Spillover of lobsters from the Western Sambo Ecological Reserve: Scientific Report

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Abstract: The movement dynamics of spiny lobster (*Panulirus argus*) were studied with respect to the boundaries of the Western Sambo Ecological Reserve (WSER) to estimate spillover rates during June and July 2004. Lobster movement patterns were determined through the used of coded sonic tags placed on lobsters which were released within a grid of sonic receivers. In addition to movement data, lobster abundance was estimated using diver surveys with a tag-recapture component to estimate a probability of missed lobsters. A habitat map for the sonic receiver grid area was produced by means of a towed underwater camera and onboard computer running a realtime GPS habitat characterization data entry program. The principal bottom type is sand/mud followed by sea grass. Home range analysis suggests a weak preference for sea grass by larger lobsters and sand/mud for smaller lobsters. Our initial estimate of daily spillover from the central portion (Hawk Channel) of WSER is approximately fourteen lobsters per day during the summer. Both movement data and diver observations have shown that the adult lobsters residing in Hawk Channel are important members with regard to the overall fecundity of the lobster population. We are now certain that adult female lobsters living in Hawk Channel mate with males in Hawk Channel. Then these females migrate to the fore-reef approximately

three kilometers to the south to spawn. The movement data suggest that females return to Hawk Channel and that many repeat this mating/spawning cycle.

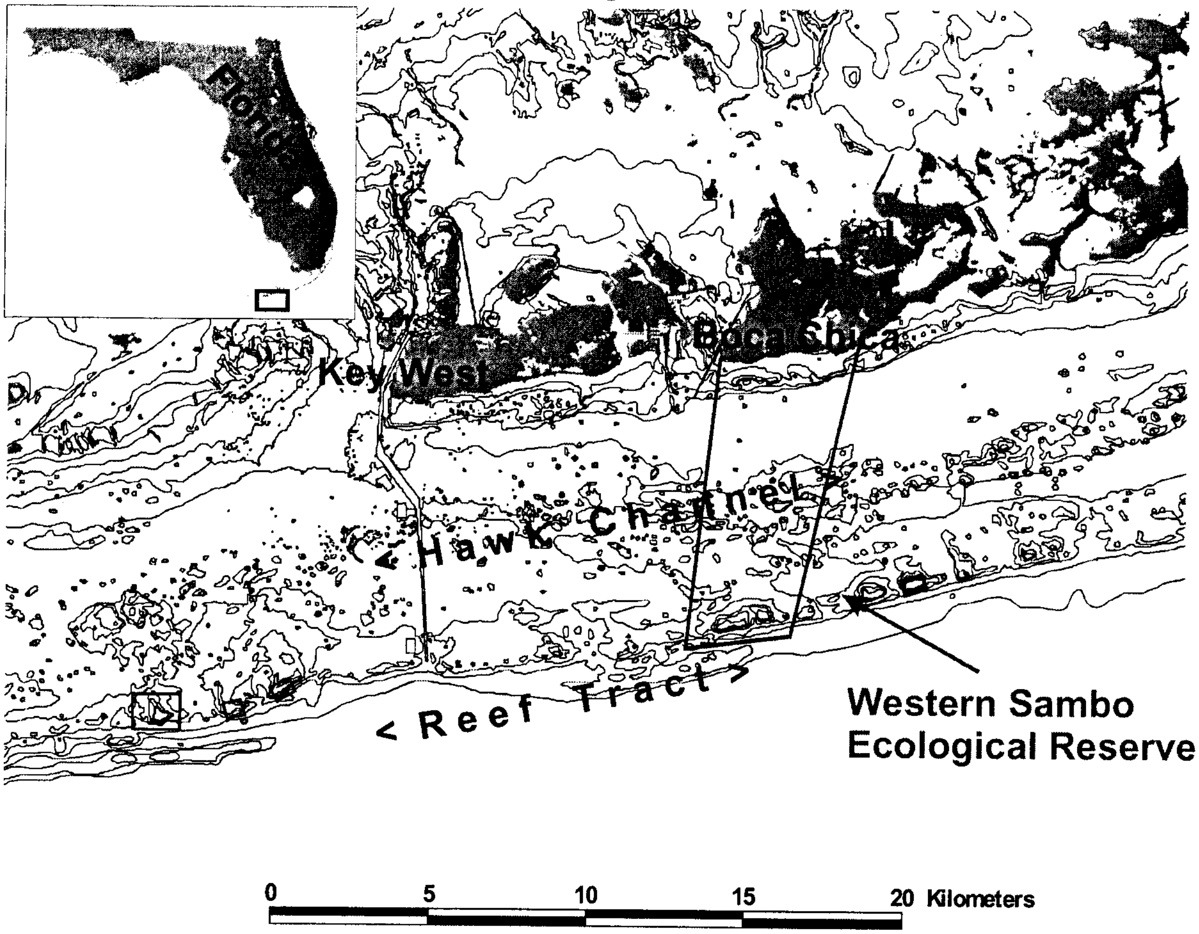
Introduction:

On July 1, 1997, the Western Sambo Ecological Reserve (WSER) was established within the Florida Keys National Marine Sanctuary (FKNMS) by the National Oceanic and Atmospheric Administration (NOAA). One of the purposes of an ecological reserve is to provide for the replenishment of marine life into the surrounding areas (Department of Commerce, 1996). Spillover is the specific term used to describe replenishment by movement of adult or sub-adult animals rather than dispersal of eggs or larvae.

The Western Sambo Ecological Reserve is a 3,000 ha rectangular reserve extending from the shoreline around the Boca Chica US Navy Air Station to the Western Sambo reef (Figure 1). The reserve is four km wide at the air station and nearly 3 km wide at the reef track. Spiny lobsters are found throughout the reserve and their primary daytime habitats are the reef track along the southern boundary and the patch reefs throughout the central area of the reserve. An accurate estimate of the amount of patch reef habitat is not known. The latest survey conducted of the region characterizes more than 50% of the habitat as unknown. The large percentage of unknown habitat was due to the turbid water conditions at the time of this assessment (Florida Marine Research Institute, 2000)

The primary objective of this study was to estimate the performance of the Western Sambo Ecological Reserve from the perspective of spiny lobster spillover from the reserve to the surrounding fishery. Estimating the potential of the WSER for lobster spillover requires two basic parameters; (1) the probability of lobster movement through time including distance and bearing and (2) an estimate of the abundance of lobsters in the WSER. The method used to estimate spillover involves analysis of lobster movements through the use of sonic tags placed on the lobsters and a grid of sonic receivers and the use of diver-based abundance surveys with antennae tag marking. Other goals of this study were to determine basic home range and habitat utilization and characterize lobster movement patterns.

Figure 1. Location of the Western Sambo Ecological Reserve



Methods:

Field methodology: The principal field methods used in this study are diver-based population assessments of patch reefs, habitat mapping through the use of underwater cameras, and movement characterization through the use of sonic tags and a network of receivers among the patch reef habitat.

VR2 sonic receivers

The sonic receiver is a device that passively "listens" at the 69 kHz frequency for coded signals from other devices such as "pingers" or sonic tags. The receivers are initialized using a special magnetic probe and an interface to a computer through the serial port. The receiver contains a nonvolatile memory chip that contains information about the project typed in by the investigator during initialization. In addition, a clock is started which is set to the time of the computer. When a sonic tag signal is successfully detected by a receiver, the receiver will record the code from the tag and the time to the nearest second as kept by the clock within the receiver.

Field deployment and retrieval of sonic equipment

Sonic receivers were placed in a grid-like pattern around the eastern border of WSER in Hawk Channel. The grid is deployed prior to deploying the sonic tags. The distance between the sonic receivers was determined through two preliminary experiments that included systematically moving receivers and tags known distances apart. We determined that tags could be reliably detected up to 600 m in unobstructed (i.e.; flat soft bottom) areas (FWRI data). Receivers within two meters of the bottom detected tags as well or better in some cases than receivers 10 meters off the bottom. Broad rough hard bottom areas greatly reduced detection distances in a manner that was difficult to predict. For example, sometimes a receiver could not detect a tag within 50 meters but a receiver 200 meters away could detect the same tag. However, while acoustic "reflections" and "shadows" reduced reliability to detect tags, these effects did not completely prevent detection. Tall narrow (less than 10 meters wide) hard bottom pinnacles had no noticeable effect on the detection of tags.

For field deployment, VR2 sonic receivers were attached to a stand comprising a one foot by one foot concrete base with an eye bolt and six-foot length of PVC pipe embedded in the concrete. Receivers were cable tied to the top portion of the pipe with a safety lanyard running from the receiver to the eye bolt on the concrete stand. The sonic receivers were lowered to the bottom using a rope looped through the eye bolt (Figure 2).

