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An Investigation into the Scallop Parasite Outbreak on the Mid-Atlantic Shelf: Transmission Pathways, Spatio-Temporal Variation of Infection and Consequences to Marketability : Final Report

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Final Report

An Investigation into the Scallop Parasite Outbreak on the Mid-Atlantic Shelf: Transmission Pathways, Spatio-Temporal Variation of Infection and Consequences to Marketability

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Contents

Project Summary

A disease epizootic has developed that threatens one of the most valuable fisheries in the US. The U.S. sea scallop (*Placopecten magellanicus*) fishery landed $512 million worth of scallop meats in 2017 (NMFS, 2018). This fishery is based on landings of scallop adductor muscles only, with the remainder of the scallop discarded at sea (NEFSC, 2018). During the spring of 2015 both industry and scientific assessment crews noted unprecedented numbers of a parasitic nematode in the adductor muscle of captured scallops (Figure 1). The presence of the parasite in the adductor muscle is expressed through macroscopic lesions, or cysts. These lesions are rust-brown to orange/brown in color with a typically elongated shape, ranging from 2 -12 mm in length and 1 - 4 mm in width. Nearly all lesions were observed along the exterior edge of the adductor muscle between the mantle velar folds of both valves opposite the catch muscle (sweet-meat). This location on the adductor muscle is anatomically adjacent to the kidney-adductor muscle attachment site and opposite of scallop intestine and anus.

Figure 1. Sea scallop adductor muscle exhibiting multiple lesions consistent with infestation of the larval nematode. *Sulcascaris sulcata*.

Infected scallops were observed in the southern portion of the stock and corresponded with the re-opening of three spatial management areas in this region. The wide distribution of the observed parasite is of concern from a product marketability standpoint and may represent the early stages of an expansion of parasite prevalence and intensity. Preliminary investigations suggest that the nematode observed is *Sulcasaris sulcata* (Rudders and Roman, 2018a). Previous studies have documented several other important molluscan fishery species (surf clams, calico scallops, bay scallops and channeled whelk) serve as intermediate hosts for this nematode, which uses sea turtles (*Caretta caretta*, *Chelonia mydas and Lepidochelys kempii*) as a definitive host (Lichtenfels et al., 1978; Barber et al., 1987; Greiner, 2013). Given this life history, an expansion of the scallop infestation may lead to an epizootic across multiple fisheries. Very little, however, is known about the basic biology, range and seasonality of this parasite, or the controlling processes that could contribute to an epizootic outbreak in the sea scallop stock.

Historically high host abundances as a result of fishery management strategies, in combination with abiotic factors including rising ocean temperatures due to climate change may be independently or synergistically creating conditions that support increased parasite prevalence in the scallop population and altering transmission

dynamics among other hosts. Traditional paradigms of host-parasite transmission dynamics indicate that higher host densities facilitate greater rates of transmission via increased contact rates of susceptible hosts with infected hosts (Anderson and May, 1978). This basic concept of density dependent transmission has led to hypotheses about controlling disease by 'fishing down the parasites' by effectively reducing host densities to levels below those that facilitate high rates of transmission (Dobson and May, 1987). Opportunities to test such hypothesis have, to our knowledge, not been possible to date. Moreover, the concept is complicated by the presence of multiple hosts, age-structured effects and other factors leading to a need to understand dynamics at the level of the community of hosts present (Holt et al., 2003; Krkosek, 2010; Wood et al., 2010; Johnson et al., 2015). Understanding the basic biology and community ecology of *S. sulcata* is key to developing successful management strategies for the fishery.

Given the relative paucity of information related to the ecological and fishery implications of the nematode, the goals of our project were to provide information about this parasite, its spatial distribution, seasonality and mechanisms that might lead to epizootic outbreak conditions in the fished sea scallop stock. In addition to understanding key ecological and life history processes, we conducted applied studies related to post- harvest processing of nematode infected meats. Important questions addressed were: 'Do parasite loads change over the fishing season?', 'Are infected scallops, discarded meats and viscera able to infect other scallops?', and 'What is the spatio-temporal scale of the nematode distribution in the scallop stock and how does that vary both within and between years?' Insight into these processes is critical to the management of the fishery in the face of what could be catastrophic devaluation of landed product on a potentially massive scale. We achieved our objectives through a combination of targeted sampling efforts, complimentary observations from fishery independent surveys, laboratory based experiments and work on post-processing and marketability of infected adductor meats.

Results from this study showed the spatial extent of infected scallops is confined to the southern portion of the Mid-Atlantic resource area with a patchy distribution in the northern extent of infected scallops in the Elephant Trunk. Nematode infections increased with scallop size and potentially sex, where females may have a higher probability of being infected compared to males. There was modest temporal variation in the number of lesions observed per scallop, with a decline in the number of lesions per scallop observed in November for the targeted sampling observations. This variation may be related to water temperature, as water temperature declines the number of lesions per scallop decreases. No temporal variation was observed with respect to the number of infected scallops in an area and areas of higher intensity i remained highly infected over the course of the study. There was no evidence of scallop to scallop transmission in an experimental setting. Laboratory experiments also

found that nematodes died at higher temperatures, including the temperature of the human body. A survival study indicated heavily infected scallops had higher mortality rates. Post-processing of raw scallops to reduce the appearance of lesions was unsuccessful, but broiling infected scallops reduced the appearance of lesions.

Project Background

Marine diseases are well known to have important economic and ecological consequences (Lafferty et al., 2015). Oyster diseases caused by parasites (Ford and Tripp, 1996; Ragone Calvo et al., 2003; Bushek et al., 2012; Ford and Bushek, 2012), viruses (Pernet et al. 2012; Paul-Pont et al., 2014) and bacteria (Davis and Barber, 1999; Maloy et al., 2007) have caused excessive mortality in both wild and farmed oysters leading to major economic and ecological losses (Kemp et al., 2005; Mann et al., 2009; Lafferty et al., 2015). Catastrophic disease mortality has also been documented across a wide range of taxa including crustaceans (Shields, 2012; Lafferty et al., 2015), abalone (Freidman et al., 2014; Lafferty et al., 2015), echinoderms (Lessios et al., 1984; Scheibling and Hennigar, 1997) and corals (Patterson et al., 2002; Kim and Harvell, 2004). In addition to the impact to individual species, these events have been associated with the disruption of ecological functions (Altizer et al., 2003; Knowlton, 2004; Miner et al., 2007). Similar studies examining disease dynamics in the deeper nearshore shelf benthos are lacking, yet equally critical to understanding these often-complex interactions and to managing ecologically and economically important marine systems (Holt et al., 2003; Krukosek, 2010; Wood et al., 2010; Johnson et al., 2015). Previous studies have document nematodes in calico scallops and other major molluscan fisheries along the Atlantic seaboard (Sprent, 1977; Lichtenfels et al., 1978; Deardorff, 1989). The surprising prevalence evident in the scallop stock, beginning in 2015, may represent a precursor to an epizootic outbreak that has already caused problems with marketability of scallop meats.

Fishery management is demonstrably improved when spatial disease surveys and data are included in fishery management strategies. An outstanding example is the Delaware Bay oyster fishery which was nearly ended by the appearance of MSX and Dermo disease, yet swift management actions and adaptations have allowed the fishery to persist (Powell et al., 2008). Specifically, restructuring the fishery from a transplant fishery to a direct market fishery with strict area management of quotas and harvesting has not only allowed the fishery to continue, but has stabilized the catch and provided the opportunity for expanding the stock. Annual stock assessments explicitly include a spatial assessment of disease prevalence in order to estimate disease-induced mortality. Another example is the abalone fishery along the west coast of the US where spatially explicit disease surveys were able to identify sources of disease transmission and propose management strategies to minimize effects on wild populations (Lafferty et

al., 2015 and Ben-Horin et al., 2015). Understanding the spatial patterns in prevalence of nematode infestations in scallops will provide crucial information to direct management of this valuable fishery. This will also aid in incorporating disease prevalence and spatial scale into the assessment of the stock. The 2018 benchmark assessment for sea scallops included a discussion of the effect of nematode infections on scallops, but was unclear about the impact of infections on the fishery or the health of scallops (NEFSC, 2018).

Marine ecosystems are comprised of complex food web pathways, with many taxa evolved to feed as generalists that switch prey as prey abundances vary. Marine disease systems likewise include many complex interactions and community level effects on transmission pathways (Holt et al., 2003; Johnson et al., 2015). Recent results from experiments conducted during a National Science Foundation-funded Ecology and Evolution of Infectious Disease program demonstrated that certain components of the macrobenthic community can alter a host's pathogen exposure in an estuarine marine disease system (Ben-Horin et al., 2015).

In 2015, commercial fishermen began reporting observations of rust or brown lesions in the adductor muscle of the sea scallop, *Placopecten magellanicus.* This was not the first instance of the commercial industry observing these lesions; in 2005 industry reported similar observations, but the infections did not persist. During the Virginia Institute of Marine Science's (VIMS) 2015 fishery independent scallop dredge survey, the scientific crew began to monitor adductor muscles for the presence and prevalence of lesions. This monitoring is ongoing and has continued through 2018. VIMS scientists identified the larval anisakid nematode *Sulcascaris sulcata* as the cause of the lesions present in sea scallops in the region through both genetic and histological examination (Rudders and Roman, 2018a).

The life history, physical characteristics and appearance of *S. sulcata* have been well described by several authors in relation to marine mollusks (Cobb, 1930; Lichtenfels et al., 1978; Lichtenfels et al., 1980; Berry and Cannon, 1981). The species has four larval stages, with the third and fourth stages found in marine mollusks. Marine mollusks act as an intermediate host, while several species of sea turtle including loggerhead (*Caretta caretta*), green (*Chelonia mydas*) and Kemp's Ridley turtles (*Lepidochelys kempii*) serve as final hosts for the adult stage (Lichtenfels et al., 1978; Barry and Cannon, 1981; Greiner, 2013). Adult nematodes reside in the gastrointestinal track of turtles (Barber et al., 1987; Deardorff, 1989; Gračan et al., 2012; Greiner, 2013). Turtles become infected by consuming diseased mollusks as the adult nematodes undergo sexual reproduction, eggs are released into the water column in the feces (Barry and Cannon, 1981; Deardorff, 1989; Barber et al., 1987; Gračan et al., 2012). Nematode larvae progress through the first two stages of development in the water column/benthos and enter marine mollusks and where they progress through the final

two stages of larval development (Berry and Cannon, 1981; Barber et al., 1987; Deardorff, 1989). Third and fourth stage larvae are tubular worms coiled within an encapsulated sheath in the soft tissue and present as brown, rust or yellow colored lesions or cysts with a typically elongated shape in marine bivalves (Lichtenfels et al., 1978; Barry and Cannon, 1981; Barber et al., 1987; Deardorff, 1989).

As observations of infected scallops have continued, several important research questions have been raised by industry, scientists and fishery managers. These questions relate to the spatial extent and variability of infections, as well as, infection transmission, post processing to improve marketability and impact on human health. To answer these questions, the project developed several goals and objectives:

1. Identify the spatial extent of this parasitic nematode in the scallop stock during the 2016 and 2017 fishing seasons.
2. Investigate the seasonal and annual variability of parasite prevalence and intensity in scallop adductor muscles.
3. Test for relationships among area management strategies, scallop densities and parasite prevalence.
4. Perform laboratory-based experiments to understand parasite shedding and transmission mechanisms.
5. Evaluate post-harvest processing techniques to improve market acceptance of affected meats.

Methods

Data Collection

Fishery Independent Data

Annual data on the intensity and prevalence of nematode infected scallops were collected during VIMS Mid-Atlantic (MA) fishery-independent sea scallop dredge surveys conducted onboard commercial fishing vessels from 2015 – 2018. Intensity is defined as the number of lesions observed on an infected scallop, and prevalence is the number of scallops infected out of scallops sampled expressed as a percentage. The VIMS survey utilizes a stratified random design and the sampling domain extended from the Virginia/North Carolina border to south of Block Island (Figure 2). Each year, approximately 450 randomly selected stations were sampled (Figure 2).

The vessels simultaneously towed two dredges. A National Marine Fisheries Service (NMFS) sea scallop survey dredge, 8 feet in width equipped with 2-inch rings, 3.5-inch diamond mesh twine top and a 1.5-inch diamond mesh liner was towed on one side of the vessel. On the other side of the vessel, a 14 foot Coonamessett Farm Foundation Turtle Deflector dredge equipped with 4-inch rings, a 10-inch diamond mesh twine top and no liner was utilized. A Star-Oddi inclinometer was placed on the survey dredge to record dredge angle, temperature and depth.

Standard VIMS sampling protocols were used on all surveys (Rudders and Roman, 2018a). Dredges were fished for 15 minutes with a towing speed of approximately 3.8 - 4.0 kts and a scope-to-depth ratio of 3:1. Sampling of the catch was performed using the protocols established by DuPaul and Kirkley (1995). For each station, the entire scallop catch from each dredge was placed in baskets. Depending on the total volume of the catch, a subsample was measured to record sea scallop length frequency.

In addition to length data, biological information was collected from scallops across the survey domain. At each station, 15 scallops were randomly selected from across the size range of observed animals. The shell height of each sampled scallop, scallop was measured to the nearest mm and the adductor muscle was carefully removed and weighed on a Marel motion compensating balance to the nearest 0.5 gram (g). Biological characteristics including reproductive state, sex, presence of shell disease, presence of nematode lesions and meat quality were recorded. For nematode observations, presence/absence data and the number of lesions observed on an individual scallop were recorded.

