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Movement types of an Arctic benthic fish, Shorthorn Sculpin (*Myoxocephalus scorpius*), during open water periods in response to biotic and abiotic factors

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Abstract

Shorthorn Sculpin (*Myoxocephalus scorpius*) are among the most numerous consumers in the Arctic nearshore marine habitats. Despite this, little is known about their movement ecology or predator-prey interactions, particularly with Arctic Cod (*Boreogadus saida*), an important forage fish in the Arctic. Using acoustic telemetry, the movements of tagged Sculpin and Cod were quantified based on specific locations using a Vemco Positioning System during open water when both species were present in the nearshore. Movement trajectories of Sculpin distinguish three unique types, foraging and feeding behaviour and large transiting movements. The relative time of each of these movement types were correlated to biotic (presence of large numbers of acoustically tagged Arctic Cod) and abiotic factors (% ice coverage and temperature). This study provides unique data on the movement, feeding ecology and behaviour of an abundant arctic benthic fish that demonstrates similar movement types to temperate fish. However, further study is needed to specifically quantify the trophic interactions of these important fish and impact on food webs in the rapidly changing Arctic.

Key Words: Shorthorn Sculpin (*Myoxocephalus Scorpius*), Arctic Cod (*Boreogadus saida*), acoustic telemetry, trophic ecology, Ocean Tracking Network

Introduction

The marine ecosystems of the high Arctic are dynamic, with large seasonal changes in light and temperature, which in turn influence the growth and abundance of primary producers (Walsh 2008). These systems support numerous endemic and transient marine mammal and sea bird species which in turn feed on fish and macroinvertebrate biomass (Hobson et al. 2002). Arctic Cod (*Boreogadus saida*) are one particularly important forage fish species in the Arctic as they link lower and upper trophic levels and represent a key prey item for larger consumers due to their high abundance, high latitudinal distribution and high energy content (Hobson & Welch 1992; Hop & Gjosaeter 2013). A second abundant fish species found in coastal Arctic ecosystems is the Shorthorn Sculpin (*Myoxocephalus scorpius*). While not as favourable a prey item as Arctic Cod for larger consumers (Yurkowski et al. 2015; Quakenbush & Bryan 2010) its distribution overlaps with Arctic Cod, especially during open water periods where they congregate in nearshore areas (Matley et al. 2013). Despite their importance to arctic food webs, very little is known about the movement and behavior of Shorthorn Sculpin or their interaction with Arctic Cod.

Shorthorn Sculpin are benthic and can reach a size of 30 cm, with a wide distribution from temperate to Arctic waters (Robins & Ray 1986). Their diets consist mainly of benthic invertebrates (Cui et al. 2012), however, some juvenile and adult fishes have been identified in Shorthorn Sculpin stomachs (Kallgren et al. 2014; Cardinale et al. 2000), and stable isotope analysis has found that these fish couple benthic and pelagic energy pathways with as much as 50% of their consumed carbon coming from pelagic sources (McMeans et al. 2013; Landry et al. 2016). One study on the southern end of Baffin Island found Arctic Cod in the gut contents of Shorthorn Sculpin (Dick et al. 2009). Although cod made up 1% of prey items in the sculpin stomachs, they represent a much larger energy and biomass source than invertebrates per amount of mass consumed, and it is possible that Arctic Cod represent an important prey item for Shorthorn Sculpin at higher latitudes. Shorthorn Sculpin represent an abundant secondary consumer in high Arctic systems; this along with their ability to couple multiple energy pathways (both pelagic and benthic) make them an important fish species in these systems especially through the regulation of lower trophic levels via predation (McCann et al. 2005). However, data is lacking on the foraging behaviour of this species, in particular how their behaviour changes in response to changing environmental factors including the presence of different prey items.

Analyzing movement types of aquatic organisms is often used in unison with spatial and temporal information to discern different types of behaviours, particularly those associated with foraging and habitat preference (Cunjak et al. 2005; Brill et al. 2005). They can also be used to examine inter-species interactions in the form of predator-prey relationships (Meyer et al. 2010; McMahan et al. 2013). Integrating both habitat preferences and species' interactions can determine where and when individuals are feeding, and potentially which species they feed on (Fitzpatrick et al. 2012). Acoustic tracking can also elucidate foraging behaviours of animals that are understudied, yet potentially significant in the food web of a community (Vaudo 2011). Trophic ecology studies have largely focused on top predators because they are thought to act as food web stabilizers (Paine 1966) and would therefore be critical to an ecosystem (Papastamatiou et al. 2010; Heithaus et al. 2002). However, our knowledge of foraging behaviour and species' interactions of lower trophic level consumers, primary and secondary that can couple multiple energy pathways, is lacking in many ecosystems, particularly in the Arctic (McMeans et al. 2013).

Acoustic telemetry has become more common in assessing aquatic organism spatial ecology, with advancements in technology allowing for deployment on a wide variety of aquatic organisms ranging in size and global distribution (Hussey et al. 2015). Passive acoustic tracking can be used to collect large amounts of data over long-term periods (up to 10 years) while decreasing the relative amount of effort in terms of field time (Hussey et al. 2015; Heupel et al. 2006). Further, studies have made use of the Vemco Positioning System (VPS), which relies on data derived from acoustic tracking to quantify fine scale movements and habitat use of tagged individuals (Espinoza et al. 2011; Farrugia et al. 2011; Furey et al. 2013; Andrews et al. 2011).

To date, few studies have examined Sculpin movements (Ovidio et al. 2009; Deboer et al. 2015) and none have related to the foraging ecology of any Sculpin species. Acoustic telemetry is non-lethal and provides data that are more temporally sensitive than stable isotope or stomach content analysis, the most common methods for assessing foraging ecology, which are influenced heavily by isotopic turnover rates or what the individual had recently eaten relative to time of capture, respectively (Buchheister & Latour 2010). The objectives of this study were to: i) apply novel techniques to an important but understudied benthic fish consumer in the high Arctic and identify and quantify distinct movement types of Shorthorn Sculpin using acoustic telemetry, and, ii) examine how these types correlate to environmental factors and the presence of Arctic Cod. This study utilized a Vemco Positioning System (VPS), that provides specific locations of tagged fish by triangulating its position through detections of groups of three or more receivers (Lowe et al. 2011). We hypothesize that Shorthorn Sculpin will demonstrate differentiable movement types common to benthic fish in temperate regions and these will vary with abiotic and biotic factors. Specifically, we hypothesize that the presence of Arctic Cod will elicit types indicative of feeding behaviour in Shorthorn Sculpin, either because of direct predation on the cod or feeing on a common prey item of both fish. The general descriptions of Shorthorn Sculpin foraging ecology as well as species-specific interactions (Sculpin and Cod) will help to fill in knowledge gaps in an otherwise under-studied food web.