Figure 2. Sonic receivers were deployed on a pvc pipe and concrete stand. The stands were lowered with a rope fitted through an eye bolt in the concrete base.

The second preliminary experiment was a small scale dress rehearsal of this project. Twenty sonic receivers were placed 200 meters apart into a five by four grid and ten sonic tagged lobsters were placed into this grid (Figure 3). This experiment established that spiny lobster positions could be estimated to within 10 to 20 meters when lobsters were on soft bottom habitat but also that most lobsters traveled outside the grid part of the time and so home ranges could not be determined.

On June 3, 2004, we placed 24 sonic receivers into a staggered grid 300 to 600 meters apart (Figure 4) in order to extend the spatial coverage of the grid. The extended grid was used to better determine home range sizes at the cost of precision in determining lobster positions. This grid was placed south of the preliminary study because the water was extremely turbid to the north. Four additional sonic receivers were placed north of the reef crest within WSER and approximately 3 km south and west of the grid. These receivers were placed in these positions to detect any tagged lobsters that might approach the reef crest. The two reasons for the westward shift their placement was due to the west of south bearing we observed in egg bearing females leaving the grid during the 2003 pilot study and this placement would help us estimate potential retention of egg bearing females within WSER who migrate to the fore reef to spawn. When placed in the water, the position was marked with differential GPS and a marker surface buoy was placed next to each sonic receiver.

Figure 3. The 2003 (late June - July) deployment of 20 sonic receivers along the eastern boundary of WSER. Receivers were 200 meters apart.

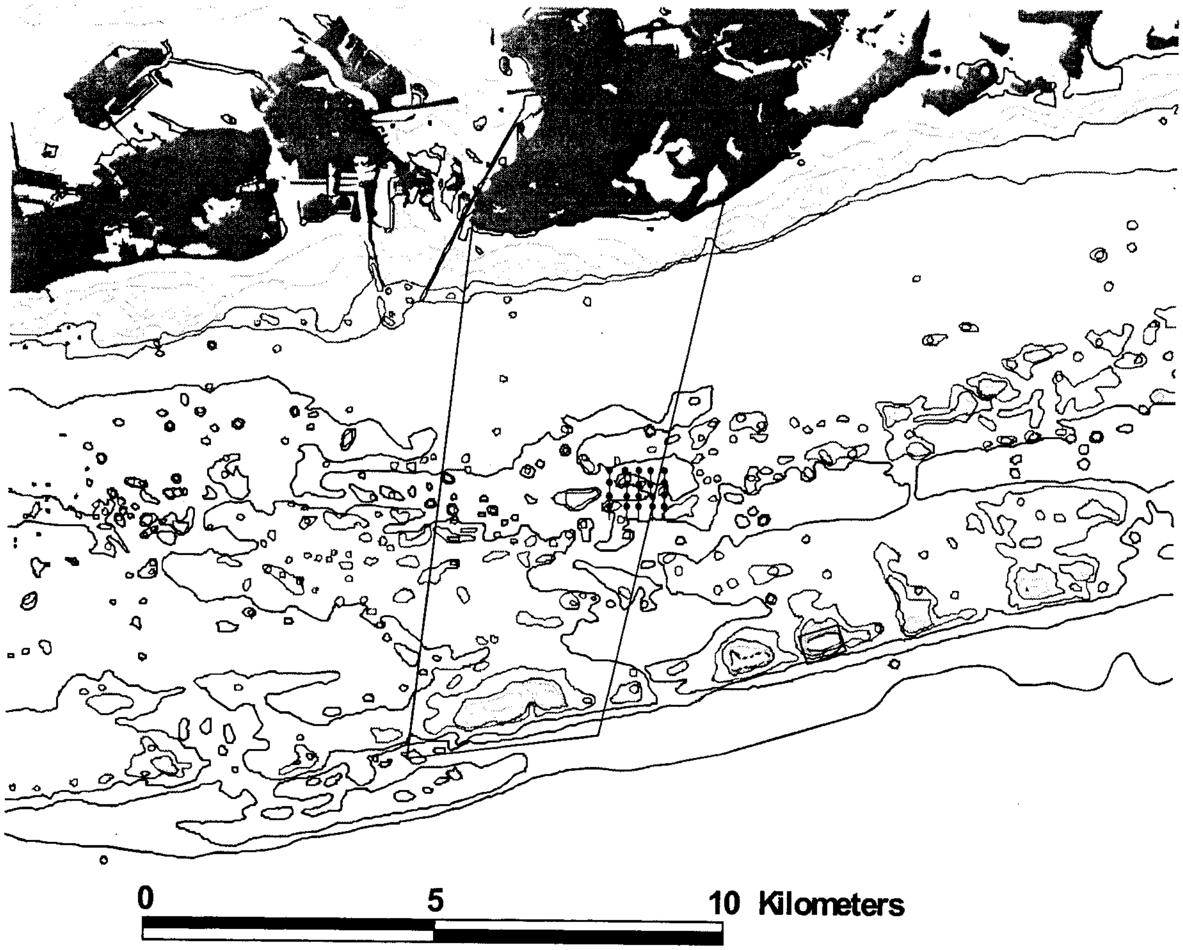


Figure 4. The 2004 deployment of 26 VR2 receivers from June - July. Receivers were placed from 300 to 600 meters apart along the eastern border of WSER with additional receivers place along the approaches to the fore reef of WSER.

On July 27, 2004, all receivers were recovered using divers to fix a line to the eye bolt of the stand, and personnel onboard to retrieve the line and the receiver. All receivers were found in an upright state and active (i.e.; batteries working).

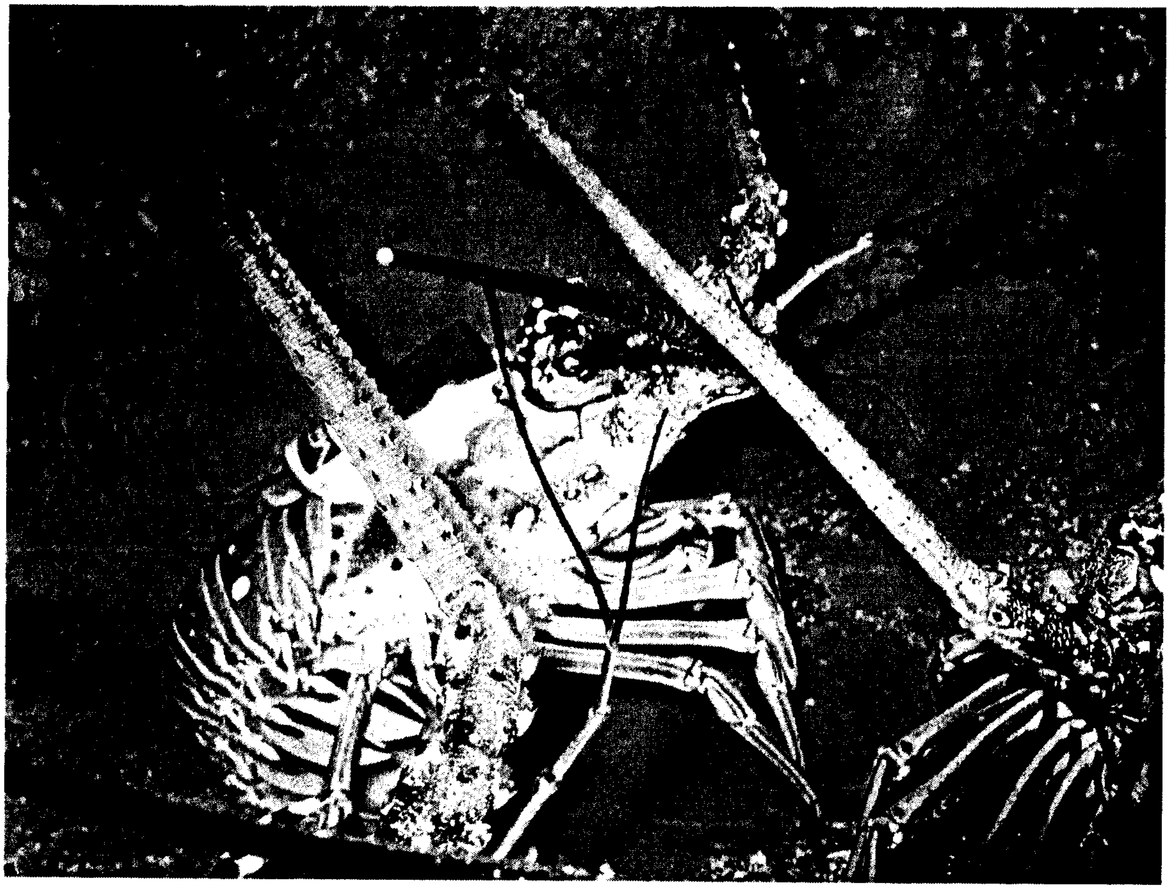
Sonic tags

The sonic tags used in this study were a VEMCO V16 4K coded pinger tag. Each tag's dimensions were 16 mm diameter and 58 mm long. These tags are among the more powerful tags for their size with a power rating of 158 dB *re* μPa at one meter. They have a four-digit code that is emitted (ping) in a randomized interval between 60 and 183 seconds. The randomization of ping time reduces the probability of signal interference between tags. Tags were activated in the laboratory two days prior to field deployment. The electrical lead ends of wires were trimmed and soldered and then coated with a silicone sealant. The activation of each tag was confirmed by placing the tag next to a VR2 receiver.

