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An Analysis of Spatial Distribution of an Isolated Bahamian Population of the Lined Seahorse,
Hippocampus erectus, via Nearest Neighbor, Hot Spot, and Buffering Assessments

Running header: Spatial distribution of the lined seahorse

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Abstract

Understanding the spatial distribution of animal populations is essential for placing their social interactions into context and developing hypotheses about reproductive, feeding, and predator-prey behaviors. A particular population of the lined seahorse, *Hippocampus erectus*, is found in an isolated salt water lake, Sweetings Pond, on the island of Eleuthera, Bahamas. This ecosystem provided a unique opportunity to study the space use of a high density seahorse population in its natural environment. Examination of clustering patterns across time of day, aggregations by size and sex, habitat impact by season, and predator influence on overall spatial distribution were conducted. These questions were analyzed and tested for significance via geographic mapping utilizing nearest neighbor analysis, hot-spot analysis, and the buffering tool. It was concluded that this population of seahorses forms clusters during the nighttime compared to uniform dispersal seen during the daytime. The average seahorse total body length increased with increasing depth regardless of sex. This population is also positively correlated with algae cover in both the wet and dry seasons and display active avoidance of potential predators. Sweetings Pond provided the ideal conditions to be able to study a population in its natural environment. The unprecedented conclusions drawn from this field study provide critical information regarding the natural ecology, behavior, and future conservation efforts of this vulnerable seahorse species.

Keywords: clustering, conservation, *Hippocampus erectus*, spatial

Introduction

The spatial distribution of a population is vital to understanding their sociality and mating system. One hypothesis of singing in humpback whales for communication of location was supported by measuring the space use of these animals (Frankel et al. 1995). This finding provided a solid foundation for the expansion of the role of singing in humpback whales from conventional understandings. Having knowledge on the mating system of animals can influence our knowledge of the space use of population. When investigating a promiscuous rodent, it was determined that there was a complete lack of territoriality over small and often overlapping home ranges (Borremans et al. 2014). In this rodent's case there was no need to aggressively defend a large area, since the rodent is able to mate multiple times across many mates. However, obtaining this spatial data can be quite challenging especially when studying organisms of conservation concern and thus often low density populations. Different ways to acquire such spatial data for seahorses have been proposed which include, governmental research, scientific diving surveys, citizen science, and fisher interviews (Aylesworth et al. 2017). Diving surveys were used to gather data to further understand the various factors contributing to the spatial distribution of a seahorse population.

The mating system of seahorses is commonly defined as monogamous or sexually reproducing with one mate within and sometimes across breeding seasons (Vincent and Sadler 1995, Woodall et al. 2011). This system has been shown to affect space use in the context of small home range sizes of monogamous *Hippocampus whitei* likely due to mate fidelity (Vincent et al. 2005). It has also been shown that *H. whitei* males found furthest apart from one another were observed to have the greatest degree of asynchrony, which is the lack of concurrence of

fertility during the male fertility time period (Vincent et al. 2004). These studies demonstrate the close interaction between spatial distribution and the mating system of a population.

Assessing spatial organization of animals can reveal underlying causes of observed social behaviors. For example, high density populations of *Hippocampus abdominalis* were found to display social promiscuity in courtship behaviors even though genetics revealed strict monogamy (Wilson and Martin-Smith 2007). The increased availability of nearby seahorses in high density populations was a driving factor for this particular social interaction. When *H. abdominalis* were studied in a low density population most individuals were found alone and when they were found in aggregations there was no pattern with regards to sex (Martin-Smith and Vincent 2005). The availability of conspecifics within a particular space is seen to be critical factor in the ability to display social behaviors. *Hippocampus breviceps* was seen to form mixed-sex social groupings in specific core areas when the sex ratio was 1:1 for males and females. The adults had small but overlapping spatial areas that allowed for consistent social encounters (Moreau and Vincent 2004).