Methods

Study Site

Field work was conducted in Resolute Bay (N 74.68, W 94.85), located at the south side of Cornwallis Island, Nunavut, Canada opening south into Barrow Strait (Figure 1). The Hamlet of Resolute is located at the north end of the bay where untreated sewage is emitted via pipeline. There is a fuelling station on the west side of the bay and three freshwater stream inputs (1 on the west shore, 2 on the east). The surrounding shoreline is composed of gravel, rock and glacial shale with soft substrate and sparse amounts of macrophytes along the bottom of the bay. The maximum depth of the bay is ~ 30 m towards the head and near the centre with a shallower panicle rising to 2 m deep at the entrance of the bay.

Fish Tagging

Shorthorn Sculpin and Arctic Cod were both collected from 26 July to 4 August 2012. Sculpin were caught by gill net (gradient mesh sizes 0.5”^{2} to 4”^{2}) set in three locations (west, north, and east side of the bay), while Arctic Cod were caught by jigging with hook and line from the same locations in the bay (Figure 1). After capture, the fish were placed in holding tanks filled with bay water and either transported back to the Polar Continental Self Project (PCSP) research lab, or to a tagging station set up on the shore of the bay (depending on weather conditions). Fish were anaesthetized using MS222 (4 g: 20 l of sea water), and once non-responsive (2 – 5 minutes) fork length (FL; for Cod only), total length (TL) and weight (WT) measurements were taken. Fish were then placed in a sponge cradle for surgical insertion of the acoustic transmitter (i.e. tag), with continuous gill irrigation with sea water from a squeeze bottle. A small anterior incision (~ 8 mm) was made into the peritoneal cavity of the fish, the transmitter was inserted into the cavity (Vemco V6 transmitter for Arctic Cod, Vemco V9AP transmitter for Shorthorn Sculpin) and the incision was sewn closed using two Vicryl sutures (Ethicon VCP423, 3-0 FS-2 cutting). All materials including transmitters were sterilized using 10% betadine prior to surgery. Surgeries ranged from 2 to 4 minutes in duration, and upon completion fish were placed into recovery tanks and allowed to recuperate for ~ 1 h. All fish were released in masse back into their original capture sites in the bay, and were observed swimming away. Twenty-Five Shorthorn Sculpin were tagged, of which 17 were used in the analysis of movement types (due to 8 having < 3 bursts per individual), and 85 Arctic Cod were tagged and 77 successfully monitored throughout the study period. The TL of Shorthorn Sculpin used in the analysis ranged from 23.0 to 36.0 cm (27.8 ± 0.6, mean ± SE) and the FL of Arctic Cod ranged from 15.0 to 26.1 cm (19.1 ± 0.2).

Acoustic Telemetry

Acoustic data collected between 5 August and 23 October 2012 was used for this study, which included the open water period (Aug – Oct) and ran from the time of deployment of the receivers until the onset of ice formation at the beginning of October in Resolute Bay. Both species of tagged fish were tracked using an acoustic array composed of 59 stations (Figure 1). Stations consisted of a rock anchor attached to an ORE Port ME acoustic release (Edgetech, West Wareham, MA, USA) in turn attached to a float to keep the station vertical. Vemco VR2W acoustic receivers (Amirix Systems Inc, Bedford, Nova Scotia, Canada), 69 kHz were attached to a V-cup below the float facing down. Tagged fish each had their own individually coded transmitter that relayed information to receivers in the bay. The stations were deployed at the beginning of the study period and left in the water until the following summer when they were retrieved and the data was downloaded. Nineteen V9-sync tags and 17 V6-sync tags were deployed across the array in fixed locations to assess array performance (for a full description of receiver range testing and detection rates see: Kessel et al. (2015)) and to calibrate the locations of listening stations and measure the effects of positioning error. This calibration data was used for Vemco Positioning System (VPS) processing that uses the detections of groups of three or more receivers to triangulate the positions of tagged individuals based on the difference in time it takes for detections to reach each receiver (Lowe et al. 2011).

Identifying Sculpin Movement Types

Shorthorn Sculpin detections that had a horizontal positioning error (HPE) of > 37 were removed from the dataset, as detailed in McLean et al. (2014). The HPE represents the radius of estimated circular error related to each VPS position (Espinoza et al. 2011) and this filtering allowed for a relatively small amount of positioning error without decreasing the dataset significantly (22,687 detections in total, 1,814 detections filtered and removed). To define movement types of Shorthorn Sculpin, movement trajectories from 5 August to 23 October 2012 were analyzed using the ADEhabitatLT packing (Calenge 2011) in R (version 3.2.4). This package analyzed all of the detections for each individually tagged Sculpin (trajectories) across the entire study period and grouped them into "bursts" or segments based on time between detections (30 min). For example, if an individual went undetected for more than 30 min the current burst ended and a new one began when they were redetected once again. A time frame of 30 min was chosen because it allowed for the creation of a large number of bursts while still maintaining a high enough resolution to capture changes in movement types between subsequent bursts. Only bursts with 5 or more relocations (detections) were used in the analysis (1,158 bursts in total, 373 filtered and removed). In this way, each tagged fish had a catalogue of bursts associated with it ranging from 5 to 100s of detections per burst. In order to distinguish between different movement types, bursts were characterized using the following variables: sum of total distance, mean turn angle (relative angle, Calenge 2011), mean bearing (absolute angle, Calenge 2011), mean depth (derived from pressure censors in the V9AP tags), mean rate of movement, mean acceleration (taken from V9AP accelerometry data) and linearity ratio that was calculated by dividing the distance between relocations by the total distance where a value of 1 indicates a more linear or straight path and a value approaching 0 indicates a less linear path (Heupel et al. 2012). A correlation plot was produced using the R package Corrplot (Wei 2012) and the above defined variables associated with each burst that had a correlation of > 60% were removed due to redundancy. A within sum of squares analysis was then used to determine the number of clusters that bursts could be grouped into and the package Cluster (Maechler et al. 2002) was used to perform a K means cluster analysis that assigned bursts to identified clusters that represented unique movement types. A multivariate analysis of variance (MANOVA) was used to distinguish between significant differences in the variables associated with each cluster/movement type (significance level $p < 0.05$).