To tag lobsters in the field, lobsters were captured by SCUBA divers using tickle sticks and nets. A running log of the size and sex of each tagged lobster was kept to insure that a variety of sizes and approximately equal number of male and female lobsters were tagged. The minimum practical size for a tagged lobster is about 70 mm CL. Lobsters to be fitted with a sonic tag were brought to the boat and placed into a large tray partly filled with water. The tray allowed us to dry the top of the lobster carapace with a towel while the lobster could keep its gills wet. Tags were affixed to the carapace using an underwater plumbing repair epoxy. Although the epoxy will adhere on wet surfaces, we found that a damp surface permitted greater adhesion of the epoxy than a wet surface. A portion of the clay-like epoxy was molded by hand into a shape similar to the sonic tag. The epoxy was placed along the carapace of the lobster, then the tag was pressed down into the epoxy with the emitter end of the tag resting next to the horns and posterior to the eyes (Figure 5). The epoxy was further molded onto the carapace with special attention given to pressing the epoxy around the spines to insure a secure fit. The lobster was retained in the holding tray for approximately 15 minutes to permit sufficient hardening of the epoxy. Divers then returned each lobster to its den.

Twenty-five lobsters were tagged and released on patch reefs on June 6 and 7^{th}, 2004. An additional fourteen lobsters were tagged and released on June 16^{th}, 2004. The ten-day gap between tagging sessions was due to bad weather and poor water visibility.

Figure 5. Lobster fitted with a sonic tag. This was a test tagging, normally the two wires are soldered together and covered with epoxy.



Antenna tagging lobsters

Population assessments were performed on eighteen patch reefs, half inside the WSER and half outside. A single patch reef population assessment consisted of SCUBA divers completely searching a patch reef for three consecutive days. The multiple day searches permit us to estimate the amount of daily turnover of lobsters on a patch. When a lobster was found, divers estimated size and recorded sex then placed a numbered tag unique to a given patch reef on one antenna. On rare occasions when there were more than twenty lobsters on a patch reef, tagging stopped at twenty and divers completed survey by quickly counting the remaining lobsters. The other antenna received a color coded tag, a green tag on the first day and an orange tag on the second day the lobster was not already tagged. The third day assessment required only observation of lobsters and recording of tags.

Habitat mapping

We have a towable "fin" that we have modified to accommodate an underwater video camera. Through a cable, we can view the bottom and characterize habitats. With a laptop computer attached to a differential GPS, we have a software application we wrote that permits the user to press keys that indicate a bottom type while the computer queries the GPS for the current position. In the field, the camera is towed at two the three knots and the observer entered a habitat characterization approximately every ten to twenty meters of travel. The boat towing the fin, crossed the sonic receiver array in east-west transects with approximately sixty meters between transects.

Laboratory methodology and analysis:

When the sonic receivers were returned to the laboratory, they were immersed into a fresh water bath (prior to the cleanup) and all the receivers were "pinged" with a single pinger. This "reference" ping permits all the clocks on board each receiver to be synchronized. Because of variation in clock speed between processors, the time recorded by a given sonic receiver can drift by several minutes from other sonic receivers. In the post processing of the data, the time among all sonic receivers is synchronized. After each sonic receiver was cleaned, data were downloaded onto a computer using a magnetic probe through a serial port connection.

After all data were downloaded, the "reference ping" (see above) was located in the data from each sonic receiver. Once the slowest clock was identified, the time from all receivers was synchronized to this receiver using a simple linear function based on the number of seconds of drift between the two given sonic receiver clocks.

Once the time was adjusted for every sonic receiver, a large database was created by concatenating all receiver telemetry and adding latitude and longitude fields to the dataset. An estimated lobster position database was derived from all the sonic receiver telemetry. Positions were estimated by calculating an average latitude and longitude of all sonic receivers recording pings from a given sonic tag during a one hour time span. The average latitude and longitude were weighted by the number of pings recorded by the sonic receivers (i.e.; a centroid). A running list of centroids were calculated over one hour time periods with an advance in time set for fifteen minutes (a running mean). The one hour and fifteen minute parameters were determined by trial and effort to provide reasonably smooth time series of centroids.

Spatial analysis

Spatial analyses were conducted using the derived centroid data in Arc View using the Spatial Analyst, Tracking Analyst, Geoprocessing Wizard, X-Tools, and Animal Movement Analysis (Hoodge, 2000). Distance, velocity, and bearing between consecutive centroids were calculated using a script I wrote.

Home ranges were calculated using the minimum convex polygon to insure that all possibly used habitats were included within the home range.

Population estimates

Diver-based surveys have been used for many years to estimate abundance of lobsters (FWRI data). Some diver surveys have been time base (Catch per unit effort, CPUE) and others have been area based. Diver-based population estimates have one error term that has been very difficult to measure. Diver surveys generally occur during daytime when lobsters typically hide in crevice-like shelters to avoid daytime predators. While this behavior concentrates lobsters into predictable and generally searchable habitats, some individuals may and do shelter in places that a diver cannot see. Still other lobsters may be partly visible and out of reach of catch gear. In previous surveys, the "unknown" lobster (one that for example is counted but size and gender not determined because only a body part was visible and it was out of reach of catch gear) makes up approximately 10% of the total population (FWRI data). Another source of error in diver surveys can be due to poor visibility.

To estimate abundance, we used an approach that combined elements of complete diver surveys of patch reefs with a repetitive tag-recapture effort. Whereas a single complete diver survey has a probability of underestimating the population due to missed lobsters, a twenty-four-hour tag recapture survey can estimate the probability of a missed lobster. Unfortunately, the estimated probability of highly hidden lobsters using a tag recapture survey can be biased if immigration and emigration occur between surveys.

The two most likely reasons for missing tagged lobsters twenty-four hours later are: (1) a lobster was present but not seen or (2) a lobster emigrated to a different patch reef (other factors such as predation and death are assumed to have a very small probability). A means to calibrate the probability of emigration is possible by using the sonic tag movement data and the inter-patch reef distance distribution. Determining lobster daytime positions can be used to determine a frequency at which lobsters change their sheltering habitat from one patch reef to another. Unfortunately lobster daytime positions are very difficult to estimate because lobsters tend to seek shelter in rocky crevices during the daytime. Hard substrates distort or block the sonic signal which reduces the reliability of the calculated centriods. To retain as much information regarding denning positions of lobsters, we calculated where possible, positions (centroids) for three time periods: (1) the position between 4 and 7 a.m. (presumably a den seeking period); (2) 9 and 4 p.m. (presumably a denning period); and (3) 7 and 9 p.m. (presumably a den exiting period). Estimates of daytime positions of lobsters were calculated when one of the following three conditions was met: (1) if data were available for all three time periods, the average position of all three estimates was used (2) if data were available for only the daytime or if daytime was available and only either den seeking or den exiting was available, the daytime estimated position was used, and (3) if data were available for den seeking and den exiting, the average of those two positions was used. These calculations were also performed on the data collected from the 2003 pilot study to provide an additional calibration curve. The 2003 pilot study provides potentially better estimates of shorter distances because the sonic receivers were placed closer together but because we tagged only ten lobsters and the project was conducted over a shorter time frame, far fewer position estimates can be calculated. The resulting inter-daily distances traveled were plotted as a cumulative distance frequency curve with Table Curve.

From the habitat map we calculated the nearest neighbor distance for all patch reefs using Arc View and plotted a frequency distribution of these distances as well. Distances were measured from patch center to center and also from patch reef edges. The probability of emigration is equal to the probability of a lobster moving a distance that exceeds the weighted average of the nearest neighbor distance between patch reefs.