Environmental aspects can also contribute largely to the space use of a population. Qin and colleagues (2017) illustrated the possibility of *Hippocampus mohnikei* undergoing a seasonal inshore-offshore migration triggered by water temperature, therefore affecting the spatial distribution of the population across time. The physical habitat within a species' environment can also impact the spatial distribution of populations. Space use of *Hippocampus guttulatus* on varying habitat types was described, and a difference in habitat preference between juveniles and adults was found (Gristina et al 2017). In this case, spatial separation was driven by substrate type and age of the individual animal. *Hippocampus whitei* demonstrated a stronger preference for dense seagrass beds with a separation being found with smaller seahorses residing deeper in

the beds. This study also demonstrated the importance of predator and prey presence with more seahorses located in areas with higher prey densities and lower predator densities (Manning et al. 2018). Altogether, a wide diversity of environmental factors exists within an ecosystem affecting the spatial distribution of populations.

The lined seahorse, *Hippocampus erectus*, has known established populations along the Western Atlantic Ocean as far north as Nova Scotia, Canada and as far south as the southern tip of Brazil (Boehm et al. 2015, Silveira et al. 2014). Many populations also reside in the Gulf of Mexico and the Caribbean Sea surrounding many of the Caribbean and Bahamian islands. In these places, the lined seahorse is commonly found on mangroves, seagrasses, marine algae, and coral reefs (Dias et al. 2002), with seahorses in general also found on many human-made structures (Clynick 2008). They are known to feed on planktonic organisms such as mysids, copepods, and amphipods (Woods 2002, Teixeira and Musick 2001). While crabs, rays, and large fish are known to feed on seahorses in the open ocean (Kleiber et al 2011), the known seahorse predators in the pond include spider crabs (*Mithrax spinosissimus*), Caribbean reef octopus (*Octopus brierus*), and Nassau grouper (*Epienephalus striatus*). The lined seahorse is within the family Syngnathidae which is characterized by male gestation and birth of offspring. *H. erectus* is also suggested to be monogamous, sexually reproducing with one mate within breeding seasons (Teixeira and Musick 2001). With the ability to study this Sweetings Pond population in its natural habitat, it was determined that these seahorses exhibited nocturnal behavior which is unusual for this family of fish.

Sweetings Pond is a geographically isolated anchialine lake that runs about one mile long and half a mile wide. There is a daily tidal flush with the surrounding Atlantic Ocean through the porous limestone that separates the lake from the ocean. While salt water is able to flow through

the lake, no organisms to our knowledge can naturally enter or exit this system (Rose et al 2016). With this geographic isolation came a decrease in diversity within the lake when compared to the surrounding ocean, with 50 different families of fish recorded in the Atlantic Ocean and only 15 families within Sweetings Pond (Masonjones et al 2019). However, it seems that this lack of fish diversity and low density of predators has allowed the lined seahorse (*Hippocampus erectus*) population to flourish within the lake. The mean landscape seahorse density found within the lake was determined to be 0.14 ± 0.013 ind. m^{-2} (max. 0.66 ind. m^{-2}) compared to the global mean seahorse density of 0.06 ± 0.021 animals m^{-2} (Masonjones et al. 2019, Masonjones and Rose 2019). Sweetings Pond contains at least 10 species of algae and a combination of other substrates such as sponges, bivalves, and tunicates (Masonjones et al. in prep). Since marine algae is most abundant within the pond and is also common across seahorse habitats within the Atlantic Ocean, it was chosen as a focal factor in understanding space use of these organisms. The combination of isolation and high densities of seahorses allows for robust scientific methodology within the pond to explore diverse spatial distribution questions.

Overall, providing a holistic view of spatial distribution and its driving factors for this *H. erectus* population will allow for better conservation efforts of this threatened species. The goals of this study were to determine the presence of clustering patterns, define the relationship of aggregations between sex and total body length, understand the impact of benthic habitat cover on seahorse density, and to discern the effect of predators on seahorse behavior.

Methods

This study utilizes diving surveys along transects to gather spatial information on a seahorse population to assess social interactions and the potential associations with reproductive, predatory, and environmental factors. It was predicted that animals would be found in clusters

during the nighttime due to known higher densities. Since the lined seahorse is defined as monogamous, we expected there to be aggregations of males and females of similar size. With the known effect of high quality habitat with increased animal density we anticipated both percent algae cover and the diversity indexes to be positively correlated with seahorse density. The last trend we expected to see was an increase in the mean number of seahorses around predators during the nighttime due to an increase in both seahorse and predator densities during that time.

