AN ABSTRACT OF THE THESIS OF

Thomas P. Calvanese for the degree of Master of Science in Fisheries Science presented on December 5, 2016.

Title: Movement Patterns of Rockfishes at the Redfish Rocks Marine Reserve, Oregon

Abstract approved:

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Scott A. Heppell

The effects of Marine protected areas (MPAs) on adult fish populations depend on the degree of protection provided, which is partly a function of MPA size and the spatial extent of fish movements. The Redfish Rocks Marine Reserve (RRMR) and MPA, located on the south coast of Oregon near Port Orford, went into effect on January 1, 2012. The boundaries of the RRMR were informed by the experience of local fishermen, but without explicit knowledge of the movement patterns of individual fish. One of the intended effects of this reserve was to provide protection for Pacific rockfishes that had been targeted there by the live fish fishery. We conducted a 17-month acoustic telemetry study to document the movement patterns of 20 individuals (6-7 each) of China Rockfish *(Sebastes nebulosus)*, Quillback Rockfish *(S. maliger)*, and Copper Rockfish *(S. caurinus)* at Redfish Rocks, Oregon. Objectives were to (1) estimate residence times for individuals of each species, (2) evaluate spatial and temporal movement patterns, and (3) analyze the relationship between habitat attributes and movement patterns. Our results demonstrated that this small (6.78 km^2)

no-take marine reserve provides refuge for a substantial portion of the local population of these demersal residential fishes, due to those species' high site fidelity to this patch of high relief rocky reef habitat located within the Redfish Rocks Marine Reserve.

Movement Patterns of Rockfishes at the Redfish Rocks Marine Reserve, Oregon

by
Thomas P. Calvanese

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APPROVED:

Major Professor, representing Fisheries Science

Head of the Department of Fisheries and Wildlife

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Thomas P. Calvanese, Author

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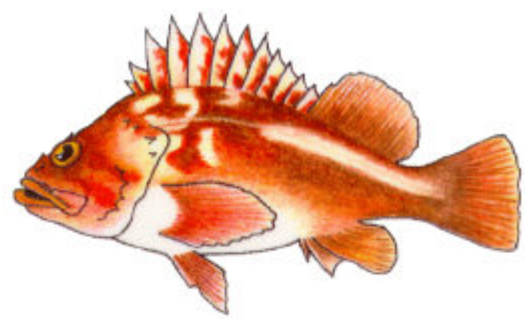
Mahalo Nui Loa.

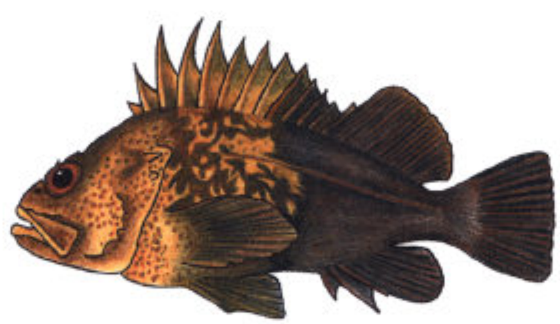
This work is dedicated to the magnificent fishes of the genus *Sebastes*.

Long may they thrive.

Sebastes nebulosus



Sebastes caurinus



Sebastes maliger

(drawings from California Department of Fish and Wildlife)

TABLE OF CONTENTS

Introduction

Global capture fishery production in 2014 was 93.4 million metric tons, while annual global per capita fish consumption reached a record high of 20 kg (FAO, 2016). An estimated 56.6 million people were engaged in capture fisheries and aquaculture in 2014; approximately two-thirds of these are engaged in culturally important fisheries (FAO, 2016). Even as aquaculture production increases, the demand for wild fish continues to increase as human population grows, resulting in overexploitation of many fish populations (Holmlund & Hammer, 1999; Worm et al., 2006). In response, efforts to restore marine ecosystems and rebuild fisheries are underway around the world (Hilborn et al., 2003; Worm et al., 2009).

Fisheries in the Northeast Pacific are among those that have suffered historic overexploitation (Parker et al., 2000) including many species of Pacific rockfishes of the genus *Sebastes* (Love et al., 2002). The Pacific rockfishes are a diverse group, and there are more than 60 species of *Sebastes* found off the coast of California, Oregon, and Washington (Clay et al., 1985; Lea et al., 1999). Several species of rockfish have high commercial value and have been heavily targeted for decades, resulting in population declines, declarations of fishery disasters (Conway & Shaw, 2008), and subsequent management interventions to limit harvest (Ralston, 2002). These interventions have included bycatch reduction measures (Lewison et al., 2011), reduced quotas (Copes, 1986), and the establishment of spatial management measures, such as the Stonewall Bank Yelloweye Rockfish Conservation Area, and several marine protected areas (MPAs) (Lubchenco et al., 2003). The emergence on the U.S. West Coast of a market for live fish has increased fishing pressure on certain high-value near shore rockfish species, including China *(Sebastes nebulosus)*, Quillback *(S. maliger)*, and Copper *(S. caurinus)* Rockfish (The Research Group, LLC, 2013), leading to restrictions on the recreational harvest of these species in 2016 (Oregon Department of Fish, 2016).

Rockfishes possess life history characteristics that make them very vulnerable to overfishing (Levin et al., 2006). These include long life (Haldorson & Love, 1991; Leaman, 1991), late maturity (Echeverria, 1988; Love et al., 2002), and evolutionary isolation (Magnuson-Ford et al., 2009). Furthermore, increased fishing intensity leads to age truncation (Stewart, 2011), which results in a loss of spawning stock biomass and a reduction in reproductive output (Berkeley et al., 2012).

Long life and delayed maturity are adaptive responses to the temporally variable environments in which these species have evolved, where conditions suitable for larval survival are episodic, and so reproductive effort is spread over many years to increase the probability of reproductive success (Sogard et al., 2008). Long life provides individuals with increased opportunities for successful reproduction; still, these species exhibit low lifetime productivity due to low reproductive success in most years (Berkeley, et. al, 2004). These characteristics also contribute to the slow recovery of these populations once they have been overexploited, and contribute to the population level effects of overexploitation such as lower productivity due to loss of spawning biomass (Parker et al., 2000). In addition, fishing typically targets larger individuals, introducing selective pressure against larger, older female rockfish, also known as BOFFFFs, or big old fat fecund female fish, which are known to be relatively more fecund, and contribute a greater proportion of productivity to their respective populations (Hixon et al., 2014). This bet hedging reproductive strategy and the effects of fishing on long lived rockfish populations provides a strong argument for management strategies designed to conserve old-growth age structure in these species (Hixon et al., 2014).

One way to promote the restoration of populations in general and such an age structure in particular in these exploited populations of long lived rockfish is to create no take Marine Protected Areas that allow females to live to old age, thereby preserving their reproductive potential and promoting a more robust contribution to the population. In order to achieve this, however, reserves would need to be of sufficient size to protect a suitable number of reproductively mature individuals. For the rockfishes, many nearshore species are demersal and have been found to have small home ranges, so they are likely to benefit from small reserves such as the one at Redfish Rocks.

MPAs are defined by the International Union for Conservation of Nature (IUCN) as: "Any area of intertidal or subtidal terrain, together with its overlying water and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part or all of the enclosed environment" (Kelleher & Kenchington, 1991). MPAs can be a viable component of fisheries management strategies aimed at restoring biodiversity and functioning ecosystems and at rebuilding age structure and biomass to help recover overfished stocks (Botsford et al., 2007; Chateau & Wantiez, 2009; Gell & Roberts, 2003; Hixon et al., 2014; Roberts et al., 2001). More recently, there is evidence that MPAs may also contribute to the resilience of marine communities to climate impacts (Micheli et al., 2012).

While there is evidence of increased biomass within MPA boundaries (Stobart et al., 2009), a fundamental ecological consideration for both conservation and fisheries management goals for MPAs is whether movement of protected species will be contained within MPA boundaries and whether adult animals will spill over into surrounding, fishable waters (Frisk et al., 2014; Grüss et al., 2011; Kaplan et al., 2006; Kerwath et al., 2009; Topping et al., 2006). The proper balance between protection within MPA boundaries and potential for spillover beyond them is dictated by MPA size and movement patterns of the species contained within protected areas (Kerwath et al., 2013); it appears that spillover of adult fish (Abecasis et al., 2015) is dependent upon the relationship between MPA size and home range of adults (Abecasis et al., 2009; Afonso et al., 2016; H Dingle & Drake, 2007; Kramer & Chapman, 1999; Moffitt et al., 2013). In addition, seeding of larvae outside of MPA boundaries (Kaplan et al., 2006) is dependent on factors such as larval dispersal distances vs. MPA network spacing (Cowen et al., 2007; Gunderson et al., 2008). Furthermore, there is a relationship between the degree of protection of adult females due to movement patterns, and the increase in larval production from those that become older and more fecund under the protection of the MPA (Sogard et al., 2008). Much is yet to be discovered about these basic ecological attributes for many species, and without this knowledge efforts to establish effective MPAs may prove unsuccessful (Sale et al., 2005). This means that baseline information about movement patterns of species of interest is essential to accurate long term assessment of the success of MPAs (Buxton et al., 2014; Halpern et al., 2009).

By moving, animals find food, avoid predation, locate mates, and find environmental conditions favorable to their survival (Hugh Dingle, 2014; Holyoak et al., 2008; Nathan, 2008; Nathan et al., 2008). Historically, tag and recapture studies have been used to gather data on the movements of individuals, but there are limitations to this method. This technique provides information about initial tagging location, and location of subsequent capture, but little information about the intervening period (Abecasis et al., 2009). In addition, results are influenced by fishing effects during tagging efforts, lack of reporting of recovered tags, and tag loss (D. Parsons & Egli, 2005). Furthermore, recovery occurs only where there is active fishing. Passive acoustic telemetry, on the other hand, can provide detailed information about the movement patterns of individual fish over longer periods (Donaldson et al., 2014) without the need to recapture animals. Advances in aquatic telemetry have recently enabled the gathering of environmental data, such as temperature and depth, providing a more in-depth perspective on the relationship between fish movements and their environment (Hussey et al., 2015).

The State of Oregon established the Redfish Rocks Marine Reserve (RRMR) and MPA in 2009, and harvest restrictions, including no-take regulations for the 6.78 km^2 research reserve, went into effect in 2012 (75th Oregon Legislative Assembly, 2009). The boundaries of the RRMR were proposed before any detailed study was conducted of the movement patterns of commercially important species in the RRMR/MPA. Given the relatively small size of the protected area, it is important to determine the movement patterns of fish inside the RRMR, their habitat associations, and the probability that the RRMR is large enough to encompass the spatial extent of average daily movements of individual adult fish.

The importance of considering habitat attributes in an area under consideration as an MPA has long been recognized and appreciated. Rockfish are known to associate with particular types of structure and substrate, and a number of studies have examined the relationship between habitat and behavior in rockfish in order to improve habitat suitability models and predictions used to inform MPA design and placement (Iampietro et al., 2008; Johnson et al., 2003). Advances in remote sensing such as multibeam and backscatter sonar are providing more detailed information about habitat structure and substrate composition, combined with verification of substrate composition using grab sampling. High quality underwater imaging is allowing direct observations of fish behavior and species identification and physical measurements in depths not easily accessed visually before. These tools are being used in multidisciplinary studies of fish behavior and habitat associations to inform MPA design and placement and the monitoring of MPA effects once established (Yoklavich et al., 2000).

The goal of this study was to assess the movement patterns of three species of rockfish targeted for protection in the RRMR; China Rockfish, Quillback Rockfish, and Copper Rockfish. My objectives were to (1) estimate residence times for individuals of these species, (2) evaluate significant spatial movement patterns, and (3) analyze the relationship between habitat attributes and movement patterns. To accomplish this, we conducted a 17-month acoustic telemetry study to characterize the movement patterns of individuals of these species at the Redfish Rocks Marine Reserve. This work is intended to support more accurate prediction of reserve effects, and to inform future monitoring activities and decisions concerning the adaptive management of the RRMR.

Materials and Methods

Ethics Statement: Animal protocols were approved by the Institutional Animal Care and Use Committee at Oregon State University. The Oregon Department of Fish and Wildlife granted a take permit for capture, surgical implantation of tags, and release of the animals at Redfish Rocks. The tagging procedure was conducted under aseptic conditions after the induction of atonic immobility to minimize suffering (Wells et al., 2005), and all efforts were made to avoid injury to fish.

Study Site

The 6.78 km^2 Redfish Rocks Marine Reserve (RRMR), named after the abundant populations of Vermillion *(Sebastes miniatus)*, Yelloweye *(Sebastes ruberrimus)*, and Canary *(Sebastes pinniger)* Rockfish that attracted fishermen to the area, is located on the southern coast of Oregon approximately 15 km south of Cape Blanco and, along with the adjacent Marine Protected Area, extends three nautical miles to the boundary of state waters (Figure 1). The protected area was implemented in 2012 by the State of Oregon to protect species, habitat, and biodiversity (Oregon Department of Fish and Wildlife & Marine Resource Program, 2012). The seabed is characterized by six emergent pinnacles, surrounded by boulders, cobble and sand. A detailed bathymetry map was created using high-resolution multi-beam sonar, and subsequently used to classify bottom habitat types and extent (Amolo, 2010).

Tagging

During three tagging excursions between May 1, 2011, and December 7, 2011, we used hook and line gear to capture 20 fish and then surgically implanted small acoustic transmitters (V13P–1H, Vemco; 6mm x 13mm, 158 dB re 1uPa @1m) (VEMCO, 2011). All tagged fish were of adult size (Echeverria, 1988; Grebel & Cailliet, 2010) (Table 1), and tags were less than 2% of body mass (Bridger & Booth, 2003; Brown et al., 1999; Jepsen et al., 2005). Transmitters were programmed to emit a 69-kHz coded pulse at random 150 - 250s intervals (200s nominal range) for an expected battery life of 562 days. Acoustic receivers can record only one transmission at a time, so transmitters are programmed to emit signals at randomly spaced intervals between 150 – 250 seconds in order to avoid data loss due to harmonic interference from repetitive simultaneous signals arriving at receivers. None of the species tagged exhibited clear external sexual dimorphism, and we did not determine the sex of tagged individuals in this study.

Once a fish of the target species was captured, the hook was carefully removed, and the fish examined for signs of barotrauma (Hannah et al., 2008). We then inverted the fish in a custom made surgical cradle, covered its eyes with a seawater soaked cloth, and induced an atonic immobility reflex by directing a vigorous flow of fresh seawater through the branchial chamber following Wells et al.

(2005). During the procedure, we recorded fish total length and then proceeded with the tag implantation surgery. Once the fish was flaccid and no longer responsive, a small incision was made between the base of the pelvic fins and the vent, and a sterilized transmitter inserted carefully into the abdominal cavity. The incision was closed using monofilament surgical sutures and two to three interrupted surgeon's knots. We applied triple antibiotic to the surgical wound to promote healing. We placed an external T-bar (Floy©) tag in the dorsal musculature of the fish to identify tagged fish to local fishermen and other researchers who might have encountered fish tagged for this study. To minimize surface time and subsequent risk of barotrauma, these procedures were completed by trained surgeons, as rapidly, efficiently, and safely as possible. Mean time from capture to return to the water, including surgery time, was 8 minutes (±4 min).

Immediately upon completion of the tagging procedure, each fish was placed in a recompression and recovery cage fitted with a closed circuit underwater camera, and lowered to capture depth, or up to 40 feet, for observation. Once the fish recovered it was released at the location where it was captured (figure 1) by tripping the release of the cage's trap door from the surface, allowing the fish to swim free of the cage.

Acoustic receiver array deployment and data retrieval

An array of 34 VEMCO VR2 and VR2W omnidirectional acoustic receivers was deployed inside the Redfish Rocks Marine Reserve from August, 2011, to January, 2013 (Figure 2). We performed a preliminary test *in situ* to estimate the detection range of acoustic receivers before deploying the array, as follows: we secured three VR2 acoustic receivers to individual moorings, then anchored them in a horizontal line spaced apart at 100m intervals. We fixed an acoustic transmitter (VEMCO transmitter model V16-4H, transmitting a coded signal at 69 kH at a fixed delay of 15 seconds) to a fourth mooring anchored 100 m from the first receiver. The three receivers were thus at distances of 100, 200, and 300 meters from the stationary tag. Each receiver recorded detections from the fixed tag for 2 hours. We retrieved each receiver and confirmed that each was functioning by downloading detection data. After determining that 100% of transmissions were detected at the 100-meter distant receiver, we relocated that receiver to 250 meters from the test transmitter to refine estimates of detection probability. We allowed the system to record detections from the transmitter tag for 2 additional hours. Based on those results, and consultations with staff from VEMCO© we determined that the optimal distance between receivers would be no greater than 250 meters. Receivers deployed in the interior of the study area were placed based on an array design developed by Vemco staff to minimize acoustic shadows resulting from pinnacles, to increase the probability of detection of tagged fish there. This resulted in overlapping detection ranges and increased coverage of the acoustic array in this area (Figure 2).

We placed receivers approximately 200 meters inside the reserve boundary to ensure the detection range of the receivers encompassed the reserve boundary but to minimize the probability of detection of tagged fish when they were located outside the reserve. We did not place receiver moorings in the area shoreward of the 10-fathom contour because of the likelihood of diminished detection probability due to high levels of acoustic interference from breaking waves, and the probability of substantial gear loss due to very high-energy near shore conditions.

In addition to the RRMR array, we placed a small array of 4 receivers between the southwest corner of the RRMR and adjacent Island Rock, located outside the protected area. This array was intended to detect potential movements of tagged fish between the RRMR and nearby comparable habitat at Island Rock (Figure 2).

To enable continuous assessment of detection range for the duration of the study, we deployed two fixed location sentinel tags at representative sites within the receiver array. We deployed these sentinel tags at the beginning of the study using subsurface moorings, and left them in place for the duration of the study. We maintained the receiver array year-round to enable the collection of movement data during the entire study period and through all seasons – most telemetry studies conducted on the Oregon coast have retrieved equipment prior to the winter season to minimize gear loss during high-energy ocean conditions common during that period.

