and temporary to long-term or rotating closures. For fisheries management, temporary closures can allow the population time to recover, but also balance the economic demands of the industry (Dinmore *et al.* 2003, Caddy and Agnew 2004). In the late 1960s, the Icelandic herring fishery collapsed following increased fishing pressure and poor environmental conditions. In 1971, a five-year closure was enacted to rebuild the spawning biomass. After the fishery reopened in 1975, seasonal spawning biomass had increased and restrictions were kept in place to protect areas of overwintering (Jakobsson and Stefánsson 1999).

Seasonal area closures can be less effective because without additional management strategies, seasonal closures concentrate fishing effort directly outside the closure area and on either end of the closure period (Dinmore *et al.* 2003). Seasonal and temporary closures during the spawning season have not been successful for mobile species such as haddock and yellowtail flounder because once the spawning season ends, so does the protection provided by the closure (Halliday 1988, Murawski *et al* 2000). Rotational closures allow for protection interspersed with fishing efforts, but if recovery during the closed periods does not match or exceed the decline during open periods,

rotational closures will be insufficient to allow for long-term population recovery (Williams *et al.* 2006, Cohen and Foale 2013). Closures specifically located in spawning grounds or prime habitat offer greater protection than closures placed in randomly selected areas that fishers are willing give up from their territory (Jaini and Paredes 2008).

Scallop Closures

Closures have successfully aided in the recovery of scallop populations due to their limited mobility and nature as a benthic species. On Georges Bank, closures have been widely used for the management of groundfish stocks. In 1994, following a collapse of many groundfish species, two large-scale closure areas totaling 10,887 km^2 were implemented on Georges Bank (Murawski *et al.* 2000; Stokesbury 2002). In 1998, after four years of the closure, the total harvestable biomass had increased by a factor of 15 and by 2004, close to 80% of the federal fishery scallop biomass on George's Bank was located in closed areas (Murawski *et al.* 2000, Hart and Rago 2006). This area has since opened on a rotational basis, giving the population time without fishing pressure to produce larger size-classes which contribute to greater total egg production than smaller size-classes (DiBacco *et al.* 1995).

Successful closures within the federal scallop fishery led the Maine Department of Marine Resources (DMR) to widely adopt closures as a management practice at the state level (Murawski *et al.* 2000, Stokesbury 2002, Davies *et al.* 2015, DMR 2016b). The Maine state scallop fishery is currently using targeted and rotational closures over three different zones to sustain the scallop fishery. In Zone 2, a 10-year rotational management plan began in the 2012-2013 season that keeps 2/3 of the coast closed for two consecutive years, while rotating the open 1/3 every year to allow for spat rebuilding and population growth (DMR 2016b). In Zone 1, limited access areas and targeted closures protect spawning areas and locations of high juvenile densities (DMR 2016b). The Midcoast Maine Collaborative Scallop Project aims to determine if the small-scale closures used by DMR will allow in-shore scallop populations to recover (Cleaver 2015).

Source/Sink Dynamics

While a closure prevents fishing in a specific area, no physical barriers exist to prevent movement of a species outside of the closure. This ability to move in and out of the closure allows for spillover effects. By protecting one area, benefits also extend to adjacent areas, often seen through increased populations, sizes, and recruitment (Halliday 1988, DiBacco *et al.* 1995, Stokesbury 2002, Halpern *et al.* 2009, Davies *et al.* 2015). The source and sink dynamics of metapopulations are important factors that drive closure success. In areas where a population has low recruitment retention, that population becomes a source for other metapopulations (Pulliam 1988). Current patterns are a large driver of source and sink dynamics as larvae do not necessarily settle in the same area as the source, causing larval transport away from the source to other populations (Carr and Reed 1993, Jaini and Paredes 2008). On Georges Bank, the scallop metapopulation is made up of three subpopulations that are sustained through high larval retention due to current patterns (Gilbert *et al.* 2010). In the Gulf of Maine, current patterns are the likely cause of lower genetic homogeneity of scallop populations in Penobscot and Casco Bay compared to Gouldsboro and Cobscook Bays, which have localized current systems that lead to high larval retention (Brooks 2004, Owen and Rawson 2013).

Midcoast Maine Collaborative Scallop Project

In the spring of 2013, Midcoast Maine scallop fishers, scientists and policy makers gathered to discuss the possibility of implementing a small-scale closure area on Lower Muscle Ridge area of western Penobscot Bay to assess the impacts of the small-scale closure on the local scallop population. This area once supported a stable scallop population that has declined in recent years. Fishers believed that a closure would allow the scallop population time to rebuild to previous high levels of harvest due to the suitable habitat in the area. In June of 2013, in collaboration with DMR, the fishers recommended closing a three-mile by one-mile section of Lower Muscle Ridge for three years. In June of 2016, a second recommendation was made to continue to keep the area closed to fishing (Cleaver 2015).

Since the summer 2013, annual surveys of adult and larval populations have been conducted to determine the impacts of the closure on the population size. The adult

population has been measured through dive surveys and drop camera studies, while spat bags have been used to understand the dynamics of the larval population. Growth rates are studied using age rings on the scallop shells (Chute *et al.* 2012). In addition, genetic research is being conducted to understand the dispersal of scallops in the Muscle Ridge area. The Midcoast Maine Collaborative Scallop Project research efforts has been coordinated by Caitlin Cleaver at the Hurricane Island Foundation with collaboration of fishers from Friendship, South Thomaston and Tenants Harbor, and with the participation of the Island Institute, Maine Center for Coastal Fisheries, Maine Department of Marine Resources, Maine Sea Grant Cooperative Extension, University of Massachusetts Dartmouth, University of Maine, and Husson University (Cleaver 2015)

Research Goals

Scallop population dynamics occur at fine scale because of the importance of habitat suitability and larval transport. Although a closure might be successful in one location, it might not have the same effects in another because of differing oceanographic factors, habitat suitability and connectivity to other populations (Owen and Rawson 2013; Jaini and Paredes 2008; Davies *et al.* 2015). While there is much research regarding the Georges Bank scallop population, there is less known about the dynamics of coastal scallop populations in Penobscot Bay. Better understanding of the larval dynamics in a closure area is critical to evaluating the recovery potential of the population and for future population stock levels. This study uses data collected from spat bags to determine the impact of the closure on the larval scallop population. This study seeks to determine if larval abundance 1) has changed over the three-year closure period and 2) varies inside the closure area as compared to adjacent fished areas.