The analysis of daily movement does not cover the probability of a lobster moving off the grid (because a daily movement distance cannot be estimated). Two estimates of grid emigration were produced. The first estimate is a simple empirical estimate by counting the number of lobsters that left the grid after tagging within 12 (the first night after tagging) and 36 hours (the second night after tagging) divided by the total number of tagged lobsters. The second estimate is produced by taking the number of grid leaving events from all the lobsters and dividing that by the total number of days tagged lobsters remained on the grid. The sonic receivers were designated as inside or edge receivers. Edge receivers were those receivers around the perimeter of the grid. A grid emigration event was defined as any lobster who has moved to such a position for more than 48 hours where only edge receivers "hear" it or when edge receivers are the last receivers to "hear" a signal from a lobster that disappears. The position estimates of each lobster were also analyzed using Tracker Analyst (an Arc View extension) to confirm grid emigration. The probability of this type of movement is equal to the number of emigration events divided by the total number successful tracking days.

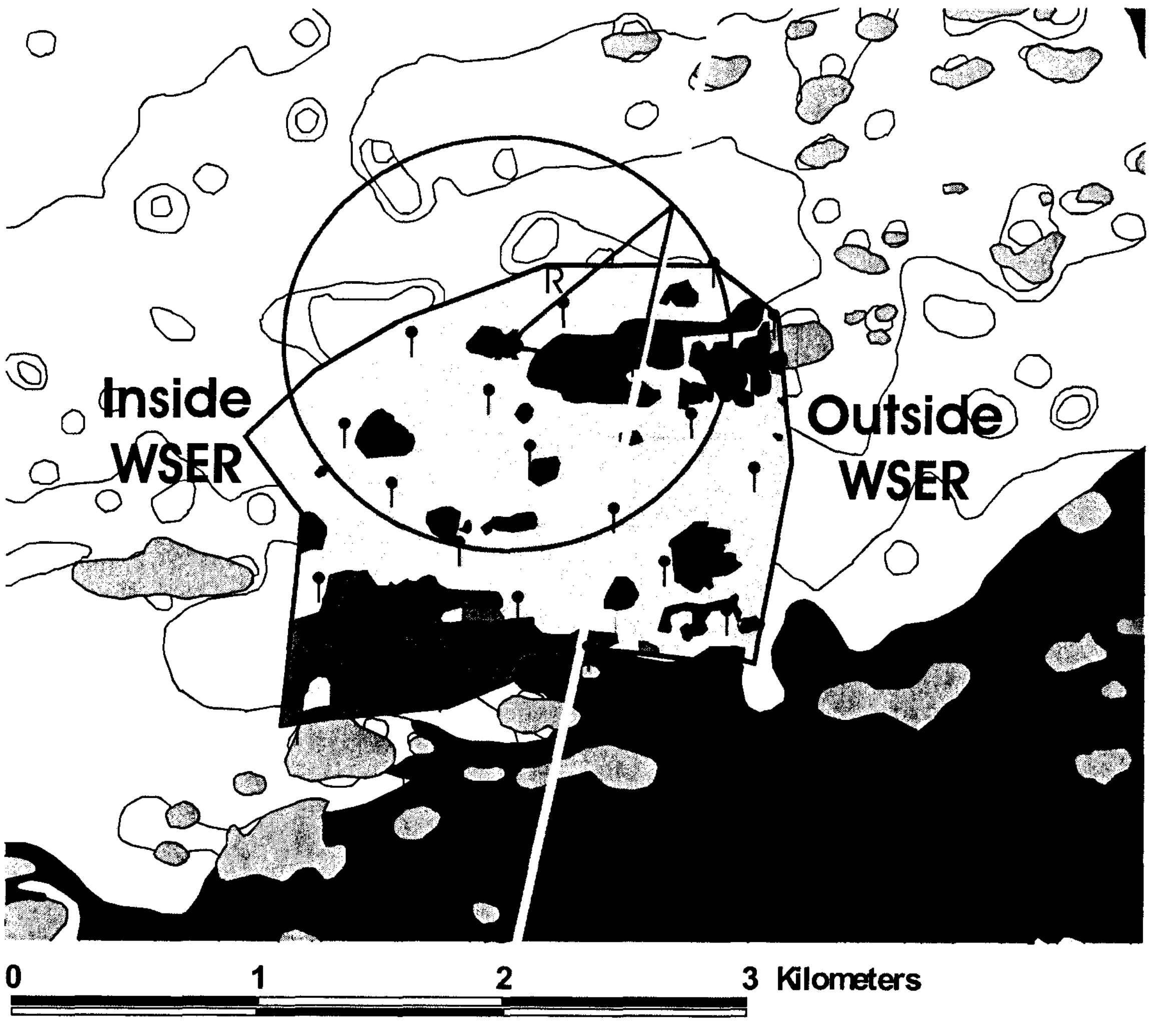
The likelihood of missed lobsters is determined by one minus the sum of the probability of a lobster moving a distance greater than the average inter-patch distance plus the probability of grid emigration.

Complete dive surveys with tag-recapture were performed on eighteen patch reefs.

Spillover estimates

A crude estimate of the probability of a given lobster crossing the WSER boundary is equal to the probability of a net daily movement exceeding the distance from a given patch reef to the WSER boundary and the net movement needs to be in a direction that would move a given lobster across the boundary. A simple monte carlo computer program was created using the actual mapped distances of patch reefs to the boundary, the average abundances of lobsters inside and outside the WSER, and the net daily movement probability curve. In the program, an average number of lobsters "populates" each patch reef, then a net daily movement figure is picked randomly from the net daily movement curve. If the amount of movement selected does not exceed the distance from the patch reef to the WSER boundary then a spillover counter is scored as zero. If the movement exceeds the distance from the patch reef to the WSER boundary then a probability of spillover is calculated. The distance traveled (R) divided by the distance to the patch reef (D) is equal to the cosine of an angle that describes half of the probability of spillover (Figure 6).

Figure 6. The probability of spillover for each monte carlo event is estimated by dividing the distance from the patch reef to the WSER boundary (D) by the expected distance (R) of travel by a "lobster" in some random direction in the simulation program. This ratio (D/R) equals the cosine of the angle shown in this right triangle. That angle multiplied by two and divided by 360 (degrees in a full circle) is the estimated probability of spillover for any given event in the simulation.



A second random number is selected to determine if the simulated lobster has crossed the WSER boundary. If the number selected is within the portion of the angle described in Figure 6, then spillover has occurred. The program keeps a tally for each "lobster" on each "patch reef". Because by chance, the distances of patch reefs we mapped within the WSER are generally further from the WSER boundary, than the distance of patch reefs we mapped outside the WSER, this would create a bias that might not exist if a complete habitat map were available. We therefore ran the simulation assuming an equal number of patch reefs and distances both inside and outside the WSER. This assumption "forces" the ratio of the number of lobsters leaving the WSER to the number of lobsters entering the WSER to be equal to the ratio of observed abundances (i.e., three lobsters leaving to one lobster entering), however, the simulation will provide a first estimate of the number of lobsters crossing the WSER boundary. Once a good habitat map is completed, a better spatially explicit simulation will be created. This initial monte carlo simulation was run 100 times using the same initial conditions (i.e., each patch reef inside the WSER is populated with the mean number of lobsters found during our population surveys).