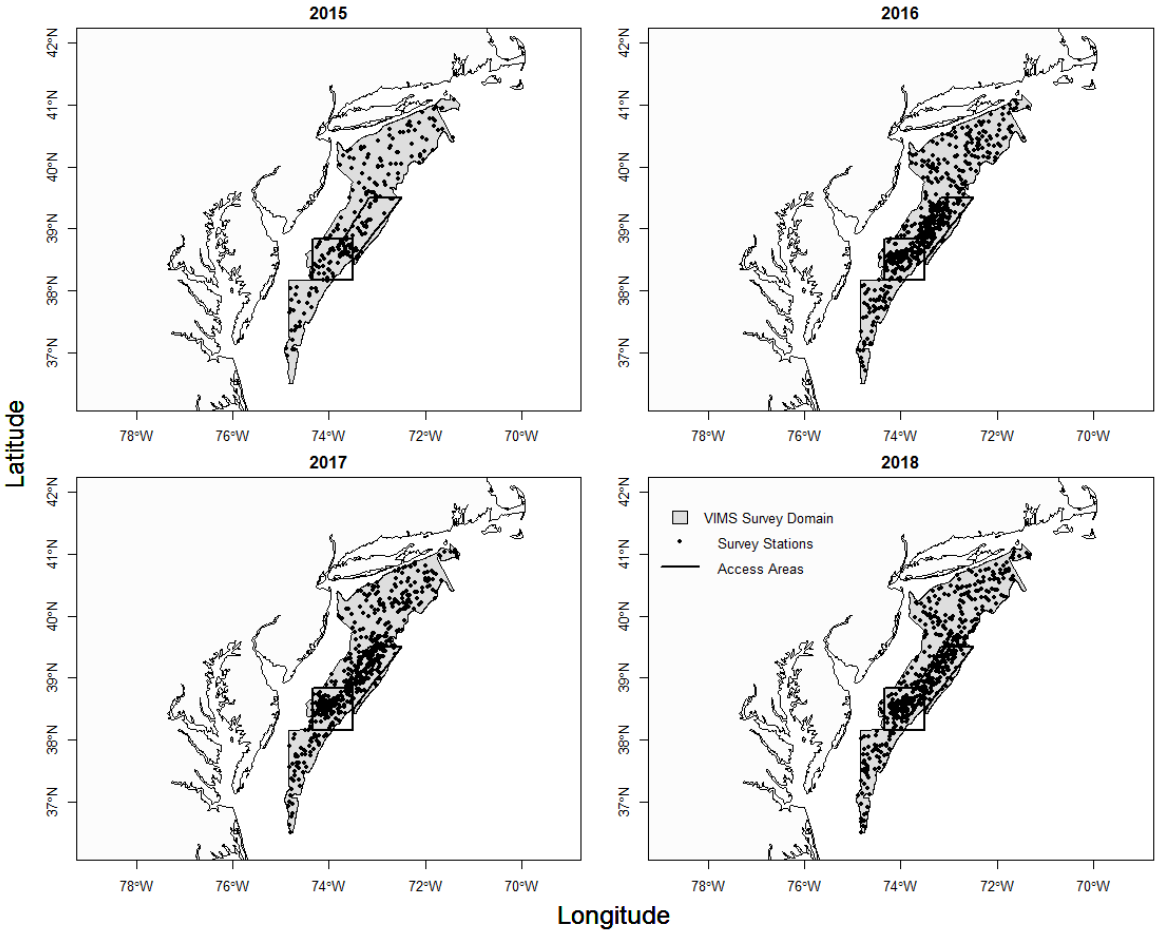

Figure 2. Mid-Atlantic survey domain (gray) along with survey stations (black points) completed by year for 2015 - 2018 for the VIMS sea scallop dredge survey.

Targeted Fishery Sampling

In addition to the annual sampling conducted during the VIMS resource surveys, more intense sampling was conducted in 2016 and 2017 onboard commercial vessels out of Cape May, NJ. The study site consisted of area in the Elephant Truck (ET) and Hudson Canyon (HC) Access Areas (Figure 3), also referred to collectively as the Mid-Atlantic Access Area (MAAA). Data from the VIMS 2016 annual resource survey regarding infection prevalence and intensity were used to inform site selection for the targeted sampling events. Six sampling trips were conducted over the two-year period. Within the study site, three nematode infection intensity areas were defined: low, medium and high. Site selection was completed on the first trip and determined based on nematode prevalence in scallops examined. Within each intensity-level, three sampling sites were selected and reoccupied on all trips, for a total of nine sites

sampled per trip. The low intensity sites were located in the HC and are referred to as the HCCA sites. The medium intensity sites were located in the ET Flex area (also referred to as ET Close) and are referred to as the Inside sites. The high intensity sites were located in the traditional ET area (ET Open) outside of the ET Flex area and are referred to as the Outside sites.

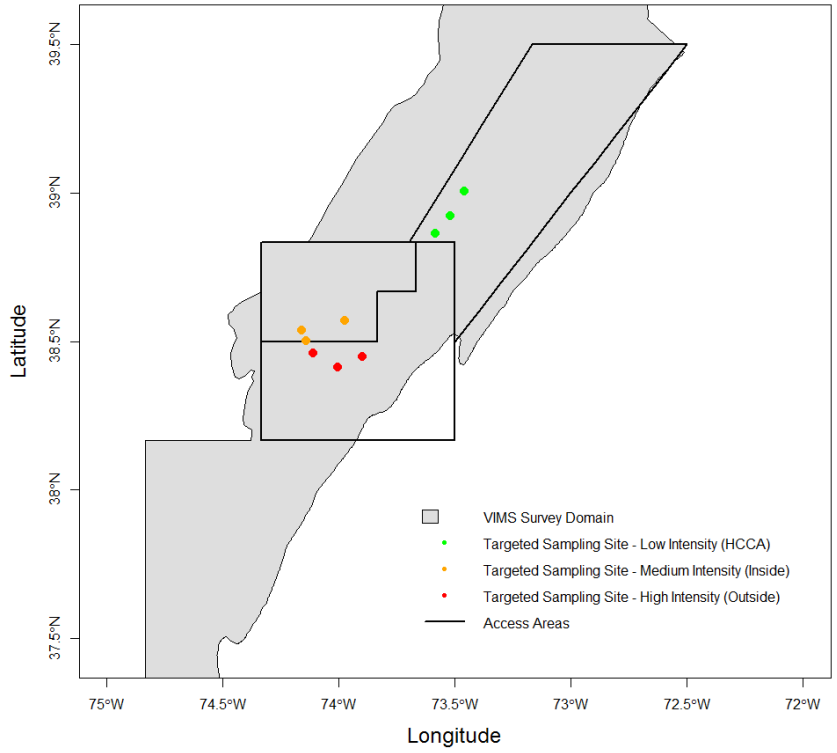

Figure 3. Study area and targeted sampling site locations by nematode intensity level and reference name.

The commercial vessels used protocols similar to the VIMS resource survey sampling protocols (see above). The vessel towed the NMFS survey dredge, and catch was sorted following similar procedures. The total volume of scallop catch was recorded, one basket of scallops was measured to obtain the length frequency distribution of the catch and a random sample of 50 scallops were sampled for biological information. The same information on shell height, meat weight, sex, reproductive stage, presence of shell blister disease and nematode infections was recorded for each scallop.

Laboratory Based Experiments

Live scallops and adductor meats were also retained during the targeted sampling trips for transport to Rutgers University Haskin lab for laboratory experiments.

Experiments focused on shedding, transmission, nematode and lesion observations, tolerance to temperature and scallop survival. Scallops were either retained in recirculating chiller systems or whole on ice during the trip. The number of scallops retained varied by trip. Scallops placed in the chiller systems were separated into different systems based on infection level. Scallops were grouped into a heavily infected or lightly/uninfected group based on site intensity level. Other live scallops were preserved on ice and selected by size class. Ten scallops were selected by small, medium and large sizes. The number of adductor muscles collected on a trip also varied.

Shedding Experiment

Scallops were placed into individual buckets with filtered seawater once they arrived at the lab for the shedding experiments. Six replicate shedding experiments were performed with scallops collected from each sampling trip. In September, 15 buckets were used and an additional set of three tanks contained 10 scallops each. Five scallops from individual buckets and all scallops from one bin were shred on days 6, 12 and 19 to mimic predator damage or discard of meats and soft tissue while fishing. Water was replaced daily and examined under a dissecting scope pre- and post-shredding for nematodes. In November, 29 scallops were placed into individual buckets with five of those shucked and shred prior to being placed into the buckets and five of the others shred on days 2, 3, 6 and 7, looking for nematodes and replacing water daily as in September. In January, 30 scallops were placed into individual buckets and 10 scallops were shucked and shred on day 2, 7, and 10. In March, 10 scallops were shucked and shredded on days 8, 9, and 13. In May and July, 10 scallops were shucked and shred on days 3, 4, and 5.

Transmission Experiment

Following each sampling trip, scallops from relatively uninfected sites were distributed in a raceway and subsequently exposed to shucked scallops from heavily infested sites (Figure 4). Control comparisons were performed with relatively uninfected scallops held in control tanks and not exposed to shucked, infected scallops. In September 2016, 98 lightly infected scallops were dosed 3 times over the course of one week with a total of 61 shucked infected scallops containing 148 lesions (dose = 1.5 lesions per scallop). In November 2016, 67 lightly infected scallops were dosed 5 times over eight days with 108 shucked infected scallops containing 238 lesions (dose = 3.6 lesions per scallop). In January 2017, 127 lightly infected experimental scallops were dosed 5 times over three weeks with 152 shucked infected scallops containing 401 lesions (dose = 3.2 lesions per scallop). In March 2017, 128 lightly infected experimental scallops were dosed 5 times over three weeks with 152 shucked infected scallops containing 393 lesions (dose = 3.1 lesions per scallop). In May 2017, 130 lightly infected experimental scallops were dosed 2 times over one week, once before

and once after a complete mortality event in the infected dosing tanks, from a total of 60 shucked infected scallops containing 218 lesions (dose = 1.7 lesions per uninfected scallop). By the day after the second dose, 83 percent of the experimental scallops were dead. In July 2017, 96 lightly infected experimental scallops were dosed twice within a week of collection (dose = 2.3 lesions per uninfected scallop). The experimental tank also held an equal number of scallops from heavily infected sites, separated in labeled trays, in order to increase potential contact with nematodes.

Figure 4. Image of scallops from relatively uninfected sites distributed in a raceway for transmission experiments.

Nematode and Lesion Observations

During the September, January, March, May and July sampling trips, 30 scallops per tow (10 per small, medium and large size classes) were bagged and stored on ice. These scallops were processed in the lab as on the boat, tracking the recorded tow data for each individual. All lesions from the tow specific scallops collected in January, March, May, and July 2017 were dissected within two days of landing, squashed on a microscope slide with a coverslip, and examined microscopically for nematodes. Live nematodes (n=129) were extracted and refrigerated in seawater in 96-well plates (Figure 5) for subsequent measurement.

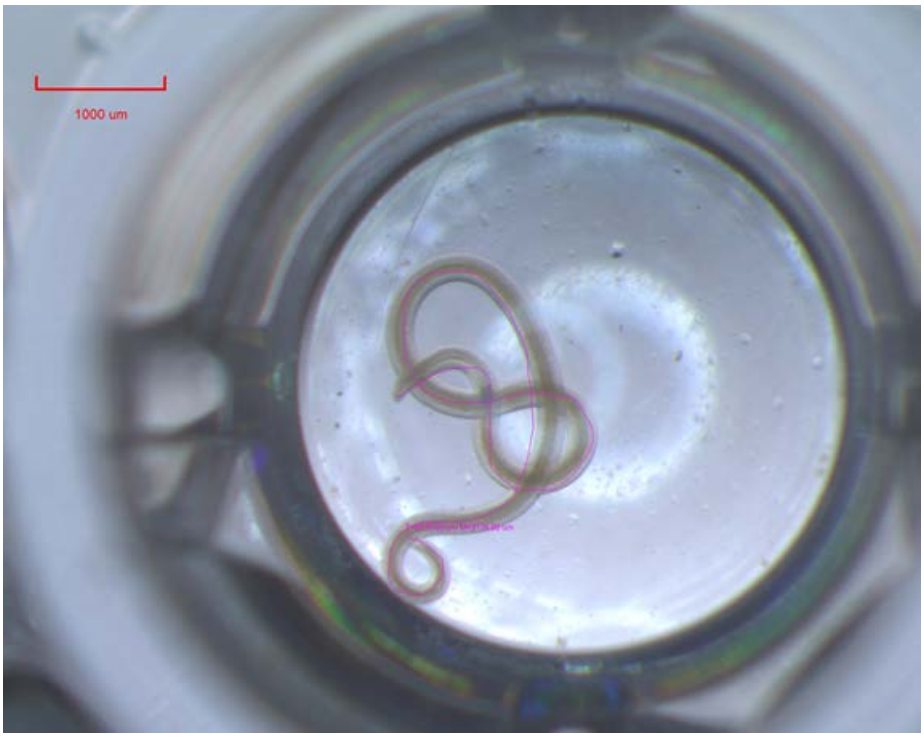

Figure 5. Nematode extracted live from a lesion for length measurement.

Tolerance to Temperature Experiment

Although not part the scope of work for the proposed project, nematodes extracted from lesions were exposed to various temperatures to evaluate tolerance. Nematodes (n = 20 per treatment) were placed in water baths of 37°C, 56°C, 75°C and 95°C, with controls held at 4°C and room temperature (18-23°C).

Survival Experiment

In July, additional tanks were set up to determine survival rates of scallops with varying degrees of nematode infection. Dead animals were removed daily, measured, and lesions counted. After 60 days, all remaining survivors were sacrificed and examined.

Post Processing Techniques

The rust–brown lesions created by encysted larval nematode worms contrasts with the cream-white color of the sea scallop meat in which they embed, thus causing an economic problem due to scallop aesthetics. This contrast is unforgiving in the scallop market, as is viewed as a quality defect though the muscle itself shows no signs in loss of quality. The larval worm itself is small and transparent, and is largely not the marketing problem; the dark lesion formed around the worm is. We explored the visual

effect routine processing has on the overall appearance of infected raw and cooked scallops which may lead to an acceptable product form.

As with many raw seafood products, generally recognized as safe (GRAS) processing aids are used for various quality and/or marketing reasons. In sea scallops, there exists a sizable market for processed scallops in which GRAS substances are used to control moisture and extend shelf-life. Various forms of food grade phosphates, together with other salts, are routinely used by industry for such purposes. Phosphates tend to solubilize surface proteins (the positioning of most lesions in scallop meats), resulting in muscle translucency and glassy appearance. The effect of phosphates on lesion pigmentation was tested. Scallops presenting with a low prevalence of lesions were processed in a solution of 2.5 percent sodium tripolyphosphate (STPP) plus 1 percent NaCl for 6 hours. Other GRAS adjuncts have been used in scallop processing as whitening agents. The effect of a whitening agent in scallop processing to lighten the pigmented tissue of nematode lesions was tested with the application of citric acid in STPP processing.

Cooking denatures the scallop protein and typically results in scallops appearing opaque, which would also highlight the darker pigmented lesions. The moisture content in processed scallops, especially around the meat surface to depths related to the degree (duration) of processing, largely steams scallop protein during most cooking methods, with the water content too high to allow browning of the muscle. Scallops marketed as dry or lightly processed scallops do not generally possess the artifacts of phosphate processing, notably additional moisture in surface muscle tissue. These scallops are of higher value due to less water weight, but also because they are a market form that white tablecloth restaurants use for entries since they caramelize (browning) when cooked (broiled) due to low water content. This browning under high heat cooking was tested to see how well the rust-brown lesion would blend into the broiled scallop. Unprocessed scallops with lesions were broiled in an electric broiler oven. Scallops were arranged on a self-draining broiler pan, placed in oven 12cm from preheated electric broiling coil, and held in oven until cooked to an internal temperature of 70°C (~4 minutes).

Data Analysis

Fishery Independent Data

Data collected from the biological assessments were used to examine the prevalence, intensity and spatial distribution of infected scallops. Prevalence was defined as the number of scallops observed to be infected as a percentage of all scallops sampled at a given station. Intensity was defined as the mean number of lesions observed in infected scallops at a given station. The spatial distribution of

nematode infections was estimated with an inverse distance weighted interpolation (IDW) method for both prevalence and intensity. IDW was used to estimate infections for areas unsampled by the VIMS survey using point data from sampled stations by year (Fortin and Dale, 2006). IDW was conducted in R with the gstat package (R Core Team, 2006; Benedikt et al., 2016). Maps depicting the spatial distribution were compared across all years (2015 - 2018) to document the spatial extent and examine for temporal shifts in the distribution of infected scallops.