The data for this study were collected over four sampling days in March and two sampling days in August of 2018. The month of March falls within the dry season and the month of August falls within the wet season for the Bahamas. All data was collected from the north end of the pond in the Caves site (Figure 1). In March, a total of twelve 30 meter long by 2 meter wide transects were laid perpendicular to the shoreline with increasing depth. Two extra transects were laid the first sampling day parallel to the shallow transects but farther offshore. No additional deep transects were laid for the rest of the sampling period due to a low density of animals recorded. It was decided that our sampling efforts and resources were best spent closer to shore. The start of each transect was approximately thirty meters apart from one another with the transects on either side of the site entrance being about sixty meters apart. In August, three of the transects with the highest seahorse densities were resampled to provide seasonal data for analysis (Figure 1).

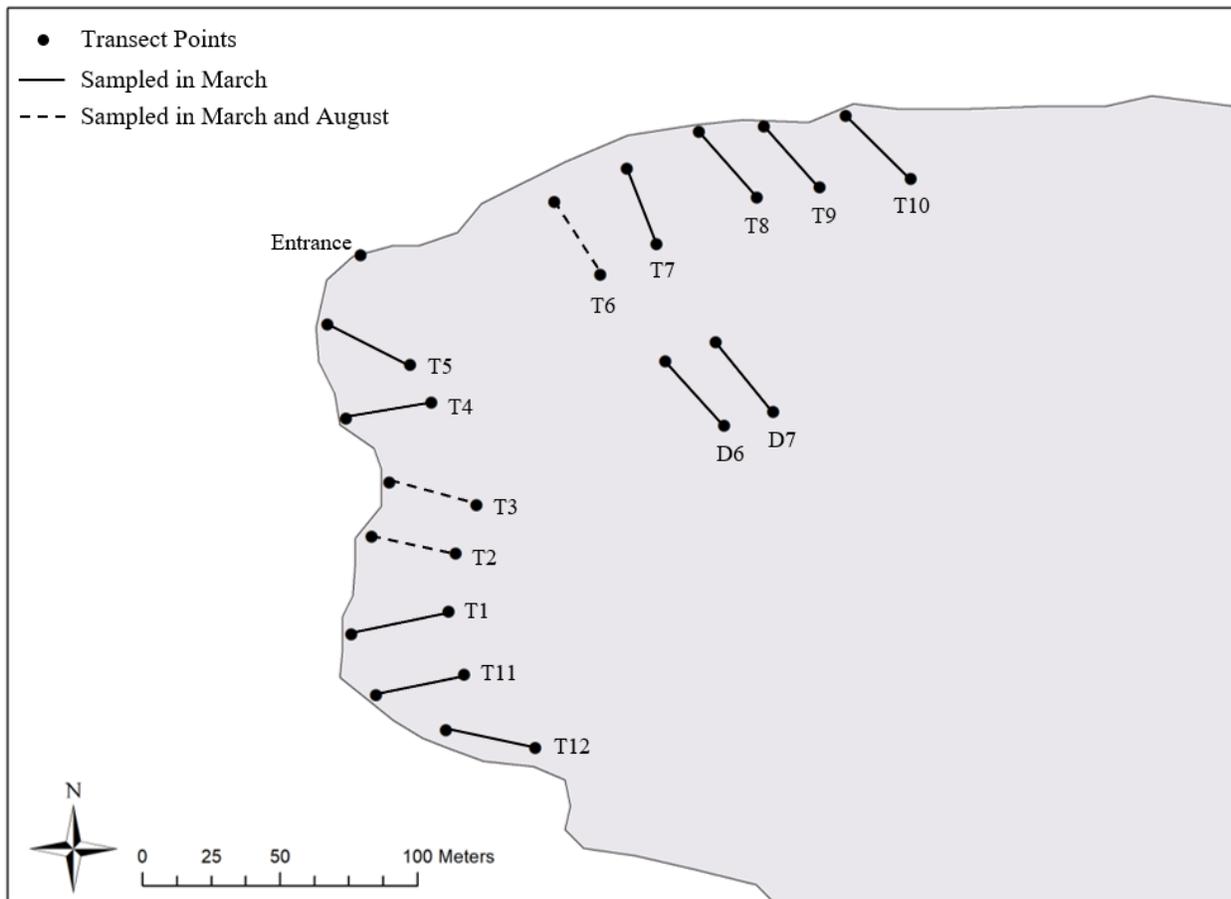


Figure 1: Location of Sweetings Pond research site (25°21'40''N, 76°30'40''W). Layout of the sampling transects at the north end (Caves site) of Sweetings Pond on Eleuthera, Bahamas. The three dotted lines represent the resampling event that occurred during the wet season. Transects D6 and D7 represent deep water transects, with only two being laid and sampled due to resources and available time. Map projected in UTM Zone 18N, WGS84.

During the daytime, the transect start point was recorded via a GPS unit and marked physically with a float attached to a weighted string to allow for easy visual recognition for nighttime work. The transect tape was then secured at the starting point and swam thirty meters perpendicular to the shore. Another float was also placed to mark the end of the transect. The tape was secured in the substrate at the end point and the coordinates were recorded via the GPS

unit. Transect tapes were left during the day to ensure comparable sampling locations for the nighttime. Along the swim back to the starting point, a picture was taken of the benthic habitat at every meter for a total of 31 photos for each transect. One diver conducted a two meter belt (four meters total) survey for seahorse predators, including crabs, octopus, and grouper. Two other divers conducted a one meter belt (two meters total) survey for seahorses. When a seahorse was identified, time, depth, location on the transect line, sex, gravidity, and perch height (the distance from the sea floor to the top of the seahorses head) were all manually recorded. A photograph was taken for the substrate of the seahorse for later identification of their holdfast, the seahorse's overall body, and a close up of the head region. The seahorse was never touched during the day as to avoid skewing locations and prevent the seahorses from moving from their original location.