Environmental Variables

Environmental measurements were collected by an oceanographic station (Satlantic STOR-X and a Seabirds Electronics 37-SIP CTD) submerged at the centre of the bay, which provided dissolved oxygen (%), salinity (PSU), and water temperature (°C) over the course of this study. Daily sea ice cover (%) in the bay was obtained from the Canadian Ice Services archives (ec.gc.ca/glaces-ice), and daily photo period (h) taken from the time and date archives (timeanddate.com). The proportions of each Shorthorn Sculpin movement type for each day of the study period ($n = 84$) were normalized by removing zeros (where no detections occurred for a movement type) and ones (where a particular movement type had a proportion of 100%, i.e., only movement type quantified on that day) leaving 68 days from the study period. To examine variation in the occurrence of identified movement types with abiotic factors (photo period (h), ice cover (%), and water temperature (C)) a multivariate multiple regression was used that compared daily proportions of each movement type (dependent variable) from all individuals detected in the bay against daily changes in environmental factors (independent variables). The regression ran all movement types simultaneously against the selected abiotic factors.

Effect of Arctic Cod Presence

Arctic Cod distribution in Resolute Bay is not uniform during open water periods, although large schools spend the majority of their time in the northern head of the bay (Kessel et al. 2015). To account for this, Shorthorn Sculpin MTs across the bay were separated into three different zones, with MTs shown within each zone (Table 1, Figure 4). Each fish detection was allocated to a zone based on which listening station, or groups of receivers it was detected by (Table 1, Figure 1C). Zone 1 was located in the northern head of the bay and was associated with high Arctic Cod abundance (Kessel t al. 2015), while zone 2 was on the western opening of the bay and zone 3 on the eastern opening and both were designated areas of low Arctic Cod abundance. The relative abundance of both species was calculated in each zone by dividing the number of detections per hour by the number of unique individuals detected per hour. Relative abundance was used due to Arctic cod schooling in large numbers generating a large amount of detections in a particular zone compared to Shorthorn sculpin detections in the same zone over a given time frame. To test whether Shorthorn Sculpin movement types are different when Arctic Cod are in the same area a binomial regression (1 = movement type was displayed, 0 = movement type was not displayed) for each type in each zone was conducted against relative Arctic Cod abundance by the hour.

Results

Both species were detected for the majority of days in the study period (82 days out of 84 for Sculpin, and 74 out of 84 for Cod) (Figure 2). Results from detection range testing indicated that the receivers had a minimum effective range of 10 m and a maximum effective range of 130 m during the study period (see: Kessel et al. 2015 for full details).

Sculpin Movement Types

Shorthorn Sculpin movement trajectories were broken down in to a total of 785 bursts from all tagged fish, ranging from 7 to 112 per individual. Three unique movement types were identified represented by the three different clusters that bursts were grouped into (Figure 3, where movement types (MTs) of the same number are the same type, and a, b represent the same type taken from different individuals). Bursts were grouped into MTs based on significant differences between the following variables: sum of distance, mean rate of movement, depth, and linearity. All individuals displayed all three MTs over the course of the study, however MT2 occurred the most often (522 bursts) and MT3 occurred the least (67 bursts). One or more variables were significantly different among the three identified movement types (Table 2): MT1 had a significantly higher sum of distance (187 ± 74.0 m) and mean rate of movement (0.03 ± 0.03 m s^{-1}) than MT2 (36.9 ± 23.3 m, 0.01 ± 0.01 m s^{-1} respectively); and MT3 had a significantly higher sum of distance (784 ± 39.2 m), rate of movement (0.06 ± 0.06 m s^{-1}), occurred in significantly deeper water (16.8 ± 5.22 m) and had a significantly higher linearity ratio (0.54 ± 0.34) than both MT1 and MT2. MT3 was the longest type, representing fish covering the most distance with increased speed, along more straight trajectories, MT1 covered less distance, occurred at slower speeds and was less linear than MT3, and MT2 was spatially shorter, slower, and less linear than both other MT. Spatially, MT1 and MT2 predominantly occurred in the nearshore areas of Resolute Bay in shallower waters, especially in the northern head of the bay and the east and west opening of the bay, whereas MT3 mainly occurred near the centre of the bay in deeper waters (Figure 4).

Environmental Variables

The multivariate multiple regression revealed that the proportion of MT2 per day decreased over the course of the study and had a significant positive relation to photo period ($p < 0.001$, $R^2 = 0.47$). Conversely, MT3 increased towards the end of the study period and had a significantly negative relation to photoperiod and a significantly positive relation to ice cover ($p < 0.01$, $R^2 = 0.44$). All movement types occurred during daylight and periods of darkness, however, as the amount of daylight per day decreased the proportion of total Shorthorn Sculpin movement types switched from occurring during daylight to occurring during periods of darkness.

Effect of Arctic Cod

Zone 1 had the highest number of unique Arctic Cod detected (77) per hour, highest mean relative Arctic Cod abundance (3.98) and the most hours sampled when both Shorthorn Sculpin and Arctic Cod were present at the same time (494 hrs) compared to the two other zones (Table 1). This is consistent with a previous study that found Arctic Cod prefer the northern head of Resolute bay during open water periods (Kessel et al. 2015). Sculpin Movement types in zones 2 and 3 showed no significant relation to the relative abundance of Arctic Cod, however in zone 1 MT2 increased significantly (z value = 2.152, $p <0.05$) and MT1 decreased significantly (z value = -4.294, $p <0.001$) with an increase in the relative abundance of Arctic Cod per hour (Figure 5).