A mixed effect generalized additive model (GAMM) was developed to predict the probability of a scallop being infected with nematodes. GAMMs were developed using forward selection with several fixed effect explanatory variables: shell height (mm), sex, total density (scallops/m^2), average depth (m), average temperature (°C) and year. An additional fixed effect, a tensor product of latitude and longitude was included to account for the spatial component of infected scallops. Station was treated as the random effect to account for correlation between scallops caught at the same station (Pinheiro and Bates, 2000; Zuur et al., 2013). For continuous variables, a penalized regression spline was used as the smoother and smoothing functions were selected with generalized cross validation. Restricted maximum likelihood was used for smoothness selection (Wood and Scheipl, 2014). Sex and year were included as categorical variables. Year and location were retained in all models. Fixed effect variables were added based on a variable's contribution to the Akaike Information Criterion (AIC), and the preferred model was selected as the model with the lowest AIC (Burnham and Anderson, 2002). Variables were retained if the AIC was reduced by 3 or more units. The gamm4 package in R v. 3.3.2 was used to fit all models (R Core Team, 2016; Wood and Scheipl, 2014).

Targeted Fishery Sampling

Biological data collected from individual scallops were analyzed to look at several areas of concern in regard to nematode infections. Prevalence and intensity have the same definition as described above in the Fishery Independent Data Analysis section. The intensity and prevalence of nematode infections was summarized by intensity level and trip. Mean intensity and prevalence by trip and intensity level were also plotted with 95 percent confidence intervals. This information allowed us to detect seasonal variation in infection rates as a function of intensity level. The relationship between shell height and mean number of lesions was also assessed visually through length frequency plots by intensity level and trip. Overall marketability of scallops was evaluated by intensity level and trip to determine if nematode infections affected product quality. A shell height meat weight (SHMW) relationship was developed to determine if the presence or intensity of nematode infections impacted meat weight. A generalized linear mixed model (GLMM) was developed following similar methods employed by

VIMS to estimate SHMW relationships for annual resource surveys (Rudders and Roman, 2018a; Rudders and Roman, 2018b). The relationship between shell height and meat weight was estimated with a GLMM (gamma distribution, log link, random effect at the station level) incorporating trip, nematode incidence (number of lesions), nematode presence/absence data, maturity stage and intensity level as explanatory variables (Pinheiro and Bates, 2000; Zuur et al., 2013). Explanatory variables were added based on a variable's contribution to the AIC, and the preferred model was selected as the model with the lowest AIC (Burnham and Anderson, 2002). Variables were retained if the AIC was reduced by 3 or more units. Analysis was completed with the glmer function in the lme4 package in R v. 3.3.2 (Bates et al., 2015; R Core Team, 2016).

Results

Fishery Independent Data

The spatial distribution for prevalence of nematode infected scallops by year is shown in Figure 6 and intensity in Figure 7. Summary information by Scallop Area management Simulator (SAMS) Area regarding infected scallops and sample sizes are provided in Table 1. As reported by commercial fishers, the highest percentage of infected scallops was found in the southern portion of the MA resource area. There was a decline in infections with increasing latitude across all years, and this pattern holds for intensity as well. Scallops located off of Virginia through Delaware have been more heavily infected across all years compared to scallops from New Jersey north. Prevalence of infected scallops from Virginia through Delaware ranged from 21 to 47 percent, annually, while 2 to 13 percent of scallops located off of New Jersey were infected. Scallops off of Long Island had the lowest infection rates (0.5 – 4 percent). Intensity across the MA resource was similar to prevalence. Scallops south of New Jersey had a greater number of lesions observed per scallop. There was a decline in the number of lesions observed per scallop as latitude increased. Some infected scallops have been observed in the northern portion of the MA resource area, but the number of infected scallops is much lower and more diffuse in their distribution.

Some temporal changes in the distribution of infected scallops were observed when looking at the spatial distribution across years. In 2015, when reports began, the majority of heavily infected scallops were south of 38° N. In 2016, the range of severely infected scallops expanded northward to Delaware and slightly less infected scallops were observed off the coast of New Jersey. A contraction of infections and severity of infections occurred in 2017. The locus of infected scallops was observed from northern Virginia to New Jersey. The range of infections expanded again in 2018, and was similar to that observed in 2016.

The preferred GAMM indicated year, latitude, longitude, sex and shell height had an impact on the probability a scallop was infected with a nematode (Table 2). The model explained 30 percent of variation in nematode infected scallops. Model fit was satisfactory (Figure 8). The probability of being infected over time increased from 2015, when VIMS began recording observations of nematode infected scallops, although from 2016 – 2018 the odds of infection were similar between years (Table 3). Female scallops were also more likely to be infected compared to male scallops or scallops of unknown sex (Table 3). Partial effect plots for shell height and the tensor project of latitude and longitude are shown in Figure 9. There is a latitudinal gradient in the probability of being infected. This result is similar to the idw interpolation of intensity and prevalence estimated from the VIMS resource survey data. The probability of being infected also increases as a function of shell height.

Table 1. Number of scallops assessed for nematode infections by SAMS Area and year during VIMS annual resource assessment surveys. The total number of scallops sampled along with the minimum and maximum number of lesions observed, total number of lesions and number of infected scallops is included. Intensity is the mean number of lesions observed in infected scallops and prevalence is the number of scallops observed to be infected as a percentage of all scallops sampled. The last four columns provide summary information for each SAMS Area pooled across years.

SAMS Area	Year	Number Scallops Sampled	Minimum Incidence	Maximum Incidence	Number of Lesions	Number of Scallops Infected	Intensity	Prevalence	Total Number of Scallops Sampled	Total Number of Lesions	Total Number of Infected Scallops	Average Prevalence
VIR	2015	3	0	4	8	2	4.00	0.67	58	8	2	0.03
	2016	10	0	0	0	0	0	0				
	2017	45	0	0	0	0	0	0				
	2018	0	0	0	0	0	0	0				
DMV	2015	198	0	7	210	90	2.33	0.45	1,118	1,676	569	0.51
	2016	333	0	12	728	234	3.11	0.70				
	2017	426	0	9	401	145	2.77	0.34				
	2018	161	0	13	337	100	3.37	0.62				
ET_Open	2015	386	0	5	65	46	1.41	0.12	2,791	2,546	1,063	0.38
	2016	814	0	11	847	366	2.31	0.45				
	2017	791	0	9	759	315	2.41	0.40				
	2018	800	0	18	875	336	2.60	0.42				
ET_Close	2015	280	0	3	50	35	1.43	0.13	2,337	1,800	803	0.34
	2016	603	0	9	438	216	2.03	0.36				
	2017	653	0	12	524	240	2.18	0.37				
	2018	801	0	16	788	312	2.53	0.39				
HCS	2015	254	0	2	2	1	2.00	0.00	3,939	671	436	0.11
	2016	1,380	0	8	317	211	1.50	0.15				
	2017	1,162	0	5	185	109	1.70	0.09				
	2018	1,143	0	6	167	115	1.45	0.10				
NYB_inshore	2015	147	0	3	3	1	3.00	0.01	817	162	93	0.11
	2016	257	0	6	61	35	1.74	0.14				
	2017	271	0	5	65	34	1.91	0.13				
	2018	142	0	3	33	23	1.43	0.16				
NYB	2015	299	0	1	2	2	1.00	0.01	2,787	268	185	0.07
	2016	765	0	4	91	69	1.32	0.09				
	2017	916	0	4	72	46	1.57	0.05				
	2018	807	0	6	103	68	1.51	0.08				
LI	2015	592	0	1	2	2	1.00	0.00	4,631	133	107	0.02
	2016	1,282	0	2	22	18	1.22	0.01				
	2017	1,333	0	2	26	21	1.24	0.02				
	2018	1,424	0	3	83	66	1.26	0.05				
BI	2015	11	0	0	0	0	0	0	340	0	0	0.00
	2016	90	0	0	0	0	0	0				
	2017	119	0	0	0	0	0	0				
	2018	120	0	0	0	0	0	0				
Total		18,818			7,264	3,258						

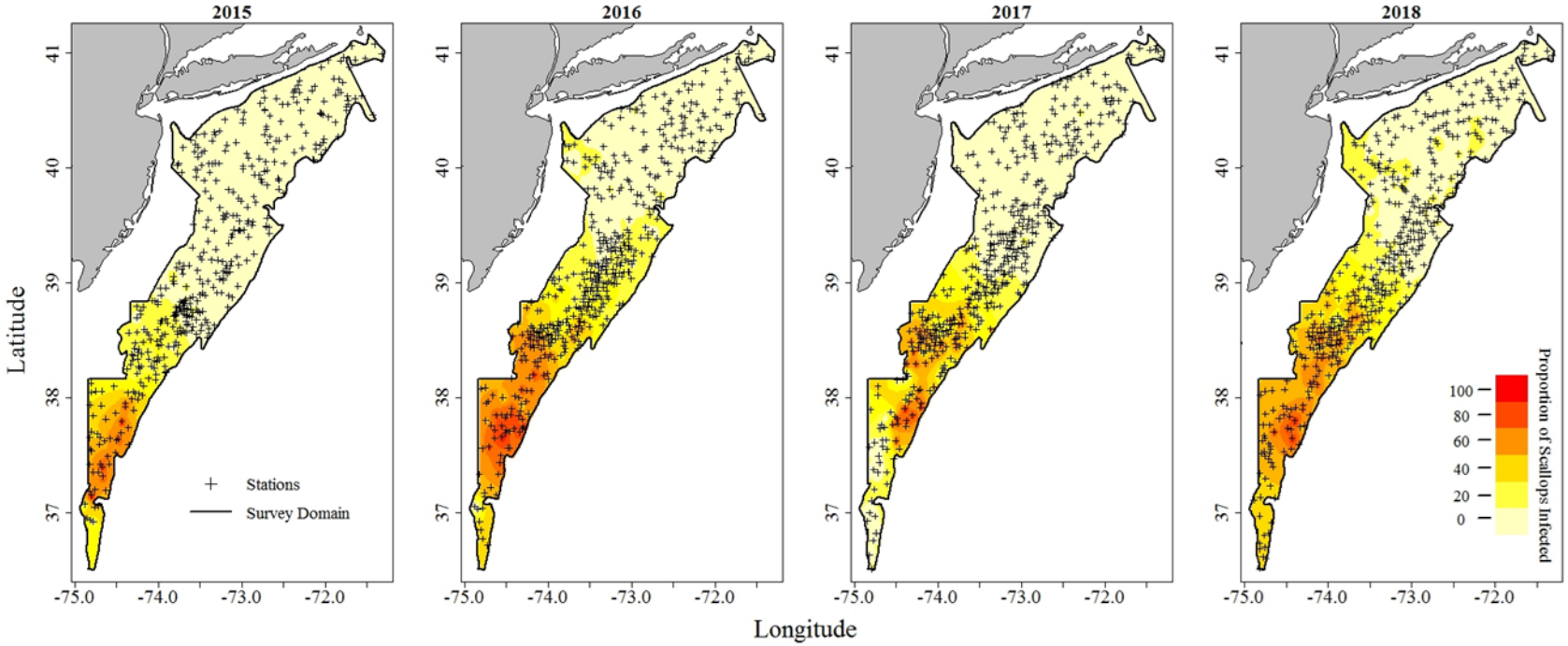

Figure 6. Inverse distance weighted interpolation of prevalence of infected sea scallops in the MA survey area by year with station locations where biological assessments were conducted. Prevalence is defined as the number of sea scallops observed to be infected as a percentage of all sea scallops sampled at a given station.

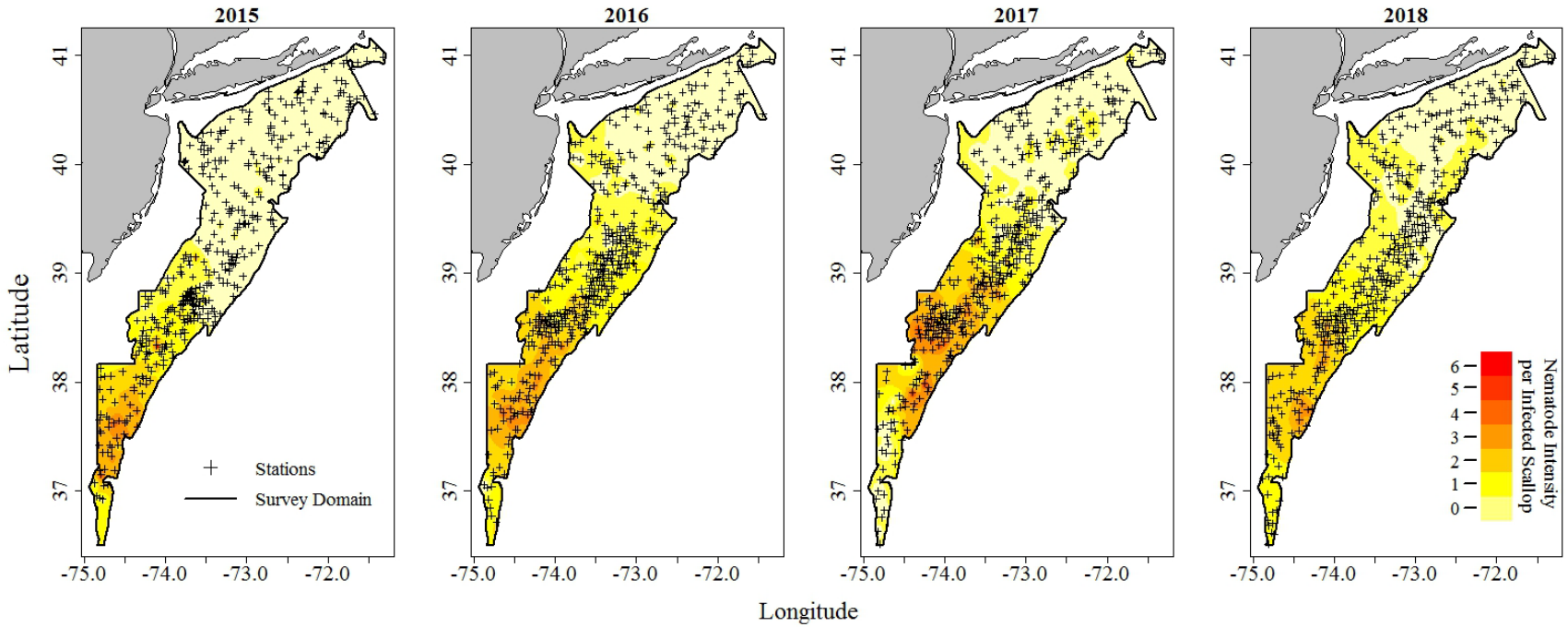

Figure 7. Inverse distance weighted interpolation of intensity of infected sea scallops in the MA survey area by year with station locations where biological assessments were conducted. Intensity is defined as the mean number of lesions observed in infected sea scallops at a given station.

Table 2. GAMMs developed to model the probability of a scallop being infected with nematodes. Predictor variables, AIC and delta AIC (model AIC-lowest AIC) are included. Model 6 in bold is the preferred model. Smoothing functiong are indicated by s(variable).