During the nighttime, the beginning of the transects were located via the floats placed earlier in the daytime. Sampling for predators and seahorses was conducted under the same methods as during the daytime. The same values were recorded, with the only difference being the additional photographs taken during the nighttime. A picture was taken of the seahorse's substrate and then the seahorse was placed on a one centimeter grid and held in place with a piece of clear plexiglass. A photograph of the overall body and a close up of the head were captured for later analysis of body measurements and head patterning. The seahorse was then placed back on the substrate it was initially found on. After sampling was completed, the floats and transect tape were removed as to leave nothing behind to disturb the ecosystem.

All photos and recorded data were entered into a Microsoft Access Database (version 16.0). Through this database, ImageJ (version 1.50i) was used to measure snout length, head length, trunk length, tail length, body width, pouch width, and pouch length all in millimeters

using the protocol outlined in Vallejo and González (2014). The sum of the head length, trunk length, and tail length was defined as total body length (in mm). Each seahorse was also designated a latitude and longitude coordinate point using a mathematical algorithm that took into consideration the starting and ending points of the transect, the location along the transect, and the side of the transect the seahorse was recorded.

The Coral Point Count (version 4.1; Kohler 2006) program was utilized to measure percent algae, percent open habitat (which is defined as an area having no vegetation), Shannon's diversity index (Spellerberg and Fedor 2003), and Simpson's diversity index (Simpson 1949) for the benthic habitat photos. These values were determined by establishing an area of analysis for each photograph which was determined to be 900 cm² as this was the maximum area visible across all benthic photographs. Thirty random points were created across the area of analysis with each point being designated a benthic type based on the background behind each point. The program was then able to calculate the percent algae cover, percent open habitat, and the diversity indices for each benthic picture. Using the same algorithm for the seahorses, we were able to assign a latitude and longitude for each benthic photo. The benthic habitat coordinates were then associated with their proper data extracted from the Coral Point Count program.

ArcMap (version 10.7) was used to analyze all questions addressed in this study. To determine clustering patterns, seahorse data points were separated by transect, time of day, and season. Nearest neighbor analysis in the spatial statistics toolbox was then conducted on each group of seahorses with the output providing a significantly clustered, dispersed, or insignificantly random pattern. Statistical analysis was performed in R (version 3.5) by running a Chi Square test of clustering pattern against time of day. Season was combined for this analysis due to the smaller sample size in the wet season.