METHODS

Study Area

The Lower Muscle Ridge Closure is a three-mile by one-mile area located in Western Penobscot Bay, about 1.5 nautical miles from the closest mainland point (Figure 3). The closure spans the Muscle Ridge Channel between Whitehead and Seal Islands on the western edge of the channel to Graffam, Pleasant and Two Bush Island on the eastern

edge of the channel (DMR 2016b). This community-implemented closure was established in the spring of 2013 and has since been closed to scallop fishing, allowing for three years of reproduction. Closure boundaries are programmed into fishers' navigation systems and during SCUBA dive surveys, observations have indicated scallop dredge marks at sites outside of the closure but not at sites inside of the closure, showing that fishers are largely respecting the closure boundaries (Personal Obs. July 2016).

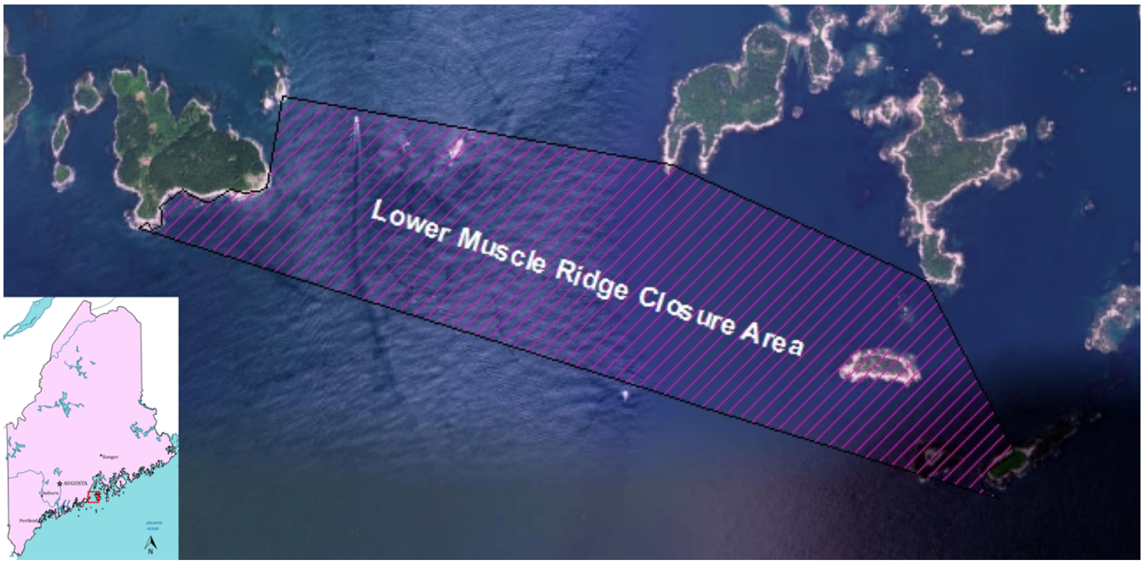

Figure 3. Map of the Lower Muscle Ridge closure area.

Spat Bags

Spat Bag Deployment

We deployed 36 spat bags inside and outside the Lower Muscle Ridge closure area over three years to collect scallop larvae during their earliest life stage when they are floating in the water column (Figure 4). Spat bags are commonly used to collect wild seed for aquaculture operations and enhancement projects (Schick and Feindel 2005). In this study, spat bags served as a metric to gauge the abundance of larval scallops in different areas surrounding the closure. We constructed spat bags using an outer mesh bag and a finer inner piece of hard mesh plastic. When scallops are in their larval form, they are small enough to pass through the fine outer mesh and then settle on the hard, inner mesh to start growing. As they grow, they become too large to pass back through the outer mesh bag and remain trapped inside.

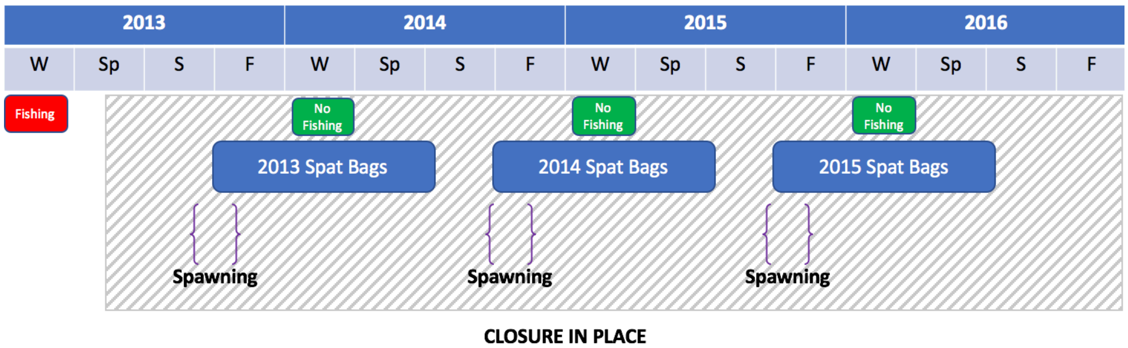

Figure 4. Project timeline showing the timing of when spawning occurs, when spat bags are in the water, and if fishing pressure occurred, broken down by year and season. Season designations are as follows: 'W' = winter, 'Sp' = spring, 'S' = summer and 'F' = fall.