Model	Variables	AIC	ΔAIC
1	~ s(Latitude + Longitude) + Year	12,746.30	995.83
3	~ s(Latitude + Longitude) + Year + s(Shell Height)	11,760.43	9.96
4	~ s(Latitude + Longitude) + Year +s(Shell Height) +Temperature	11,762.42	11.95
5	~ s(Latitude + Longitude) + Year + s(Shell Height) + s(Density)	11,758.09	7.62
6	**~ s(Latitude + Longitude) + Year + s(Shell Height) + Sex**	**11,750.47**	0
7	~ s(Latitude + Longitude) + Year + s(Shell Height) + Sex + s(Depth)	11,751.41	0.94

Table 3. Preferred model parameter estimates for Model 6 for the parametric terms (top) and smooth terms (bottom), along with standard errors, effecitve degrees of freedom, Chi square statistic and P-Values.

Parameter	Parameter Estimate	Std. Error	P Value
Intercept	-4.70	0.16	<0.0002
Year 2016	2.20	0.16	<0.0002
Year 2017	2.29	0.16	<0.0002
Year 2018	2.40	0.16	<0.0002
Sex Male	-0.19	0.05	<0.0002
Sex Unknown	-0.17	0.16	0.2734
Smooth Terms			
	Effective Degrees of Freedom	Chi square	P Value
t2(Longitude, Latitude)	3.00	1,460.90	<0.0002
s(Shell height)	5.79	608.50	<0.0002

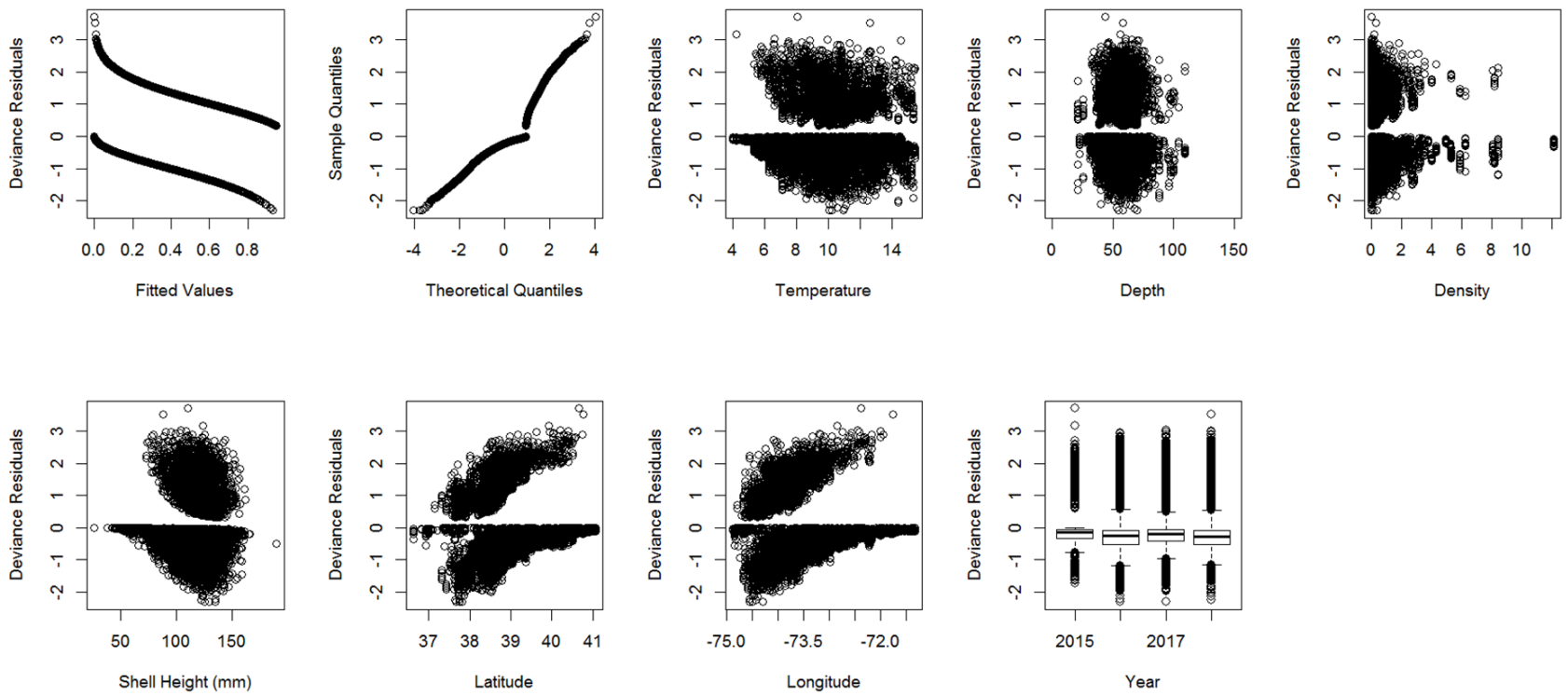

Figure 8. Model disagontic plots for the preferred GAMM (Model 6). Deviance residuals are plotted against the predicted values on the logit scale (top left), follwed by a Q-Q plot. The remaining plots are deviance residuals plotted against predictor variables.

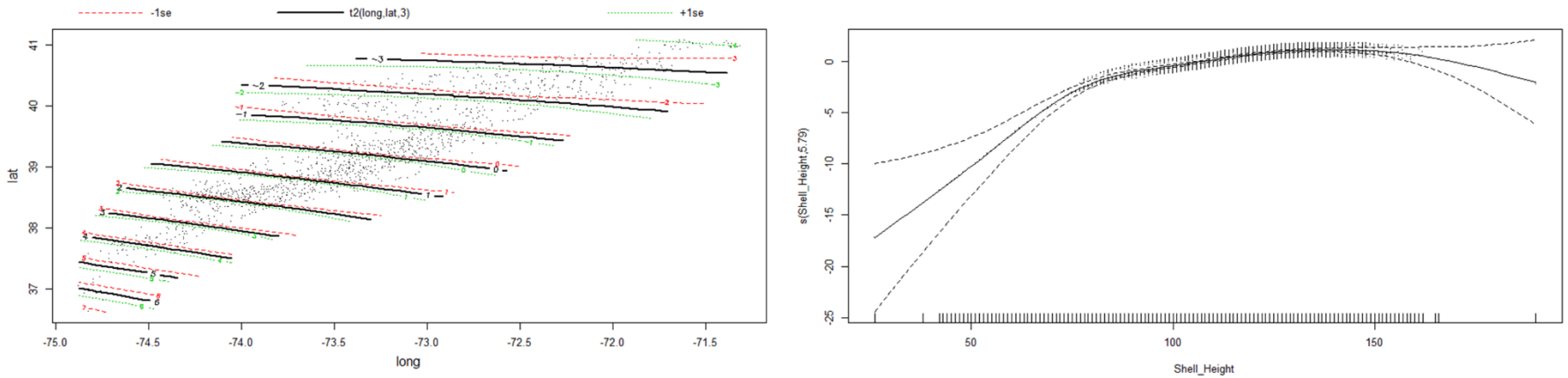

Figure 9. Partial effect plots for the tensor product of longitude and latitdue (left) and shell height (right) for the preferred GAMM (Model 6).

Targeted Fishery Sampling

Six sampling trips were conducted from September 2016 through September 2017 (Table 4). All trips, with the exception of trip 5, departed from Cape May, NJ. Data were collected during VIMS' 2017 resource survey on trip 5. All nine sampling sites were reoccupied on each trip (Figure 3).

Table 4. Summary information for sampling trips.

Trip	Vessel	Port	Trip Start Date	Trip End Date
1	*F/V* Elise G	Cape May, NJ	9/8/2016	9/9/2016
2	*F/V* Elise G	Cape May, NJ	11/14/2016	11/15/2016
3	*F/V* Elise G	Cape May, NJ	1/9/2017	1/10/2017
4	*F/V* Elise G	Cape May, NJ	3/6/2017	3/7/2017
5	*F/V* Sea Hawk	Seaford, VA	5/8/2017	5/18/2017
6	*F/V* Nancy Elizabeth	Cape May, NJ	9/12/2017	9/18/2017

Intensity and prevalence of nematode infections across intensity levels was relatively consistent (Table 5). Low intensity stations had the lowest intensity (1.15 – 1.65 mean number of lesions per scallop) and prevalence (0.13 – 0.19 percent of scallops infected) of nematode infections across all six trips. The medium and high intensity stations exhibited similar patterns across all trips. Medium intensity level trip intensity ranged from 1.36 to 2.03 lesions per scallop and the percentage of infected scallops ranged from 0.31 to 0.46. The high intensity level trips had the greatest percentage of infected scallops across all trips (0.45 – 0.63), and the greatest mean number of lesions observed per infected scallop (1.75 – 2.43). The average number of infected scallops per intensity level, pooled across all trips, followed a similar trend of increasing prevalence with intensity level. When comparing mean prevalence across trips by intensity level, no temporal variation was observed (Figure 10). For intensity, there was some variation in the mean number of lesions counted per infected scallop (Figure 11). For low and medium intensity levels, an increase in lesion count was observed between trips 2 and 4 from November through March. High intensity sites had the lowest number of lesions observed on trip 2 as well.

Table 5. Number of scallops assessed for nematode infections by intensity level and trip for targeted fishery sampling. The total number of scallops sampled, along with the minimum and maximum number of lesions observed, total number of lesions and number of infected scallops is included. Intensity is the mean number of lesions observed in infected scallops and prevalence is the number of scallops observed to be infected as a percentage of all scallops sampled. The last four columns provide summary information for each intensity level pooled across trips.

Intensity Level	Trip	Number Scallops Sampled	Minimum Incidence	Maximum Incidence	Number of Lesions	Number of Scallops Infected	Intensity	Prevalence	Total Number of Scallops Sampled	Total Number of Lesions	Total Number of Infected Scallops	Average Prevalence
LOW	1	149	0	4	34	22	1.55	0.15	906	215	147	0.16
	2	150	0	2	23	20	1.15	0.13				
	3	150	0	3	32	25	1.28	0.17				
	4	156	0	5	45	29	1.55	0.19				
	5	151	0	4	43	28	1.54	0.19				
	6	150	0	4	38	23	1.65	0.15				
MEDIUM	1	151	0	8	97	53	1.83	0.35	903	613	339	0.38
	2	150	0	3	64	47	1.36	0.31				
	3	150	0	6	94	50	1.88	0.33				
	4	152	0	6	132	65	2.03	0.43				
	5	150	0	7	104	55	1.89	0.37				
	6	150	0	9	122	69	1.77	0.46				
HIGH	1	150	0	14	140	68	2.06	0.45	904	1,072	487	0.54
	2	150	0	5	126	72	1.75	0.48				
	3	151	0	10	204	86	2.37	0.57				
	4	153	0	12	214	96	2.23	0.63				
	5	150	0	8	233	96	2.43	0.64				
	6	150	0	11	155	69	2.25	0.46				
Total		2,713			1,900	973						

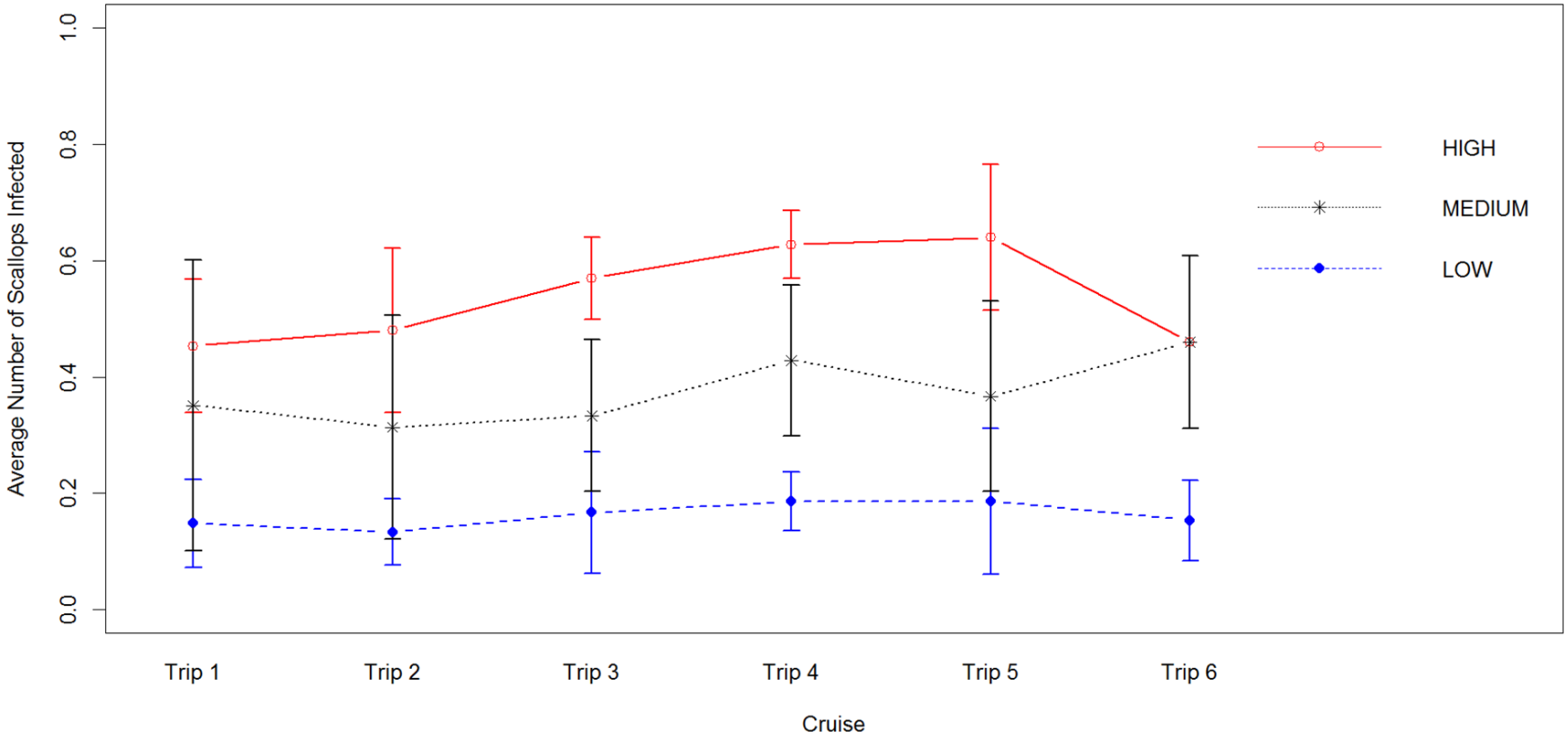

Figure 10. Mean number of infected scallops (prevalence) with 95 percent confidence intervals by intensity level and trip.