To determine aggregations of seahorses by sex and total body length, a hot spot analysis (Getis-Ord Gi) was conducted in ArcMap. Seahorse data points were separated by sex with only nighttime data being included since it was the only sampling time where the seahorses were able to be measured against a standardized grid. Season again was not separated out due to the smaller sample size in the wet season.

To understand habitat influences on spatial distribution the buffering tool in ArcMap was used. A 0.75 meter buffer was created around each benthic habitat point as this was the minimum area needed to encompass a seahorse point along a transect. The spatial join feature was then used to determine the number of seahorses within each buffer. Since the transects were in the same location across time of day, their benthics were also identical which allowed for both daytime and nighttime seahorses to be included in this analysis. This data was then statistically analyzed in R using a Pearson correlation test to determine the relationship between the number of seahorses and percent algae cover, percent open habitat, Shannon's diversity index, and Simpson's diversity index. This test was split between wet and dry season due to the possible differences in substrate habitat across season.

The role of predators on seahorse distribution was also conducted using the buffer tool in ArcMap. A 1 m buffer was created around each predator point with the spatial join feature again being used to count the number of seahorses within that buffer. The predator and seahorse data were divided by time of day and season with mean number of seahorses per predator being calculated for analysis.

Results

The output from the nearest neighbor analysis gave 0 clustered, 15 dispersed, and 1 random transect during the daytime for a total of 16 total day transects analyzed. There were 7

clustered, 5 dispersed, and 5 random transects during the nighttime for a total of 17 total night transects analyzed (Figure 2). There was one daytime transect where no seahorses were detected and therefore no clustering pattern could be assigned. Statistical testing showed that there are significantly higher clustering patterns of seahorses during the nighttime when compared against the daytime ($X^2 = 14.65$, $df = 2$, $p = 0.0006589$).

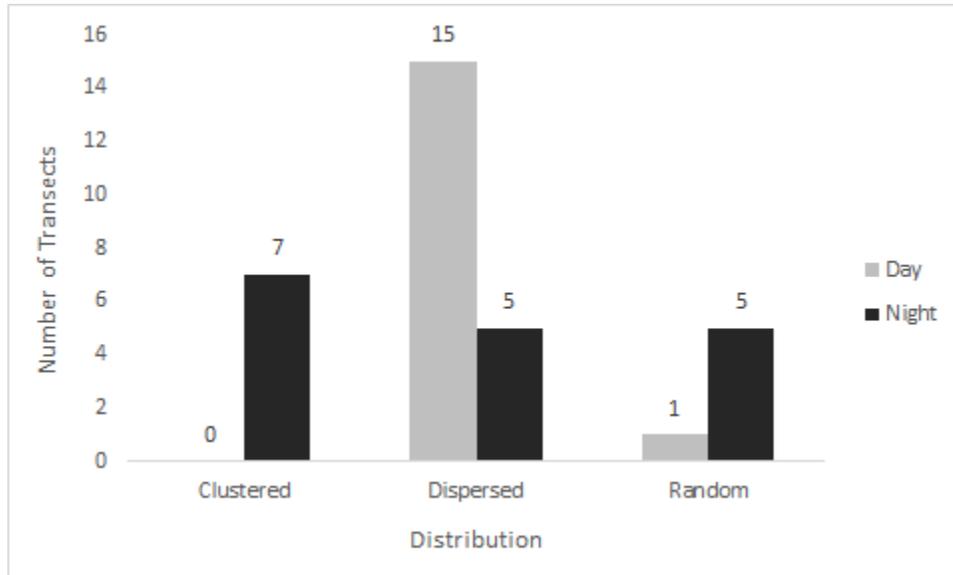


Figure 2: The clustering patterns found between nighttime and daytime combining both the wet and dry season are demonstrated. The main differences being observed with all the clustered distribution occurring during the nighttime and the majority of the dispersed distribution occurring during the daytime.