Spat bags are deployed on lines, each of which contains five bags. The first bag is set approximately 1.8 meters from the bottom of the line and each subsequent bag is spaced 1.8 meters from the previous. Spat bags are set in September and remain in the water throughout the winter. The spat bags are collected the following year in late May or early June. Due to storms, harsh winters, and fishing gear, many bags are lost during the winter.

In early October of 2013, we deployed 12 lines of spat bags. We set three lines north of the closure, three lines within the closure, and three lines just south of the closure. We set an additional three lines further south of the closure to test the possibility of experiencing different currents further offshore such as the Western Maine Coastal Current (Figure 5). In June of 2014, we recovered six of the 12 lines, giving a recovery rate of 50%. In 2014, we set 12 lines in Lower Muscle Ridge with the same spatial distribution as 2013 (Figure 6). In June of 2015, we recovered four of the 12 lines, giving a collection rate of 33%. In 2015, we set 12 bags in Lower Muscle Ridge with the same distribution as the past two years (Figure 7). In June of 2016, we recovered four lines, giving a collection rate of 33%.

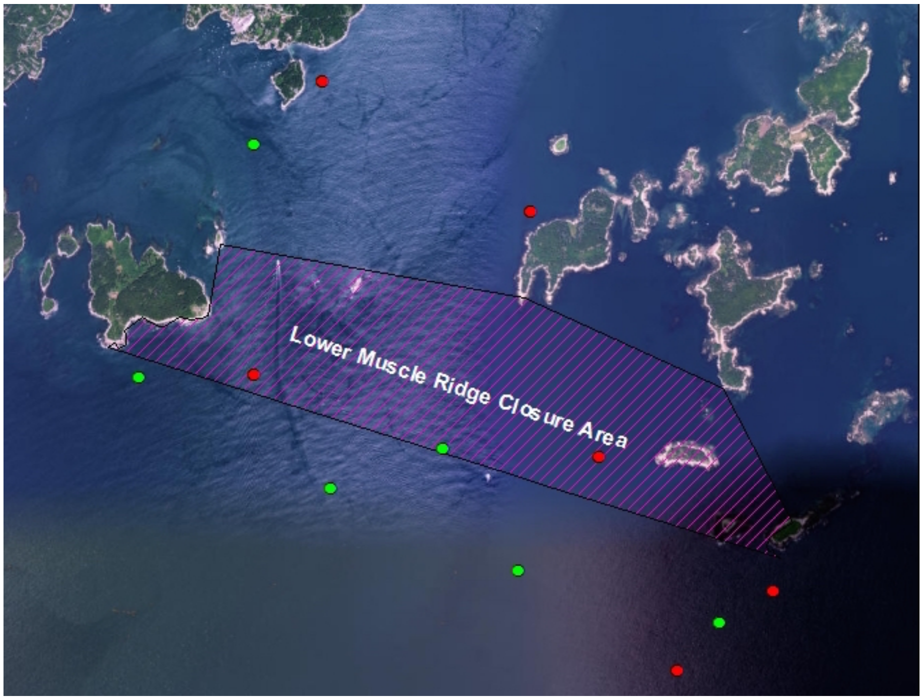

Figure 5. Locations of the 12 deployed spat bags in 2013. Green points represent spat bags that were recovered, while red points represent spat bags that were lost.

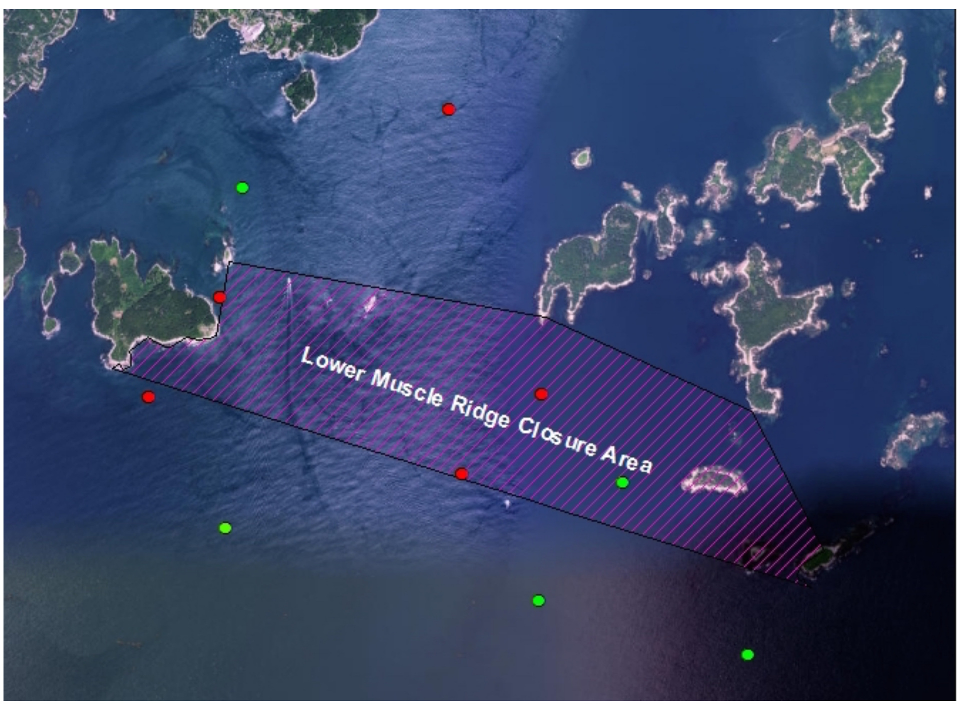

Figure 6. Locations of 10 of the 12 deployed spat bags in 2014. Two of the spat bags had incorrect coordinate points and could not be mapped. Green points represent spat bags that were recovered, while red points represent spat bags that were lost.