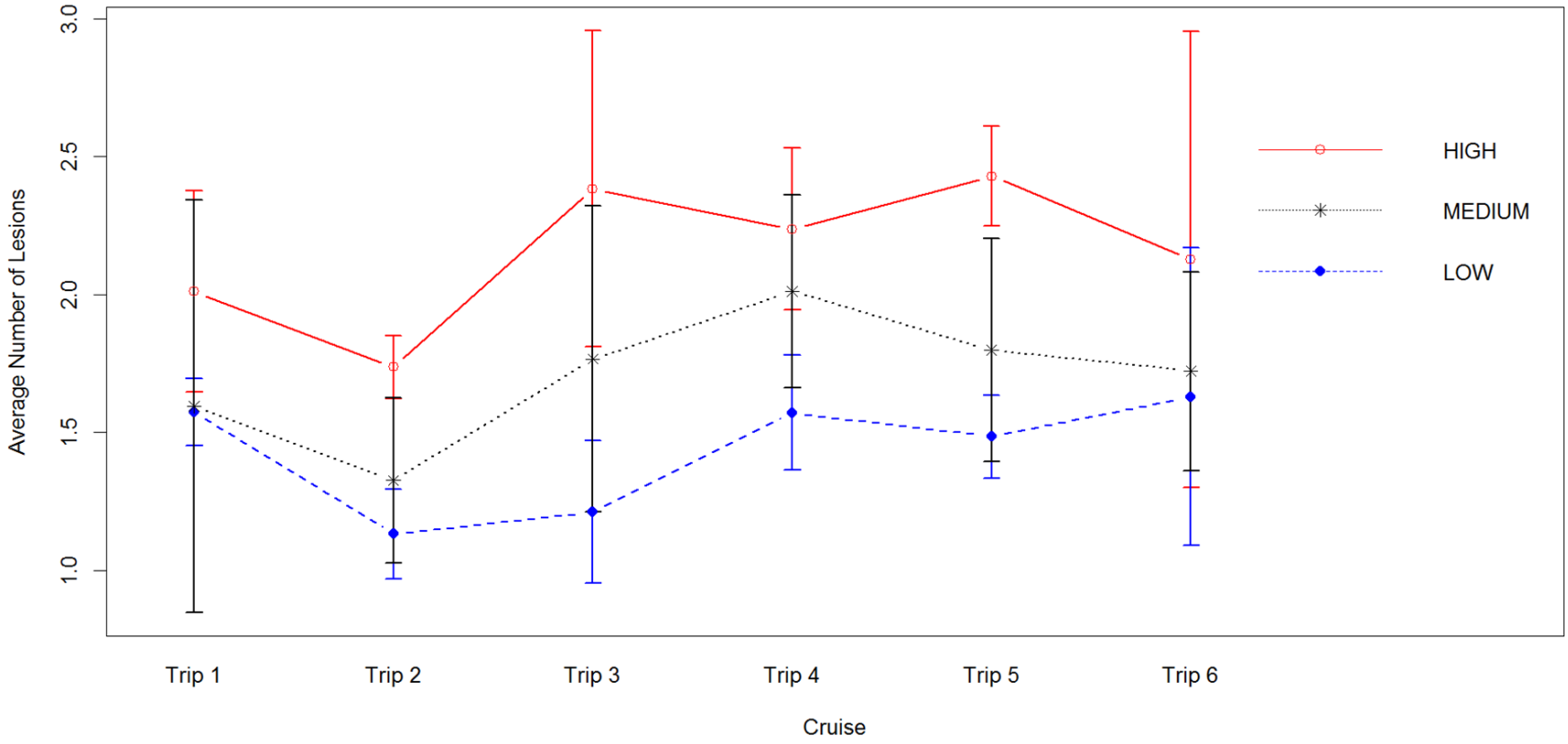

Figure 11. Mean number of lesions observed on infected scallops (intensity) with 95 percent confidence intervals by intensity level and trip

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The number of lesions observed in scallops increased with shell height across all three intensity levels (Figure 12). This relationship held across individual trips (Figure 13). The greatest number of lesions per scallop was found in the high intensity level stations. The number of lesions as a function of shell height was also greatest in the high intensity level compared to the other two levels. For example, a 60 mm scallop had more lesions in the high intensity level compared to the medium or low intensity levels.

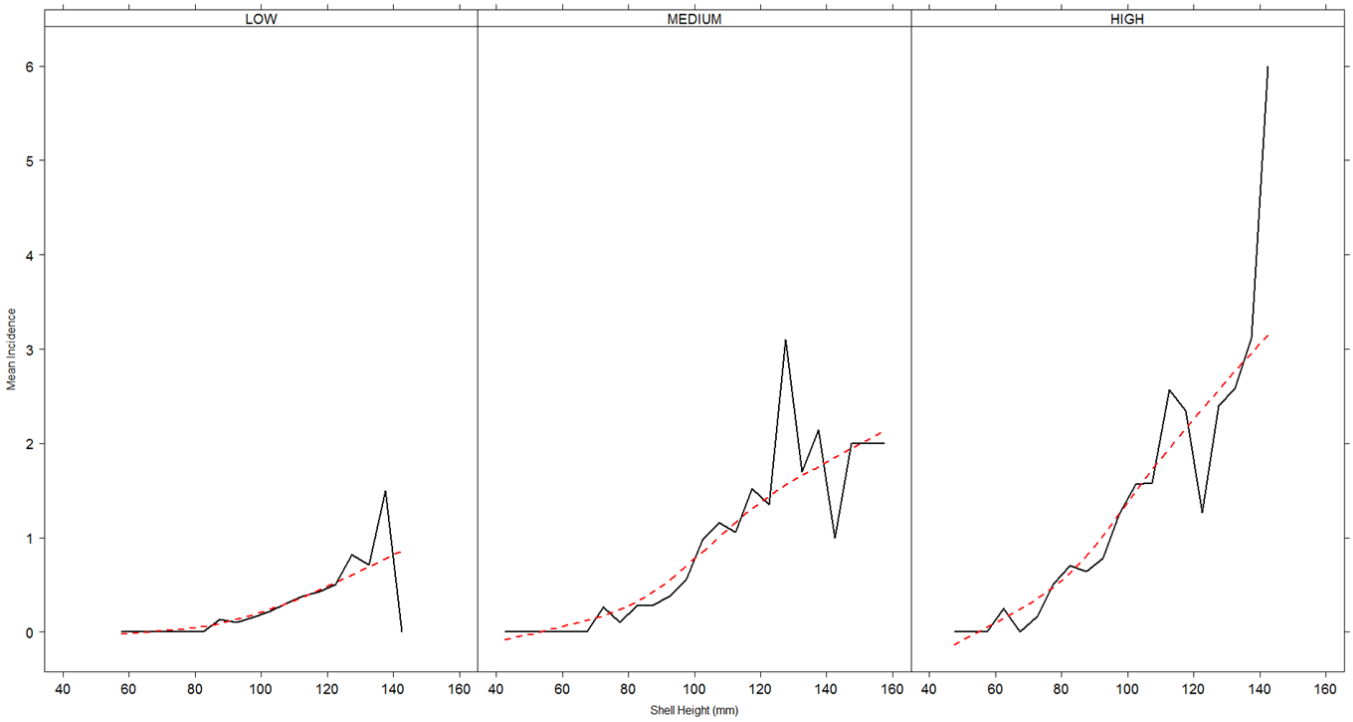

Figure 12. Mean number of lesions observed per infected scallop as a function of shell height with a loess smoother by intensity level.

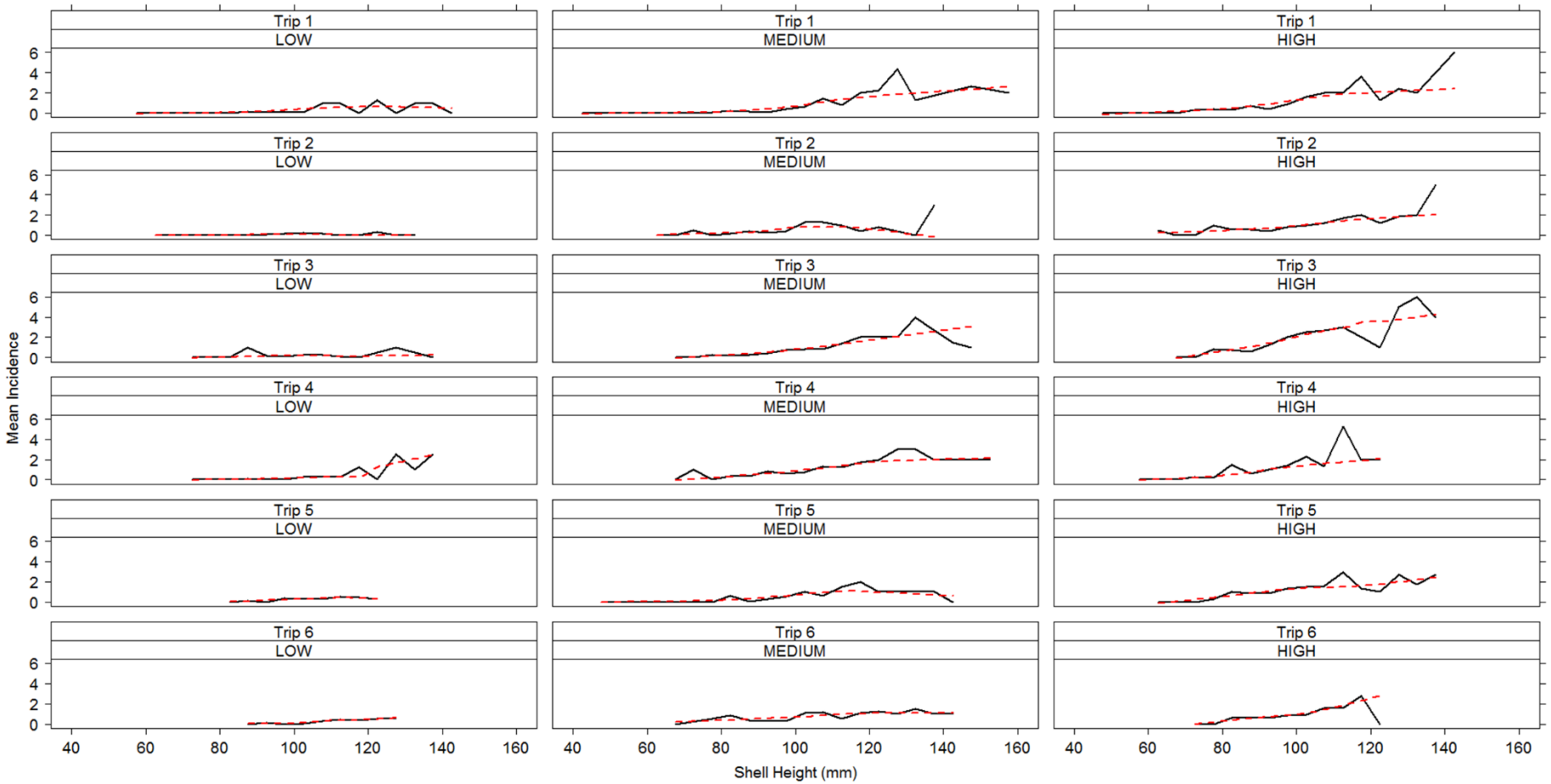

Figure 13. Mean number of lesions observed per infected scallop as a function of shell height with a lowess smoother by intensity level and trip.

Exclusive of nematode lesions traditional metrics of scallop marketability was not impacted by the presence of nematodes. Scallop meat quality (i.e., overall marketability, color and texture) was considered excellent across all intensity levels and trips (Table 6). Shell blister disease was also not regularly observed. The sole reason why scallops would be considered unmarketable in the study site is the presence of nematode lesions on the adductor muscle. The average weight fluctuated over the course of the study for all three intensity levels, and is likely a result of spawning condition.

Table 6. Summary information on market quality conditions assessed by intensity level and trip. Average meat weight is in grams. The next four columns indicate the percentage of scallops classified in the excellent category for overall marketability, adductor meat texture, adductor muscle color and presence of shell blister disease. Intensity is the mean number of lesions observed in infected scallops and prevalence is the number of scallops observed to be infected as a percentage of all scallops sampled.

Intensity Level	Trip	Average Meat Weight (g)	Percentage of Scallops with Excellent Marketability	Percentage of Scallops with Excellent Texture	Percentage of Scallops with Excellent Meat Color	Percentage of Scallops with no Shell Disease	Intensity	Prevalence
LOW	Trip 1	17.52	99%	99%	99%	100%	1.55	0.15
	Trip 2	13.66	99%	77%	99%	100%	1.15	0.13
	Trip 3	13.6	97%	97%	100%	95%	1.28	0.17
	Trip 4	15.42	100%	97%	100%	98%	1.55	0.19
	Trip 5	21.84	97%	95%	100%	96%	1.54	0.19
	Trip 6	21.49	99%	99%	100%	99%	1.65	0.15
MEDIUM	Trip 1	14.68	93%	98%	99%	100%	1.83	0.35
	Trip 2	9.8	95%	89%	97%	100%	1.36	0.31
	Trip 3	12.79	93%	91%	99%	99%	1.88	0.33
	Trip 4	12.54	99%	97%	100%	99%	2.03	0.43
	Trip 5	15.02	98%	98%	99%	100%	1.89	0.37
	Trip 6	19.56	87%	87%	97%	98%	1.77	0.46
HIGH	Trip 1	13.28	93%	97%	99%	95%	2.06	0.45
	Trip 2	11.69	99%	82%	99%	98%	1.75	0.48
	Trip 3	8.6	90%	90%	99%	94%	2.37	0.57
	Trip 4	10.33	99%	97%	100%	97%	2.23	0.63
	Trip 5	16.05	86%	85%	98%	91%	2.43	0.64
	Trip 6	17.38	97%	99%	100%	98%	2.25	0.46

The preferred GLMM for the SHMW relationship indicated shell height, trip, maturity stage and intensity level affected meat weight (Table 7). Neither nematode presence/absence or the number of lesions affected meat weight. Meat weight was greatest at the low intensity levels sites and lowest at high intensity sites (Table 8). There was no significant difference in meat weight between the medium and high intensity sites. The preferred model explained 76 percent of the variation in the data. Model diagnostics plots are provided in Figure 14. Deviance residual plots indicate the model fit was satisfactory.

Table 7. GLMMs developed to model the relationship between meat weight and predictor variables. Predictor variables, AIC and delta AIC (model AIC-lowest AIC) are included. Model 5 in bold is the preferred model.

Model	Variables	AIC	ΔAIC
1	~ Shell Height + Trip	12,663.36	34.04
2	~ Shell Height + Trip + Incidence	12,665.11	35.79
3	~ Shell Height + Trip + Presence	12,665.31	35.99
4	~ Shell Height + Trip + Stage	12,635.46	6.14
5	**~ Shell Height + Trip + Stage + Intensity Level**	**12,629.32**	**0**

Table 8. Preferred fixed effect model parameter estimates for Model 5, along with standard errors, and P-Values.