Hot spot analysis for juveniles revealed 3 transects, two with significant (at least 95% confidence) hot spots, where fish are statistically higher than the average total body length for juveniles, and one significant cold spot, where fish are statistically lower than the average total body length for juveniles. There were also two juvenile fish in the deepest sampled part of the pond which were much higher (99% confidence) than the mean juvenile body length. Male seahorses had 6 transects, three with significant hot spots and three with significant cold spots.

Female seahorses had 3 transects, two with significant hot spots and one with significant cold spots. Again, two female fish were seen in the deepest sampled area of the pond with much higher mean female total body length (Figure 3).

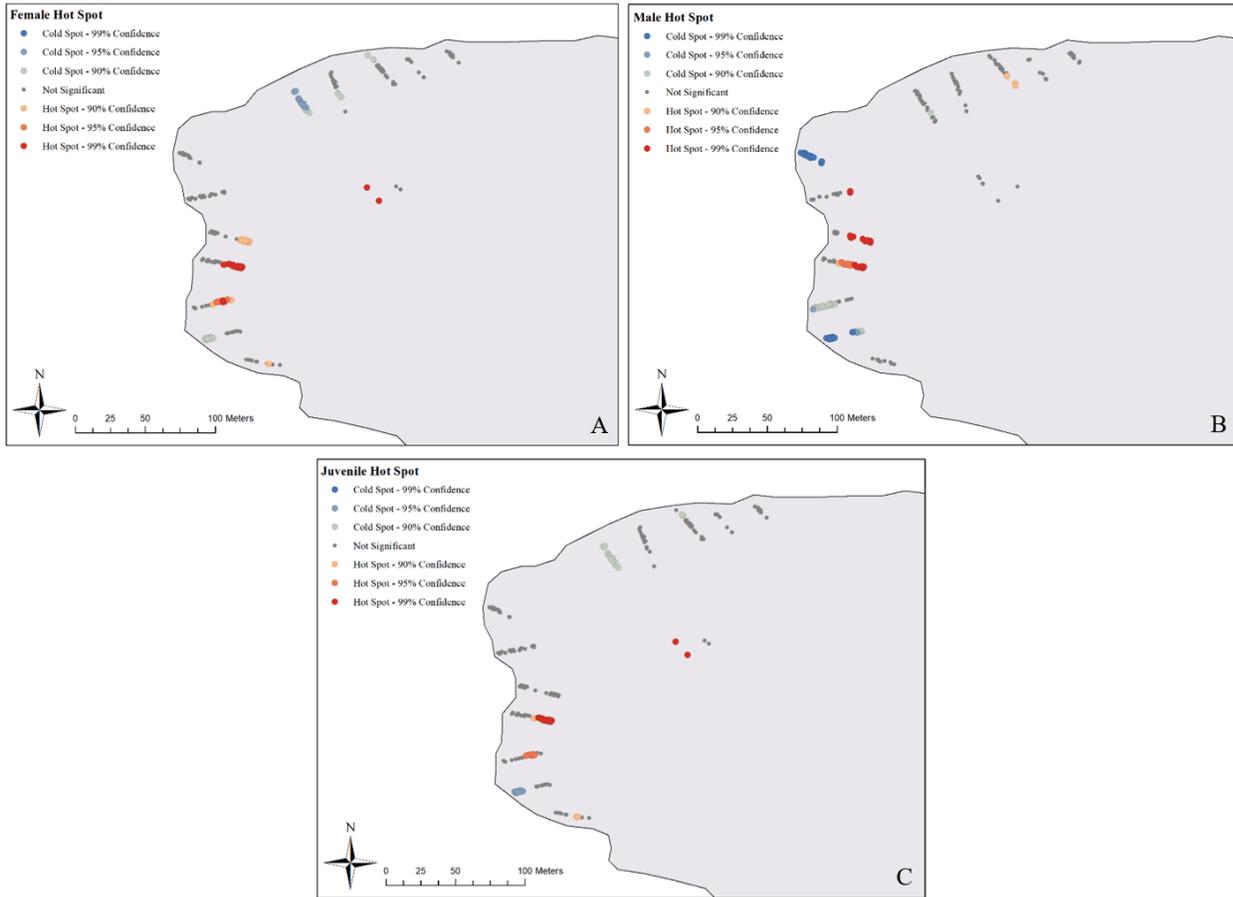


Figure 3: Hot spot analysis maps conducted across sex for total seahorse body length (mm) where darker red points represent statistically higher total body lengths than the average and darker blue points represent statistically lower total body lengths than the average. Panel A: female hot spot map reveals three significant transects; Panel B: male hot spot map reveals six significant transects; Panel C: juvenile hot spot map reveals three significant transects.