Acoustic receiver moorings were designed in consultation with commercial crabbers and built to maintain position during the high-energy winter storm season. We used a 100 to 120-pound anchor constructed of ship's chain, joined to the mooring line using stainless steel hardware, and attached the receiver to duraplex™ line fitted with an eight-inch trawl float to hold the receiver upright off the bottom. This was attached to a length of floating crab line, followed by a length of sinking crab line, and fixed to a two-buoy surface expression with a flag trailer to increase visibility, based on designs used for commercial crab traps. (Figure 3).

Receiver moorings were hauled about every 6 months to download tracking data from acoustic receivers to the software package VUE (VUE User Manual, 2014). Once telemetry data were retrieved we returned the receiver mooring to its assigned station to maintain positional reference. Displaced receiver moorings were returned to location as soon as possible once discovered. Lost receivers were replaced as soon as possible using another receiver, when available. Fouling of moorings and receivers with marine organisms was a problem both for retaining gear and for interference with signal detection. Fouling organisms were removed from moorings and receivers during each data retrieval trip using mechanical means, and as often as possible between data collection. The acoustic receiver array was retrieved at conclusion of the study.

Data Analysis

Analyses of telemetry data were performed using *MS Access* 2013, R (Team and Others 2013), Arc GIS (Esri 2011), and PRIMER-E (Clarke, 2015). An individual fish was considered present on the array if it was detected at least twice in a 24-hour period, so single detections in a 24-hour period were considered potentially spurious, and were not included in the analysis. Data were processed further to remove days from the analysis when it was determined that detection probability of acoustic receivers fell below 50%, which could be due to ambient noise from storm activity, for instance. We defined days of poor detection performance as those during which transmissions from a sentinel tag in a known location were not detected by at least 2 of 4 proximate receivers located approximately 100 meters distant. This resulted in more conservative estimates of residency, but increased confidence in our evaluation by reducing type 2 error (failing to detect a transmission from a tagged fish due to ambient noise or obstruction when it is, in fact, present). These calculations were used to produce an abacus plot of fish presence during the monitoring period. Fish tagged after the initiation of the study on August 1, 2011, were monitored once they were tagged and released. Monitoring ceased either when a transmitter tag expired, or when the receiver array was removed at conclusion of the study (Figure 4).

Residence Index

A residence Index (RI) was calculated to analyze how much time tagged fish spent within the protection of the no-take RRMR, or in proximity to Island Rock during the study period. The Residence Index was calculated as the proportion of days a tagged individual was detected on the array during the monitoring period between August 1, 2011, and January 23, 2013, resulting in a Residence Index (RI) score for each fish between 0 and 1 (Table 1). ANOVA was performed to determine whether Residence Index differed by species.

Spatial Significance

The number of tag detections for each fish at each receiver was used to identify significant movement patterns. The Spatial Analyst Tool in Arc GIS was used to execute a hot spot analysis using number of detections at each receiver. This tool identifies clusters of high numbers of tag detections (hot spots) and clusters of low or zero values (cold spots). The results include Z scores for spatial significance of hot spots and cold spots, which were then visualized using the KDE tool in ArcGIS.

Habitat Influence

To examine whether habitat attributes were predictors of fish movement patterns, Principal Component Analysis (PCA) was performed with PRIMER-E and R. Habitat attributes were calculated for non-overlapping receiver stations covering an area within 250-meters of each receiver. In the central area of the receiver array, non-overlapping receiver stations were used to ensure independence among stations.

A matrix of potentially influential habitat attributes was generated. Habitat metrics were generated from a mosaicked bathymetry layer with $2m^2$ resolution provided by the Oregon Department of Fisheries and Wildlife, and a Seafloor Habitat Shapefile created by the Bureau of Ocean Energy Management, NOPAA and OSU (SGH v4.0 physiographic habitat) (Goldfinger et al., 2014). Values for habitat attributes were calculated using the Benthic Terrain Modeler in Arc GIS 10 (Esri, 2011). Average bottom depth was calculated from bathymetry data produced during previously conducted multibeam sonar surveys. Habitat attributes used in the analysis included average depth, maximum slope, average slope, heterogeneity of habitat types (number of discrete types of habitat per station), maximum rugosity (VRM), and average rugosity for two extent levels - one 36 km^2, and the other 100 km^2, percent rock, percent cobble, percent sand, and distance to emergent pinnacle, or island.

A scree plot was used to examine the amount of variability explained by each of the 10 axes produced during the Principal Component Analysis, and based on results, the first three axes were retained for further analysis. The eigenvalue for PC1 was 5.92, and this axis explained 59% of the variability in the habitat attributes used for the analysis. The second axis, PC2, had an eigenvalue of 1.79, and explained another 17% of the variability in the habitat attributes. The amount of variability explained by the first two axes was 77%, and since the eigenvalue for axis 3 was 0.89, and it explained an additional 8% of the variability, no further analysis of this axis was performed. Interpretations of PC1 and PC2 were based on the values of the habitat score correlations, or loadings. Positive values on PC1 were interpreted as areas distant from pinnacles, with low levels of heterogeneity and percent rock, with shallow slopes and low rugosity (VRM). Negative values for PC1 were interpreted as areas close to pinnacles, with higher scores for heterogeneity, percent rock, and rugosity, and steep slopes. Positive values for PC2 were interpreted as describing deeper areas, with fewer boulders, and negative values were interpreted as describing shallower areas with more boulders. A bi plot was produced using PC1 and PC2 as axes, and plotting each receiver station against these two axes to visualize the results of the Principal Component Analysis. (Figure 5)

Linear regression was used to analyze the relationship between the composite of habitat attributes represented by the two PCA axes, and fish presence at each receiver station by regressing the average residence index for each species at each station against PC1 and PC2 scores, and using R^2 values to evaluate goodness of fit of the relationship. This analysis was used to examine species habitat associations based on long-term observations such as those performed during this study.

Results

Detections

We tagged 20 fish for this study; 7 China and 7 Quillback Rockfish, and 6 Copper Rockfish, and all fish were detected by multiple receivers. During the study period from August 1, 2011 to January 23, 2013, the receiver array detected and recorded 440,933 coded tag transmissions (Table 1). We removed 112 days from the analysis due to poor detection performance by the receiver array of transmissions from a stationary tag in a fixed known location. We removed days from the analysis when transmissions from the stationary tag were only detected by fewer than 2 of the 4 receivers located approximately 100 meters distant from the stationary tag. This low detection probability could have been due to sonic interference from storms or other confounding conditions. Detection data were then analyzed for the remaining 451 days, or 80% of the total days available.

Residence

We calculated a Residence Index (RI) for each tagged fish (table 1), and mean RI's for each species. Individual RI ranged from 0.15 to 0.99 and mean RI for all fish was 0.63 ± 0.06. Mean (± SEM) RI was 0.65 ± 0.10 for Copper Rockfish, 0.56 ± 0.10 for Quillback Rockfish, and 0.68 ± 0.13 for China Rockfish. Mean RI did not differ among species due to high within species variance and small sample size (one way ANOVA, [F(2, 17) = 3.59, p = 0.719]). A boxplot was created to display the distribution of RI values for each species. Half of the China Rockfish were highly resident, with RI scores above 75% (Figure 6).

Two fish (10%) exhibited low residence, defined as being detected on the receiver array less than 25% of the time (Residence Index = 0.15 and 0.17), and were not detected after their early presence on the array. Since this was prior to the implementation of the closure of the marine reserve, it is possible that these fish were captured or otherwise removed from the study area. Eight fish (35%) were moderately residential, defined as being detected between 25% and 75% of the time (RI between .25 and .68), and most of these individuals were detected on the array after extended periods of non-detection. The other 10 fish (50%) were highly residential, defined as being detected on the receiver array between 75% and 100% of the time (RI between .75 and .99). (Table 1)

The spatial extent of detectable individual movement patterns within the array did not vary widely, and variation in Residence Index appeared to be related to location of capture. Generally, fish tagged nearer the center of the RRMR had greater RI than those tagged and released nearer the boundary, where they were more likely to spend a portion of time outside the reserve boundaries and undetected by the receiver array. The exception to this pattern would be any fish traveling to nearby Island Rock, where they would be expected to be detected by the satellite receiver array stationed there. None of the tagged fish from the RRMR were detected on the

Island Rock receivers, and neither of the fish tagged at Island Rock were detected on the RRMR receiver array.

Movement Patterns

Cluster analysis using the Cluster and Outlier Analysis (Anselin Local Morans I) tool in ArcGIS determined that all individual fish movement patterns included spatial clusters of detections using Local Moran's *I* statistic of spatial association ($p < 0.05$). The null hypothesis of uniform distribution of movement patterns was therefore rejected, and so hot spot analysis was performed for each fish. Hotspot analysis for individual fish movement patterns revealed clusters of high values for number of tag detections, or hot spots, at certain receivers using the Getis-Ord Gi* statistic ($p < 0.05$). Density maps were created that display hot spots in red, and cool spots in blue, as a transparent layer over the habitat classification map. Cool spots are clusters of low or zero values for number of tag detections at a receiver (figures 7-26). For each fish, the location of capture, tagging, and release appears within the range of the hot spot, indicative of high site fidelity.

Habitat Associations

The 250-meter detection radius around each receiver was used to define the area of that receiver's station and used to analyze the relationship between habitat and fish residence at each station. Results of the Principal Component Analysis indicate that Axis 1 and Axis 2 of the PCA together explain approximately 77% of the variability in the habitat attributes measured for each receiver station on the acoustic array. Stations with high positive scores on PC1 were interpreted as those more distant from pinnacles, or islands, and having lower scores for heterogeneity and percent rock, with shallow slopes and low rugosity (VRM). Negative values for PC1 were interpreted as areas closer to pinnacles, with higher scores for heterogeneity, percent rock, and rugosity, and steep slopes. Positive values for PC2 were interpreted as describing deeper areas, with fewer boulders and negative values describing shallower areas with more boulders (table 2).

To determine whether the composite habitat attributes represented by PC1 and PC2 were related to the presence of tagged fish at each station, average RI for each species at each receiver station was regressed against PC1 and PC2 scores for each station. The linear relationship between PC1 and RI was significant for all three species (S. nebulosus; $p = 0.01$, $R^2 = 0.37$, S. maliger; $p = 0.0003$, $R^2 = 0.03$, S. caurinus; $p = 0.012$, $R^2 = 0.001$). For Quillback and Copper Rockfish, PC1 explained a small percentage of the variability in average residence index, and we not analyze these data further. For China Rockfish, PC1 explained 37% of the variability in average residence index ($R^2 = 0.37$, $p = 0.01$). (figure 25) For all three species, PC2 explained very little of the variability in average residence index.

The negative regression relationship between PC1 and RI for China Rockfish indicates that residence increased with proximity to pinnacles, i.e., one of the Redfish Rocks. It also indicates that China Rockfish RI increased with percent rock, rugosity, steeper slopes, and greater heterogeneity of habitat types.

Discussion

The results of this study indicate that for China, Quillback, and Copper Rockfish, the 6.78 km^2 no-take marine reserve at Redfish Rocks contains an adequate amount of suitable habitat for individuals of these species due to a high degree of site fidelity and apparent small home range size. Based on the results of an analysis for China Rockfish of the relationship between a composite habitat index and residence, this relationship explains 37% of presence for this species ($R^2 = 0.37$, $p = 0.01$) (Figure 27). The first principal component (PC1) was characterized as having a high percent rock, with high rugosity and slope in proximity to pinnacles. These results are consistent with findings of Johnson and co-workers (2003), who found China Rockfish in southeastern Alaska exclusively over complex bottoms during ROV surveys, but occasionally observed Copper and Quillback Rockfish over soft bottom.

About half of the individuals of each species were highly resident on the receiver array (RI between 0.75 and 1), with those tagged and released near the center of the marine reserve tending to exhibit higher RI scores. Many individuals exhibiting intermediate RI scores were detected subsequently by the same receivers after extended periods of absence. These individuals may have remained nearby during the study period but spent a portion of time outside the protected area, or they could have traveled further afield and then returned to their home site. Individuals that were found to have spent a portion of time outside of receiver range and undetected, were subsequently detected again on the same receivers, suggesting a high degree of site fidelity. One China Rockfish that was tagged and released in proximity to the center of the reserve disappeared from the array and was not detected again (RI = 0.15). This occurred just prior to the closure of the RRMR, and this fish may have been captured during the period prior to closure when fishing was still occurring in the area. The lack of differences in average residence index between species could be a function of the small sample size of tagged fish of each species, and high variance in RI values for individuals within a species. However, other studies have also found small home ranges for these species in similar high relief rocky habitat (Hannah & Rankin, 2011b).

The hotspot analysis indicates that individuals of all three species (China, Quillback, and Copper Rockfish), exhibit home ranges small enough to be contained within the boundaries of the 6.78 km^2 Redfish Rocks Marine Reserve if those individuals have a center of activity located close to the center of the reserve. For those individuals tagged nearer the boundary, results indicate that these individuals spend some portion of time outside the marine reserve, and thus would be exposed to fishing pressure when effort is concentrated near the boundary of the marine reserve (known as “fishing the line”). This type of fishing could lead to long-term effects by selecting for increased site fidelity, and against a larger spatial extent of movement behavior, which could cause the local population to become more residential to the reserve area (Parsons et al., 2010).

We used Principal Component Analysis (PCA) to create a composite habitat attribute index that was then used to analyze the relationship between habitat and movement patterns. Those habitat attributes that were expected to attract individuals of these species due to their affinity for high relief rocky habitat, also predicted site fidelity. Evidence of a high degree of site fidelity is supported further by the results from receivers placed near Island Rock, an area of habitat comparable to that of Redfish Rocks, and located less than 2 km distant. None of the fish tagged at Redfish Rocks were detected at this location, nor were two fish tagged in proximity to Island Rock (one Quillback Rockfish – RI = 0.77, and one Copper Rockfish – RI = 0.66), detected on the Redfish Rocks array. This is consistent with our results showing high occurrence of tag detections in proximity to the location where individuals were captured. All fish were detected at multiple receivers, and we assumed that tagged fish were mobile based on these findings. Overall, these results demonstrate that this small (6.78 km^2) no-take marine reserve provides refuge for individuals of these demersal residential species due to their site fidelity to this substantial patch of high relief rocky reef habitat located within the reserve.

The relatively small range of movement for rockfishes in this study is consistent with a small number of other acoustic telemetry studies conducted on Copper and Quillback rockfish in the Pacific Northwest. In Puget Sound, Tolimieri et al., (2009) reported small home ranges (1,500 – 2,500 m^2) for Copper and Quillback Rockfish tracked using a precision acoustic tracking system. Hannah and Rankin, (2011) who tracked Copper and Quillback Rockfishes at Stonewall Bank off the central Oregon coast, also found small range movements of individuals of these species for up to one year. Hannah and Rankin (2011) was also the only other study to our knowledge that used acoustic telemetry to study movement patterns of China Rockfish – a single individual, which also exhibited a small range of movement during their study.

A movement study of *Pagrus auratus* (Parsons et al. 2010) found evidence of differences in movement patterns between tagged fish found inside an MPA and those found outside the MPA. Their results suggest that the greater movement of individuals outside the protected area would expose that portion of the local population to increased fishing, and that this could in turn select for increased residence by removing more mobile individuals from the population. Since the range of movement for a proportion of individuals in the relatively small RRMR appears to extend beyond the boundaries of the reserve, it is possible that such selection pressures could act in the RRMR as well.

Kellner and co-workers (2008) found an increase in spillover of adult fish when they modeled crowding-induced movement and its effects on spillover beyond MPA boundaries. If individuals remain within the boundaries of the RRMR, and new individuals settle or immigrate to the protected area, over time this could lead to density-dependent emigration, and increased spillover of adults. This would contribute to the local and valuable live fish fishery, and encourage continued compliance with no-take regulations by local commercial fishermen who have supported the closure and could benefit from an increase in availability of adult fish. However, evidence of increased adult spillover could also encourage increased fishing effort at the boundary of the RRMR (fishing the line), and a long-term decline in local fish populations. In addition, the likely small populations of fish being protected at RRMR leaves them more vulnerable to localized extirpation due to chance events affecting the entire reserve, especially given their sedentary nature. Since rockfish are also protected in the MPA situated between the no-take marine reserve and the seaward boundary of state waters, individual fish that move into the associated MPA would still be protected in these deeper waters.

Ultimately, spatial management tools such as MPAs will remain one feature of a comprehensive management strategy that includes overall catch limits and a precautionary approach to harvest that is designed to ensure that the population benefits of the Redfish Rocks Marine Reserve are not cancelled out by fishing effort displacement to the areas immediately surrounding the reserve.

Further Study

An expanded acoustic telemetry study that would place receivers both inside and outside the boundaries of the RRMR would provide additional information about the home ranges of adult fishes of these and other species. As the most resident individuals remained within the boundaries of the protected area, subsequent study of density dependent effects on increased local populations would be of interest. Such effects are not likely to occur until a substantial time in the future and assume that populations in the reserve will increase in size. The effect of an increase in population density within the protected area on individuals of those species exhibiting territorial behavior would also be of interest. Larson (1980) studied territorial behavior in Gopher Rockfish *(Sebastes carnatus),* and Black and Yellow Rockfish *(Sebastes chrysomelas)*, and found evidence of bathymetric segregation maintained by interspecific territoriality and completion for shelter holes between the two species. China Rockfish are also known to exhibit territorial behavior and compete for similar habitat (Lee & Berejikian, 2009). If their population were to increase over time in the protected area, it would be of interest to conduct a study on the effect of population density on competition for habitat, and the effect on spillover for this highly residential species. Since the RRMR protects all species, understanding the effects of mesopredators, such as lingcod, on populations of other fish species would be of interest.

In addition to the fish tagged for this study, we collected evidence of hundreds of fish and other animals moving through the area. The acoustic receiver array at Redfish Rocks recorded transmissions from tagged fish that were part of other studies, including green sturgeon, *Acipencer medirostris*, being tracked for studies of the movement patterns of the ESA listed southern distinct population, and great white sharks, *Carcharodon carcharias,* tagged by researchers from Guadeloupe Island, Mexico, and Central California. Two of the three great white sharks that were detected returned to Redfish Rocks between October and March in each of the three winters the receiver array was deployed. Given the large number of detections of tagged individuals, and because to our knowledge there are no other acoustic receiver arrays within 200 miles of this study site, the placement and maintenance of a line of acoustic receivers perpendicular to shore would enhance the capability of large scale tracking networks to track the movement patterns of highly migratory species. This addition would contribute valuable data from an area that is well traveled, but poorly studied regarding the long-distance movements of marine species.