Parameter	Estimate	Std. Error	P Value
Intercept	-10.80	0.16	<0.0002
log Shell Height	2.94	0.03	<0.0002
Trip 2	-0.27	0.06	<0.0002
Trip 3	-0.32	0.06	<0.0002
Trip 4	-0.30	0.07	<0.0002
Trip 5	-0.04	0.06	0.50
Trip 6	-0.01	0.07	0.91
Maturity Stage Immature	0.11	0.05	0.05
Maturity Stage Mature	0.03	0.02	0.23
Maturity Stage Spent	0.02	0.03	0.55
Maturity Stage Ripe	0.01	0.02	0.66
Maturity Stage Unknown	0.02	0.02	0.41
Maturity Stage Spawning	-0.09	0.02	<0.0002
Intensity Level Low	0.15	0.05	<0.0003
Intensity Level Medium	0.04	0.04	0.36

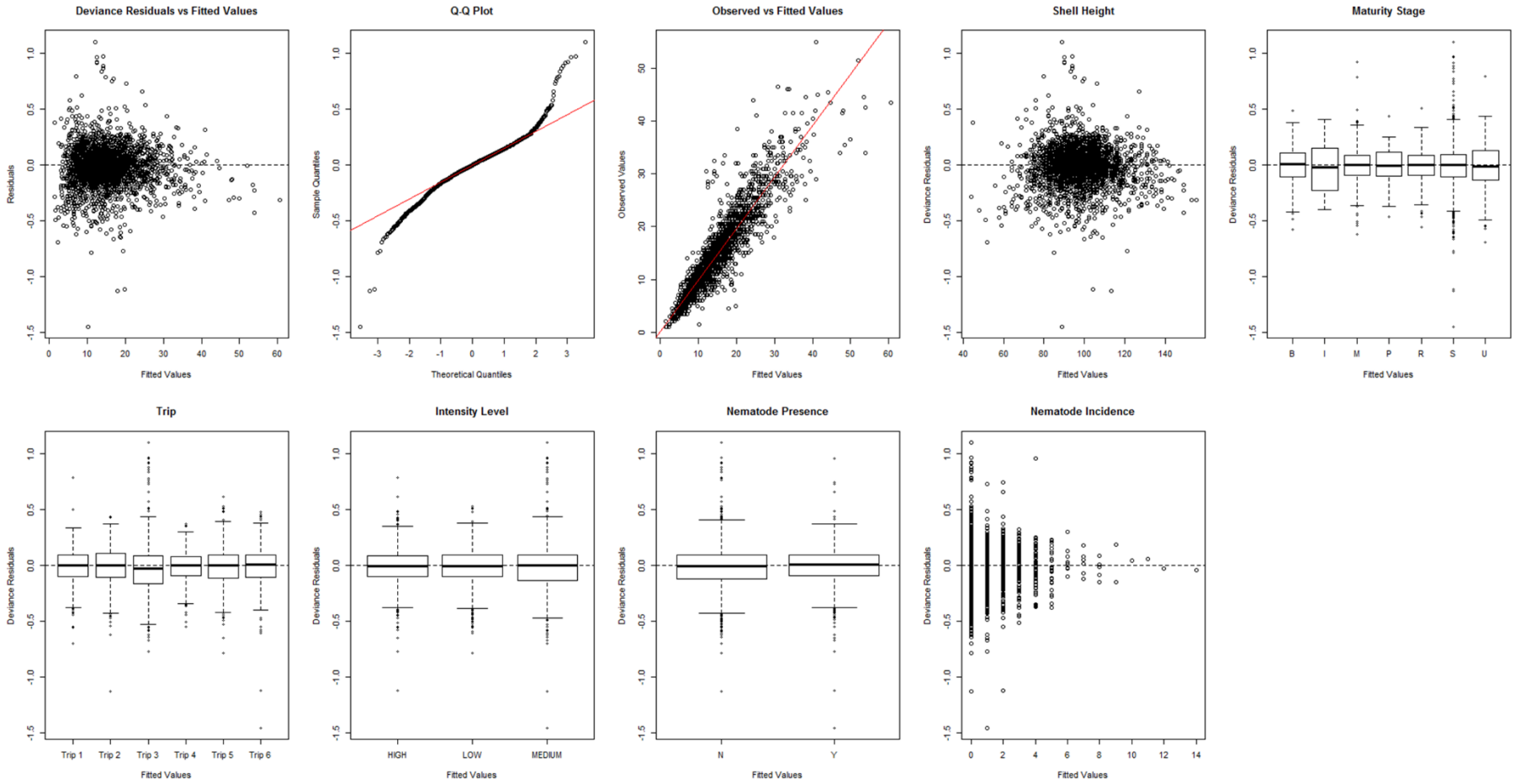

Figure 14. Model diagnostic plots for the preferred GLMM (Model 5). Deviance residuals are plotted against the predicted values, followed by a Q-Q plot and observed vs fitted values. The remaining plots are deviance residuals plotted against predictor variables.

Laboratory Based Experiments

*Shedding Experim*ent

In September, there was an increase in loose nematodes in water on the days directly following the initiation of a shredding event, but in November only one nematode was observed in the water examined after the first day. On day one in November; however, 15 nematodes were found in one bucket containing a live scallop and three buckets contained one nematode each. The single nematode observed on day 3 was in the same bucket that contained 15 nematodes on day 1. In contrast, no nematodes were observed in the water during the entire January 2017 shedding trial. In March, one nematode was found following each shredding event. In May, 6 worms were found on day 3 in unshredded scallop buckets, and 4 were found on day 4 (1 in an unshredded bucket, 3 in the shredded buckets). In July, 4 worms were found on day 3 in unshredded buckets, none on day 4, 2 on day 5 in a shredded bucket, and 1 on day 6 in a shredded bucket. Overall, nematodes were more likely to be found in the water at the beginning of each experiment (Figure 15).

Transmission Experiment

Although seasonal differences in prevalence and intensity (number of lesions per scallop) in the dosing animals were observed, there was no difference between experimental and control groups at the end of each transmission study period indicating that direct transmission among scallops did not occur over the duration of these experiments (Figure 16).

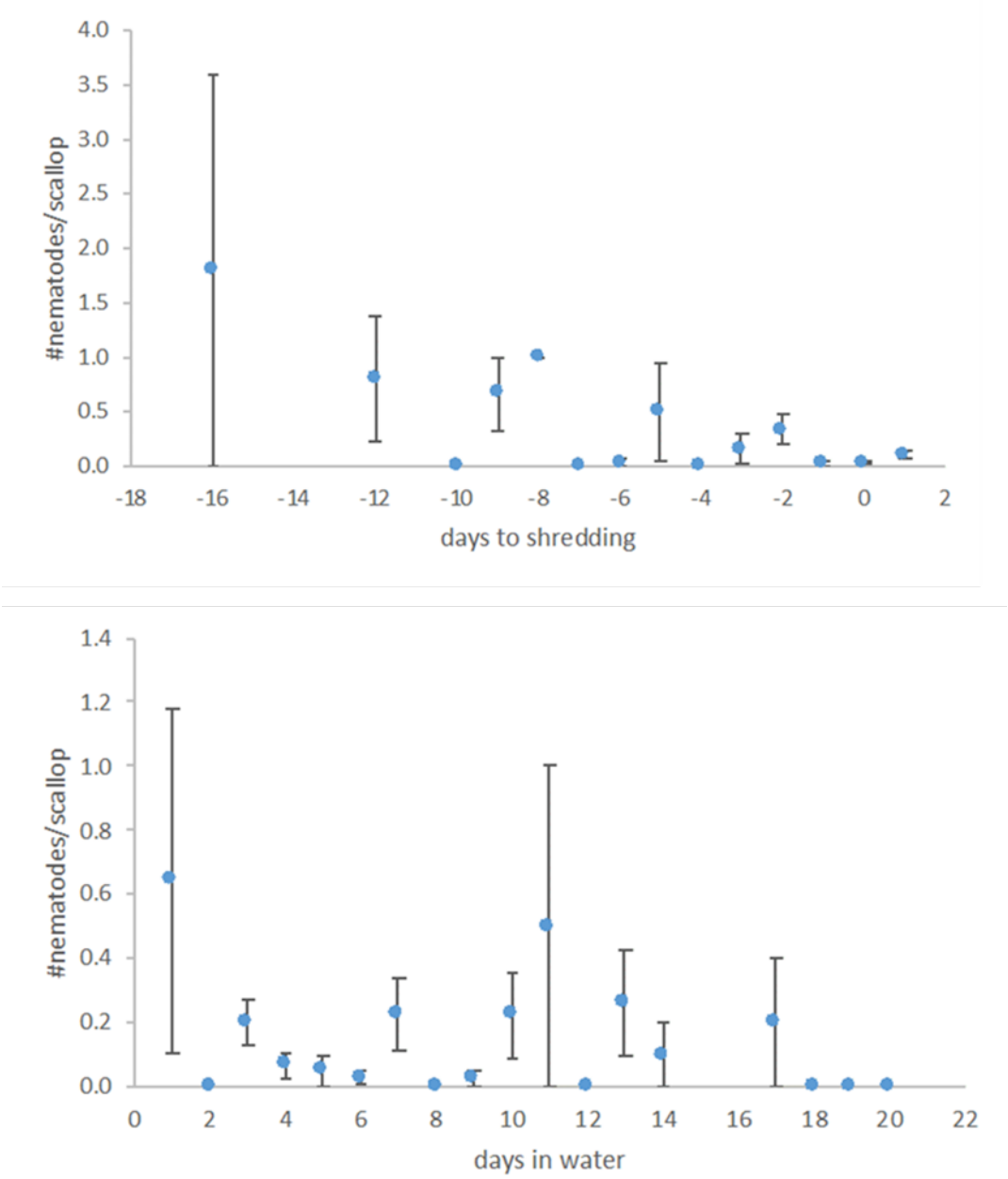

Figure 15. Results of shedding experiment. Mean number of nematodes observed per scallop bucket examined, with standard error, relative to (top) the number of days pre- or post-shredding or (bottom) the number of days in the experiment.

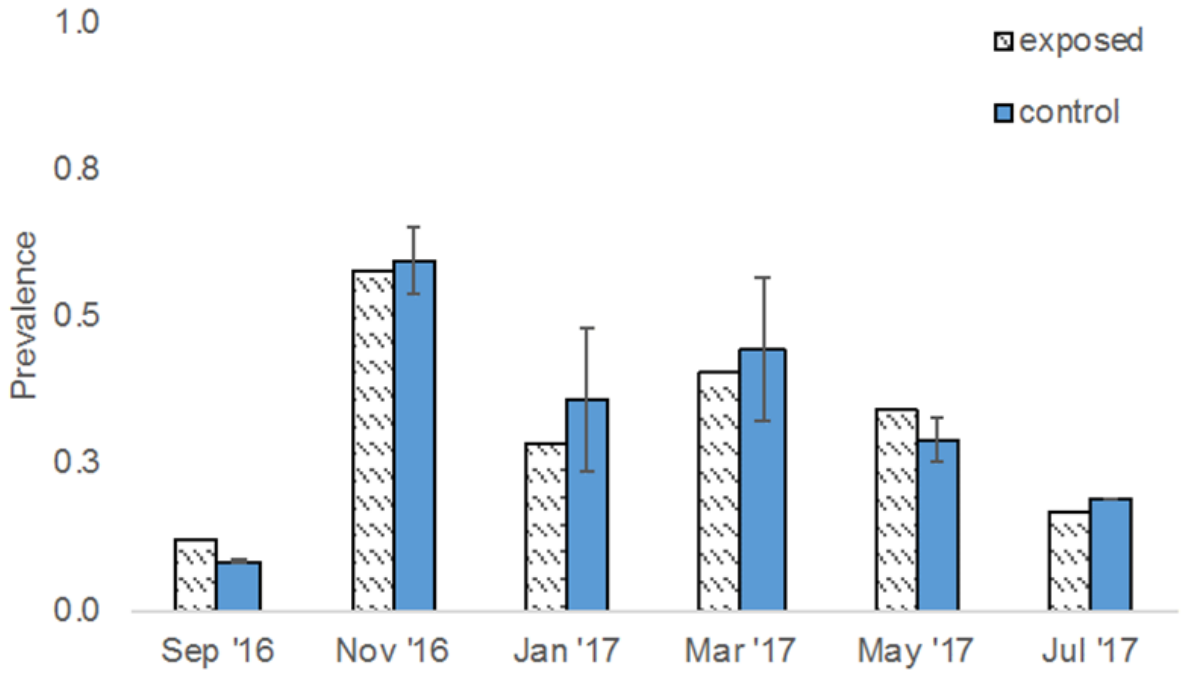

Figure 16. Final nematode prevalence from transmission study results. Error bars are the standard error.

Nematode and Lesion Observations

Most adductor muscle lesions did not contain nematodes. The percentage of lesions containing nematodes increased with each sampling from September to January, but decreased through the March and May samples, possibly indicating a seasonal cycle, as this follows the observed bottom temperature (Figure 17). In September, 20 percent of 166 lesions examined contained nematodes. In November, 39 percent of 63 lesions contained nematodes. In January, 46 percent of 273 lesions contained nematodes. In March, 39 percent of 398 lesions contained nematodes. In May, 22 percent of 490 lesions contained nematodes. In July 22 percent of 614 lesions contained nematodes. Mean nematode length increased from 6.1 mm in March (range of 2.9 - 9.8 mm) to 7.9 mm in May (range of 1.9 - 17.0 mm; Figure 18). In July, mean nematode length was 7.4 mm (range of 0.6 – 21.4 mm; Figure 18).

Site specific trends were similar in all months in regard to prevalence and intensity of infected scallops. Prevalence and intensity appear to be highly correlated ($r^2 = 0.8$). On bottom water temperature peaked in November at about 16°C and bottomed out March to May at about 8°C (Figure 19). Despite this seasonal pattern, infection prevalence and intensity generally increased throughout the sampling period (Figure 18) from September 2016 to July 2017 and nematode infection remained

relatively lighter at low infection sites and heavier at high infection sites (Figure 19). Nematodes were least prevalent in the low intensity sites. Results of a comparison between scallop size and lesion presence or intensity were consistent with previous data indicating that smaller scallops are less likely to have visible lesions (Figure 20); however, the prevalence of lesions in smaller scallops increased in January. No difference in prevalence between male and female scallops was observed.