Discussion

The three Shorthorn Sculpin movement types quantified in this study had characteristics similar to those found for Atlantic Sturgeon (*Acipenser oxyrhynchus*) (McLean et al. 2014), and were identified as foraging (MT1) and feeding (MT2) behaviours and long and straight transit movements (MT3). In this study, sculpin spent a majority of their recorded time foraging and feeding, and these activities increased during the night as the 24-hour daylight decreased and dark periods increased. Sculpin spent more time in feeding behaviour in regions with higher Arctic Cod densities, although whether this was related to predation on cod or a common prey item could not be determined. Behaviours related to sculpin spawning are unlikely, as spawning takes place in November to December and eggs hatch by late spring (Luksenburg et al. 2004), outside the period of this study. Similarly, sculpin behavior related to predation pressure would be low as adult Shorthorn Sculpin have few predators within the sheltered bay and are considered a less desirable prey compared to other fish prey species, particularly Arctic Cod (Yurkowski et al. 2015). Ship or vessel traffic has been demonstrated to influence the relative amounts of each of these three behaviors in Shorthorn Sculpin from Resolute, although not in 2012 the year of the current study (Ivanova et al. 2017, *this issue*). Given vessels are only present about 25% of the time during the study period and occurred at regular intervals, the impact of vessel traffic on this study is minimal.

Although MT1 and MT2 observed in this study are most likely associated with foraging and feeding by the Shorthorn sculpin, they could also be associated with territory guarding which has been observed with other sculpin species. For example, adult Mottled Sculpin (*Cottus bairdii*) are highly territorial and form defined home ranges (Petty & Grossman 2007). Shorthorn Sculpin were observed emitting low frequency sounds/pulses upon handling in Resolute Bay, which is known to accompany antagonistic encounters between conspecifics (Zeyl 2016) suggesting that they are also territorial. Spatial and temporal overlap did occur multiple times between different pairs of tagged individuals, identifying that Shorthorn Sculpin in Resolute Bay regularly encounter one another, and it is possible that some of these interactions involve territorial behaviour identified by MT1. However, the characteristics of MT2, many quick turns within a small area have been identified as feeding behavior in other fish studies. Salmonid feeding behaviour is associated with slower movement speeds and less linear trajectories

(Heerhartz & Toft 2015) and a decrease in swimming speed in Clownfish (*Amphiprion perideraion*) when an individual encountered a suitable prey patch (Coughlin et al. 1992), both similar to those observed in the sculpin in this study. As well, Mottled Sculpin have been found to associate within patches together when prey abundance is high (Petty & Grossman 1996). In Resolute Bay, such habitat was represented by shallow nearshore areas where numerous aquatic invertebrates were observed among gravel and cobble that are substrates associated with benthic fish foraging behaviour (field observations; Landry et al. (2016); Greenberg (1991)), where MT1 and MT2 commonly occurred. Taken together, MT1 and MT2 are more likely correlate with foraging and feeding behaviour than nest guarding.

In this study, MT2 best correlates to ambush behaviour in an area with high prey abundance, having the lowest rate of movement and smallest amount of distance covered. Unlike sturgeon, that use a more active foraging strategy (Kasumyan 1999), sculpin species rely heavily on their lateral lines to locate prey (Hoekstra & Janssen 1985). As well, some sculpin species are considered ambush predators that move less in the presence of prey to increase sensitivity to prey movements and orient themselves accordingly using neuromast cells (Janssen et al. 1999). Sculpin have also been observed in laboratory studies using quick feeding strikes from sedentary positions to capture prey (Broell et al. 2013). Thus, Shorthorn Sculpin are likely to adopt a “sit and wait” approach when a prey patch is encountered, using small scale movements, which could not be confirmed with the methods used here, to reorient their positions to coincide with prey movements and then striking when a prey item comes within a certain distance.

MT3 represents large, straight movements used by individuals when traversing across deeper areas of the bay due to higher sum of distance, rate of movement, and linearity ratio observed. This type of movement was negatively correlated to photoperiod and could be affected by vessel presence in the bay, the latter of which decreased the proportion of time in MT3 although not in the year of the current study (Ivanova et al. 2017, *this special issue*). This movement could also be associated with leaving, due to low prey or searching for better feeding patches, unfortunately there is insufficient prey data to accurately assess this.

The clear majority of detections of Shorthorn Sculpin were associated with MT1 and MT2 (10,160 in total) compared to detections associated with MT3 (3,096). There were three main areas around the perimeter of Resolute Bay where MTs 1 and 2 occurred the most, the northern head, the east opening and west opening of the bay, all of which consisted of shallower areas of 5 to 10 m that dropped off into areas up to 20 m in depth. These three areas are likely foraging grounds for Sculpin as the location in the north is subject to raw sewage input from the Hamlet of Resolute increasing the local nutrient input and productivity, and the areas near the opening of the bay are composed of a shoal and subject to upwelling effects that feed nutrients into the mouth of the bay (Millan-Nunez et al. 1982) which in turn attract prey, including macroinvertebrates. Common prey items of Shorthorn Sculpin (*Gammarus* spp., *Onisimus* spp., and Molluscs (field observations; Dick et al. 2009; Landry et al. 2017), were also observed and collected in nearshore areas where MT1 and MT2 occurred.

Environmental Effects on Sculpin movements

Shorthorn Sculpin exhibited a higher proportion of MT2 during the start of the study period (August) than towards the end (October), which was correlated to changes in photoperiod and ice cover. The decrease in MT2 and the increase in MT3 as photoperiod declined and ice cover increased suggests that in Resolute Bay, Shorthorn Sculpin were moving farther distances and doing less foraging and/or territory guarding. Marine productivity would be in decline as sunlight and temperature decreased (Dalpadado et al. 2014) and ice formation began. MT2 decreased sharply at 30% ice coverage in the bay at the beginning of October and MT3 sharply increased. This same type occurred again at the end of October when ice coverage reached ~

80 %. This could be related to less prey availability; many species of arctic amphipods have been found in association with sea ice that affords them protection from predators (Gradinger & Bluhm 2004); nearshore ice formation in Resolute Bay may act as a refuge for amphipods from Sculpin predation as they can hide within small cracks and crevices. The added cover for amphipods and other invertebrate prey would decrease Shorthorn Sculpin feeding efficiency prompting individuals to cover more area to search for prey. Changing environmental conditions may also drive Shorthorn Sculpin to deeper waters, where variability is lower and fish can acclimate more readily to dynamic changes (e.g., temp, ice cover, Kessel et al. 2015).

Only two of the tagged individuals returned to the bay after leaving near the end of October, providing evidence that Shorthorn Sculpin move to deeper waters during ice covered periods. Samples of Shorthorn Sculpin gut contents from Cumberland Sound showed an increase in deep water molluscs that were not found in plankton samples taken from shallow areas (1-3 m) where the fish were caught (Moore & Moore 1973), providing additional support for movement to deep water as ice formed.