The density of seahorses in the dry season was determined to be positively correlated (cor = 0.5403257) with percent algae cover of the benthic habitat ($t = 13.331$, $df = 431$, $p = 2.2 \times 10^{-16}$).

The same positively correlated ($\text{cor} = 0.3085953$) relationship between density of seahorses and percent algae cover was also seen in the wet season ($t = 3.0949$, $df = 91$, $p = 0.002616$). The density of seahorses in the dry season was negatively correlated ($\text{cor} = -0.2682517$) with percent open habitat ($t = -5.7809$, $df = 431$, $p = 1.427e-08$). Again, a negatively correlated relationship ($\text{cor} = -0.3536897$) between density of seahorses and percent open habitat was seen in the wet season ($t = -3.6071$, $df = 91$, $p = 0.0005054$).

Seahorse density in both the dry and wet season had no correlation ($\text{cor} = 0.05141772$; $\text{cor} = -0.02180498$) with Shannon's Diversity Index ($t = 1.0689$, $df = 431$, $p = 0.2857$; $t = -0.20806$, $df = 91$, $p = 0.8357$). The density of seahorses in both the dry and wet season also had no correlation ($\text{cor} = 0.05511318$; $\text{cor} = -0.02292672$) with Simpson's Diversity Index ($t = 1.1459$, $df = 431$, $p = 0.2525$; $t = -0.21876$, $df = 91$, $p = 0.8273$).

During the day of the dry season there were a total of 4 predators recorded with 0 seahorses being within 1 m of a predator. The night of the dry season had a total of 38 predators recorded with the mean number of seahorses per predator was 1.632. During the day of the wet season a total of 3 predators was recorded with a mean number of seahorses per predator being 0.667. The night of the wet season had a total of 13 recorded predators with a mean number of seahorses per predator of 0.846 (Table 1).

Table 1: Separation by season and time of day against the two recorded potential predators and the total numbers when combining both the predators are shown. The mean number of seahorses within a one meter radius around the predator, the sum of the total number of seahorses found within the predator radius, and the total number of predatory animals observed was recorded.

| | Crab | Octopus | Total |
|-----------------------------|-------------|----------------|--------------|
| Dry Season - Day | | | |
| Mean number of seahorses | 0 | 0 | 0 |
| Sum of total seahorses | 0 | 0 | 0 |
| Number of predatory animals | 0 | 0 | 0 |
| Dry Season - Night | | | |
| Mean number of seahorses | 1.667 | 1 | 1.632 |
| Sum of total seahorses | 60 | 2 | 62 |
| Number of predatory animals | 36 | 2 | 38 |
| Wet Season - Day | | | |
| Mean number of seahorses | 0 | 0.667 | 0.667 |
| Sum of total seahorses | 0 | 2 | 2 |
| Number of predatory animals | 0 | 3 | 3 |
| Wet Season - Night | | | |
| Mean number of seahorses | 0.75 | 1 | 0.846 |
| Sum of total seahorses | 6 | 5 | 11 |
| Number of predatory animals | 8 | 5 | 13 |

Discussion

Spatial distribution and the factors that drive it have both daily impacts on the behavior of organisms but also long term population trends that are influential in conservation efforts. The lined seahorse population in this study demonstrated clear clustering patterns based on time of day, total body length, habitat cover, and predator presence. This space use could be controlled by reproductive relationships, social interactions, and environmental factors. However, to best assess spatial distribution, we first had to understand the most active time periods for this seahorse population.