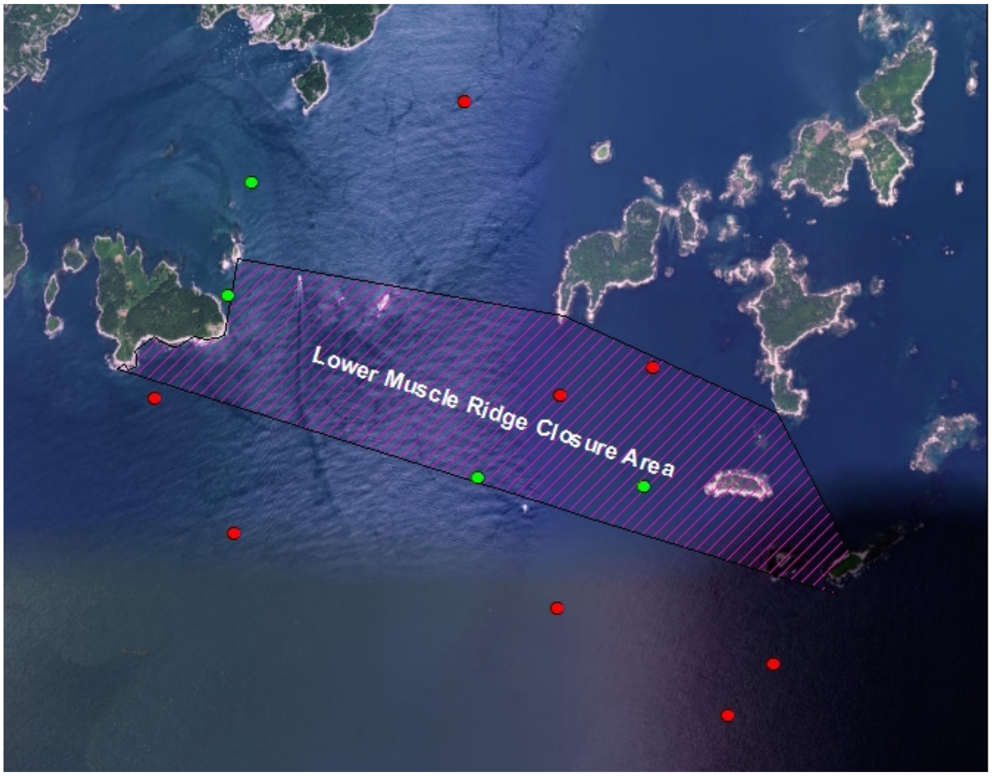

Figure 7. Locations of the twelve deployed spat bags in 2013. Green points represent spat bags that were recovered, while red points represent spat bags that were lost.

Spat Bag Processing

Following the collection of the spat bag lines, we counted all the scallops within each bag. For the spat bags of the 2013 and 2014 season, we measured the shell height - the distance from hinge line to the top of the shell - of every scallop. In the 2015 season, we measured a random subsample of 25% of the total scallops in every bag for shell height. In addition to scallop counts and shell height, we estimated the number of other organisms of interest in the bags including but not limited to clams, tunicates, mussels, barnacles, amphipods, snails, skeleton shrimp, starfish, brittlestars, nudibranchs, crabs and lacuna. We recorded the number of holes present in the bags, as an indication of the spats' susceptibility to predation.

Interviews

Due to a lack of fine scale current data for the Muscle Ridge area, I interviewed two fishers from Midcoast Maine about their perception of current directions in the

Lower Muscle Ridge area. The fishers had both fished in the Muscle Ridge area for at least 20 years, primarily for lobster but also for scallops during the winter harvest season. I was granted approval from the Institutional Review Board at Colby College in December before interviews began. The interviews were conducted over phone between January and March 2017. I recorded and took notes during the interviews and fishers were identified only by an assigned number to keep responses anonymous (Appendix 1).

Data Analysis

I used RStudio version 0.99.491 to analyze the data (RStudio 2015). Because of the low number of replicates, spat bags were grouped into two areas, inside and outside the closure. To determine if individual spat bags on the same line were independent of each other and to negate depth in the water column as a factor impacting abundance, I ran a one-way ANOVA (analysis of variance) looking at the interaction term of bag line and bag position. The one-way ANOVA showed that individual spat bags were independent of bag line, allowing each spat bag to be used as an independent replicate ($p<0.05$).

To see if there were significant differences in scallop abundance by year and by the location of the bag line, I ran an ANOVA controlling for the bag location and year. I ran Tukey-Kramer HSD tests to see which locations and years showed significant differences in abundance.

In analyzing the results, I assumed a Before-After Control-Impact (BACI) design for this project to control for initial differences in the different areas. Data from 2013 was considered the before, as it was the baseline data before the first year of the harvest closure. To understand which years and zones were showing changing scallop abundance, I ran a general linear model with an interaction term of year and zone. I then ran an ANOVA on the general linear model to see the significance of these changes.

RESULTS

Spat Abundance

In 2013, the year prior to the implementation of the closure, an average of 37.5 spat per were collected in each spat bag inside the closure and an average of 104.76 spat

per spat bag were collected outside the closure. In 2014, the mean spat per spat bag increased to 535.4 inside the closure and to 500.8 scallops outside the closure. In 2015, the mean decreased to 462.8 spat inside the closure and to 82.5 spat outside the closure (Table 1, Figure 8).

Table 1. Number of spat bag lines and individual bags recovered and average spat abundance per bag for each year inside and outside of the closure.