The importance of networks of MPAs is recognized (Grorud-Colvert et al., 2014), and given the proximity of the Redfish Rocks Marine Reserve and MPA to the Pyramid Point MPA in Northern California (~75 km), regional collaborative research efforts focused on connectivity via larval dispersal will be of value, especially given the potential for increased productivity from protected BOFFFFs.

Conclusions

The boundaries of the Redfish Rocks Marine Reserve were proposed based on long term experiential knowledge of local commercial hook and line fishermen. They targeted China, Quillback, and Copper Rockfish as part of the live fish fishery, along with the other colorful species that gave Redfish Rocks its name, such as Vermillion, Yellow Eye, and Canary Rockfish. Although fishermen provided a wealth of knowledge of prime fishing locations for these species, they did not have direct knowledge of the movement patterns of individual fish, and revealing these patterns was the main goal of this study. Our results indicate that the presence of a substantial amount of high relief rocky habitat within the RRMR, surrounded by low relief sand habitat, likely contributes to long term site fidelity of China, Quillback, and Copper Rockfish. The result is a high level of protection for a portion of the local population of these species. In this study, 50% of tagged fish were highly resident, being detected within the protected area between 75% and 99% of the time.

Increased fishing in proximity to the reserve could result in the capture of those individuals whose home ranges are on the edge of the reserve and whose normal movements take them outside its boundaries. The acoustic receiver array used in this study was designed to provide maximum coverage of the marine reserve area, and included a smaller array around Island Rock, an area of comparable habitat located nearby (2 km). None of the fish tagged inside the Redfish Rocks Marine

Reserve were detected at Island Rock, indicating that fish that may have left the RRMR did not relocate to Island Rock.

Our results show that when non-contiguous habitat with the combination of attributes found at Redfish Rocks is available, individuals of solitary demersal species such as China, Quillback, and Copper Rockfish will exhibit sedentary behavior, rather than wandering from their home reef. For a small scale MPA such as Redfish Rocks, where there is nearly complete compliance with no take regulations, this means that a substantial portion of local populations of these species will be well protected.

LIST OF TABLES

Table 1 - Tagging and residence data for 20 fish tagged at Redfish Rocks Marine Reserve. Residence Index (RI) is proportion of days fish was detected out of days monitored.

Species	Fish ID	Tag Serial	TL (cm)	Tagging Date	Tag Expiration Date	Number of days detected	Total number of detections	Residency time (h)	Residency Index (RI)
S. caurinus	669	1097297	46	5/1/2011	11/13/2012	124	3924	1006	0.36
S. caurinus	671	1097299	49	6/27/2011	1/9/2013	235	20713	2719	0.66
S. caurinus	676	1097304	42	12/7/2011	6/21/2013	90	6750	1245	0.38
S. caurinus	677	1097305	50	12/7/2011	6/21/2013	230	28746	3966	0.96
S. caurinus	678	1097306	52	12/7/2011	6/21/2013	180	11786	2538	0.75
S. caurinus	679	1097307	55	12/7/2011	6/21/2013	191	35370	3551	0.80
S. maliger	661	1097289	36	5/1/2011	11/13/2012	57	3284	674	0.17
S. maliger	670	1097298	41	6/27/2011	1/9/2013	275	24832	3327	0.77
S. maliger	673	1097301	46	6/27/2011	1/9/2013	111	1003	434	0.31
S. maliger	674	1097302	40	6/27/2011	1/9/2013	152	17365	2474	0.43
S. maliger	675	1097303	45	6/27/2011	1/9/2013	287	32629	3883	0.81
S. maliger	681	1097309	40	12/7/2011	6/21/2013	138	20155	2380	0.58
S. maliger	682	1097310	50	12/7/2011	6/21/2013	199	37584	3329	0.83
S. nebulosus	662	1097290	31	5/1/2011	11/13/2012	320	27335	4523	0.94
S. nebulosus	663	1097291	32	5/1/2011	11/13/2012	315	27530	4534	0.93
S. nebulosus	664	1097292	37	5/1/2011	11/13/2012	273	25406	3353	0.80
S. nebulosus	666	1097294	36	5/1/2011	11/13/2012	231	24845	3110	0.68
S. nebulosus	667	1097295	38	5/1/2011	11/13/2012	338	75651	6325	0.99
S. nebulosus	668	1097296	38	5/1/2011	11/13/2012	86	14396	1640	0.25
S. nebulosus	680	1097308	39	12/7/2011	6/21/2013	37	1629	229	0.15

Table 2 - Results from Principal Component Analysis listing habitat attributes used in PCA, with first three PC eigenvalues, variance explained, and eigenvectors for habitat variables.

PCA

Principal Component Analysis

	PC1	PC2	PC3
PC Eigenvalue	5.92	1.79	0.89
Proportion of Variance	0.59	0.18	0.09
Cumulative Proportion	0.59	0.77	0.86

Eigenvectors

(Coefficients in the linear combination of variables making up PC's)

Habitat variable	PC1	PC2	PC3
Depth (M)	-0.177661644	-0.585112115	0.359550649
Heterogeneity Index	-0.312348435	0.130043625	-0.085561382
% Rock	-0.340720955	-0.283020243	-0.381618029
Slope Ave	-0.378163132	-0.034974619	0.055042175
Slope Max	-0.356176183	0.274113695	0.01441029
VRM 36 m^2	-0.37002189	0.214654634	0.080914995
VRM Max 100 m^2	-0.357103142	0.282076404	0.034973378
% Boulder	-0.222278977	-0.407975669	-0.638039181
% Cobble	-0.260000108	-0.361357334	0.541655214
Distance to pinnacle	0.321664958	-0.2482005	-0.07923524

Table 3 - PCA component loadings, used to characterize and interpret PC1 and PC2.

Component Loadings

Habitat attribute	**PC1**	**PC2**	**PC3**
Depth (-M)	-0.432138471	-0.783597144	0.33945959
Heterogeneity.Index	-0.759746293	0.174157756	-0.080780363
% Rock	-0.828758698	-0.379027965	-0.360293883
Slope_Ave	-0.919831845	-0.046838906	0.051966515
Slope_Max	-0.866351497	0.367100088	0.013605068
VRM_3_Max	-0.90002935	0.287470989	0.076393607
VRM_5_Max	-0.868606203	0.377763951	0.033019127
% Boulder	-0.540664238	-0.546371474	-0.602386672
% Cobble	-0.632415906	-0.483939005	0.511388472
Distance.to.Pinnacle	0.782407503	-0.332396472	-0.074807714

PCA

Principal Component Scores

Station	PC1	PC2	PC3
1	-1.131171314	-3.55236209	-1.646258793
2	-1.004591528	-0.304604038	0.510575935
3	0.724419071	0.75680966	0.325437861
4	4.550686616	-1.006906194	0.149811006
5	4.186432326	-0.517286504	0.121651417
6	2.021578135	0.668989148	-0.26680364
7	2.282998246	0.279609862	0.047122477
8	3.894052149	-0.101919668	0.076501425
9	0.492856479	0.262834305	-1.176996363
10	0.654112197	0.533328723	0.16584744
11	0.912244452	-0.8028946	0.136672896
12	0.519983186	-1.814319396	0.722138935
13	-0.684413717	-1.185658948	1.260131046
14	-1.649273053	1.244764988	0.775928472
18	2.130231644	0.780575882	0.077727365
19	-0.048921527	2.224931232	0.006338256
20	-0.606957245	1.266183044	-1.238219718
21	-1.292908828	2.927362867	-1.085208397
E	-2.80817372	-0.5087849	1.614639023
G	-4.321492988	-0.368356093	0.125145907
I	-3.494188148	-0.336347623	0.658664791
R	-2.393286144	0.397761578	0.989058204
T	-2.934216291	-0.843711234	-2.349905544

Table 4 - Principal Component Analysis (PCA) Principal Component Scores, used to analyze relationship between habitat attributes and fish residence.

LIST OF FIGURES

Figure Page

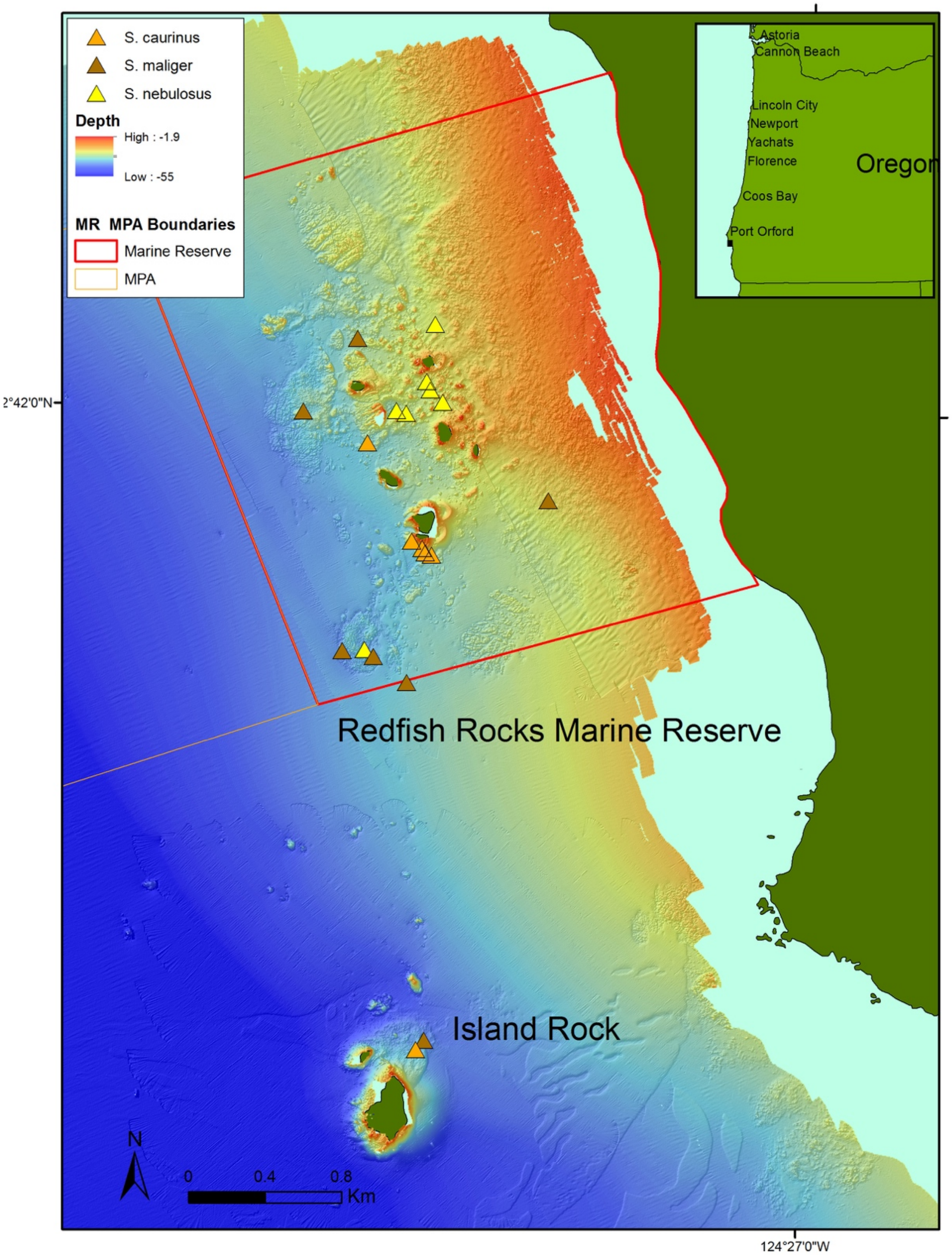


Figure 1 - Bathymetry map of Redfish Rocks Marine Reserve and Island Rock, with fish tag and release locations.

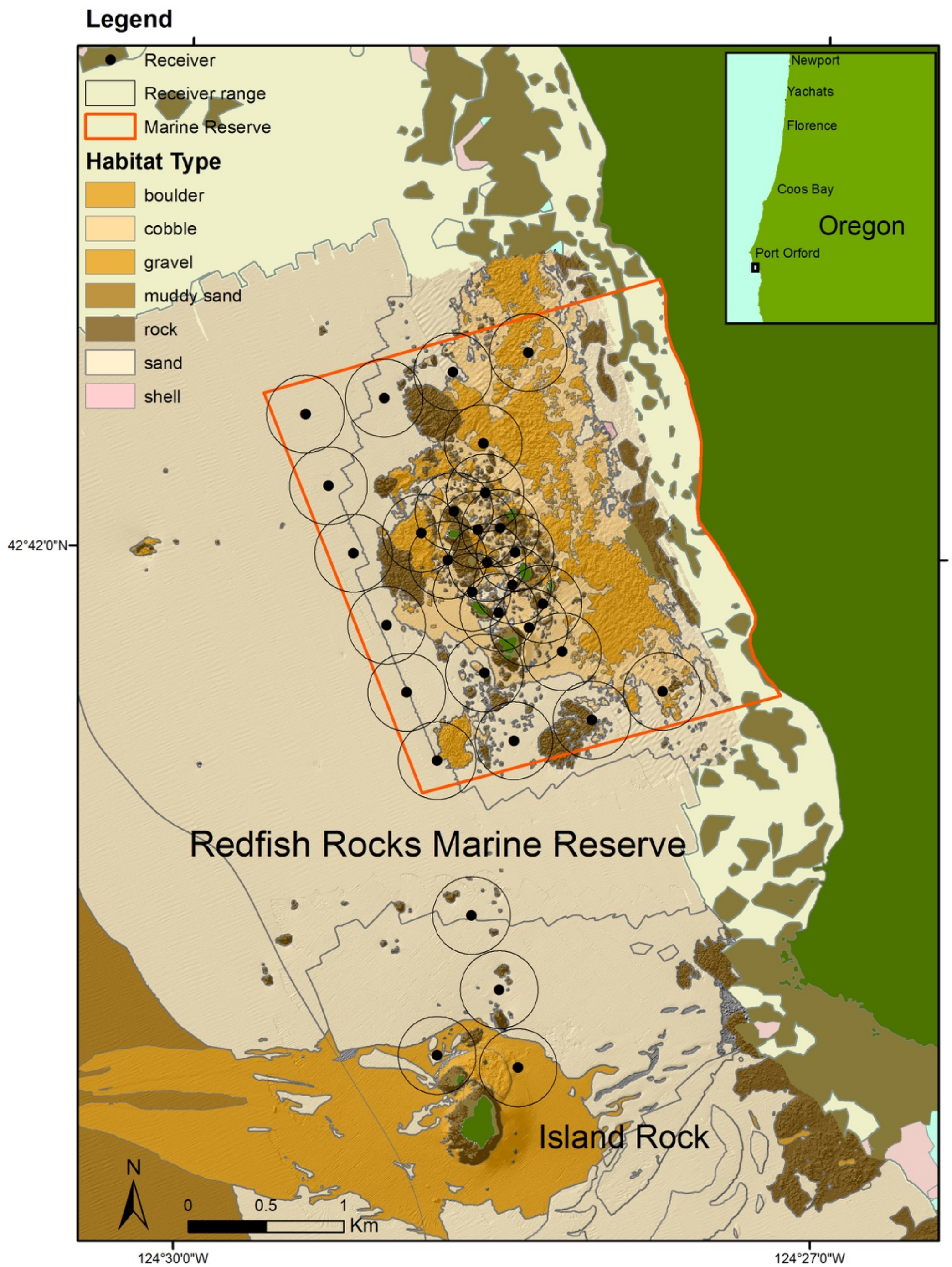


Figure 2 - Habitat Classification map of Redfish Rocks Marine Reserve and Island Rock, with locations of acoustic receivers, and 250 m detection range for each receiver.