In the past, only three seahorse species, *Hippocampus ingens*, *H. abdominalis*, and *H. comes*, have been studied and defined as exhibiting nocturnal behavior (Foster and Vincent 2004,

Martin-Smith and Vincent 2005, Perante 2002). However, the nocturnal survey conducted within Sweetings Pond provided concrete evidence (274% higher density of seahorses being recorded at night versus day) that this population of seahorses shows strong nocturnal behaviors (Masonjones et al in prep). This nocturnal study revealed the possibility of mating and feeding events being more likely during the nighttime. However, there was also an increase in predators at night eliminating reduced predatory risk being the cause of this nocturnal seahorse behavior. The study of these nighttime versus daytime ecological differences in organisms is largely understudied (Gaston 2019). Therefore, understanding when a population is most active is crucial to observing and recording behaviors. Hence, data from both daytime and nighttime was utilized in this study to assess spatial distribution and its behavioral impacts on this unique seahorse population.

The contrast between nighttime and daytime is further reinforced with the significant seahorse clustering patterns found during the night. This could indicate animals gathering for mating and reproductive purposes. If the seahorse population is attempting to find mates there would be more opportunity for choice in higher density areas. The clustering pattern could also be related to group feeding events. When feeding occurs, seahorses maintain a mostly upright body posture resulting in exposure from their habitat and a higher predation risk. Feeding during the night may reduce this exposure due to the decrease in light quantity and therefore reduced overall predation risk. To further investigate this nighttime clustering pattern, sex and total body length were assessed for potential relationships.

Even though male seahorses exhibited twice as many total hot and cold spots, there was a clear pattern regardless of sex. As the depth increased the total body length of the seahorses also increased. This finding provides support for the potential mating clustering patterns since body

size is a critical deciding factor in mate choice (Anderson 2012, Bahr et al. 2012). However, the impact of the role of depth on body size in seahorses is largely unknown. It has been found that teleost fish were found to exhibit a positive relationship with body size and depth (Smith and Brown 2002). There is a potential for other abiotic factors such as temperature and nutrient availability or biotic factors such as competition and predation risks that could also play a role in the larger body length fish being observed at greater depths.

Seahorses are a unique fish in that they rely heavily on their benthic habitat. This importance of habitat has led to the current conservation concerns regarding most species of seahorses (Woodall et al 2018, Scales 2010, Vincent et al 2011). It is understood that decreasing the available benthic structure in an ecosystem decreases the density of seahorses in that area (Masonjones et al 2010, Marcus et al 2007). The abundance and type of habitat has the potential to greatly influence the distribution of a population. It was seen here that there was a strong positive correlation with the percent algae cover and seahorse density regardless of the season. This adds to the evidence of the importance of available substrate for the overall population size. However, when Shannon's Index and Simpson's Index were analyzed, there was no correlation with seahorse density. While we have seen preference among seahorse species for particular habitats (Aylesworth et al. 2015, Gristina et al. 2015, Harasti et al. 2014) our results show that it is not the diversity of substrates but rather the amount of substrate that matters. This is confirmed with the strong negative correlation seen with seahorse density and the percent of their habitat that is open or lacking benthic cover.

While benthic habitat explains a portion of spatial distribution, how animals use their ecosystem space can also be dependent upon the presence or absence of potential predators. Three potential predators were defined as spider crabs, Caribbean octopus, and Nassau grouper.

During our study seahorses significantly outnumbered predators. With this drastic difference in densities between seahorses and predators you would expect there to be a high number of seahorses around a predator at any given time. However, it was determined that the mean number of seahorses found within a 1 meter circular radius of a predator did not exceed 2 seahorses. This demonstrates the possibility for active avoidance by the seahorses of potential predators. Predator avoidance behavior may be one of the driving forces behind the abnormally high densities observed in Sweetings Pond.

Overall, this study aimed to investigate the spatial distribution of the lined seahorse from many different angles in an isolated salt water lake. Uniting nighttime clustering patterns, increased body length with depth, positive correlations with algae cover, and predator avoidance behavior provides unparalleled insight on the ecology and behavior of a threatened seahorse species. With these results, future surveys should be conducted across multiple times of day to ensure the period of highest activity and abundance to avoid underestimating population sizes. Conservation for *H. erectus* should be revisited and emphasis on the protection of benthic habitat should be of more global concern.

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