Results:

Sonic data overview

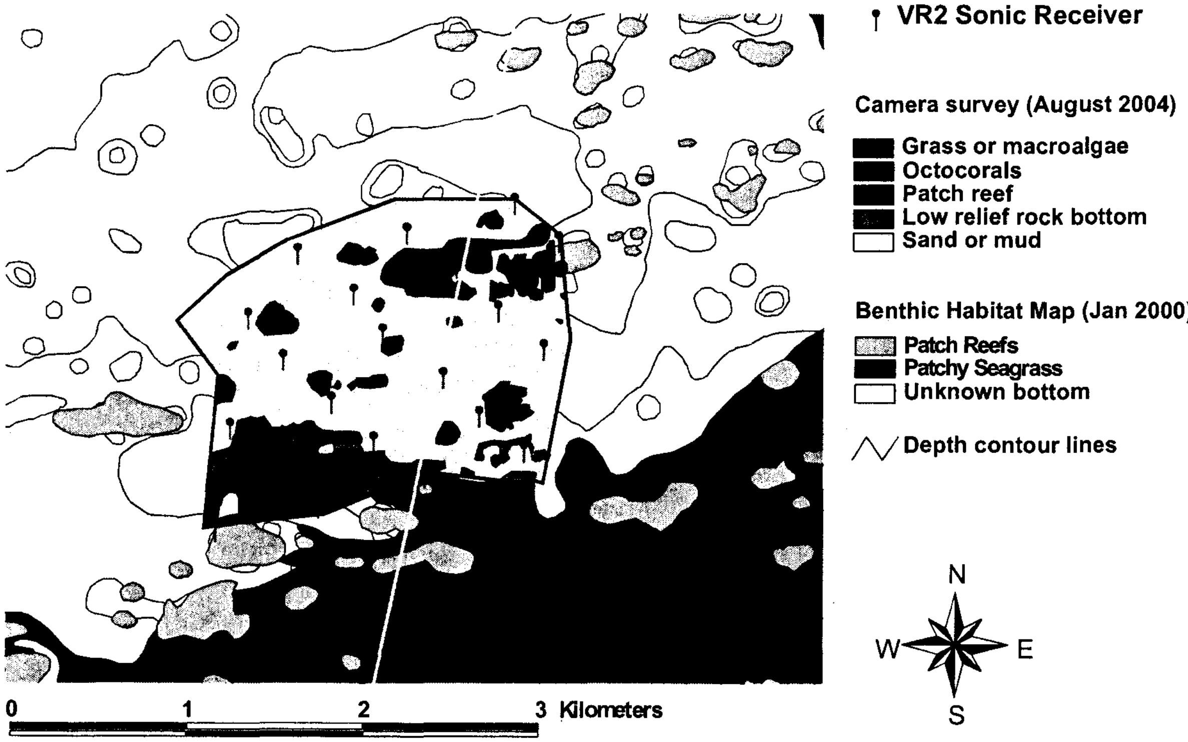
In total, the twenty-five sonic receivers recorded 324,703 pings during their fifty-five-day deployment. Of the total number of pings recorded, 252,163 pings (77.7%) came from our thirty-nine tagged lobsters, 72,219 pings (22.2%) came from our tagged fish, and 321 pings (0.1%) came from either transient fish from other sonic studies in south Florida or were erroneous records caused by multiple tag interference or other noise. Of the thirty-nine sonic tagged lobsters, only one tag failed to provide useable results. By the final week of the project, fifty-two days after deploying the first tags, twenty-five tags were still within range of the sonic receivers. Three tags "disappeared" within the grid of sonic receivers approximately a month after deployment (Table 1). The disappearing could have been due to a lobster molting

Of the thirty-nine tagged lobsters, twenty-one were males in sizes ranging from 66 mm to 134 mm carapace length. The sizes of the eighteen tagged females lobsters ranged from 68 mm to 104 mm carapace length. Fourteen of the eighteen females carried eggs at the time of the tagging.

Habitat mapping

We made more than 6,500 habitat classifications within the VR2 sonic receiver grid using the towed camera during two days in late August. Water clarity never improved enough to use aerial photography techniques and the camera had to be towed within a meter of the bottom. The total area covered with the camera was approximately 3.1 km^2 (an area equivalent to 10% of the entire WSER). A small number of habitat classifications across the center of the grid were lost due to a computer malfunction. The habitat in this area was extrapolated from surrounding observations. The predominant habitat type was sand/mud (2.2 million m^2/70%) followed by sea grass (660 thousand m^2/21%), octocorals (160 thousand m^2/5%), patch reefs (91 thousand m^2/3%) and low relief hardbottom (14 thousand m^2/>1%) (Figure 7). Because the water clarity was poor, sand could not be distinguished from mud, however, experience from our dives suggests that mud predominates to the north and sand to the south of the grid. Low relief hardbottom is probably underestimated because it may be covered by octocorals and/or covered in silt.

Figure 7. The habitat map as produced from the underwater towed camera (August 2004). Because of poor water clarity, much of the habitat described from an earlier large scale mapping project (January 2000) was unknown.

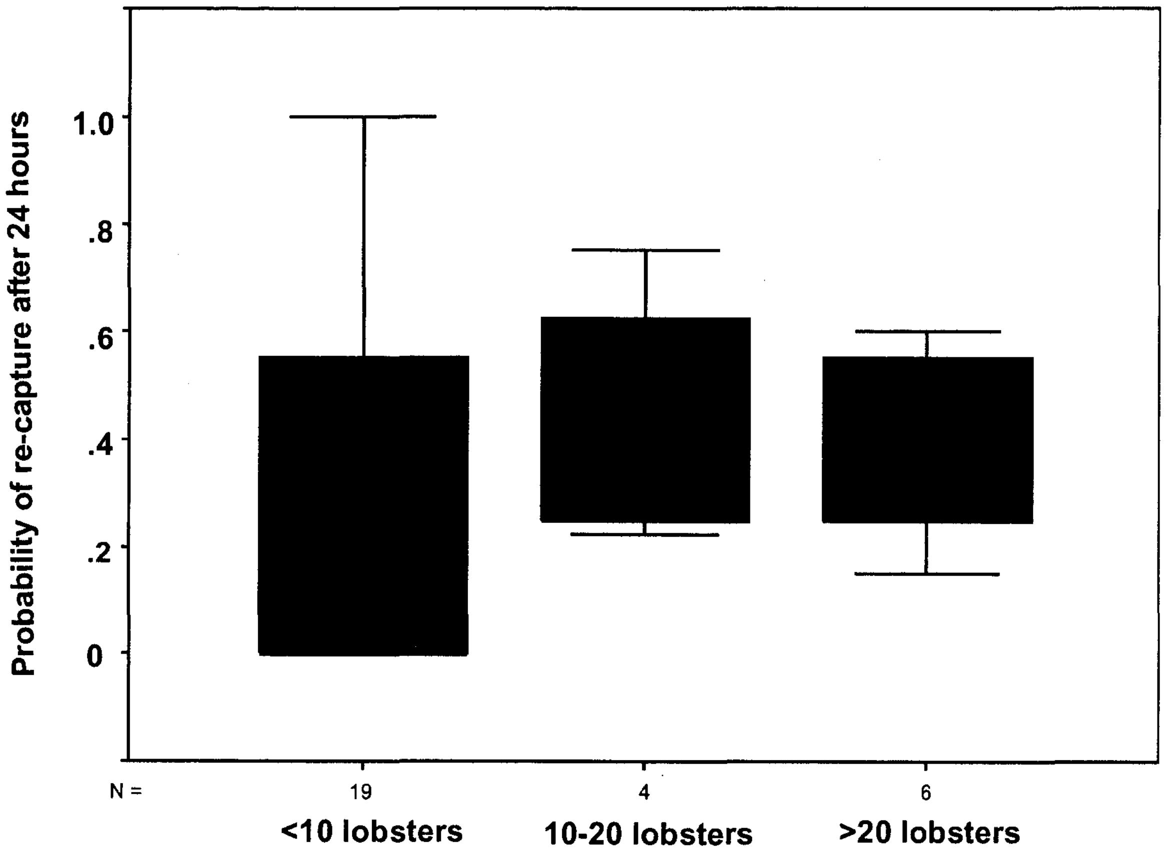


Lobster abundance

The overall mean number of lobsters found on patch reefs was 10.2 lobsters. The mean number of lobsters found on patch reefs inside WSER was 14.6 (ranging from zero to 56). The mean number of lobsters found on patch reefs outside WSER was 4.7 (ranging from zero to 25).

Overall recapture rates were less than forty percent, however, on patch reefs with few lobsters (<10), recapture rates were much lower and the median recapture percentage was 0%. Sites with 10 to 20 lobsters and more than 20 lobsters had a consistent mean recapture percentage of 42% (Figure 8).