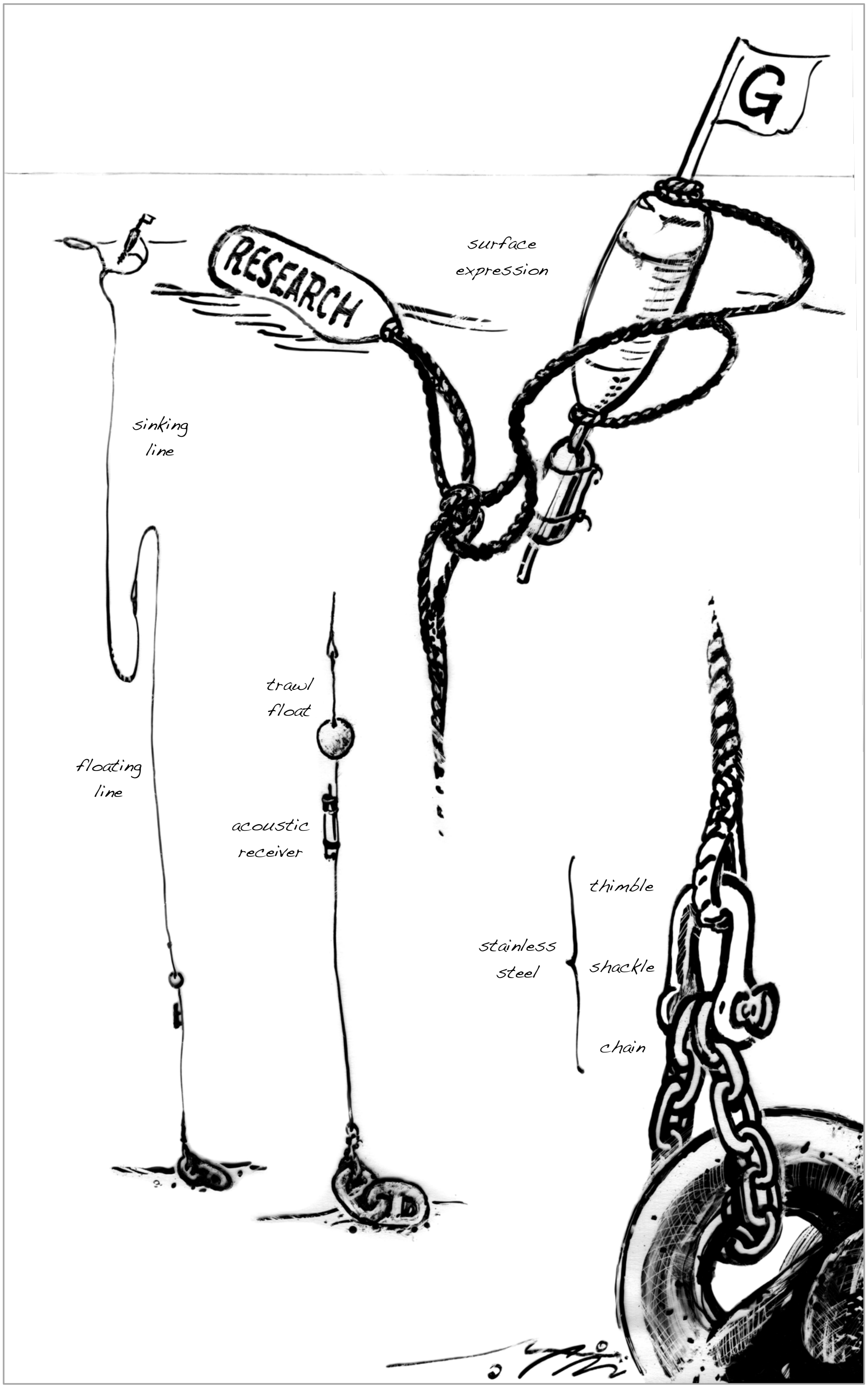


Figure 3 - Acoustic receiver mooring design. (illustration by Darren Evans)

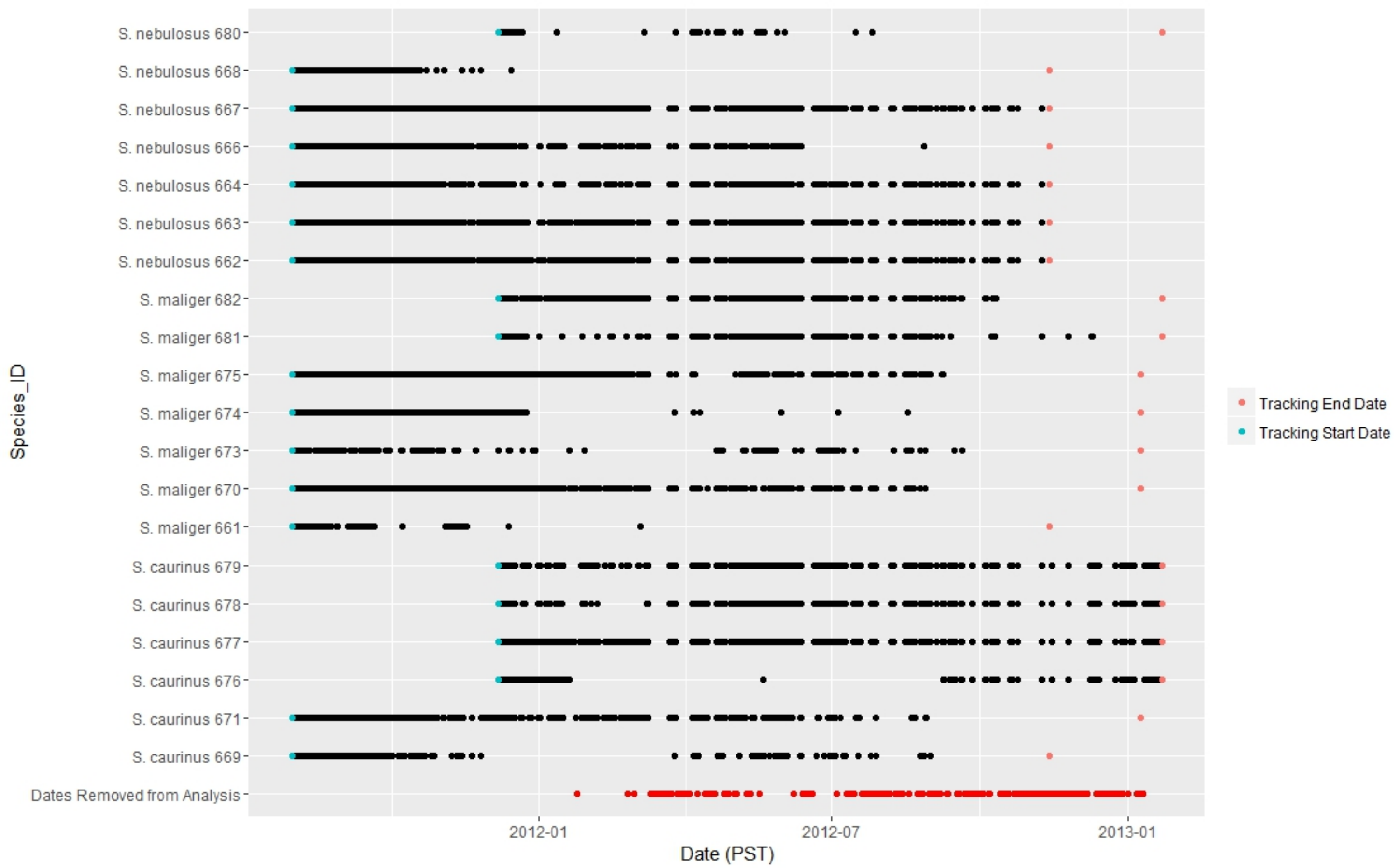


Figure 4 Plot of fish presence during the study period from August 1, 2011 to January 23, 2013. Dates were removed from analysis when detection probability was insufficient to detect the presence of transmissions from tagged fish.

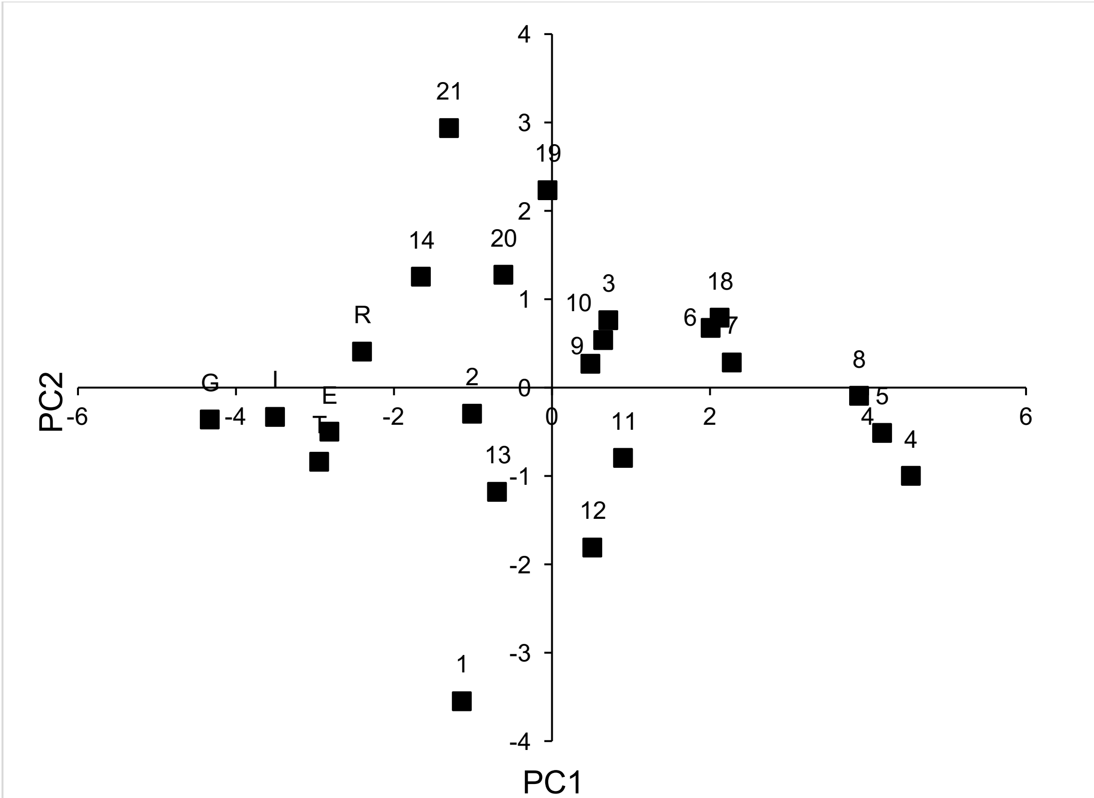


Figure 5 - Biplot of PC1 and PC2 scores from Principal Component Analysis (PCA) for each acoustic receiver station.

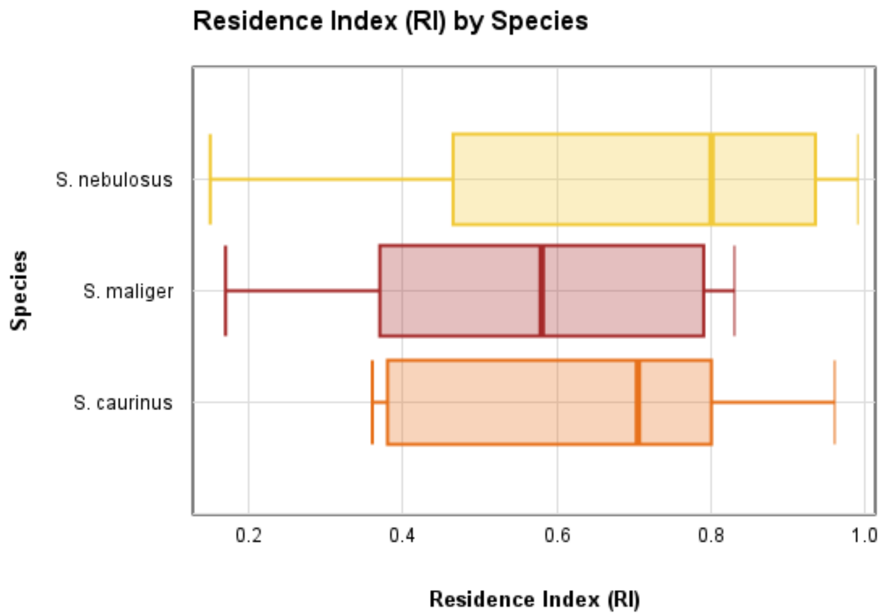


Figure 6 – Box plot of average residence index (RI) by species

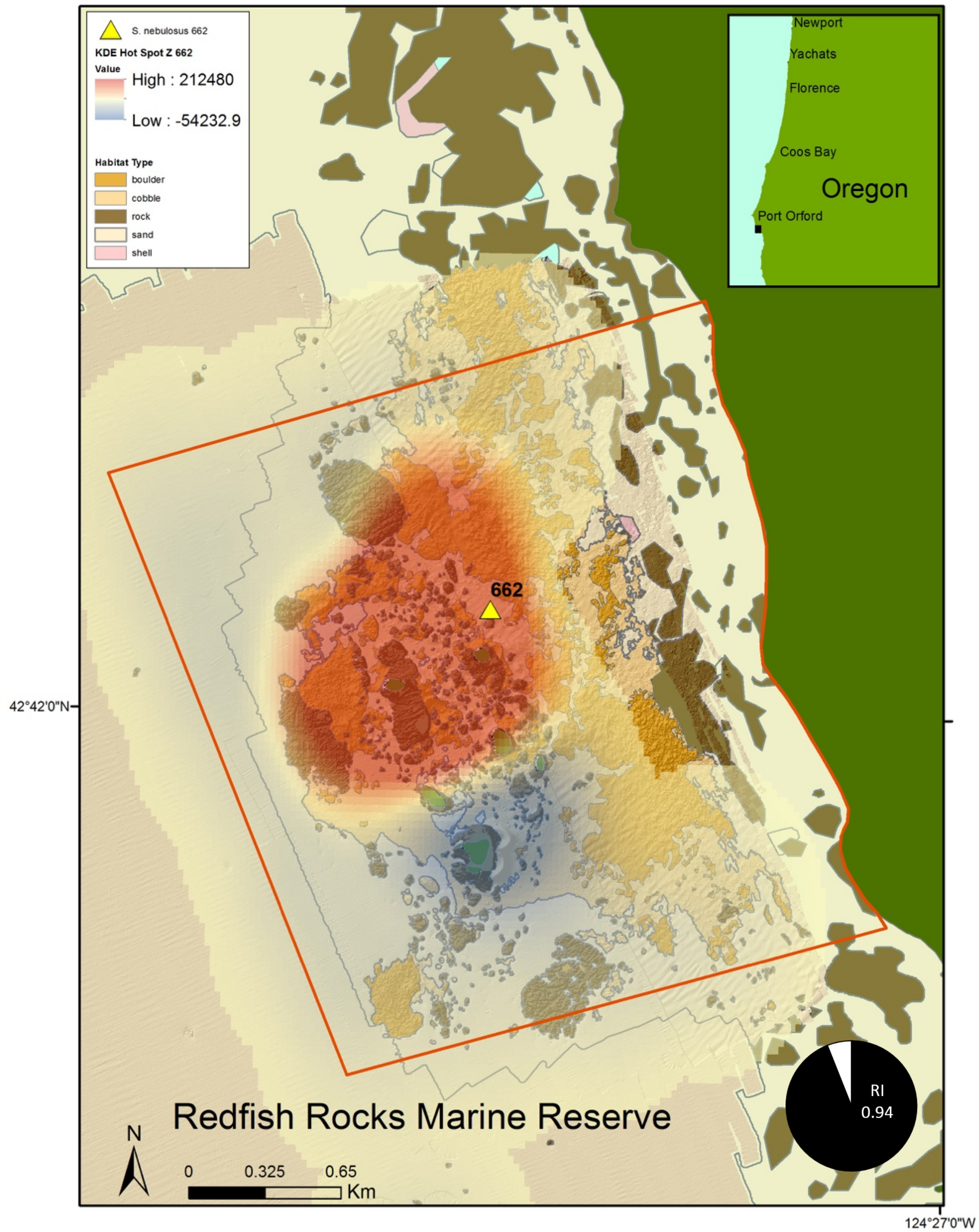


Figure 7- China Rockfish 662 - density map of statistically significant clusters, with high occurrence of detections in red, and low occurrence of detections in blue, with tagging location and habitat classification. Residence Index (RI) in pie chart.

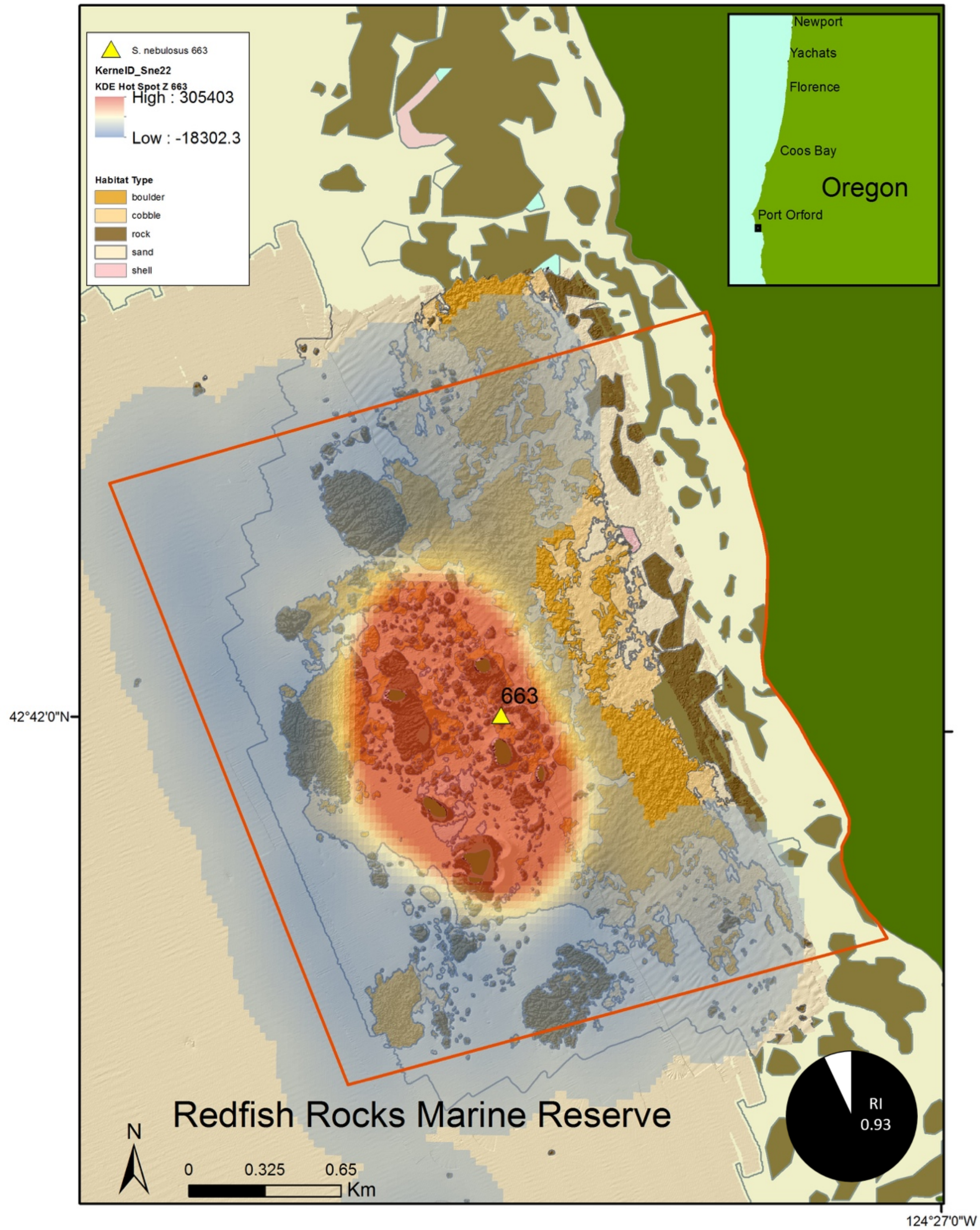


Figure 8 - China Rockfish 663 - density map of statistically significant clusters, with high occurrence of detections in red, and low occurrence of detections in blue, with tagging location and habitat classification. Residence Index (RI) in pie chart.