	Year	Number Recovered Lines	Bags	Average spat abundance/bag
Inside	2013	1	4	37.5
	2014	5	25	535.4
	2015	1	5	462.8
Outside	2013	4	20	104.8
	2014	3	14	500.8
	2015	1	4	82.5

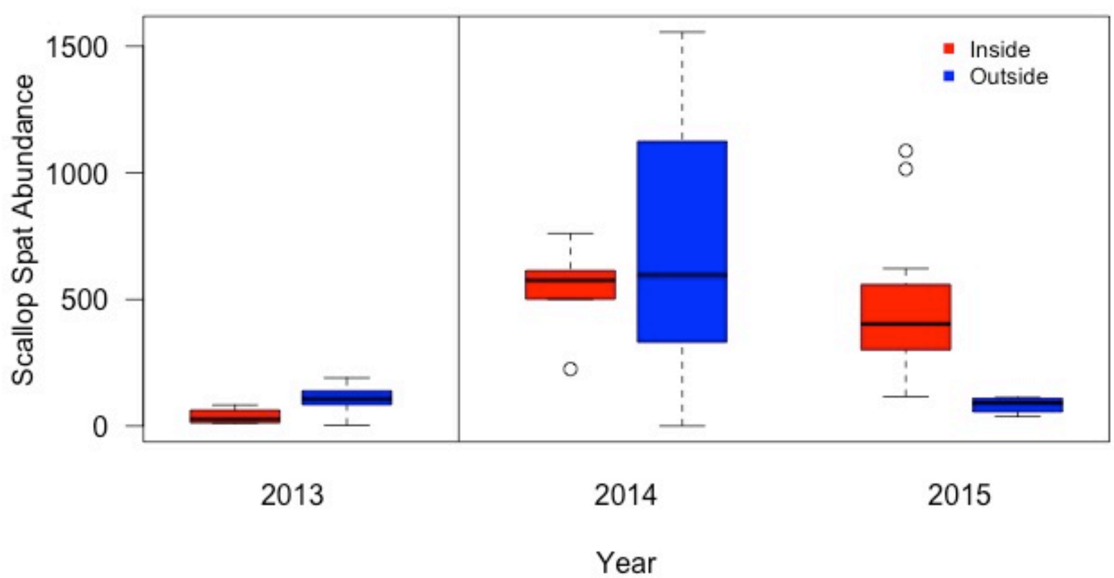

Figure 8. Abundance of scallop spat collected in spat bags in 2013, 2014 and 2015 inside and outside the Lower Muscle Ridge closure area. The black vertical line is indicative of when the closure was implemented, after the 2013 season.

Increasing Spat Over Time

The general linear model showed that spat abundance was significantly higher in both 2014 and 2015 ($p=0.0120$ and $p=0.0111$, respectively, Figure 8), as compared to 2013. There was no significant difference in spat abundance inside and outside the closure area ($p=0.30$), but rather an increase in spat to the system as a whole following the closure.

Interviews

The fishers interviewed each fished for 30-40 years in the Muscle Ridge area for both lobster and scallops. They agreed that currents in the Muscle Ridge closure area were dominated by tides, not prevailing currents. They stated that because of the Muscle Ridge channel, the prevailing currents further south in Penobscot Bay and the Gulf of Maine likely do not play a role on water movement inside the channel. On an ebb tide, the flow is to the southwest while on a flood tide it is to the northeast. They did not believe there was any seasonal variation in the tidal currents. Most of their observations were based on surface currents, but one fisher mentioned that the tide runs stronger in deeper water and is more consistent in direction than in shallow water, where the current is less strong and runs in less consistent patterns. The fishers suggested that wind patterns impact daily water flow, especially on the surface but not enough to change the dominant tidal direction. Normally, the wind is an easterly wind but this varies slightly by season. The wind is fairly predictable on a seasonal basis with a summer southwest wind that usually picks up in the afternoon. In the winter, low-pressure systems are common, causing stormy conditions that typically bring a northeast wind.

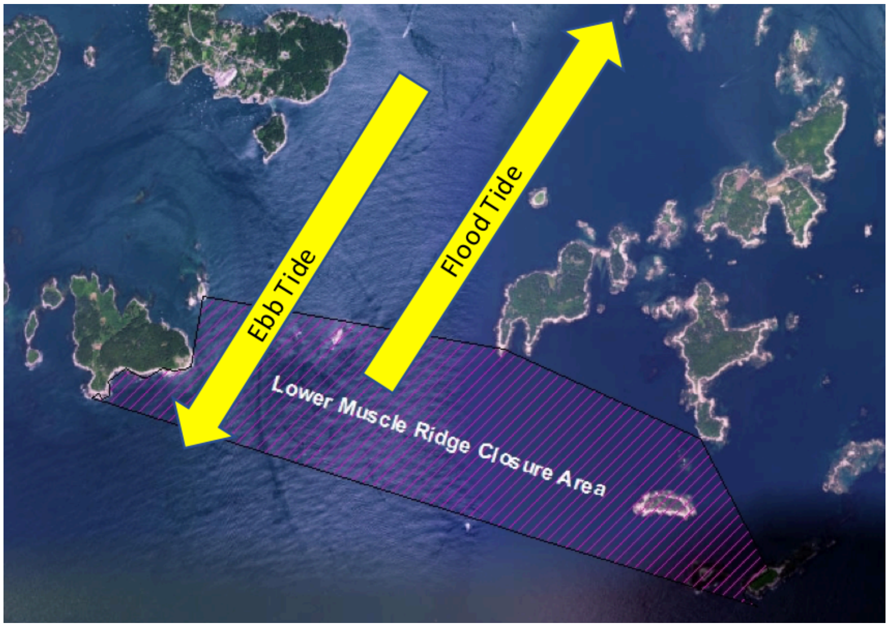

Figure 9. Direction of fisher perceived currents in the Lower Muscle Ridge Channel. On an ebb tide flow is towards the southwest while on a flood tide, flow is towards the northeast.

DISCUSSION

Increasing Spat Abundance

Spat abundance increased over the three-year study period indicating an increase of spat to the system in the Lower Muscle Ridge area. Spat abundance was higher in 2014 and 2015 ($p=0.0120$ and $p=0.0111$), post-closure years, than in 2013 before the closure was implemented. Since the closure and the removal of fishing pressures in the Lower Muscle Ridge area, the amount of spat in the system has increased. The increase in spat after the closure was implemented could be a first indication of recovery for the scallop population in the Lower Muscle Ridge area. In many Marine Protected Areas, increased larval abundance is one of the first signs of recovery even if other positive indicators are not seen until later in the closure period (Cudney-Bueno *et al*. 2009). This early sign of recovery suggests a possible increase in adult spawning scallops and an increase in larger size class scallops, the primary contributors to recruitment (NEFSC 2004).