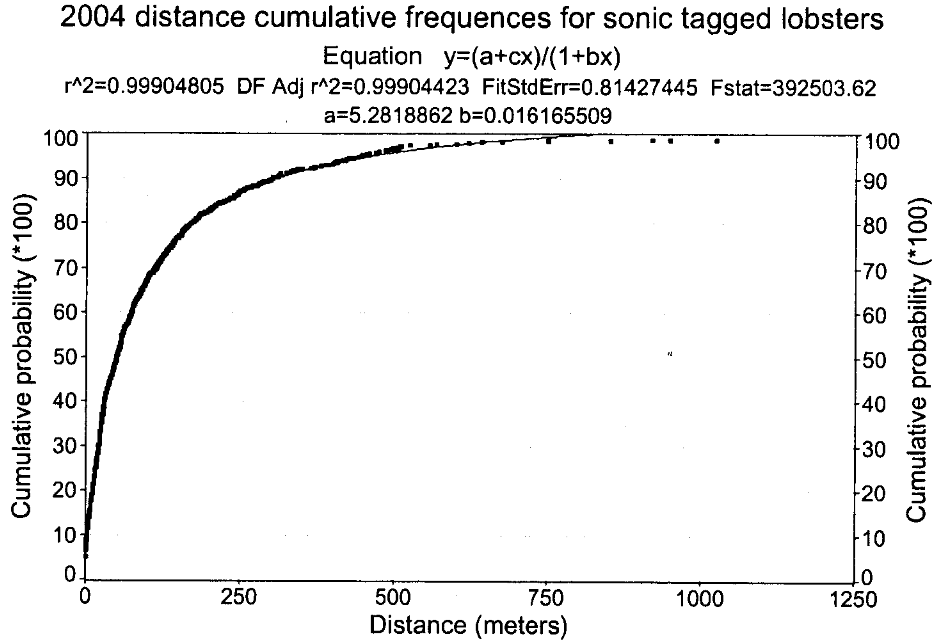
Figure 8. Probabilities of re-capturing a tagged lobster after 24 hours by abundance of lobsters on patch reefs. For cases where less than 10 lobsters were found, the median probability of re-capture was 0%. Otherwise, the probability of re-capture was approximately 42%.



From the sonic data, daytime shifts in positions of lobsters were fitted into a cumulative frequency curve (Figure 9). The equations can then be used to determine the probability of a lobster to exceed the mean inter-patch reef distance (and presumably emigrate from a typical patch reef) on a daily basis. The cumulative frequency of a lobster shifting its daytime position in meters is expressed by the equation where frequency = (5.2818862 + 1.7316522 * distance) / (1 + 0.016165509 * distance) for the 2004 sonic project and where frequency = (2.801193 + 0.67377693 * distance) / (1 + 0.0047436308 * distance) for the 2003 pilot sonic project.

The mean distance between patch reef centers and patch reef edges are 186 meters and 124 meters respectively. The estimated cumulative probability for daily shifts in lobster positions up to 186 m (center to center) and 124 m (edge to edge) is 82% and 73% from the 2004 equation or 68% and 54% using the 2003 equation. This suggests that between 18 and 46 percent of lobsters on any given patch reef emigrate from that patch reef every twenty-four hours and can still be detected on the sonic grid. To estimate the probability of lobsters emigrating completely off the grid, empirically we found that two lobsters departed within 12 hours (the first night) and two more within 36 hours (the second night) out of 38 lobsters tagged. This empirical method estimates a 5% at 12 hours to 11% at 36 hours, or an 8% average emigration rate from the grid. Focusing on emigration events (defined in methods), there were twenty-nine identifiable events where a lobster walked off the sonic grid out of 964 total tracking days for all tagged lobsters. This method estimates a 3% grid emigration rate.

Figure 9. The cumulative frequency of net daily movement of lobsters within the sonic receiver grid.



The range of estimates of daily emigration will vary greatly if one selects only the greatest or only the smallest of these estimators. The "middle of the road" estimate for daily emigration is 32% of the lobsters when the lobsters remain detectable within the sonic grid plus 5% emigration from the grid when lobsters leave the grid entirely, or a 37% total daily average emigration rate from patch reefs. These results therefore suggest that on a typical patch reef lobster population search under relatively poor water clarity conditions, approximately 21% of the lobsters were not visible or were not seen by divers. Over the three-day successive searches of patch reefs inside WSER we found an average of 146 lobsters. Adjusting this count for the probability of missed lobsters, we estimate 177 lobsters were present. The area covered by our surveys amounted to approximating 10% of the entire Hawk Channel portion of WSER. If these patch reefs constitute an unbiased sampling of the entire WSER, then the total patch reef population of WSER is 1,770 sub-adult and adult (i.e.; more than 65 mm CL) lobsters.

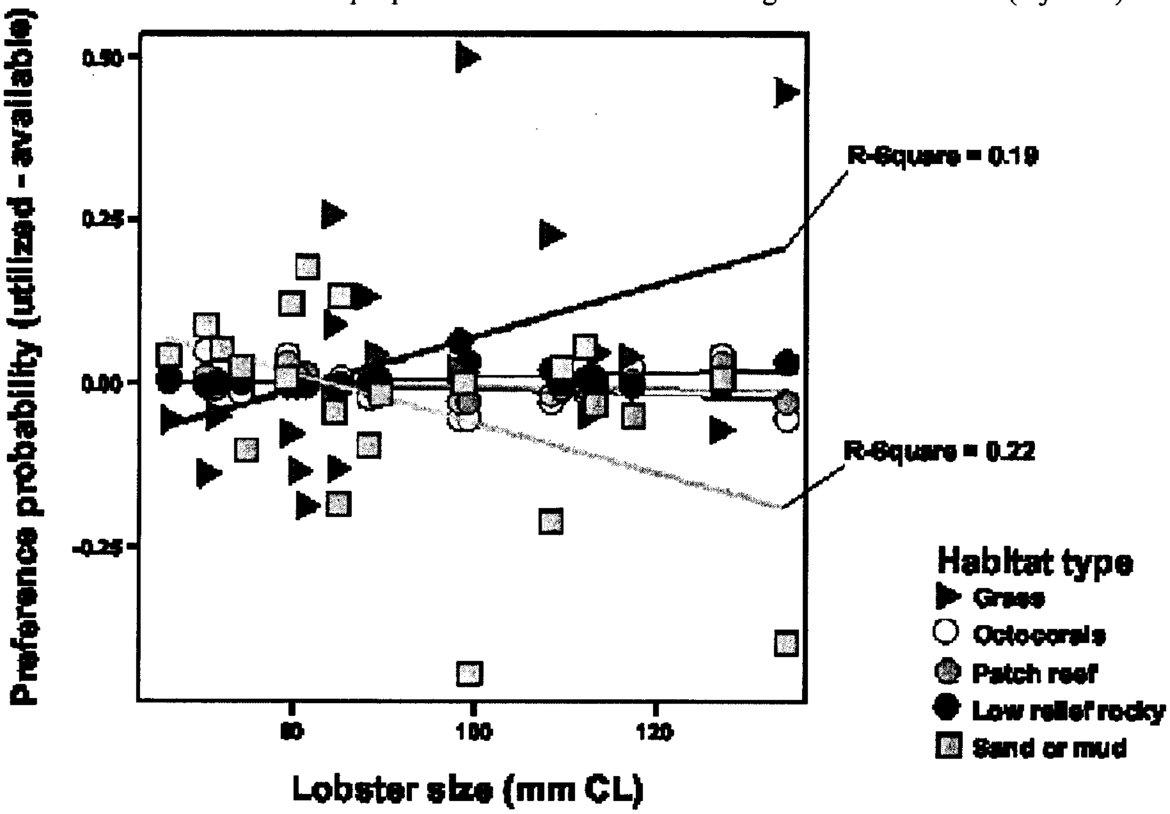
Adjusted for missed lobsters, we estimate that the typical patch reef within WSER contains 17.7 lobsters and 5.7 lobsters on patch reefs in the fishery to the immediate east (within one km) of the WSER. On a per patch reef basis, we estimate that lobsters are three times more abundant inside WSER than outside WSER.

Home ranges and habitat utilization

Estimates of home ranges (using the minimum convex polygon) of lobsters that remained within the grid for an extended period of time (one month or greater) ranged from 89 thousand square meters to nearly one million square meters (one km^2). Davis (1974) and Bertelsen et al. (2004) found circumstantial evidence that as male lobsters grow larger, movement decreases. Although size of lobster and home range were not significantly inversely correlated in this study, the smallest tagged lobster (66 mm CL) had the third largest home range (nearly 900 thousand square meters) and the largest tagged lobster (134 mm CL) had the second smallest home range (approx. 146 thousand square meters) (Table 2).

As a population, the sonic tagged lobsters utilized the various habitats within the grid in approximately the same proportion as available (Table 2). For example, approximately 22% of the area of the grid contained grass beds and the average proportion of all the home ranges within grass beds was 26%. Individual lobsters, however, varied greatly ranging from a minimum of 3% grass utilization to 71% grass utilization. Although the trends were not statistically significant, there was a mild trend where large lobsters utilize grass beds in a higher proportion than small lobsters (Figure 10).

Figure 10. Habitat preference indices by size of lobster. The index is calculated from the proportion of a given habitat in a given lobster's home range (utilized) minus the proportion of that given habitat in the region (available). An index above 0 indicates the habitat makes up a greater proportion of a lobsters home range than is available (preferred). An index below 0 indicates a smaller proportion of a lobsters home range than is available (rejected).