At the beginning of August in Resolute Bay there is 24 h of daylight, which slowly declines over the course of the month. Studies have shown that fish, including Sculpin species, in sub-Artic to high Arctic areas either desynchronize their circadian rhythms when there is a lack of environmental ques, or undergo temporal niche switching (altering temporal behaviour without altering circadian clock) depending on the time of year (Andreasson 1973; Williams et al. 2015). Types of temporal activity and circadian de/synchronization vary between species, but the activity types (number of bursts observed) of Shorthorn Sculpin in this study generally agree with those from a previous study (Andreasson 1973). Individuals appeared to be active at all times during 24 h daylight, however as the proportion of daylight each day decreased Shorthorn Sculpin MTs occurred more frequently during darkness indicating a shift to diel behaviour. These observations are similar to those found in Andreasson (1973), where Sculpin activity was observed across all hours of 24 h daylight periods but observed a shift to night-active at the end of September in sub-Artic areas associated with sunset.

Effects of Arctic Cod presence on Shorthorn Sculpin Movement Types

Although Shorthorn Sculpin have been documented with pelagic and demersal fishes in their gut contents (Kallgren et al. 2014; Cardinale et al. 2000) with some evidence that they feed on Arctic Cod (Dick et al. 2009; Landry et al. 2016) the results from this study are inconclusive regarding whether Shorthorn Sculpin actively prey on Arctic Cod, or scavenge them. The change in MTs in zone 1, a decrease in MT1 and increase in MT2, may be a result of Arctic Cod presence considering they occurred in much higher abundances and more often in zone 1 than in zones 2 and 3. However, it may also be the result of both species reacting and foraging on the same prey species or feeding opportunities, or Sculpin becoming less active and warier in the presence of large schools of Cod (Neill & Collen 1974). Stomach content data from Resolute Bay has shown that both species readily prey on the pelagic mollusc *Limacina helicina* when present during open water periods, and at least two Arctic Cod in the stomachs of Shorthorn Sculpin from Resolute Bay in 2012, although it is unknown whether they were scavenged or actively predated (Landry et al. 2016). It is possible that Shorthorn Sculpin feed on whichever prey items they can catch, as the consumption of a single adult Arctic Cod would have an energy payoff equal to that of numerous invertebrates (Hop & Gjosaeter 2013), behaviour that would agree with optimal forage theory (Werner & Hall 1974). The schooling behaviour of Arctic Cod may also make them more difficult prey to catch as large shoals of fish have been shown *in situ* to disrupt the attack sequence of ambush predators (Neill & Cullen 1974). This could hinder Shorthorn Sculpin ability to catch Cod except in rarer instances when individual Cod become separated from the school. If this were the case predation of Arctic Cod would occur less often than the predation of invertebrate prey and the increase in MT2 would not be a result of Sculpin predation on Cod.

The shortcomings in this study with respect to identifying Arctic Cod as a specific prey item may be mitigated in future studies by using acoustic tags that transmit signals more frequently to gain a higher resolution in the dataset over short periods of time, which would identify fast, fine scale movements such as feeding strikes (Broell et al. 2013). The use of predation tags could also resolve this issue (Halfyard et al. 2017), where suspected prey organisms are tagged with transmitters that can relay when predation events occur and be compared to the MTs and behaviour of tagged predators.

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Table 1: Total number of hours in which acoustically tagged Shorthorn Sculpin were detected in each zone throughout the study period (Sculpin present), and total number of hours in which acoustically tagged Arctic Cod were also present in the same zone (both species present) in Resolute Bay, Nunavut.

Zone & Associated Receiver Stations[1]	Sculpin Present (h)	Both Species Present (h)	Unique[2] Cod (min, max)	Unique[2] Sculpin (min, max)	Mean Relative Abundance Cod	Mean Relative Abundance Sculpin
Zone 1 (R1 – R5, VPS1 - VPS3)	503	493	1, 77	1, 4	3.98 ± 2.2	0.40 ± 0.28
Zone 2 (R14, R15, R19, R20, R25, R26, R31, R32, R37)	303	68	1, 50	1, 3	0.78 ± 1.7	0.36 ± 0.27
Zone 3 (R17, R18, R22, R24, R28, R30, R34, R36)	300	47	1, 49	1, 4	0.51 ± 1.4	0.33 ± 0.26

[1] See Figure 1 for received station positions and zones.

[2] Unique reflect different individuals for any given hour per zone, mean (± 1 SD) relative abundance for each species is the total number of hours when both species were present in each zone, relative abundance defined as the number of detections per hour/number of individuals per hour.

Table 2: Characteristics (mean ± 1 SD) of Shorthorn Sculpin movement type (MT) bursts in Resolute Bay, Nunavut that were significantly different between movement types (clusters). MT1 was associated with foraging, MT12 with feeding, and MT3 with long and straight transit movements.

Movement type burst	Sum Distance (m)[1]	Linearity Ratio[2]	Mean ROM[3] ($m\ s^{-1}$)	Mean Depth[4] (m)
1	187 ± 74	0.32 ± 0.33	0.03 ± 0.03	13.0 ± 4.9
2	37 ± 23	0.29 ± 0.27	0.01 ± 0.01	12.2 ± 4.1
3	784 ± 392	0.54 ± 0.34	0.06 ± 0.06	16.8 ± 5.2

[1] Sum distance is the total distance moved within a movement type burst.

[2] Linearity ratio was calculated by dividing the distance between relocations by the total distance where a value of 1 indicates a more linear or straight path and a value approaching 0 indicates a less linear path

[3] Rate of movement (ROM) was calculated from the distance travelled between relocations divided by the time between relocations.

[4] Depth was derived from pressure tags.

Figure 1: Location of acoustic telemetry project on Shorthorn Sculpin in Resolute Bay, Cornwallis Island, Nunavut (A); white points indicating acoustic telemetry receiver locations in bay (B); receiver names and white stars indicating capture points of Sculpin and Cod (C). Map source ArcGIC 10.4 (Esri, Redlands, CA, USA).