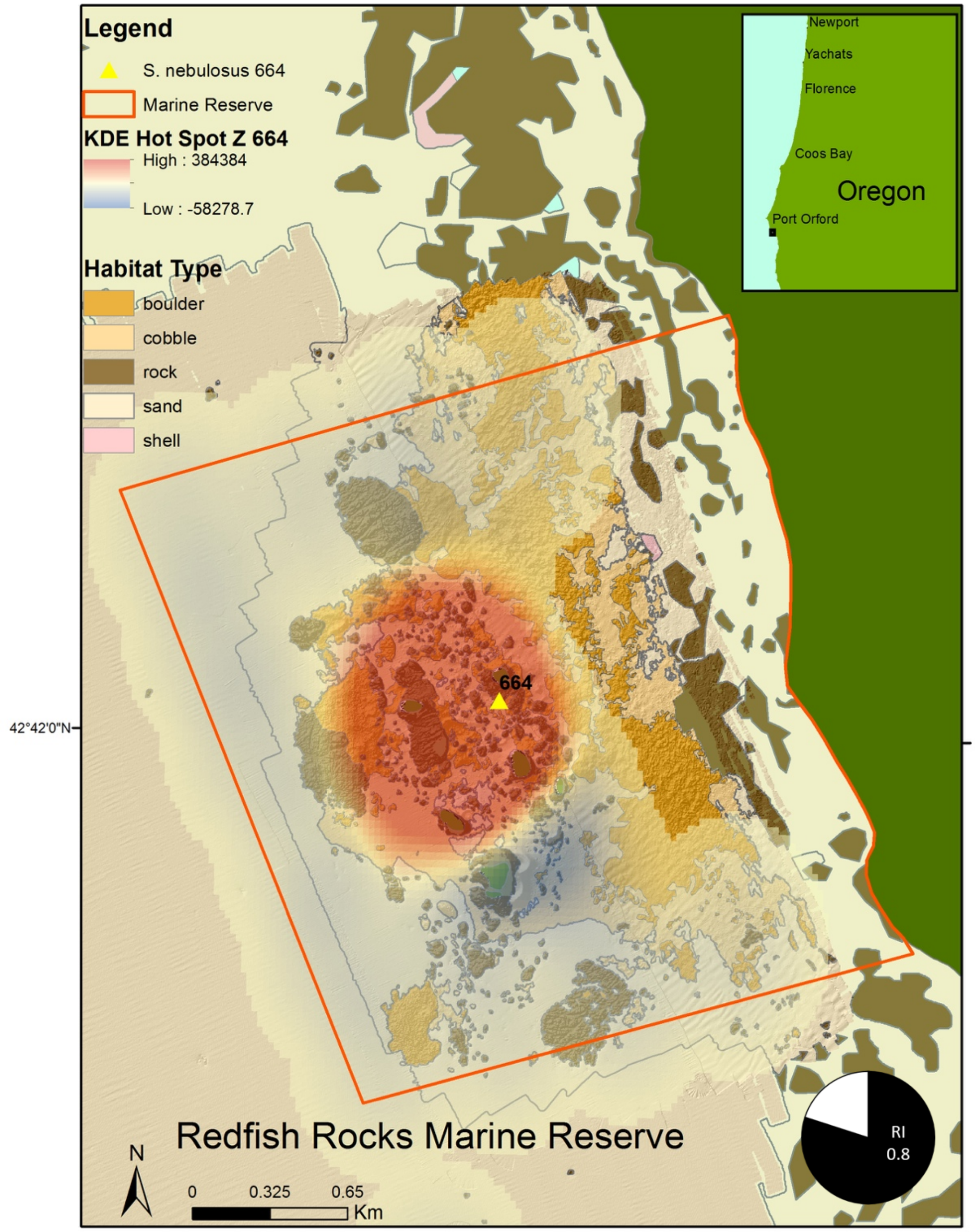


Figure 9 - China Rockfish 664 - density map of statistically significant clusters, with high occurrence of detections in red, and low occurrence of detections in blue, with tagging location and habitat classification. Residence Index (RI) in pie chart.

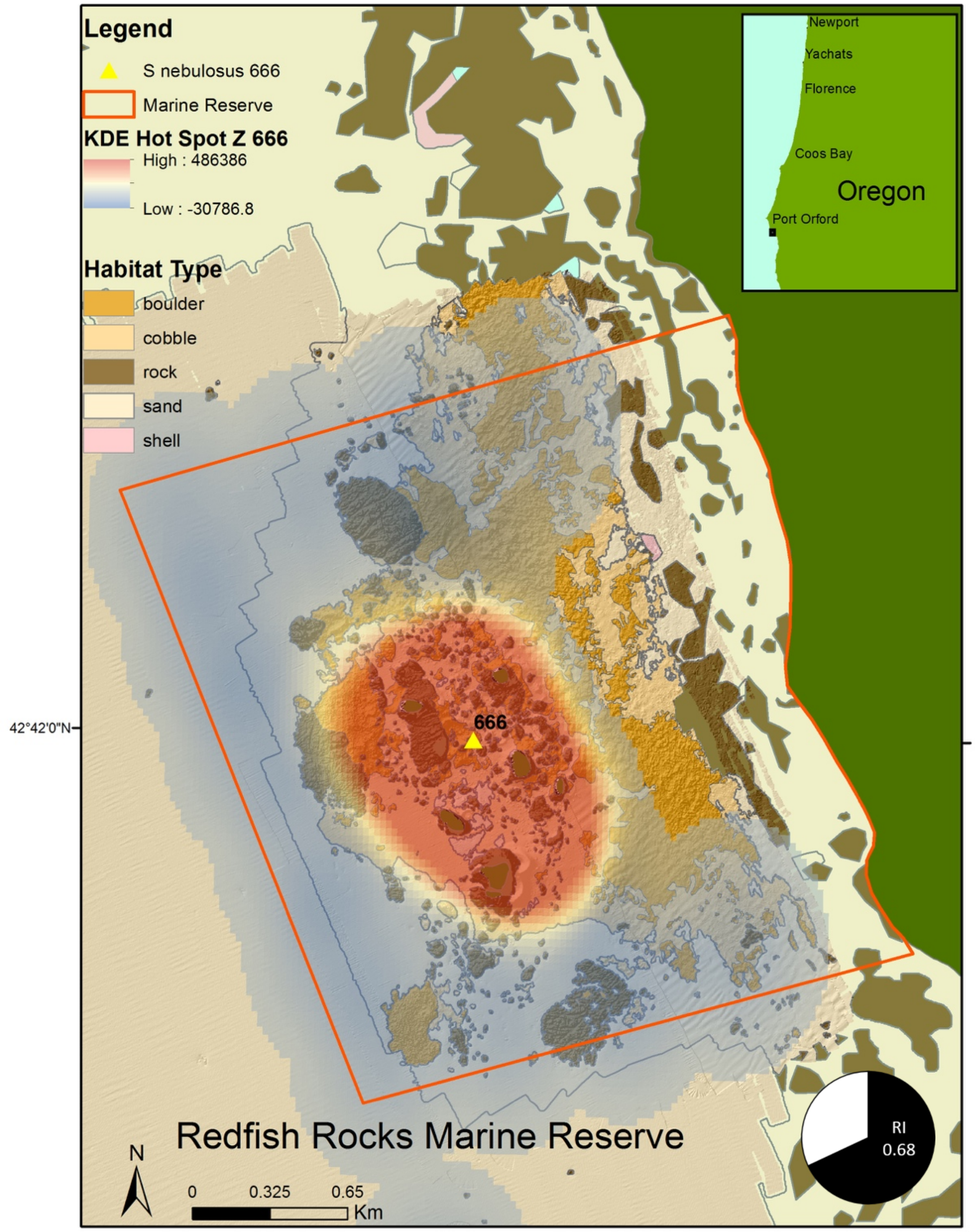


Figure 10 - China Rockfish 666 - density map of statistically significant clusters, with high occurrence of detections in red, and low occurrence of detections in blue, with tagging location and habitat classification. Residence Index (RI) in pie chart.

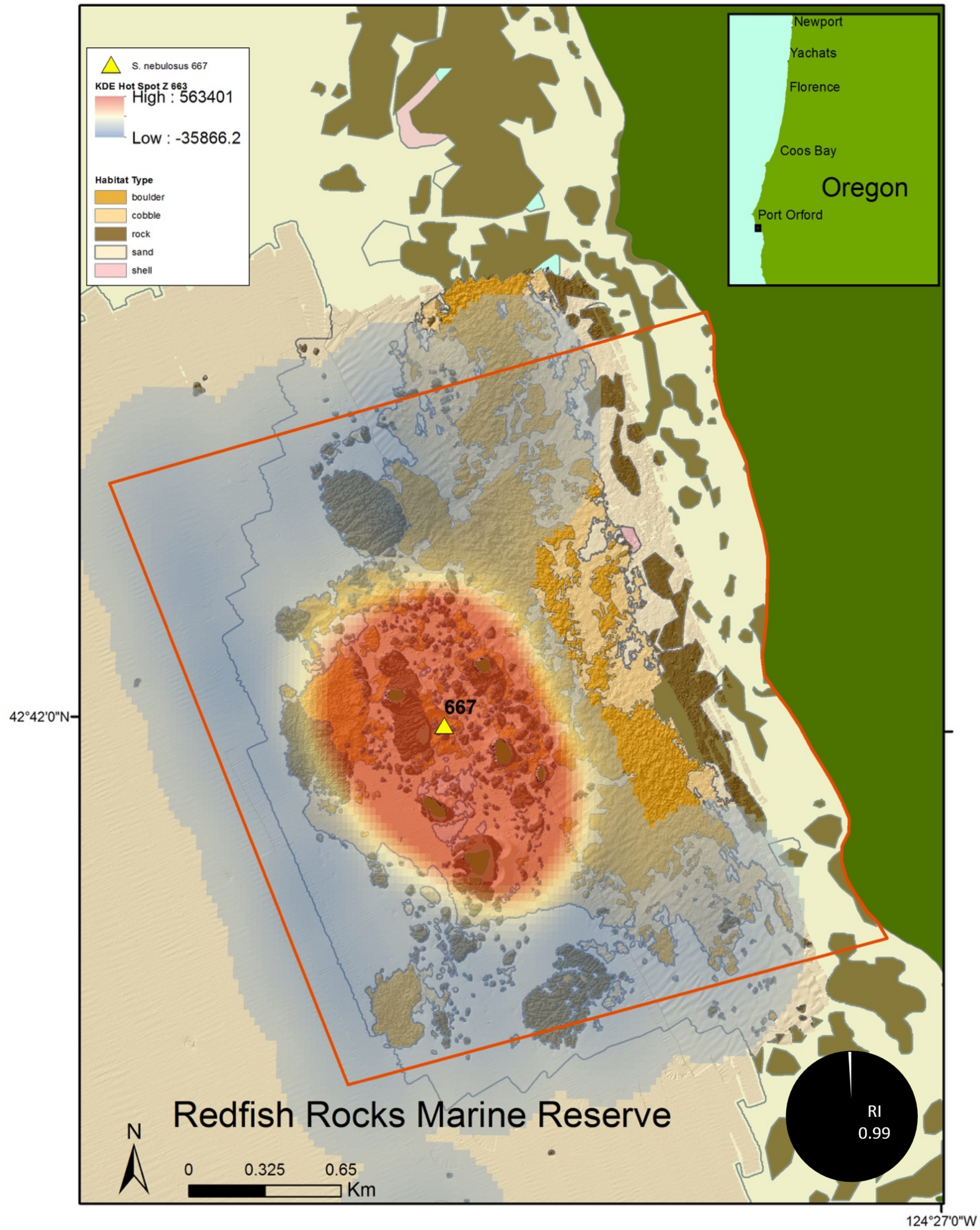


Figure 11 - China Rockfish 667 - density map of statistically significant clusters, with high occurrence of detections in red, and low occurrence of detections in blue, with tagging location and habitat classification. Residence Index (RI) in pie chart.

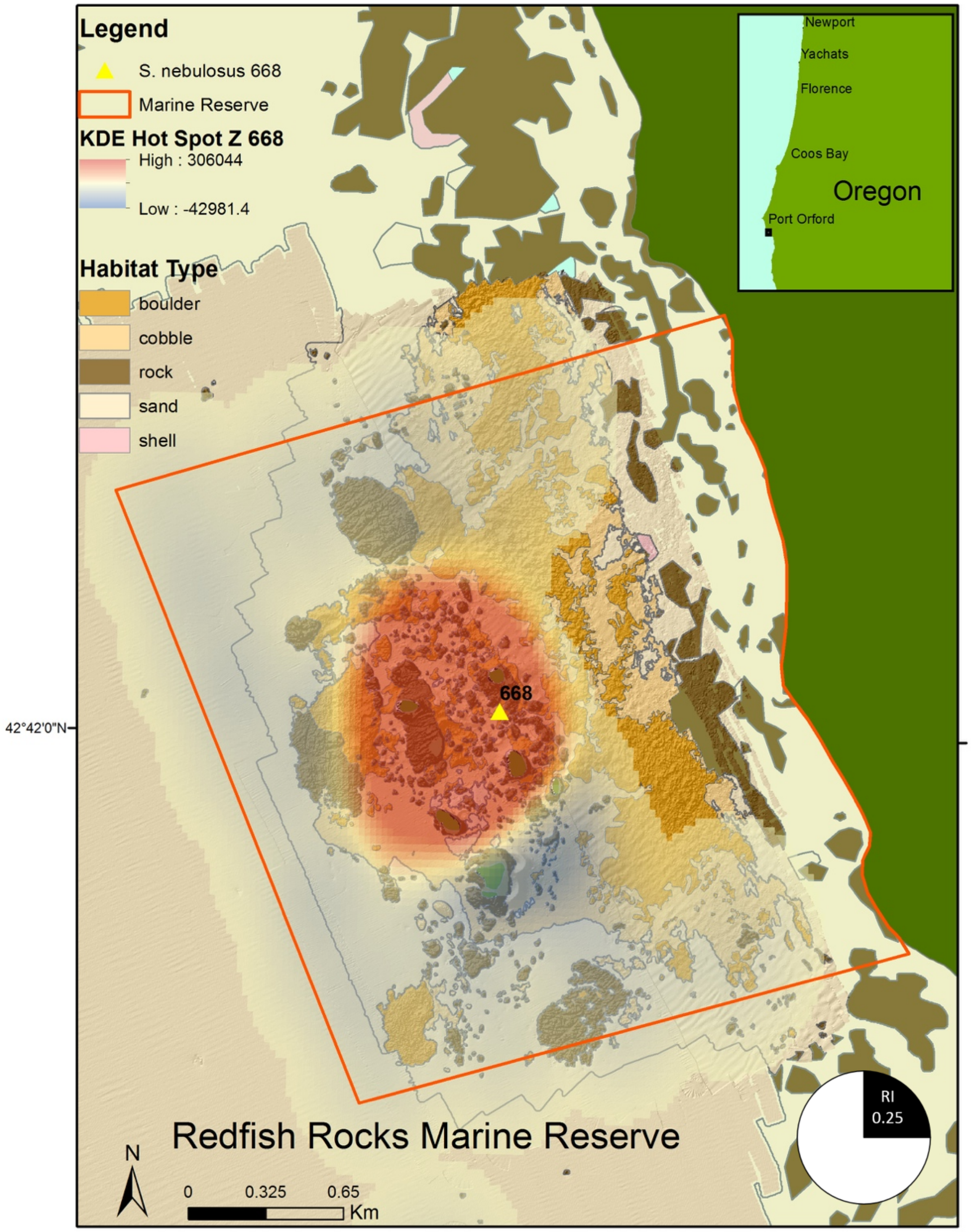


Figure 12 - China Rockfish 668 - density map of statistically significant clusters, with high occurrence of detections in red, and low occurrence of detections in blue, with tagging location and habitat classification. Residence Index (RI) in pie chart.

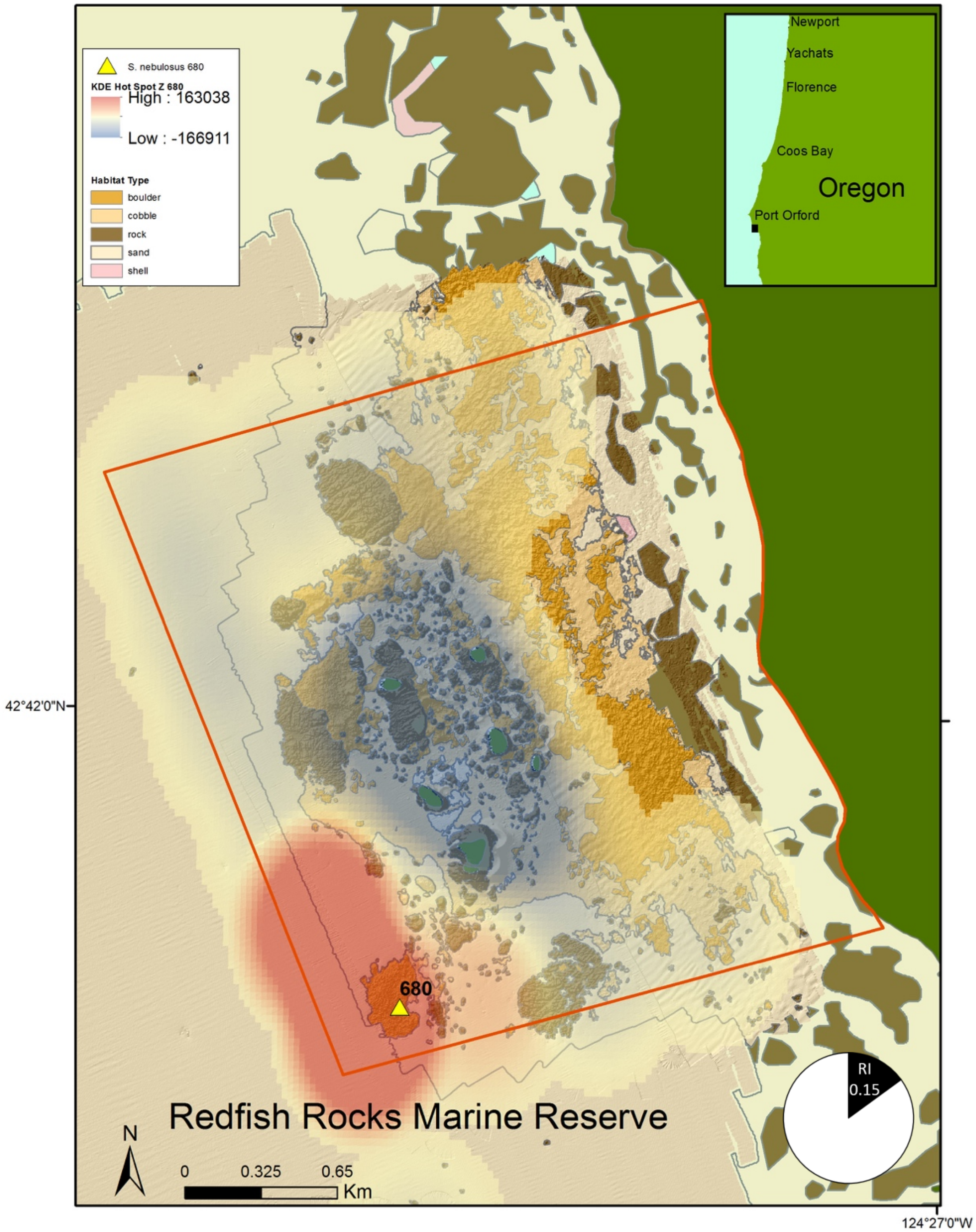


Figure 13 – China Rockfish 680 - density map of statistically significant clusters, with high occurrence of detections in red, and low occurrence of detections in blue, with tagging location and habitat classification. Residence Index (RI) in pie chart.