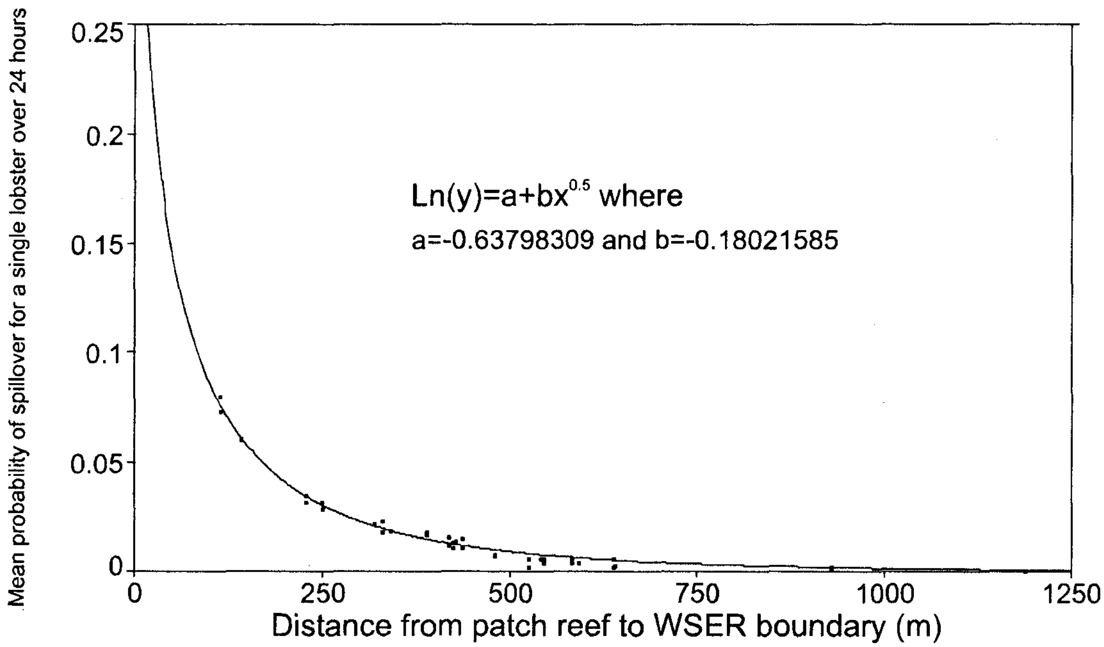


Spillover estimate

Spillover of sonic tagged lobsters into the fishery actually occurred. Two sonic tagged lobsters were captured by commercial trap fishers in August. This observation was a surprise because we did not expect lobsters to retain tags into August as we always observe a high incidence of molting of adult lobsters following the reproductive season, nevertheless, spillover from the WSER to the fishery is a fact.

To estimate a rate of spillover, we developed a monte carlo computer simulation designed to calculate the daily probability of a lobster crossing the WSER boundary using equations derived from the sonic data (see methods). The probability of spillover for a given lobster is proportional to an inverse square root function of the distance between the patch reef and the boundary (Figure 11).

Figure 11. The probability of spillover of a lobster over a 24 hour period from a given distance from the boundary of WSER. Points on the graph are results from a monte carlo simulation that uses 24 hour net movement of lobsters and the distance of a patch reef to the WSER border as measured in an Arc View cover produced from the underwater camera data.



The simulation predicts for example, a lobster on a patch reef 250 meters from the WSER boundary has a three percent chance of moving to the opposite side of the boundary in 24 hours. The output from the monte carlo simulation also predicts the daily spillover for the study area. Because the patch reefs in the study area that were outside WSER tended to be closer to the boundary than those patch reefs inside WSER a bias would be present in the simulation that overestimates the probabilities of lobsters entering WSER over those leaving WSER. This bias is not likely representative of the entire WSER. For the simulation we therefore assumed the same distribution and distances for patch reefs both inside and outside WSER by combining patch reef information on both sides of the boundary then applying lobster abundance data from inside WSER for the estimate of lobsters leaving WSER, then applying the same assumptions for outside WSER. Once a complete habitat map for WSER is completed, we will rerun this simulation using the better and more spatially explicit data. Given those assumptions, the simulation predicts that 6.9 lobsters out of a total of 414 lobsters on 24 patch reefs leave WSER daily into the fishery across a 3.2 km section of the eastern boundary. The simulation also predicts that 2.4 lobsters out of a total of 138 lobsters enter WSER from an equivalent sized area outside the boundary. The net export of lobsters across this 3.2 km section is estimated at 4.5 lobsters daily. If this estimate is representative of all WSER, then the net daily export from the Hawk Channel portion of WSER is 14 lobsters during the summer months (4.5 lobsters * 10km of Hawk Channel east and west boundaries / 3.2km boundary of the simulation). This estimate will be refined as better data are collected regarding location of all the patch reefs in and around WSER and as further post processing techniques are developed and tested on the sonic tag data (see discussion below).

Movements between the grid and fore-reef

In the 2003 pilot study, we observed on several occasions that the estimated positions of sonic tagged female lobsters would suddenly and swiftly shift toward the south and off the grid during the middle of the night. The estimated velocities by these female lobsters (approximately 300 to 400 m per hour) were among the highest observed in the pilot study (one large more than 120 mm CL male occasionally equaled this velocity). In the case of one female, she returned to the grid and the same patch reef one week after the initial departure. This female then made the same maneuver three weeks later and again returned to the same patch reef one week after the second departure. Two of the other five females tagged in the pilot study speed toward the south at night, however, we never heard those tags again. This behavior has been interpreted as a migration to the fore-reef or beyond in order to release eggs. In this study we placed four sonic receivers, 500 meters apart just to the north of the WSER fore-reef. The distance from the fore-reef to the center of the grid is approximately three kilometers. The rational for this placement was to document and time any tagged lobsters leaving the grid and reaching the fore-reef.

We tagged 17 female lobsters that were reproductively active (with eggs, ripe ovaries, or both) at the time they were tagged. One tag failed immediately and a second tag left the grid to the east and it fate is unknown. Seven female lobsters were detected by the fore-reef receivers. Three more tagged females made nighttime moves toward the south but were not detected by the receivers at the fore-reef. Three females did not leave the grid and therefore presumably released their eggs in Hawk Channel. The remaining reproductively active lobsters exited the grid without making a sudden southward move within the grid. Because we cannot determine whether they turned south after leaving the grid, we cannot determine whether they may have spawned on the fore-reef or Hawk Channel.

In the 2003 pilot study, three reproductively active female lobsters migrated to the reef front during either new moon or full moon nights. This observation led to speculation that migration to the fore-reef was somehow linked to moon phase. The 2004 larger study, however, disproved the apparent linkage between spawning behavior and lunar phase. Female lobsters migrated to the fore-reef during any moon phase.

None of the sonic tagged male lobsters were detected by sonic receivers on the fore-reef. However, in the 2003 pilot study we did observe one male that seemed to "follow" a female toward the south at night, matching course and speed but lagging approximately 200 meters behind. This apparent coordinated movement pattern between a male and female lobster has not been found in the 2004 data.

Discussion:

Spillover (earlier studies)

The Western Sambo Ecological Reserve spiny lobster population has been monitored in various ways since its inception in 1997. Diver-based surveys have been performed in the region since 1996 (Bertelsen and Cox, 2001; Cox and Sharp, 2002). These surveys have typically been conducted on fore-reef, back reef, and patch reef locations both inside and outside the reserve during the spring, summer, or fall but with an emphasis on summer sampling over time. Surveys have been conducted on a catch per unit basis with a one hour search time as the basic currency for the survey. With respect to spillover, these surveys have provided some circumstantial evidence mainly with respect to analysis of size distributions (see Bertelsen et al., 2004) and this yielded a qualitative expression of spillover (primarily by looking at the increase of spatial distribution of large males over time).

A more direct approach to spillover was attempted with two projects that contained lobster antenna tagging and lobster trap components, the first being the "Sentinel Lobster Fisheries Project" (Gregory, 2001) and then the "COP" (Cox and Sharp, 2002). By tagging a large number of lobsters with antenna tags on both sides of the WSER boundary, and by placing lines of traps on both sides of the boundary, an estimate of relative spillover might be determined. The "Sentinel" project results were inconclusive largely due to low tag returns (Gregory, 2001) perhaps due to the low number of traps used. The "COP" project used a similar tagging and trap approach but this project was more focused on spillover as traps were concentrated on the WSER boundary and there was more antenna tagging. Final analyses are pending.

The sonic tagging approach has several important advantages over more traditional tag recapture methods. One advantage is that spatial information is obtained continuously, rather than at two points in time, release and capture. Another is that information can be reliably obtained from a high percentage of sonic tags whereas recapture techniques require physically finding tagged individuals.