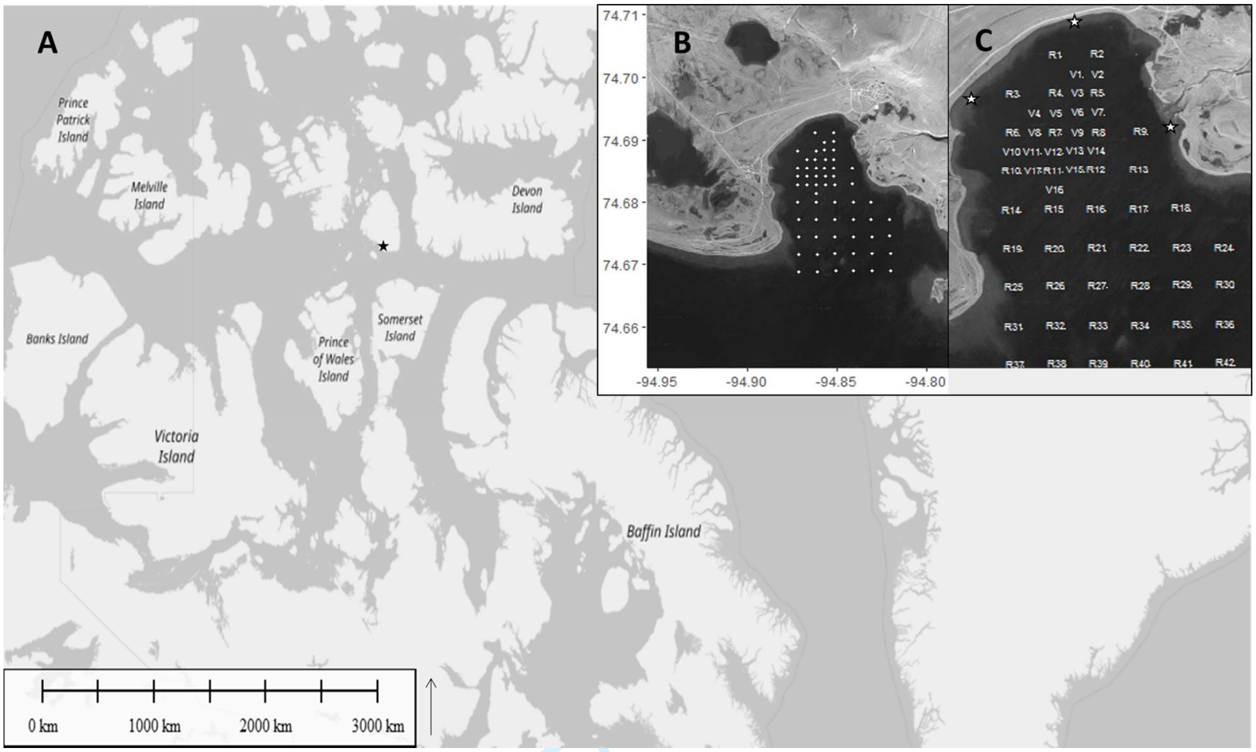
Figure 2: Number of acoustic tagged Shorthorn Sculpin and Arctic Cod by day across the study period in Resolute Bay, Nunavut.

Figure 3: Examples of the three movement types identified for acoustically tagged Shorthorn Sculpin in Resolute Bay, Nunavut. Two trajectory examples for each type are shown taken from different individuals (a and b). All movement types are compared spatially, to scale with inset of MT1a and MT2a also shown in higher resolution (not to scale) to distinguish characteristics of movement types 1 and 2 that are spatially smaller and more fine scale. The blue triangle represents start point, and red square represents end point. X and y axes represent xy coordinates based off of latitude and longitude associated with detected sculpin positions. MT1 is associated with foraging behaviour, MT2 with feeding behaviour, and MT3 with long and straight transit movements.

Figure 4: Movement types (MTs) of acoustically tagged Shorthorn Sculpin in Resolute Bay, Nunavut, coloured according to movement type. White squares represent zones used to analyze Arctic Cod abundance and related changes in Sculpin movement types. Zone one is located at the north end, zone 2 is located in the south west, and zone 3 located in the south-east region of the

Bay. MT1 is associated with foraging behaviour, MT2 with feeding behaviour, and MT3 with long and straight transit movements. Map source ArcGIC 10.4 (Esri, Redlands, CA, USA).

Figure 5: Binomial regression plot from Zone 1, demonstrating MT1 (foraging behavior) and MT2 (feeding behavior) changes in Shorthorn Sculpin related to an increase in relative Arctic Cod abundance in from Resolute Bay, Nunavut.


A
Prince Patrick Island
Melville Island
Devon Island
Banks Island
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0 km
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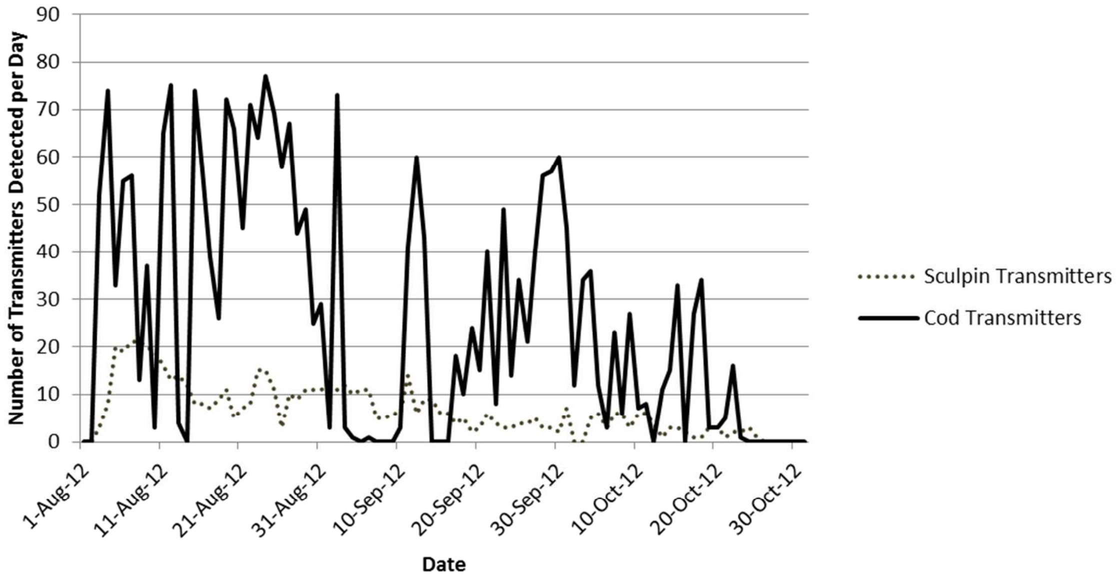
B
74.71
74.70
74.69
74.68
74.67
74.66
-94.95
-94.90
-94.85
-94.80
C
R1 R2
V1 V2
R3 R4 V3 R5
V4 V5 V6 V7
R6 V8 R7 V9 R8 R9
V10 V11 V12 V13 V14
R10 V17 R11 V15 R12 R13
V16
R14 R15 R16 R17 R18
R19 R20 R21 R22 R23 R24
R25 R26 R27 R28 R29 R30
R31 R32 R33 R34 R35 R36
R37 R38 R39 R40 R41 R42