DMR closes areas specifically for one, or a combination of three different reasons: spat production, population rebuilding, or sublegal scallops (DMR 2016b). The increase in spat abundance after the closure was put into place indicates that the Lower Muscle Ridge closure area is fulfilling at least one of DMR's goals for a scallop closure by increasing spat production. Increased spat production allows for higher juvenile densities leading to increased recruitment rates to the fishery and increasing the adult population size.

System Wide Increase

The increase in spat abundance was not only seen in the closure area, but also outside the closure area. There was no significant difference in spat abundance inside and outside the closure area ($p=0.30$), and this spatial abundance pattern indicates that there is larval transport outside the closure boundaries. This suggests that either the closure is having an impact beyond the area that is closed to fishing, or that larval transport from other regions in Penobscot bay is influencing the spat abundance in our study area, not just larval dispersal from the closure. This transport is likely occurring on a local scale, but causes a spillover effect where the closure not only impacts the space designated as closed, but also areas that are in close proximity but remain open to fishing (Lubchenco *et al.* 2003, Davies *et al.* 2015).

The spillover effect is causing increased spat abundance inside and outside the closure area, indicating the possibility that more spat will recruit to the fishery and contribute to a larger adult scallop population in both areas. Higher adult populations outside the closure offer a direct benefit to the fishery as these areas remain open to fishing. Once these scallops reach minimum size, they create areas of higher scallop densities for the fishers and improve harvest (Hart 2006, Fogarty and Botsford 2007). The spillover effect seen in this study could be a result of the closure, or also due to larger larval dynamics in Penobscot Bay. DMR implemented their rotational management plan in the 2012 and 2013 season, and through larval transport, the increased spat abundance in the Lower Muscle Ridge area could be a result from spillover of DMR's rotational closure zones. Historically, the Maine state scallop populations have seen cycles of increased and decreased population levels, but it is unclear whether that cycle is

still occurring and if so, where the Maine scallop population currently falls on the cycle (DMR 1981). Including sample sites farther from the Lower Muscle Ridge closure area would give a better indication if larval dynamics are increasing more widely in Penobscot Bay or if the increase is localized around the closure area.

Closure Impact

The Lower Muscle Ridge area is a coastal closure located approximately 1.5 nautical miles from the closest mainland point and extends across the Muscle Ridge Channel, immediately adjacent to ten small islands. Due to its proximity to shore and many small islands, factors such as tide and local water movement play a larger role in this area than they do in offshore areas such as Georges Bank. This means that coastal processes are likely more important in larval transport than prevailing current directions that are more prevalent farther offshore (Normandeau 1975, Brand 2006, Owen and Rawson 2013). This small-scale area can be looked at through a smaller lens, allowing the impacts of the closure to be seen on a local level.

When compared to the two Georges Bank closures that cover roughly 4000 and 7000 square kilometers**,** a closure covering almost 8 square kilometers has a much smaller impact (Murawski *et al.* 2000). However, it is still possible to see changes on a local level. The significant increase in spat abundance contributes to the local population dynamics and is representative of increasing juvenile populations that will later recruit to the fishery once they reach reproductive age. This suggests that the adult population contributing to the larval pool is increasing and that scallops are growing into larger size classes, and able to produce more eggs. Due to the uncertainty of current dynamics, the increase in spat could be representative of a growing population inside the Lower Muscle Ridge closure area or from increased larval transport to the area.

Population rebuilding is one goal used for closure assessment, and indicates that a closure is working (DMR 2016b). Larger size-class scallops contribute more to egg production than smaller scallops of reproductive age. Langton *et al.* (1987) found that egg production in the Atlantic sea scallop increased at the fastest rate until scallops reached age five, and then the rate of egg production slowed, but did not decline. By removing fishing pressure, scallops above the minimum harvest size are able to continue

growing to reproductive age (Gell and Roberts 2003). This local increase in recruitment helps the cycle of population growth accelerate. With more spat in the system, a higher number are likely to reach reproductive age, further increasing the adult scallop population (DiBacco *et al.* 1995).

Unlike DMR's rotational closures, the Lower Muscle Ridge closure area was targeted specifically for supporting a historic population and having suitable habitat for scallops. This allows a higher potential for recovery compared to a randomly selected location that may not be able to support a scallop population whether fishing is occurring or not (Jaini and Paredes 2008**)**. The removal of fishing pressure also impacts habitat suitability by removing the disturbance caused by scallop dredges. Scallop spat suffer from high mortality if suitable, hard substrates are unavailable. The disturbance caused by scallop dredging can minimize suitable habitat by destroying bottom cover (Merrill and Edwards 1976, Larsen and Lee 1978). Removing fishing pressure not only allows scallop populations to recover, but also allows for habitat recovery that can create a substrate more suitable for spat settlement (Thrush *et al.* 1995). Specifically targeting areas within DMR's rotational management plan for areas of historic populations and suitable habitat could allow for higher recovery rates in closure areas.

Impact of Currents

Although we saw an increase in spat over the study period, other factors besides the implementation of the closure could be responsible for the increase (Gell and Roberts 2003). We cannot directly attribute the increase in spat to the closure because we are unable to determine that the spat in the system was sourced from the adult population in the closure. Increased spat abundance could be the result of larval transport to the area from a different metapopulation that is connected through current dynamics (Davies *et al.* 2015)

Interviews with local fishers suggested that currents in the region are dominated by tides, not prevailing currents that would carry larvae outside the area. Rather, the tides flow southwest on the ebb tide and northeast on the flood tide, which would indicate that the larvae are likely to be transported throughout the channel but not be carried outside by stronger, offshore currents. The fishers' observations suggest that the population in the

Muscle Ridge area is representative of a semi-closed population structure where the larvae produced in the area by the adult scallop population settle in the same area because currents do not carry the larvae elsewhere. This supports the idea that the increased spat is sourced from the Lower Muscle Ridge area and that the closure is working to help rebuild spat production. However, this possibility is based upon observation alone and not off a current model for the area. In addition, current patterns are not always predictable. While tides might be the dominating factor for most of the year, temporal changes in current patterns could cause different larval transport depending on the spring and summer spawning events (Byers and Pringle 2006). Even within one spawning event, scallops have a long planktonic period, ranging from 40-60 days. An increased planktonic period can allow for longer dispersal distances but also could cause the larvae to be subject to different current dynamics based off of temporal variations during the planktonic life stage (Thouzeau *et al.* 1991a, Gilbert *et al.* 2010).