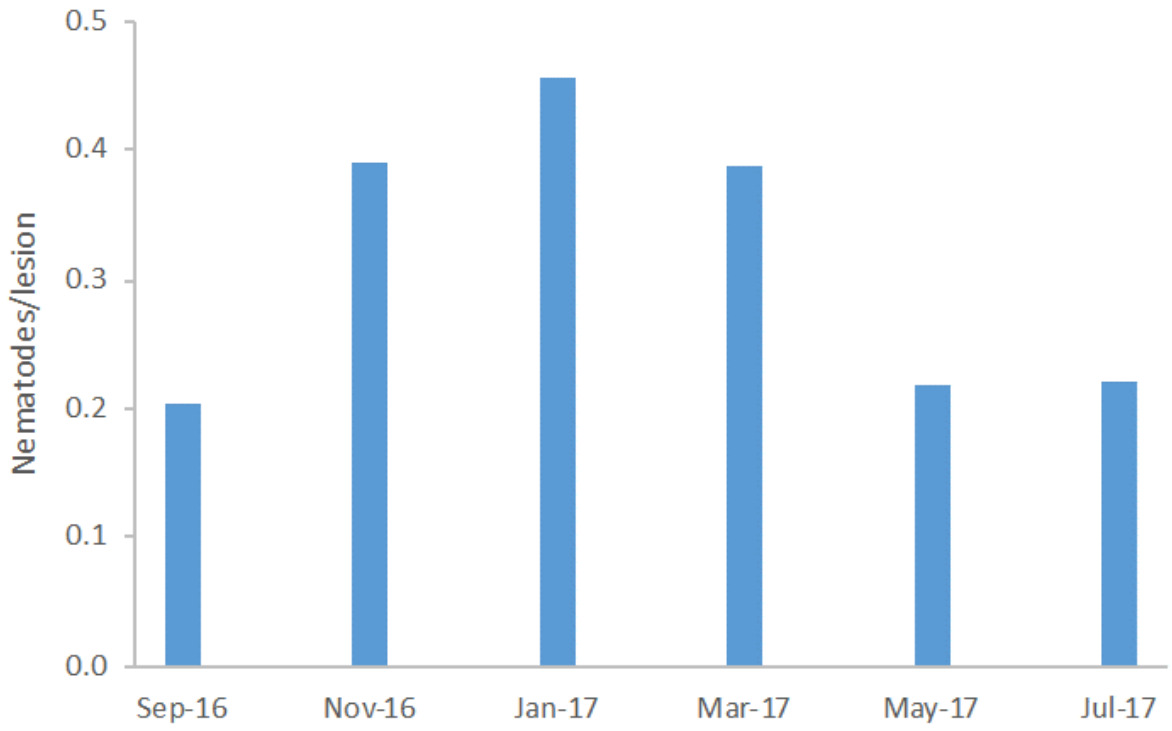

Figure 17. Nematodes per lesion for each collection.

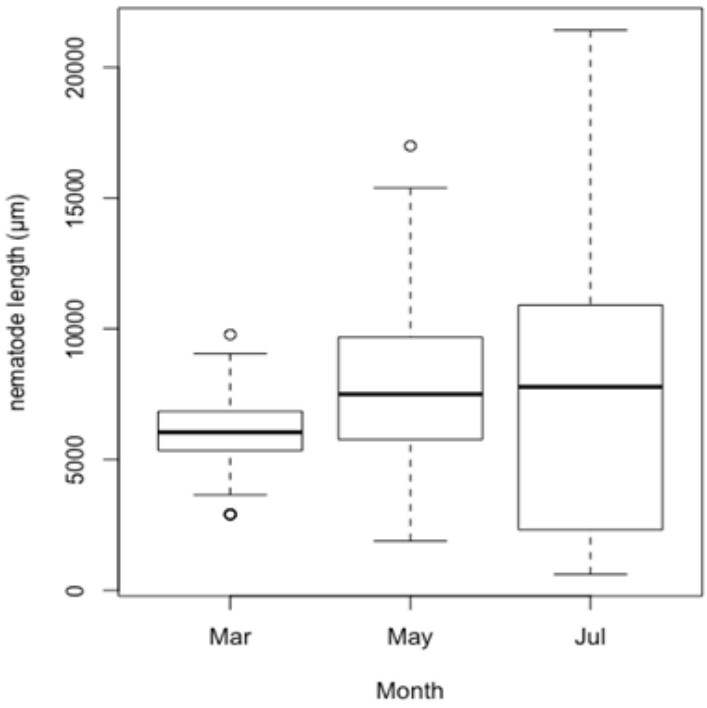

Figure 18. Mean length of nematodes extracted from tow samples in March, May, and July 2017.

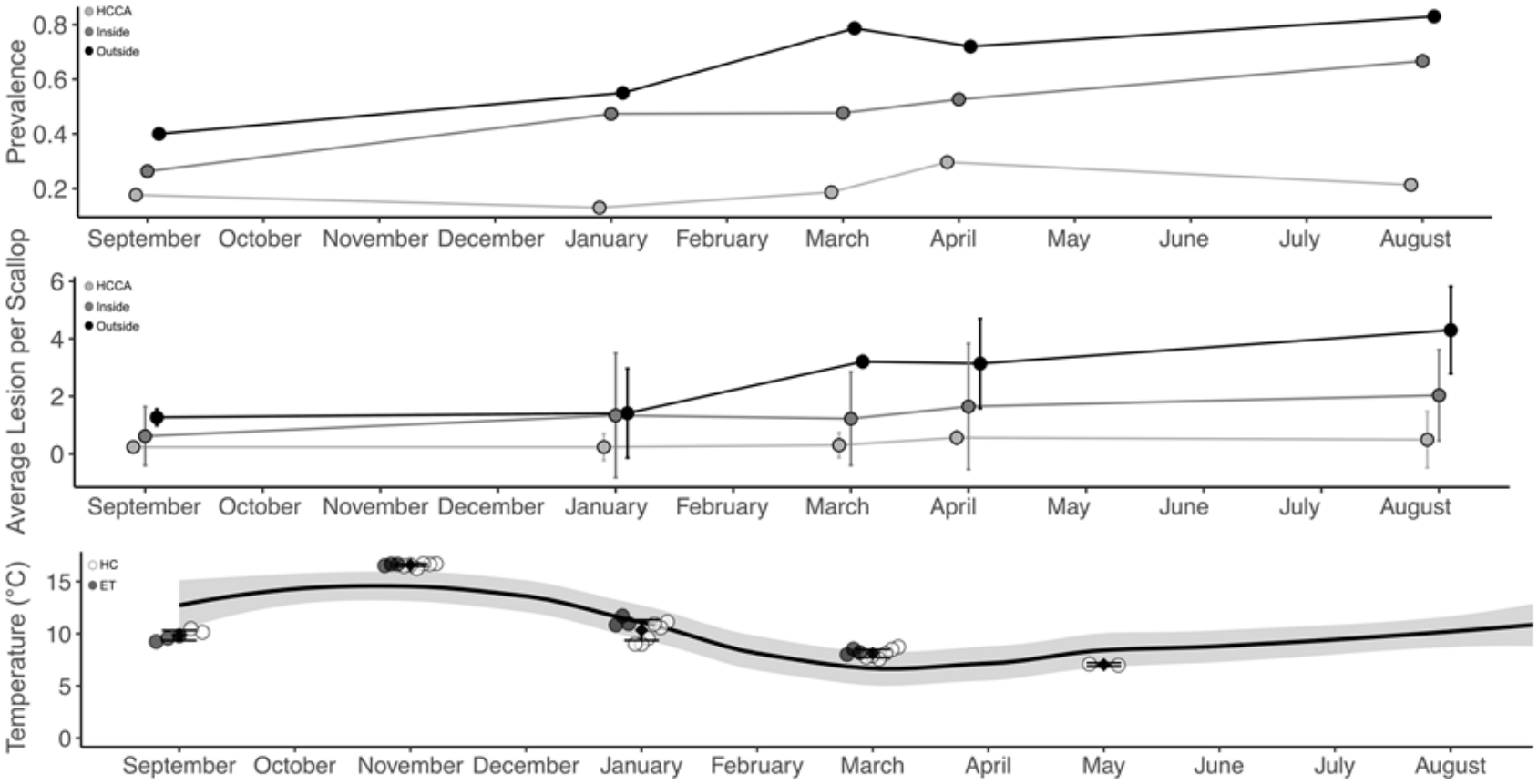

Figure 19. Lesion prevalence and intensity relative to concurrent bottom temperature.

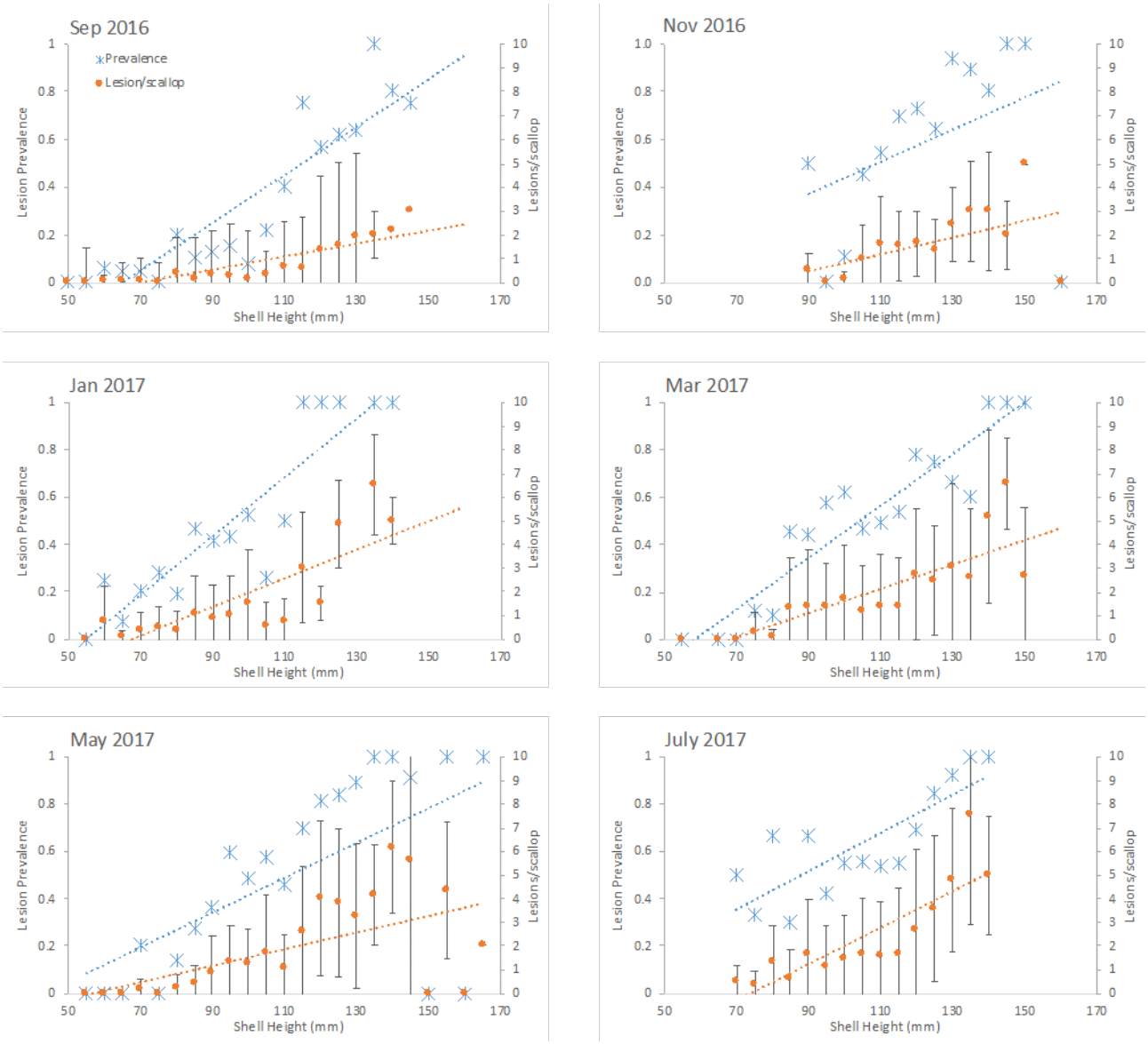

Figure 20. Relationship of scallop size and prevalence or abundance of lesions from November 2016, September 2016, January 2017, March 2017, May 2017, and July 2017 tow data and transmission study samples. Error bars represent standard deviation.

Tolerance to Temperature Experiment

Death occurred between 1 - 6 seconds at 95˚C, 3 - 17 seconds at 75˚C, 4 - 37 seconds at 56˚C, and 3.25 - 6.75 hours at 37˚C (Figure 21). Controls survived at least 24 hours at room temperature and at least 6 weeks at 4˚C.

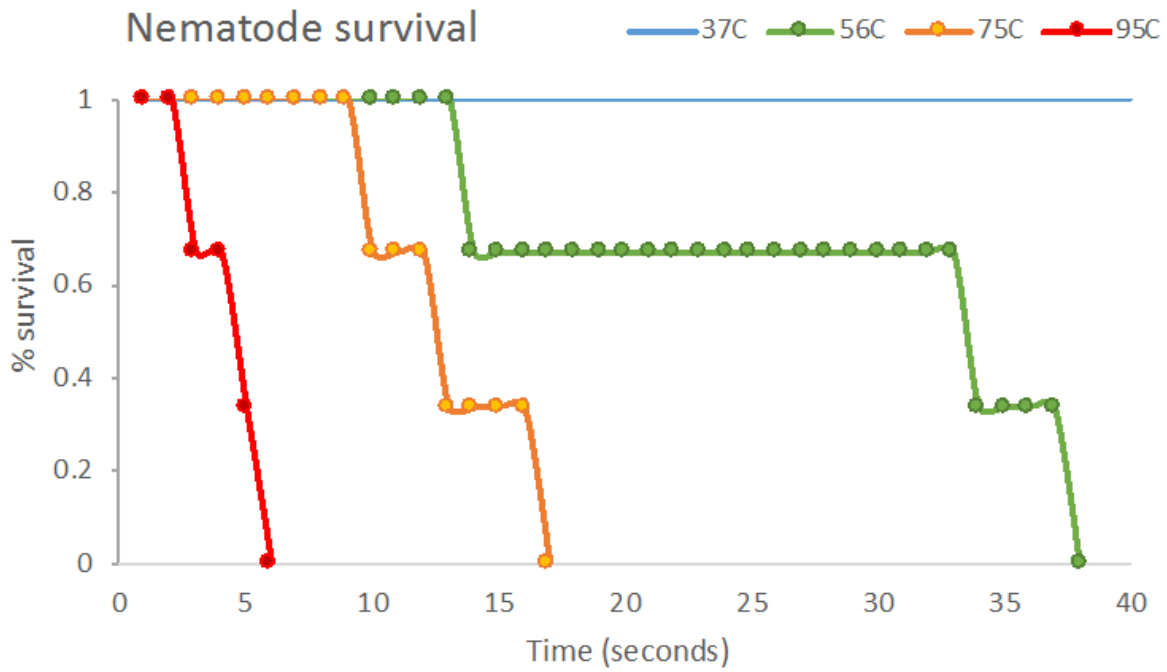

Figure 21. Nematode survival in a range of temperature treatments. Survival in the 37ºC treatment lasted 3 - 7 hrs. Nematodes held at 4ºC and 18 - 23ºC (room temperature) survived for weeks (data not shown).

Survival Experiment

Mortality peaked during the second week of the experiment and plateaued at about 5 - 6 weeks. Mortality was highest in scallops from heavily infected sites and lowest in scallops from lightly infected sites, regardless of actual infection status (Figure 22, top). Uninfected scallops had lower mortality than infected scallops (Figure 22). The number of lesions correlated positively with mortality (Figure 22, bottom).