Figure 1


Number of Transmitters Detected per Day
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1-Aug-12
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31-Aug-12
10-Sep-12
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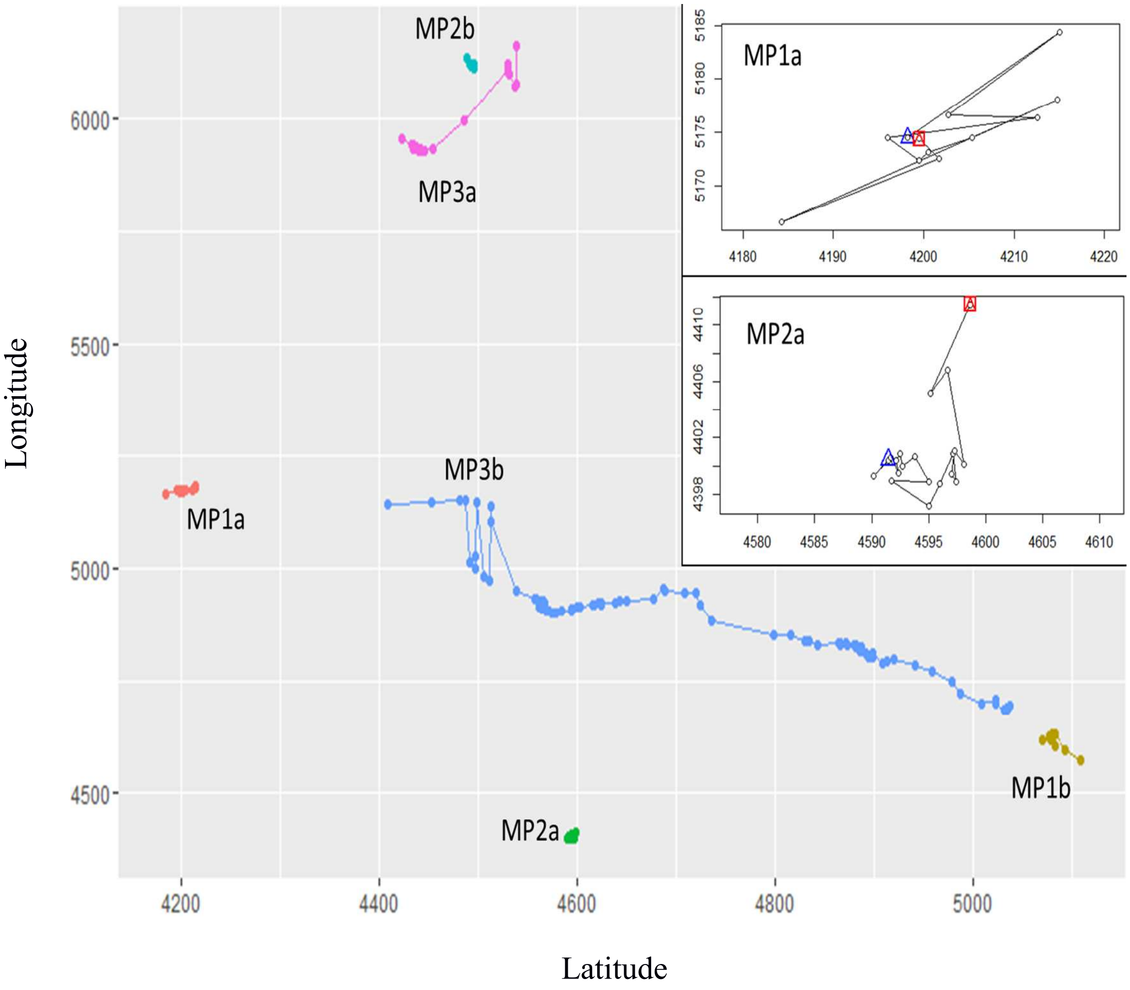
30-Sep-12
10-Oct-12
20-Oct-12
30-Oct-12
Date
Sculpin Transmitters
Cod Transmitters