Larval transport is determined both by the duration the organism is in a planktonic form, and also by current patterns. The planktonic life stage of the Atlantic sea scallop has been well studied, ranging from 40-60 days before settling, but current patterns are highly dependent on the study location (NEFSC 2004). While large-scale current models exist for the Gulf of Maine, models available for Penobscot Bay do not extend far enough west to include this study area (Burgund 1995, Xue *et al.* 2000). In addition, for a small study area located close to shore, a more detailed current model is required to fully account for the local dynamics of tides, interactions with land masses, influx of fresh water, impacts of bays and estuaries, wind and depth changes (Normandeau 1975). This causes coastal current dynamics to exist on a smaller scale than in offshore areas. Offshore currents can cause transport over thousands of miles, local factors such as tide often influence larval transport more in near-shore areas. Without the influence of outside, prevailing currents, there is a greater chance that transport is contained to the local area (Gilbert *et al.* 2010). However, genetic studies of scallops in Penobscot and Casco Bays show higher genetic homogeneity than in Cobscook and Gouldsboro Bays, suggesting greater interconnectedness amongst Penobscot Bay populations due to larval transport (Owen and Rawson 2013). This indicates that it is unlikely that all of the spat in

the area is being sourced from the Muscle Ridge population, and that larval transport is occurring at some level.

Without a current model for the area, our understanding of current patterns is based only on fishers' observations. This makes it difficult to understand if larvae are being transported into and out of the system. A high resolution current model for the Muscle Ridge area would allow for a more precise understanding of current direction and the likely direction of larval transport. A better understanding of how larvae travel in this area would add more confidence to the belief that this population is a semi-closed population with limited larval input or output. However, even if a current model existed for this area, currents are not fixed, which would still leave some degree of uncertainty as to the larval source and transport direction (Byers and Pringle 2006).

North of the Closure

Initially, when analyzing the data, three spatial designations were used - north of the closure, south of the closure, and within the closure. This analysis showed that there were higher spat abundance south of the closure, leading us to believe that currents could be flowing from the north to the south, resulting in larval transport south of the closure. Additionally, a north to south flow was supported by dominant currents in Penobscot Bay (Xue *et al.* 2000). After interviewing fishers and finding no indication of a north to south current flow, we decided on two spatial designations, inside the closure and outside the closure.

In both models, there were lower abundance outside the closure in 2015 while abundance inside the closure remained high. In 2015, only one line of spat bags was retrieved outside of the closure. This line containing four spat bags was located north of the closure, in an area between Burnt and Seal Island, outside the main channel and tucked in a cove. In both 2013 and 2014, spat bags from this location had lower average spat abundance than other spat bags retrieved from different locations outside the closure in each year. As this location is outside the main channel, it is possible that less larvae are transported into this area because the current is stronger within the main channel. Fishers also suggested that different current patterns exist around the islands because of the interaction with the landmass changes in water depth, causing tides to run in less

consistent directions with less strength in shallower water. This could cause less larval transport and exchange from the main channel into this northern spat bag location as seen through lower than average spat abundance in 2013, 2014 and 2015. Although the much lower spat abundance was seen outside the closure in 2015 than in 2014 (Figure 8), we believe this is representative of a specific area in which spillover is not occurring due to the isolated location of this line, and not of lower spat abundance outside the closure in 2015.

Adult Population

An increase in spat is a positive first sign that can lead to higher adult populations. Linking the larval population dynamics to changes in the adult populations is key to assessing the effectiveness of the closure for population recovery. Initial data analysis of adult populations inside the closure from SCUBA dive surveys shows an increase in juvenile-aged scallops. The baseline surveys from 2013 do not show any evidence of this size class in our surveys, but in 2016, the presence of juvenile size class scallops is frequent. We first saw an increase in spat abundance in 2014, and the presence of small size-class scallops in 2016 suggests that this could be the same year class that two years later, has survived and is on track to recruit to the fishery (Cleaver 2016). The increase in juvenile scallops in 2016 could be the first indication of adult population recovery, but as two-year old scallops contribute minimally to egg production, this class year will have greater impacts on population recovery as they mature and grow into larger size-class scallops by producing more eggs (MacDonald and Thompson 1985, Langton *et al.*1987). Monitoring of the adult population is still ongoing, and will be the focus for assessing the ability of the closure to rebuild the scallop population. Even with increased spat abundance, if no increases are seen in adult populations, the closure will not be a successful management tool for the scallop fishery as the harvestable biomass is made up of adult scallops, not spat.

Collection Rate

Spat abundance data was based off of the number of spat bags that were retrieved every year. One limitation to this study was the low retrieval rate of spat bags. Spat bags

are deployed in late August or September, and remain in the water until the following June. Maine winters are notably harsh, with more frequent storms causing spat bags to rip from the anchor line. In addition, some spat lines were deployed in areas that still faced fishing pressure, and gear conflicts with scallop dredges could have cut some lines loose. Although spat bags were deployed in a range of locations inside and outside the closure area, the low retrieval rate meant that we did not have spat abundance data from every location.