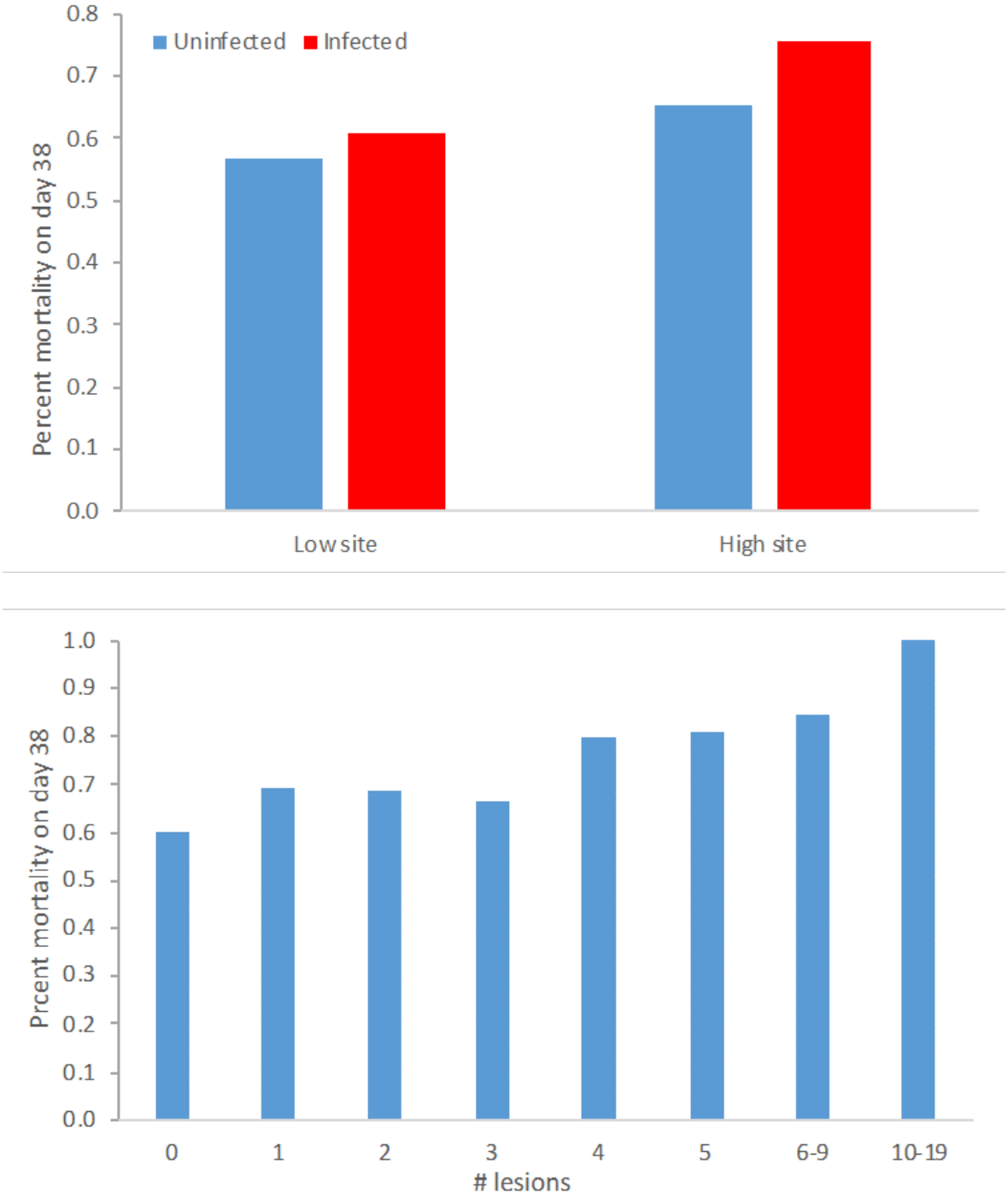

Figure 22. Percent mortality on day 38 of the survival experiment. “Uninfected” and “infected” refer to scallops with no lesions or any number of lesions, respectively; “low site” and “high site” refer to scallops from the lightly and heavily infected sites.

Post Processing Techniques

Processing with either STPP/NaCl or STPP/citric acid had no effect in reducing the visual contrast between scallop muscle tissue and lesions (Figure 23). The creamy-white color of raw scallop tissue is the most quality related characteristic of fresh sea scallops, and together with a tacky feel, and sea water odor are what constitutes a fresh scallop. Processing raw sea scallops to mitigate tissue pigment defects, as the nematode lesions, is likely only achievable by sacrificing scallop quality.

Figure 23. Appearance of rust-brown colored lesions from larval nematodes in unprocessed off-the-boat scallops (left), scallops processed with sodium tripolyphospahte (STPP) and NaCL (middle) and scallops processed with STPP and citric acid (right).

Cooking scallops caused the lesions to become less noticeable. Browning of surface proteins was achieved, mostly along edges closest to broiler coil, but with some browning along scallop edges in which lesions were located. The lesions did not change in color, but became less noticeable within the total browning effect of scallops (Figure 24).

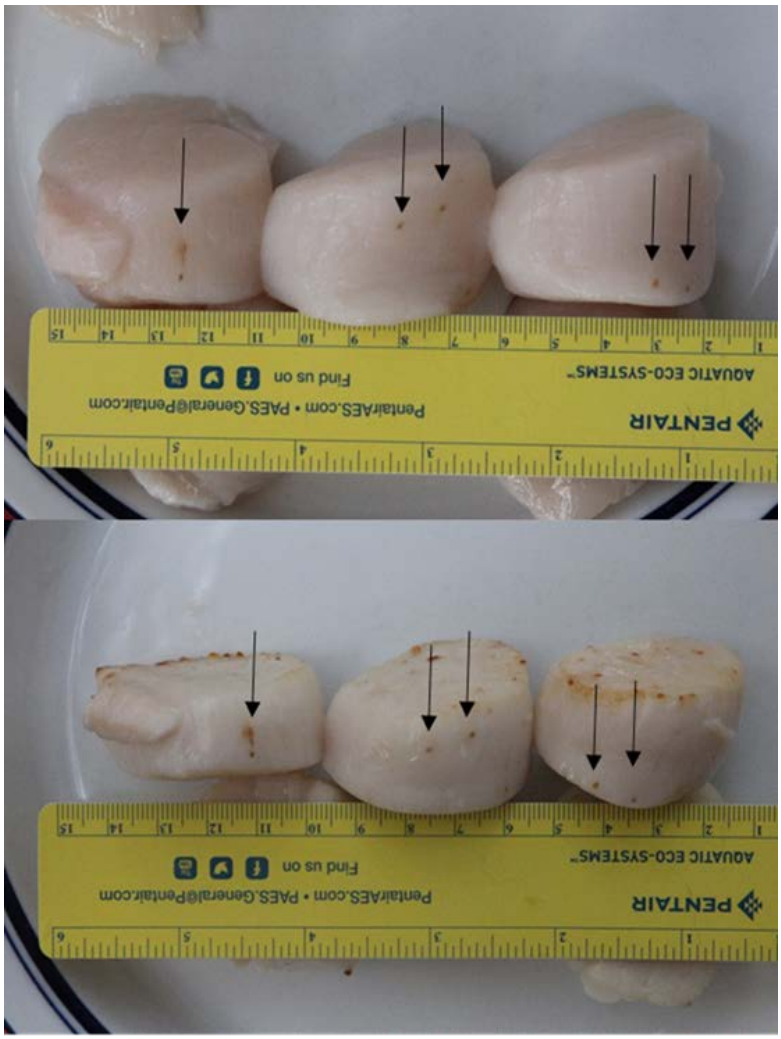

Figure 24. Appearance of rust-brown colored lesions from larval nematodes in processed raw sea scallops (top) and after broiling (bottom).

Discussion

The spatial extent of infected scallops was monitored from 2015 through 2018 during VIMS' annual resource surveys of the MA area. These data indicated the spatial extent of infected scallops was not expanding northward. No infected scallops were observed in other VIMS' surveys conducted on Georges Bank in the Nantucket Lightship, Closed Area I or Closed Area II. Also, the spatial extent in the MA area has remained relatively consistent across time and space, with the majority of infected scallops observed in the southern portion of the MA resource area from New Jersey south. The locus of infections has shifted slightly north into the Elephant Trunk since monitoring began in 2015, but very few infected scallops have been observed in Hudson Canyon or open area off of Long Island northward. Observations of infected scallops in the Elephant Trunk have been patchy. The continued presence of infected scallops may be an indication of reoccurring infections, based on the variability in nematode length and larval stages observed. The removal of infected scallops from the population may not inhibit the continued infection of other scallops in the area.

This information has been shared with the commercial fleet since 2016 through VIMS' annual Industry reports. These reports provide station-level information including coordinates, quantity of scallop catch and percentage of infected nematodes. The goal behind providing this information was to aid the fleet in avoiding areas with high concentrations of infected scallops in order to maximize effort and avoid negative economic impacts. The commercial fleet has modified fishing effort to avoid heavily infected areas as evidenced by an analysis of fishing effort in 2018 (NEFMC, 2018). Little to no fishing effort has occurred south of the Elephant Trunk Flex area. This shift in effort is a result of a combination of knowledge about the spatial extent of infected scallops, potential negative economic impacts associated with landing infected scallops and direction from companies involved in the fishery.

The target sampling component of the project provided insight on several areas of concern regarding infected scallops. Scallops in the study area were only considered unmarketable due to the presence of nematode lesions, otherwise the adductor meat color and quality were considered excellent. The laboratory component of the study concluded that scallop-to-scallop transmission of nematodes did not occur under experimental conditions, and shredding of scallop tissue could lead to parasite shedding, but this appears to vary seasonally and be of low frequency. This information is beneficial to the fishery in terms of discarding infected scallops in areas that have little to no infections. Monitoring of the different intensity level areas indicated no temporal variation in the number of infected scallops per intensity level. There was slight temporal variation in the intensity or number of lesions per scallop observed over the course of the study, and this variation may be related to water temperature. As water temperature declined, the intensity of infections also decreased slightly. The number of

lesions per scallop was also lowest in November. This information may help the industry by providing a window of time in which the fleet can harvest scallops in infected areas, but the scallops will have a minimal amount of infection and increased economic value. The study also concluded that at human body temperature (37°C) nematodes died within 3 to 7 hours and increases in temperature resulted in quicker mortality. The laboratory survival suggests a link between scallop mortality and nematode infections, with higher mortality rates associated with heavy infection relative to less infected scallops. This information is critical to understanding the effect of nematode infections on scallop survival and will provide information for use in future assessments to estimate mortality as a function of nematode presence in conjunction with continued monitoring of nematode presence.

Target sampling also collected critical biological information on nematodes in relation to scallops. The majority of lesions observed in infected scallops did not contain a nematode. The working theory behind this is that one or two nematodes in a scallop may cause several lesions. The nematode encysts in the adductor muscle and then as the nematode grows, the worm relocates in the muscle and encysts again, creating another lesion. Also the timing of when a lesion contained a nematode had a temporal trend, with the greatest number of lesions containing a nematode occurring in January. Nematode body length was also found to increase from March to July. This information may help to narrow in on a time period when infections are occurring.

Both the targeted sampling and fishery independent data provided similar findings in relation to several key aspects of infected scallops. Both data indicated that larger scallops are more likely to be infected compared to smaller scallops. The data also confirmed that heavily infected areas remain highly infected over time, even at varying temporal and spatial scales. The target sampling was conducted over a year in the Elephant Trunk and southern portion of the Hudson Canyon, while the fishery dependent data were collected on an annual basis over a much broader spatial scale. Both data sets also provide evidence for the patchy distribution of infected scallops in the Elephant Trunk area.

One area where the target sampling and fishery independent data differ is in the finding that sex contributes to a scallop being infected. The target sampling study found that both males and females were equally as likely to be infected with nematodes, while the fishery independent GLMM results indicated females had a higher probability of being infected. The difference in these two results may be a function of sample size or timing of when sampling was conducted. This issue may need further research as the targeted sampling also found that infected scallops had a higher probability of mortality. If there is an effect of sex on nematode infections in conjunction with increased mortality, then this suggests a possible higher mortality rate for female scallops. If

accurate, this could contribute to a decline in future spawning potential and should be accounted for in the management and assessment of the resource.

Post-processing of raw scallops to reduce the appearance of nematode lesions was unsuccessful. Cooking of infected scallops reduced the appearance of lesions because the lesions are similar in color to the browning that occurs on a scallop when it is broiled. This information, along with the finding that nematodes die at high temperatures, may provide some economic value to fishery to harvest infected scallops. Infected scallops can be harvested, sold and cooked without a negative impact to human health. Also the appearance of lesions would be reduced after cooking. The main issue with harvesting infected scallops is changing the perception of seafood buyers and chefs with regard to the appearance of infected raw scallops.

Presentations

Several presentations have been given at management meetings and scientific conferences regarding results from this project:

- A Preliminary Investigation into the Emergence of a Parasite in Sea Scallops. Rudders and Fisher. Sea Scallop PDT Meeting. Falmouth, MA. August 25-26, 2015.
- A Continued Investigation into the Emergence of a Parasite in Sea Scallops. Rudders and Roman. Sea Scallop PDT Meeting, Falmouth, MA. August 30-31, 2016.
- 2017 VIMS-Industry Cooperative Surveys Nematode Observations. Rudders and Roman. Sea Scallop PDT Meeting, Falmouth, MA. August 29-30, 2017.
- Investigation of the scallop nematode, *Sulcascaris sulcata*: Distribution, seasonality, shedding, transmission, thermal tolerance and host impact. Rudders, Roman, Fisher, Bushek, Munroe, Bochenek and McGurk. National Shellfisheries Association Annual Meeting. Seattle, WA. March 19-22, 2018.
- 2018 Update on the Nematode, *Sulcascaris sulcata*: Spatial Distribution and Effect on the Sea Scallop Fishery. Rudders and Roman. Sea Scallop PDT Meeting. Falmouth, MA August 28-29, 2018.
- Investigating the Impact of the Nematode *Sulcascaris sulcata*: Spatial Distribution and Effect on the Sea Scallop Fishery. Rudders, Roman, Fisher, Bushek, Munroe, Bochenek, McGurk and Galuardi. American Fisheries Society Annual Meeting, Atlantic City, NJ. August 19-23, 2018.

- Scallop Parasite Outbreak on the Mid-Atlantic Shelf: Transmission, Temporal Variation, and Consequences to Marketability, McGurk, Borsetti, Bushek, Munroe, Bochenek, Rudders and Roman. 22nd International Pectinid Workshop. Santiago de Compostela, Galicia, Spain. April 24-29, 2019.
- Observations on the Impact of the Nematode, *Sulcascaris sulcata* on the Sea Scallop Fishery. Rudders, Roman, Fisher, Bushek, Munroe, Bochenek, McGurk and Galuardi. 22nd International Pectinid Workshop. Santiago de Compostela, Galicia, Spain. April 24-29, 2019.

Manuscripts

Two manuscripts are in draft which focus on results from this project:

- Roman, Rudders, Fisher and McDowell. *in prep*. Observations on a re-emerging epizootic of the sea scallop, *Placopecten magellanicus*, resource.
- McGurk, Borsetti, Bushek, Munroe, Bochenek, Rudders and Roman. *in prep.* Scallop Parasite Outbreak on the Mid-Atlantic Shelf: Transmission, Temporal Variation, and Consequences to Marketability.

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