Figure 2


MP2b
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6000
5500
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4200
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4800
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Longitude
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MP1a
5170
5175
5180
5185
4180
4190
4200
4210
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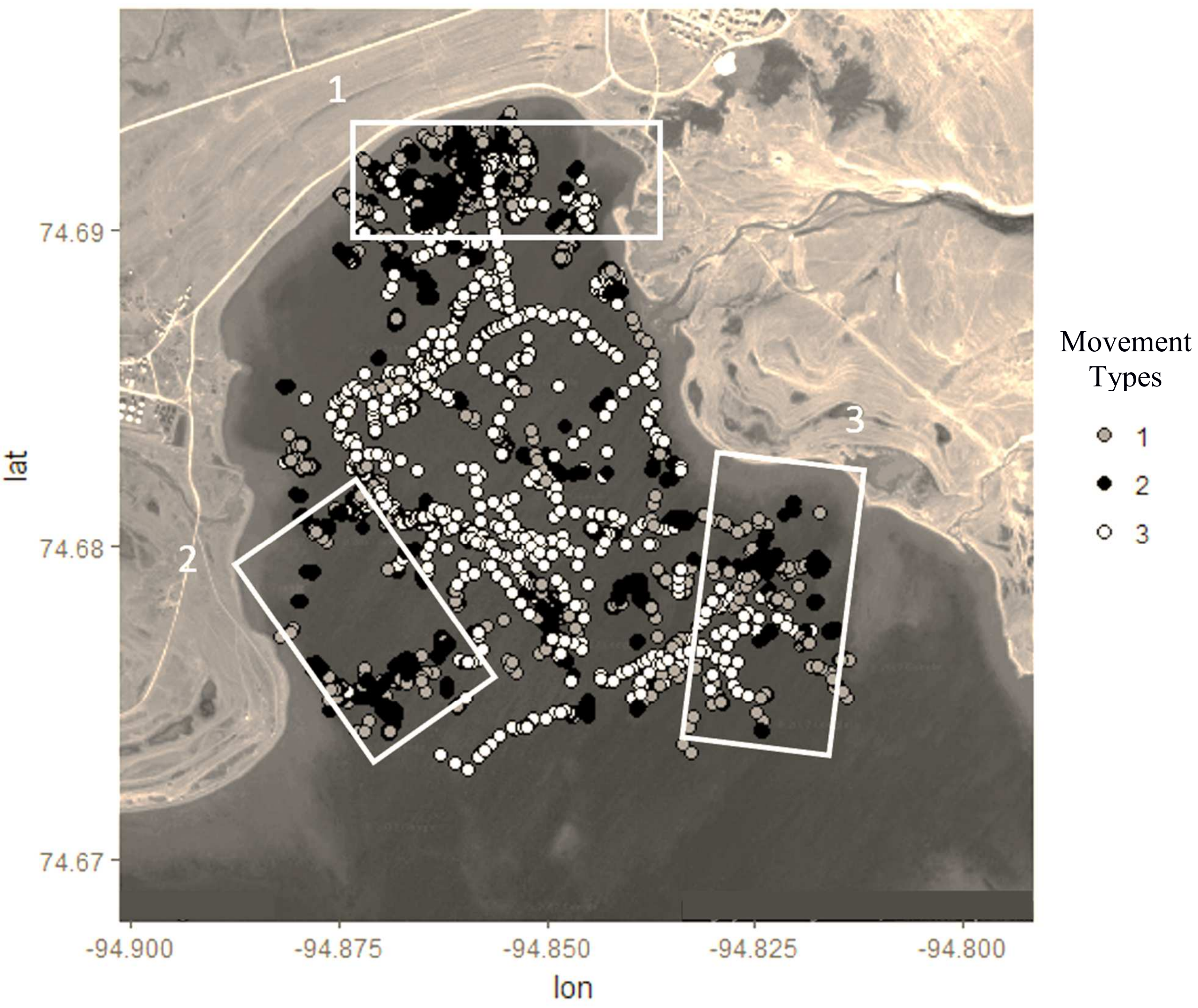
Figure 3


1
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3
74.69
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Movement Types
1
2
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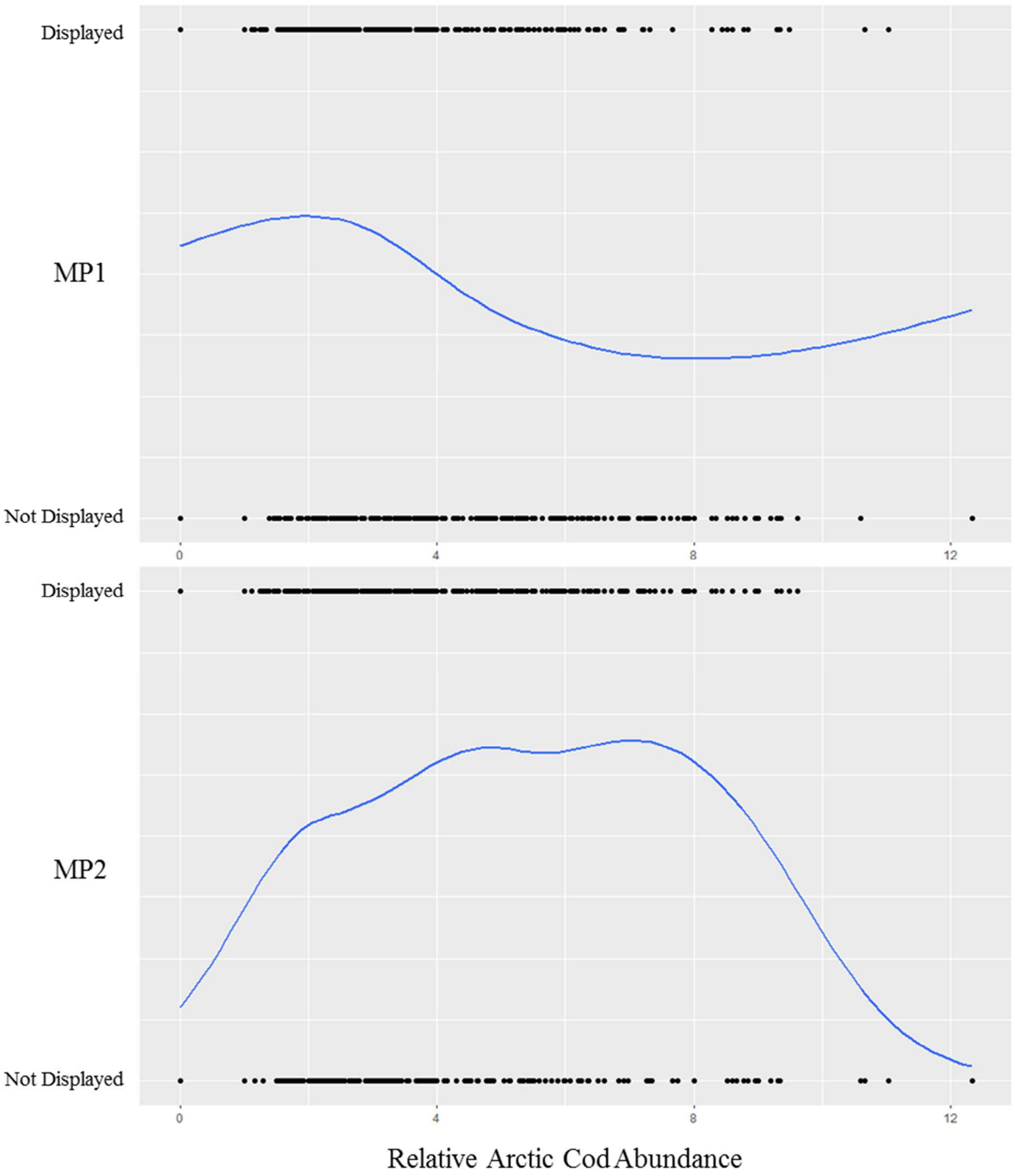
Figure 4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Relative Arctic Cod Abundance

Figure 5