In addition to having a low retrieval rate, another challenge was that bags were not retrieved from the same areas every year. Bags were deployed in nearly identical locations each season, but there was no predictor for which bags would be retrieved. This caused low replicates from some areas. In the case of 2015, only one bag was retrieved from an area north of the closure, all other bags were retrieved from inside the closure area. This restricts our data because abundance could be more representative of a single location where the spat bag was deployed, rather than an average across a larger area. Had spat bags been retrieved from the same area each year, individual locations could also be compared year to year.

Management Implications

Success of Small-Scale Closures

The Midcoast Maine Collaborative Scallop Project began when local fishers were interested in determining the ability of a small-scale coastal closure to help rebuild a local scallop population in an area that once supported a healthy population (Cleaver 2015). Although closures had helped scallop populations recover at a federal level, it was unclear whether inshore, coastal closures would have the same success as offshore closures. This analysis on the impacts of a small-scale closure on larval scallop abundance has shown that larval abundance increased after the closure was put into place, likely due to increased adult populations contributing more to the spawning seed. Increased population sizes are key result for determining the success of a closure, and this study indicates that a small-scale coastal closure can still have the same results as a large offshore closure area (Murawski *et al.* 2000, DMR 2016b).

An important consideration in fishery closures is the time scale at which the closure is effective (Halpern and Warner 2002, Beukers-Steward *et al.* 2005, Halpern *et al.* 2009). After one year of the Lower Muscle Ridge area being closed, spat abundance significantly increased. Although the increase could be due to factors other than the closure, over the two-year period of the closure, spat abundance continued to increase compared to the pre-closure 2013 spat abundance. This indicates the beginning of a trend towards increasing spat abundance over a short period of two years. The increase in spat was seen after preserving only one year of the harvestable biomass through the removal of fishing pressure. This allowed for a higher number of adult scallops to contribute to egg production the following spawning season, possibly leading to the increase in spat abundance. Additionally, DMR's rotational closures that began in the 2012-2013 fishing season in Zone 2 are managed on a two-year rotational cycle before being reopened to fishing (DMR 2016b). This study suggests that two years of a closure is enough to allow for significant spat increase, and that they will increase adult populations needed for recovery.

Marine reserves often see rapid effects in response to the removal of fishing pressure, and increased larval abundance is one of the first indicators to positively respond (Halpern and Warner 2002, Cudney-Bueno *et al.* 2009, Halpern *et al.* 2009). The recommended time for a successful closure in the scallop fishery is between 3 and 6 years (Beukers-Steward *et al.* 2005) yet DMR's rotational closures are two years, and then reopen for fishing (DMR 2016b). This study indicates that a closure of only two years seems to have a positive impact for increasing spat abundance, which can cause higher numbers of juvenile scallops after settling. Even if the scallops have not reached a harvestable size after a two-year closed period, minimum size restriction will allow them to reach that size-class if the area is opened to fishing.

Community Management

A unique aspect of the Midcoast Maine Collaborative Scallop Project is the collaboration between fishers, state regulators, non-profit organizations and scientists. The area closed to fishing in Lower Muscle Ridge was designed and agreed upon by local fishers, an unusual approach compared to most closure areas (Cleaver 2015). The fishers

decided which area they thought was both a productive monitoring area with suitable habitat and an area they were willing to stop fishing in order to understand the impacts of a small-scale closure area. The inclusion of fishers in the designation process of a closed area allowed for fishers to have more engagement in the management process and will better connect them with conservation goals for the future sustainability of their livelihood.

Recommendations

For the foreseeable future, the Lower Muscle Ridge closure area will remain closed to scallop fishing. I recommend that while the area remains closed, monitoring continues. Three years of data already exist for this area, and continued monitoring efforts could allow for the understanding of long-term impacts of a small, coastal closure that are not apparent with current data. To best manage the area for the scallop fishery, I would recommend a rotational closure length of five years, allowing scallops to grow to peak reproductive output (Langton *et al.* 1987). This five year period would also be sufficient time for the first year-classes from the closure to recruit to the fishery, increasing the adult biomass in the closure. Increased adult biomass will allow for higher scallop densities that even with fishing effort, will hopefully keep the local population at sustainable ecological and harvestable levels (Hart 2006, Fogarty and Botsford 2007).

Conclusions and Future Directions

This study has shown that a three-year closure period has significantly increased the spat abundance both inside and outside of the Lower Muscle Ridge closure area. While this increase is a potential first sign of early recovery for the resident scallop population, and could be indicative of increased adult populations and larger size class scallops, the larval source is unknown because of the uncertainty in current patterns. While the increased spat could be sourced from scallop population in Lower Muscle Ridge, the spat could also be representative of a different spawning population from larval transport. Regardless of the larval source of the spat, early data analysis of adult populations show increased frequency of juvenile size-class scallops in 2016, suggesting

that the increased spat abundance seen in 2014 have survived to juvenile age, an additional early sign of recovery.

In the spring of 2015, DMR voted to extend the time period of the Lower Muscle Ridge closed area (Cleaver 2015). This allows for monitoring that will continue into the summer of 2017, and another year of data collection. A third year of post-closure data will help inform whether the trend of increased spat abundance is due to the closure or to outside factors such as currents or high years of spat abundance because of temperature and nutrient availability. In addition, continuing to explore the dynamic of the adult population both inside and outside of the closure will link the research presented here to the larger management goals of the closure area.

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APPENDICES

Appendix 1
Interview Questions

1.Do you fish in the Muscle Ridge area? If so, for what species (e.g. lobster, scallops)?

2. How many years have you fished in that area?

3. Given your experience in the area, what direction do the prevailing currents in the closure area at Muscle Ridge flow?

4. Do these currents change on a seasonal basis? If so, can you tell me the dominant direction in winter, spring, fall and summer?

5. Are there differences between surface and deeper water currents?

6. Does the tide impact these dominant currents? If so, how? Does this change seasonally?

7. What direction does the tide run in the Muscle Ridge closed area?

8. Does wind play a role in water movement in the Muscle Ridge area? If so, what role and when?

9. Is there a dominant wind direction in the Muscle Ridge area? If so, what is it and how does it vary by season?