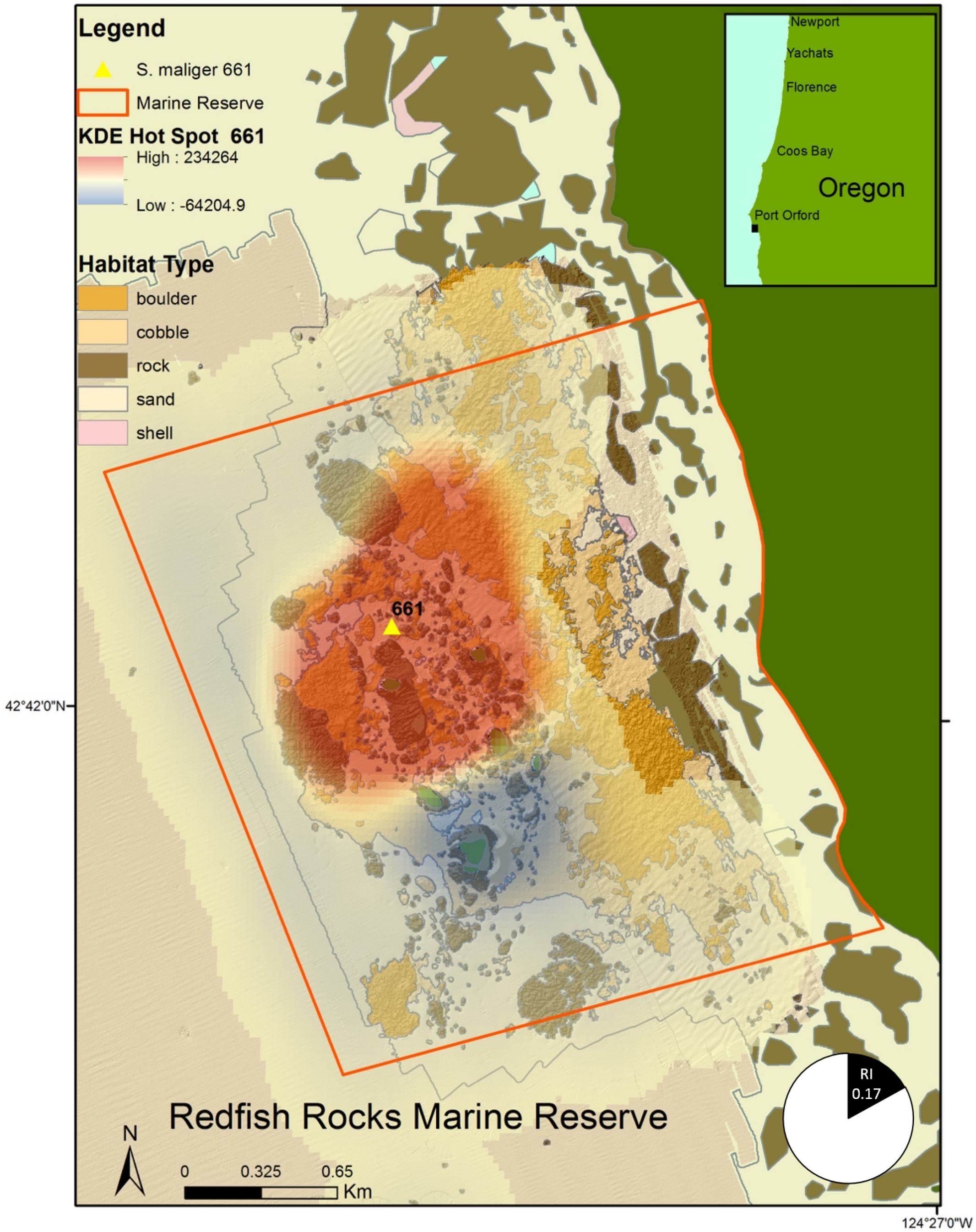


Figure 14 - Quillback Rockfish 661 - density map of statistically significant clusters, with high occurrence of detections in red, and low occurrence of detections in blue, with tagging location and habitat classification. Residence Index (RI) in pie chart.

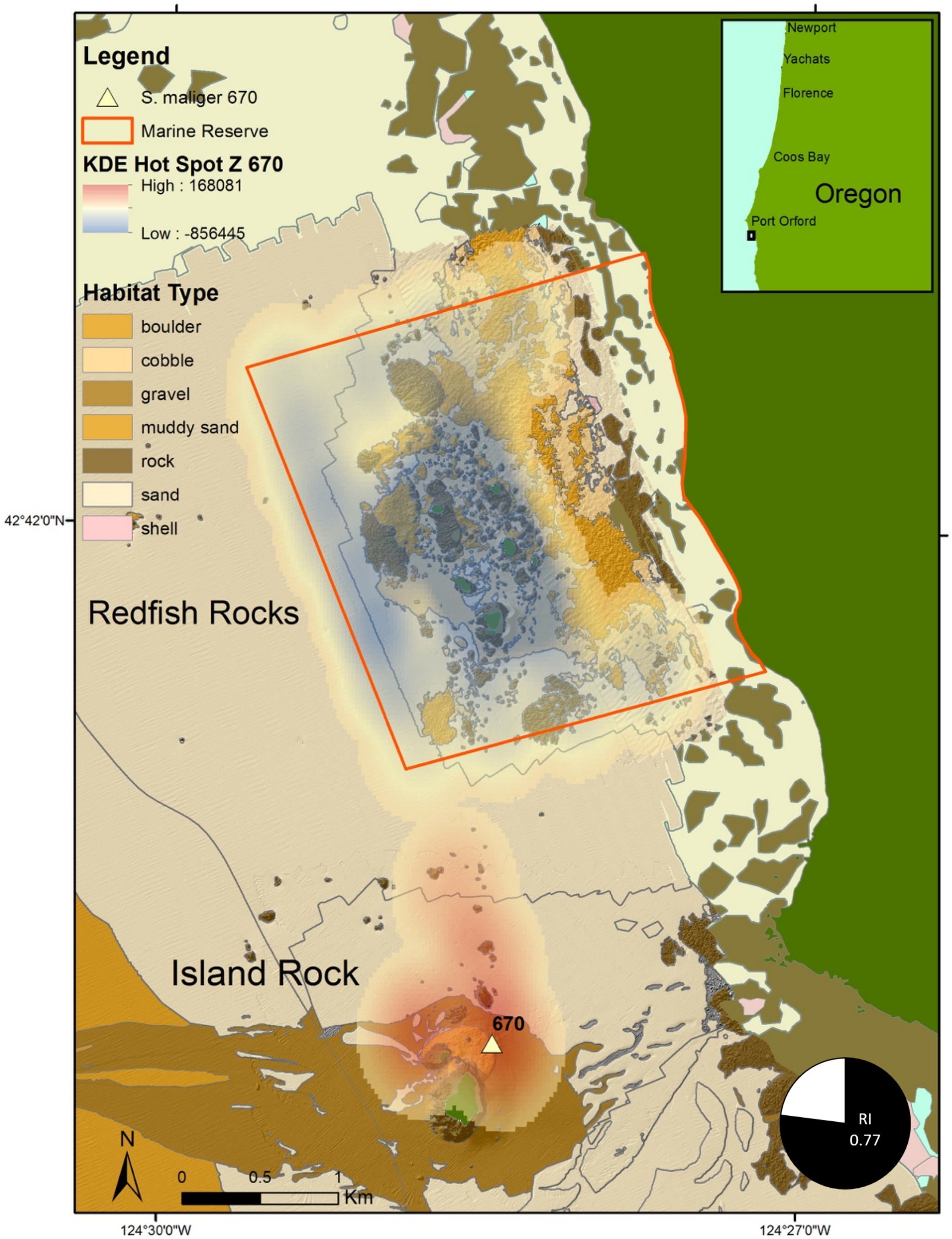


Figure 15 – Quillback Rockfish 670 - density map of statistically significant clusters, with high occurrence of detections in red, and low occurrence of detections in blue, with tagging location and habitat classification. Residence Index (RI) in pie chart.

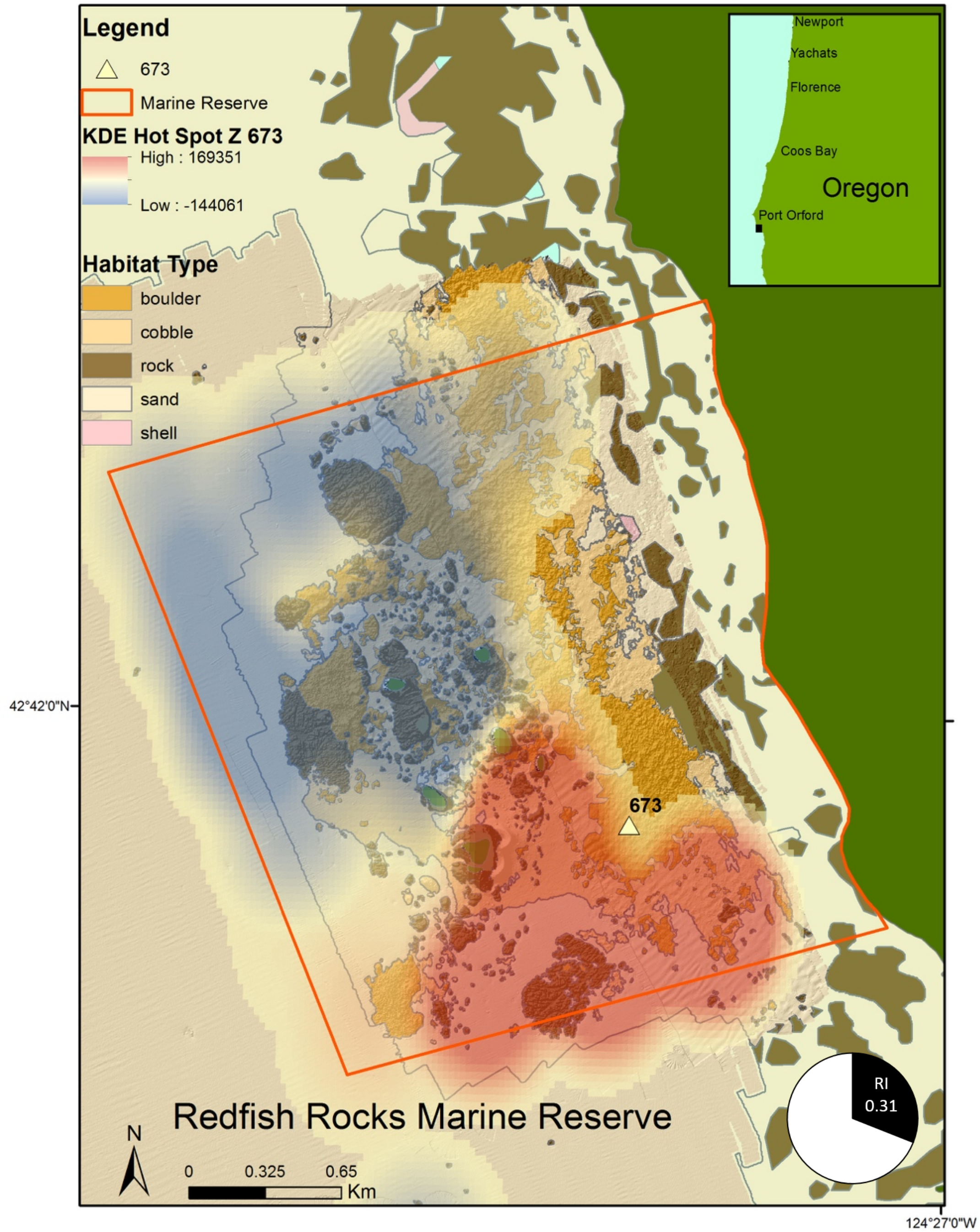


Figure 16 – Quillback Rockfish 673 - density map of statistically significant clusters, with high occurrence of detections in red, and low occurrence of detections in blue, with tagging location and habitat classification. Residence Index (RI) in pie chart.

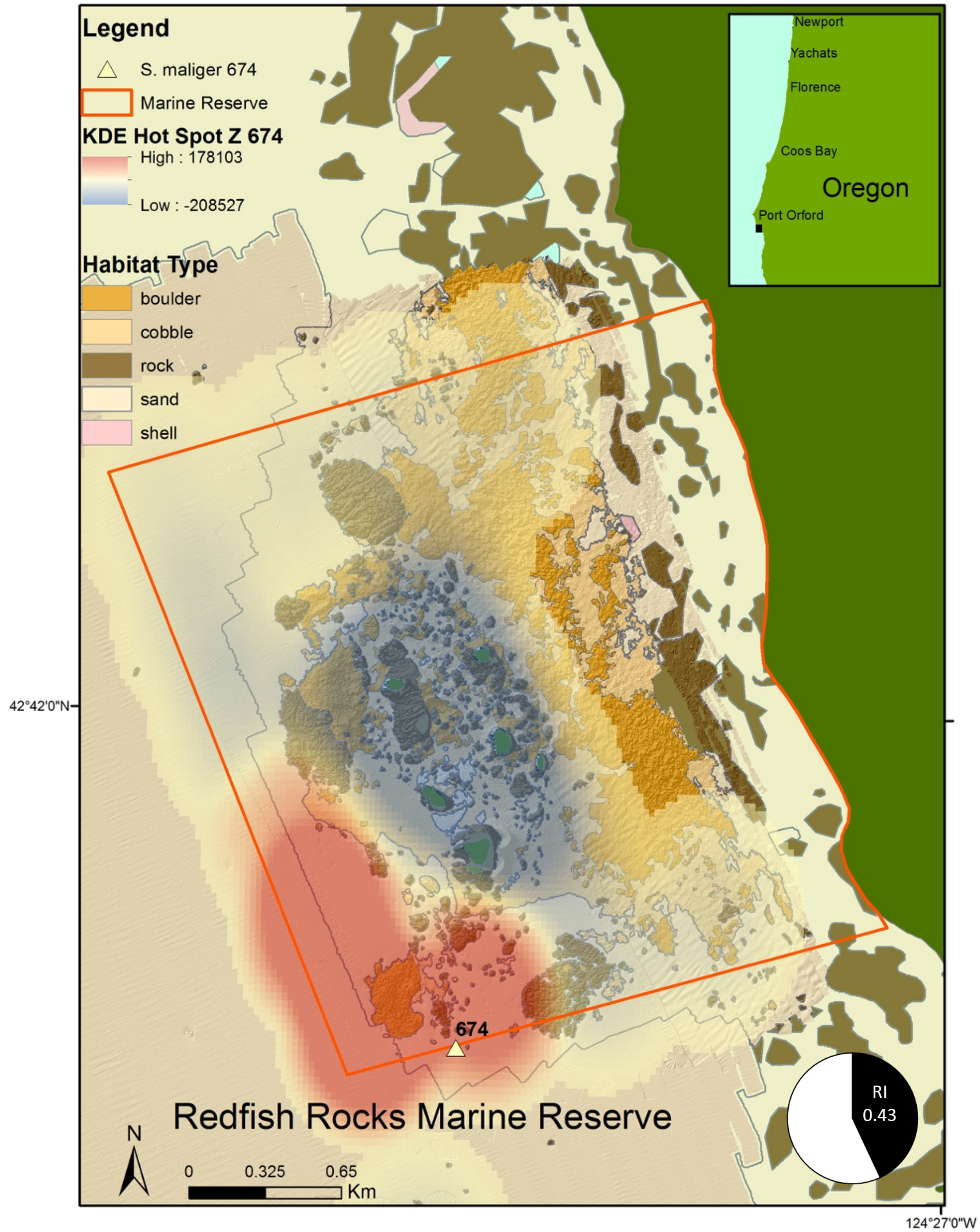


Figure 17 – Quillback Rockfish 674 - density map of statistically significant clusters, with high occurrence of detections in red, and low occurrence of detections in blue, with tagging location and habitat classification. Residence Index (RI) in pie chart.

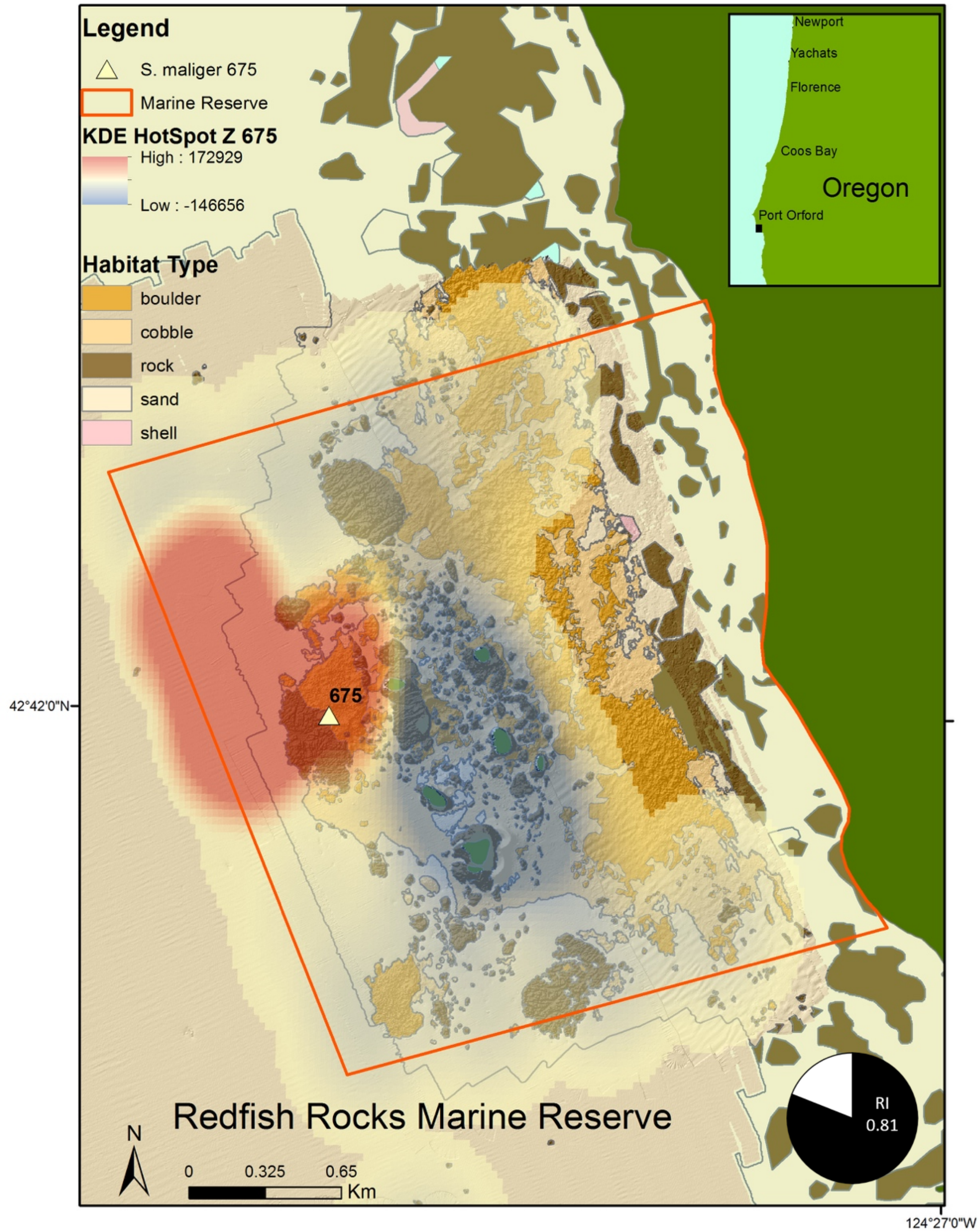


Figure 18 – Quillback Rockfish 675 - density map of statistically significant clusters, with high occurrence of detections in red, and low occurrence of detections in blue, with tagging location and habitat classification. Residence Index (RI) in pie chart.

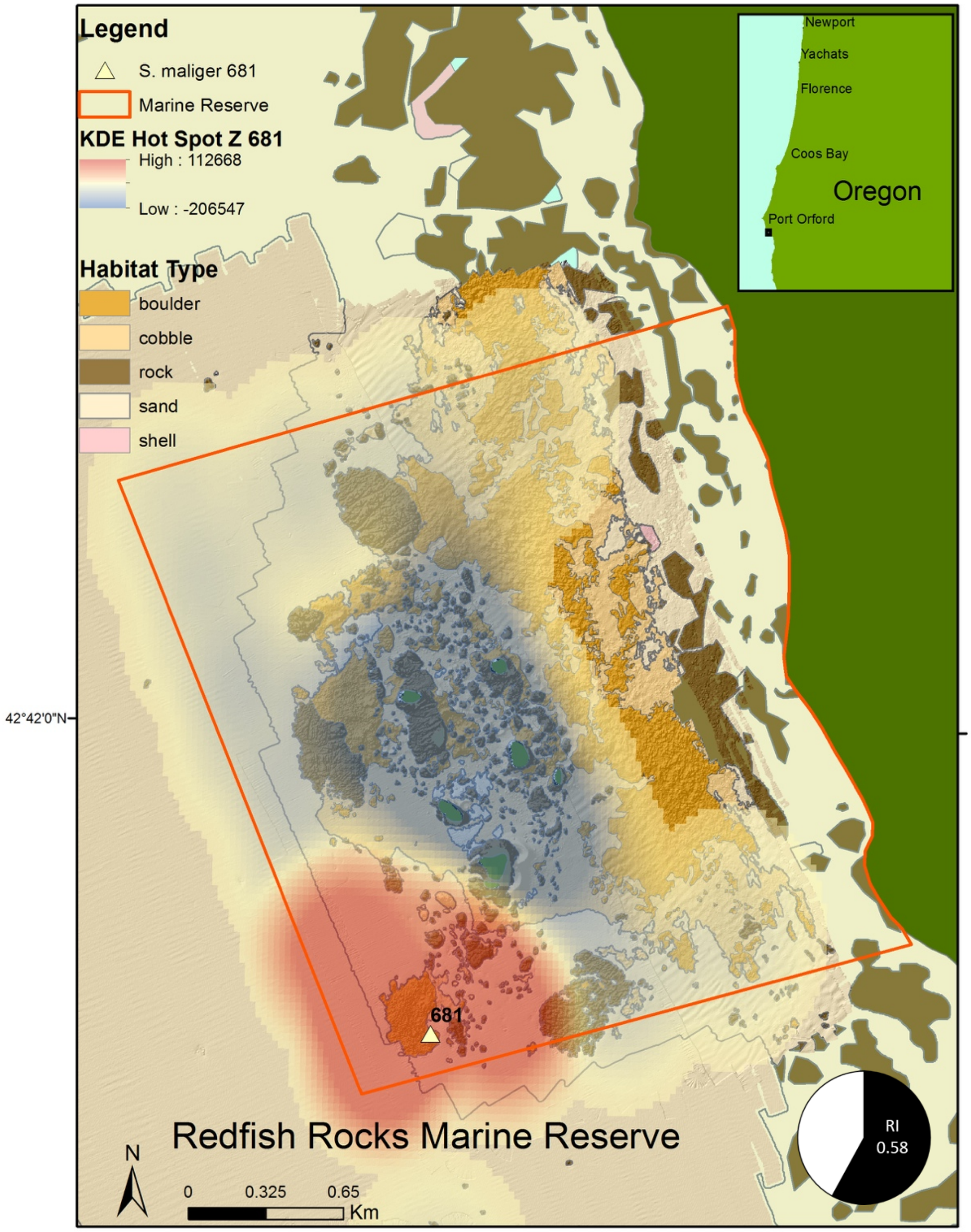


Figure 19 – Quillback Rockfish 681 - density map of statistically significant clusters, with high occurrence of detections in red, and low occurrence of detections in blue, with tagging location and habitat classification. Residence Index (RI) in pie chart.

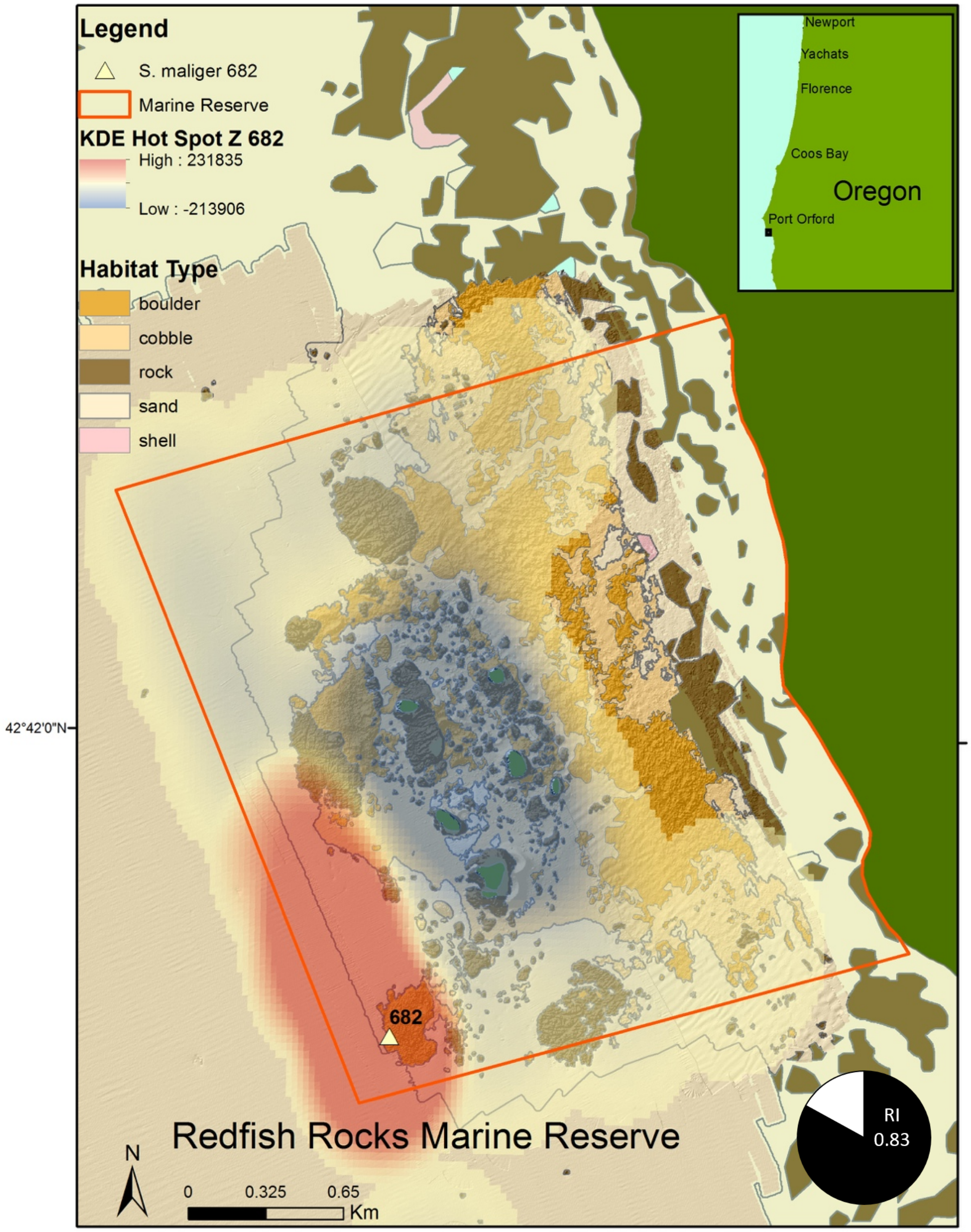


Figure 20 – Quillback Rockfish 682 - density map of statistically significant clusters, with high occurrence of detections in red, and low occurrence of detections in blue, with tagging location and habitat classification. Residence Index (RI) in pie chart.

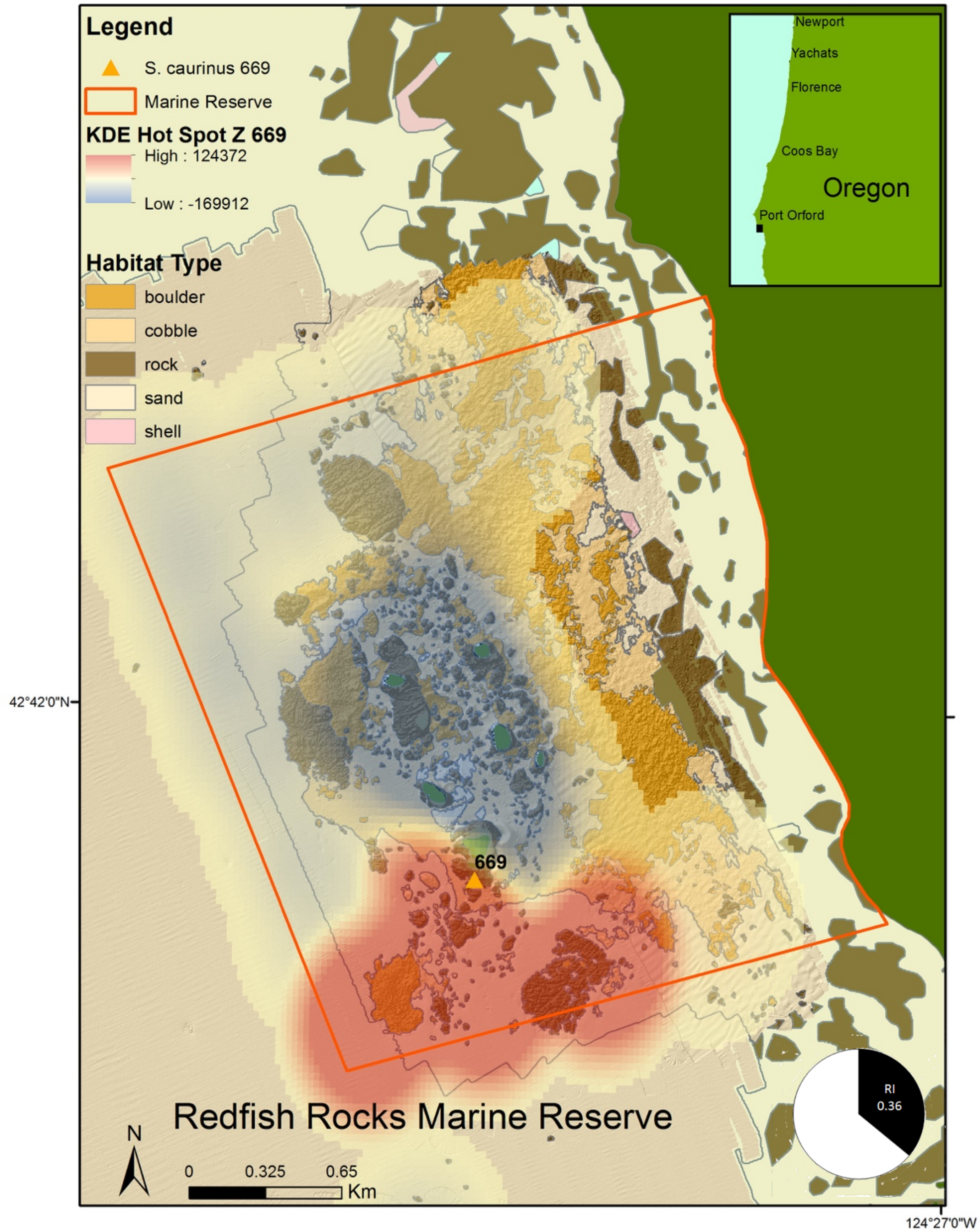


Figure 21 - Copper Rockfish 669 - density map of statistically significant clusters, with high occurrence of detections in red, and low occurrence of detections in blue, with tagging location and habitat classification. Residence Index (RI) in pie chart.

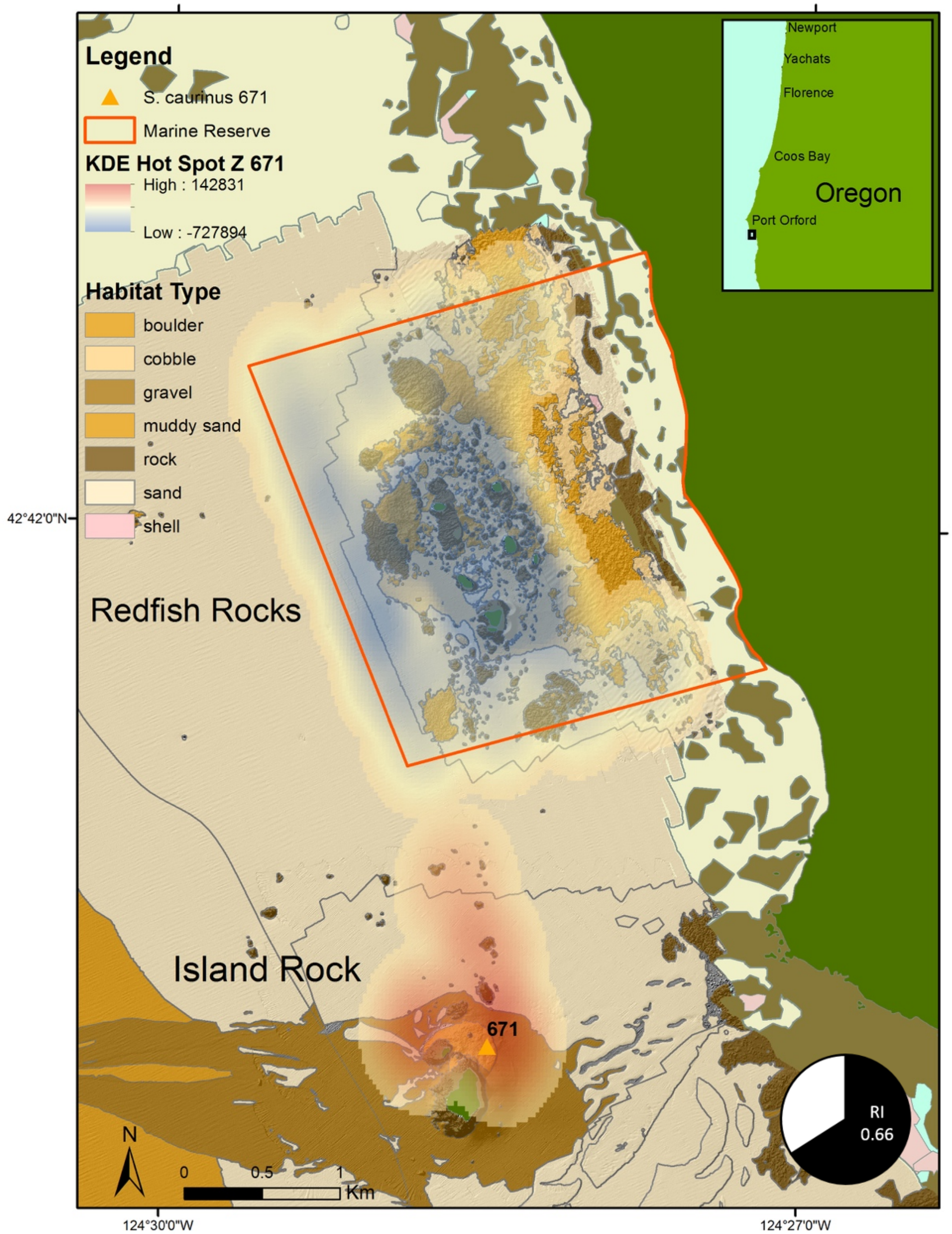


Figure 22 - Copper Rockfish 671 - density map of statistically significant clusters, with high occurrence of detections in red, and low occurrence of detections in blue, with tagging location and habitat classification. Residence Index (RI) in pie chart.

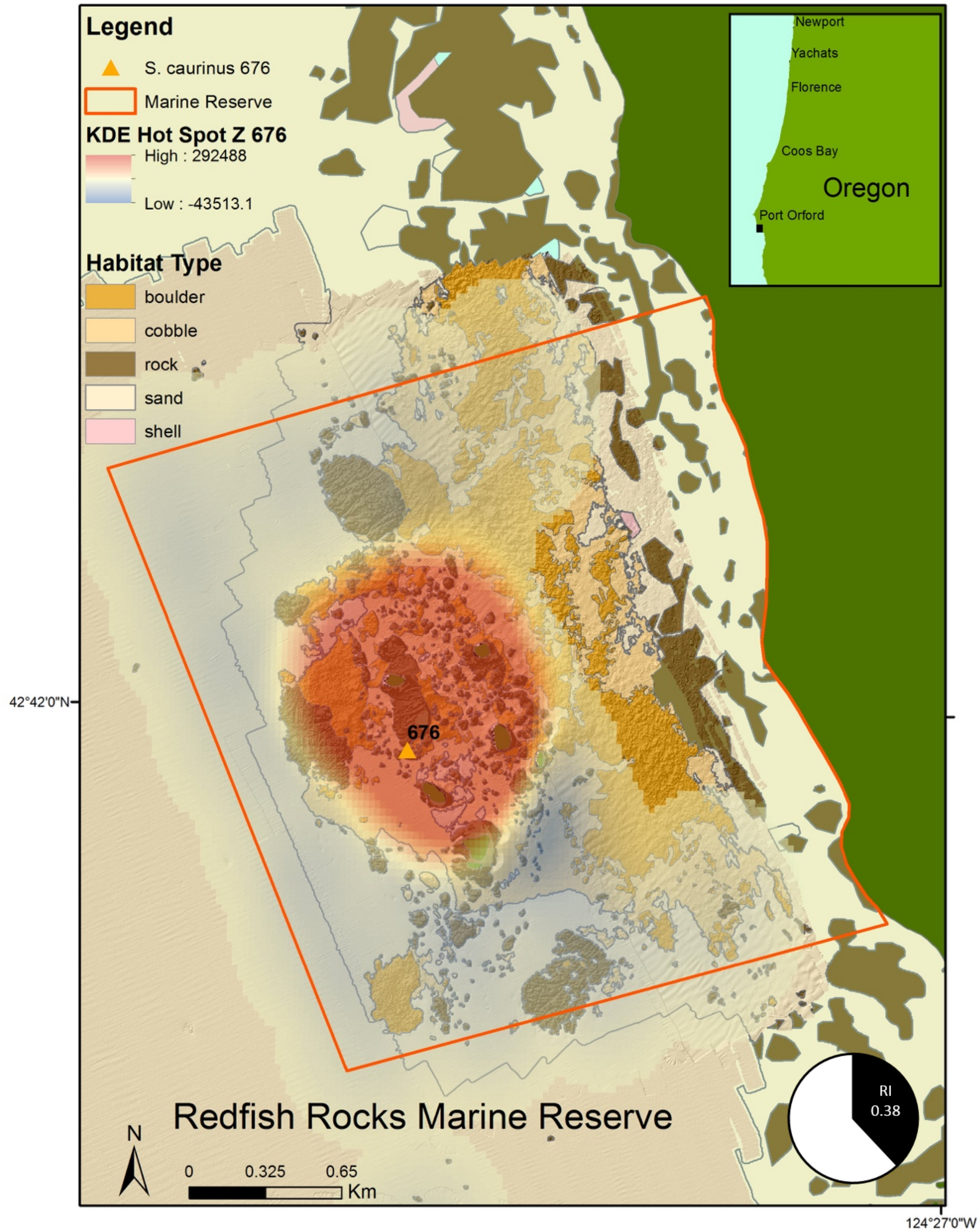


Figure 23 - Copper Rockfish 676 - density map of statistically significant clusters, with high occurrence of detections in red, and low occurrence of detections in blue, with tagging location and habitat classification. Residence Index (RI) in pie chart.

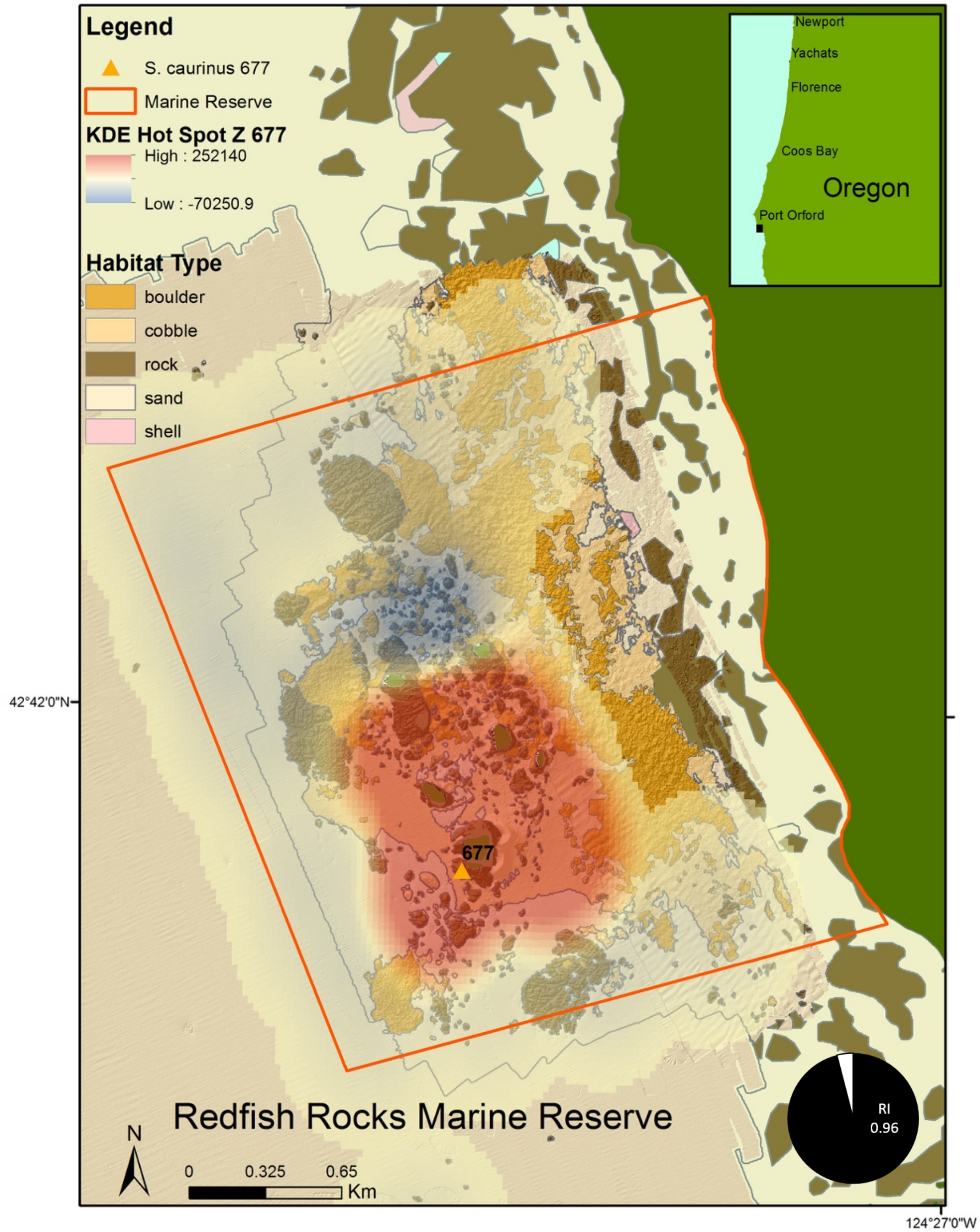


Figure 24 - Copper Rockfish 677 - density map of statistically significant clusters, with high occurrence of detections in red, and low occurrence of detections in blue, with tagging location and habitat classification. Residence Index (RI) in pie chart.

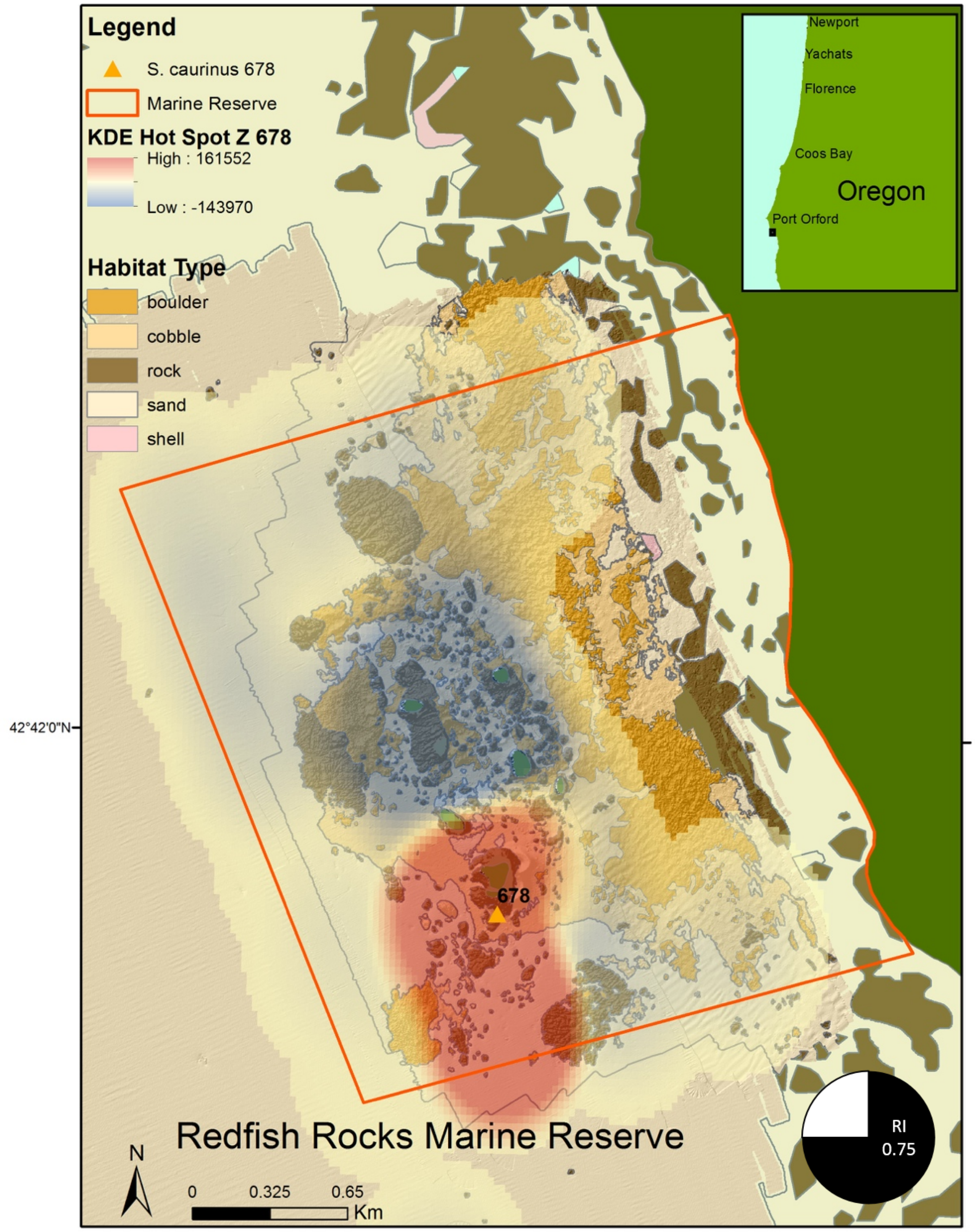


Figure 25 - Copper Rockfish 678 - density map of statistically significant clusters, with high occurrence of detections in red, and low occurrence of detections in blue, with tagging location and habitat classification. Residence Index (RI) in pie chart.

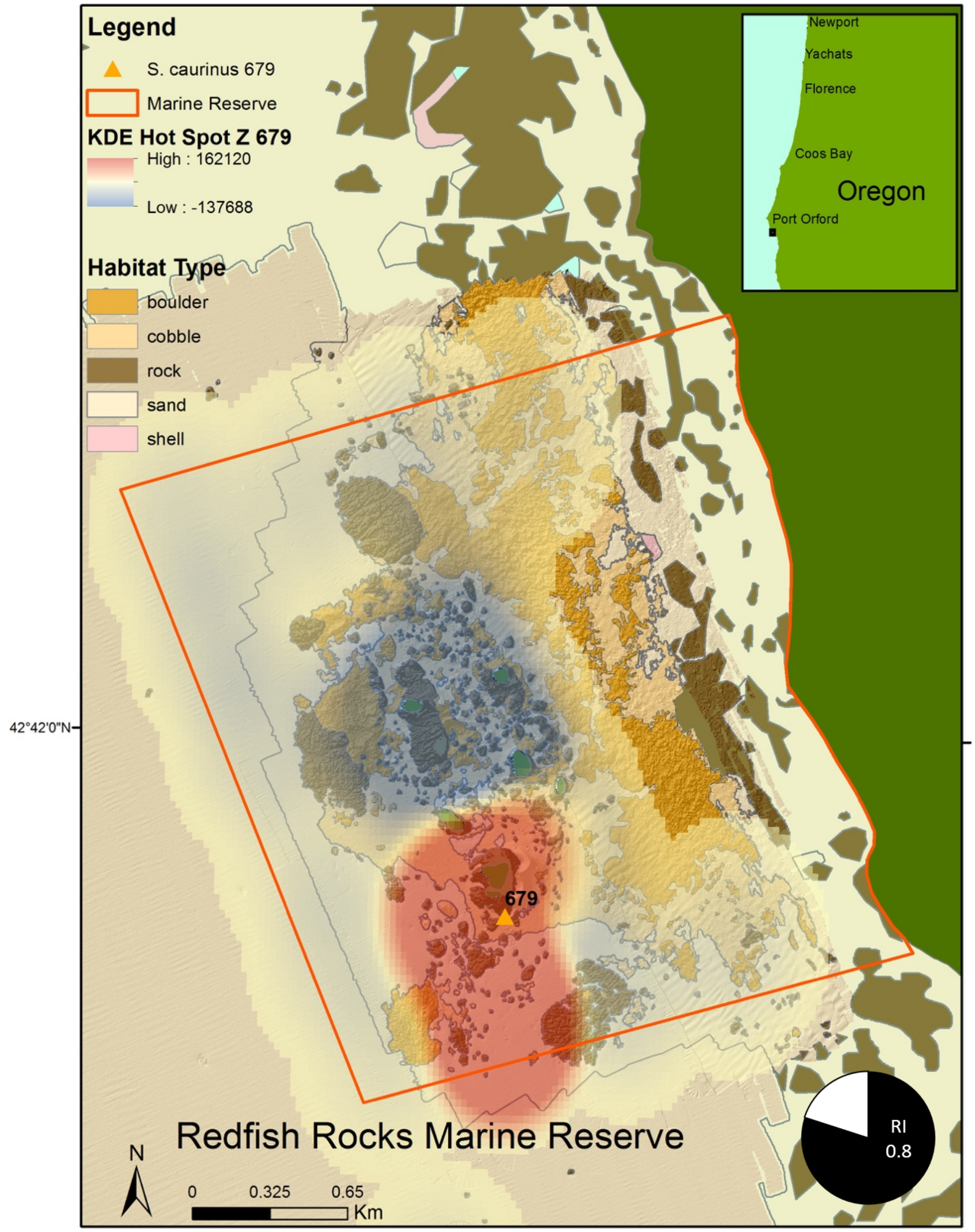


Figure 26 - Copper Rockfish 679 - density map of statistically significant clusters, with high occurrence of detections in red, and low occurrence of detections in blue, with tagging location and habitat classification. Residence Index (RI) in pie chart.

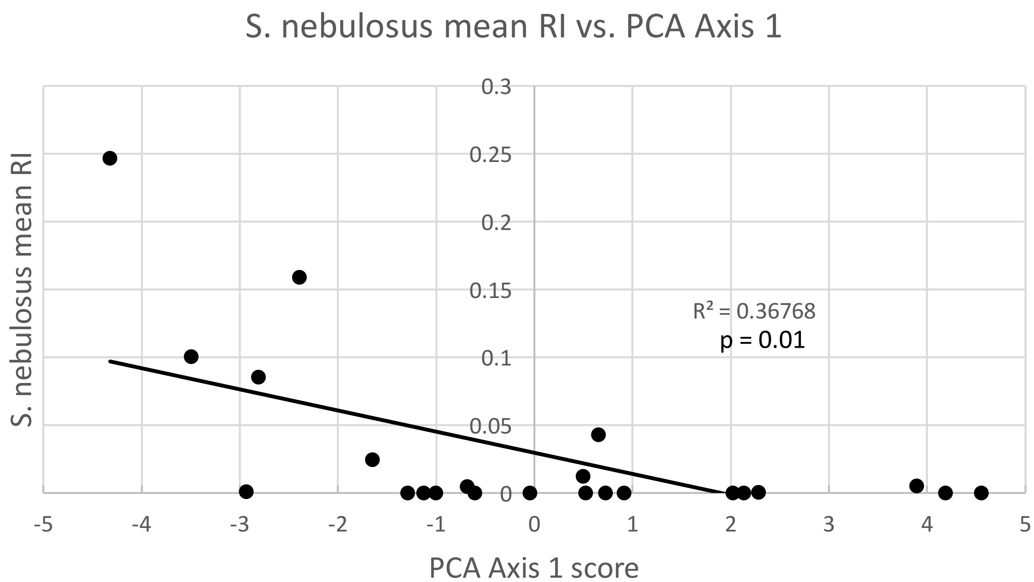


Figure 27 - Results of linear regression analysis of mean residence index for Sebastes nebulosus and PCA Axis 1 score (composite habitat index), $p = 0.01$, $R^2 = 0.368$.

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