The spatial information obtained through VR2 sonic receivers placed in a grid, need to be analyzed with caution. The sonic receiver has an omnidirectional hydro phone and these receivers were not designed for positioning estimation. In order for somewhat reliable positional information to be obtained, overlap in the detection range is required. In additional, we post process the sonic data to better align the clock speeds across all the receivers to insure that the pings from the tags are correctly collated (see methods). In the pilot study in 2003, we placed receivers 200m apart and from earlier tests determined that sonic tags could be detected from as much as 600m under good conditions (no obstructions). Fortuitously in 2003, during tests of a towed directional hydro phone system, we suspected that one sonic tagged lobster entered a trap because the hydro phones indicated a lobster around a trap with no patch reef nearby. Two days later, that trap was pulled and it contained a sonic tagged lobster. By analyzing the sonic data after the pilot study ended, we determined that the calculated position of the lobster (using one hour centroids weighted by the number of pings on the receivers - see methods) never changed by more than approximately 10 meters once it entered the trap. When lobsters enter a patch reef, however, the precision of estimated positions must certainly degrade. We do not have any information analogous to the lobster in a trap for rocky and patch reef habitats to offer any statement regarding the confidence of those estimated positions. Further analysis of the estimated daytime positions (when lobsters are most likely to enter rocky or a patch reef habitat) are beyond the scope of this report but will be investigated.

Perhaps the most difficult phase of this project was habitat mapping. The turbidity of the deeper waters (>5m) remained high throughout the spring and summer of 2004. Very strong east winds through most of the spring drove turbid waters from Florida Bay into the length of Hawk Channel from the middle to lower Keys. The best visibility came following the passage of Hurricane Charley to our west in August. The wind circulation around Charley forced offshore waters into Hawk Channel but visibility on the deeper sand and silt bottoms did not improve. Nevertheless, the habitat map we produced using a towed underwater camera agreed well with the small portions of habitat mapped during the FKNMS Zone Monitoring Program (FMRI, 2000) (Figure 7) which used aerial photographs. The primary difference between the underwater camera method and aerial photography is that the underwater camera can differentiate between deeper low rocky habitat, patch reef, and the octocoral "forests" that typically form a halo around patch reefs. These three habitats have been lumped as patch reef in earlier work. On the other hand, aerial photography has a greater potential to produce an accurate habitat map because the underwater camera is limited to relatively narrow transects. But for that potential to be realized, water clarity needs to improve dramatically. Barring such an improvement, side scan sonar may be able to produce a quality habitat map.

Future goals

These data were only completed and assembled in early September (after the habitat mapping cruise was completed between hurricanes). These data are very rich in information and this report represents only the start of the possible analyses. There are other data sets that can be added that will permit further analyses. For example, I've recently attached sun and lunar data (rise and set and moon phase) and have just begun comparing and contrasting lobster movement patterns with astronomical data. Weather observations and tidal information will be added soon. The computer model used to estimate spillover in this report can be enhanced once better habitat information becomes available. Spatially explicit modeling of movement will be possible only after more patch reef location and dimensions are known.

Regarding future sonic tag-based studies, there are several possible directions to go in which to evaluate marine reserves. One direction is a multi-species approach, where spatial partitioning or sharing of habitat can be evaluated. We have completed a very small sonic based pilot study on red and gag grouper. Preliminary results suggest comparatively high site fidelity for red grouper and widely varying home range sizes for gag grouper. Another direction would be to evaluate spiny lobster migration between Hawk Channel and the fore-reef. This study suggests that there is a large exchange of female lobsters between the two regions. A high percentage of the adult female lobsters that reside in the patch reefs of Hawk Channel migrate to the fore-reef to spawn. What are the spatial dynamics between lobsters that temporarily live along the fore-reef with those that may permanently live on the fore-reef? Still another direction would be to investigate very large scale movement patterns of lobsters by placing receivers long distances apart where lobsters are likely to seek daytime shelter. The 2003 pilot study, this study suggests, and earlier traditional tagging studies indicate this type of movement regularly occurs but little is known about the frequency, scale, and types of lobsters (i.e.,size and sex) that might be more likely to make large scale moves.

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Table 1. Summary of sonic tagged lobster's gender (M = male, F = female), reproductive status (e = eggs, Brown, Orange, None; o = ovaries, Ripe, Not ripe; s = spermatophore, Fresh, Eroded, FE = fresh over eroded, None), size (carapace length mm), days of sonic detection by the total number of possible days, number of estimated positions, sanctuary boundary departures, net and total detectable movement, and the fate of each tag.

Tag	Sex (e/o/s)	Size (mm)	Detected/ Tot(days)	position estimates	Area	(Departure /Entries)	Net (m)	Total (km)	Fate
1029	M	88	27/52	448	O	(1/2)	?	6	Disappeared within grid
1035	M	81	29/52	2,332	I	(10/10)	?	17	Disappeared within grid
1044	M	112	52/52	3,493	I	(13/13)	N 900	52	On grid
1047	M	84	42/42	26,764	I	(0/0)	0	37	On grid
1048	M	108	42/42	8,327	I	(1/1)	NW 300	72	On grid
1049	M	109	42/42	3,358	I	(0/0)	N 600	107	On grid
1050	F (O/R/E)	80	27/42	3,646	I	(1/0)	E <1,200	22	Left the grid to the east near the end of the project[1]
1051	F (O/R/E)	94	39/52	10,194	I	(4/4)	0	69	On grid[2]
1052	F (N/R/E)	70	42/42	6,228	O	(15/15)	0	126	On grid
1053	F (B/N/E)	71	1/42	1	I	(?/?)	?	?	tag lost immediately[3]
1054	F (O/R/FE)	105	33/42	9,256	I	(0/0)	SW 300	51	On grid[4]
1055	F (B/R/FE)	80	4/42[5]	317	O	(1/1)	?	3	made one trip to the reef on 7/15 then the tag was lost
1056	M	80	6/52	1,623	I	(0/0)	SW 1,600	13	Left the grid to the SW after five days
1057	F (O/N/N)	71	26/52	1,964	O	(7/7)	S 1,200	20	Left the grid to the SE after one month[6]
1058	M	117	35/52	5,317	I	(0/0)	W 200	37	On grid[7]
1060	M	98	52/52	17,601	I	(0/0)	NW 300	58	On grid
1061	F (O/R/FE)	101	26/52	2,720	I	(0/0)	0	23	On grid[8]
1062	F (O/R/E)	74	42/42	4,943	I	(0/0)	0	113	On grid
1063	M	80	23/52	771	I	(0/0)	0	17	On grid

1064	F(N/R/F)	104	18/42	3,298	I	(0/0)	?	35	Disappeared at fore reef[9]

(Table 1 cont.)

1065	M	66	47/52	14,189	O	(21/22)	W 300	91	On grid
1066	F (O/N/N)	72	2/52	511	O	(0/0)	S 800	5	Left grid to S on day 2
1067	M	127	42/52	1,795	O	(4/4)	S <1,500	54	Left the grid 7/13[10]
1068	F (O/N/E)	75	13/52	2,767	O	(5/5)	S 1,500	32	Left grid to S on 6/19
1069	M	79	51/52	21,774	O	(13/13)	NE 250	143	On grid
1070	F (N/R/FE)	81	2/52	181	I	(0/0)	SE 600	2	Left grid to SE on day 2
1071	M	134	19/52	5,888	I	(0/0)	?	6	Tag disappeared in the grid
1072	F (O/R/FE)	77	3/52	181	I	(0/0)	?	8	Left grid to SE on day 2[11]
1073	M	110	8/52	1,029	I	(0/0)	W <600	12	Left grid to W on 6/12, returned briefly on 7/7
1074	M	84	39/52	17,992	I	(0/0)	0	91	On grid, lost tag on 7/15
1075	M	113	35/42	6,841	I	(0/0)	0	53	Disappeared in grid on 7/20
1076	M	116	42/42	4,882	I	(0/0)	SW 600	97	Move to edge or outside grid on 7/15.
1077	F (N/N/N)	88	44/52	2,432	I	(0/0)	?	38	Left grid to E by jun 20[12]
1078	M	83	46/51	1,465	O	(4/4)	E <500	33	Left grid to E on 6/21
1080	F (O/R/FE)	76	2/52	165	I	(0/0)	W <600	1	Left grid to W on day 2
1081	F (O/N/U)	68	45/52	6,372	I	(1/1)	S <700	41	Left grid to S on 7/23[13]
1082	M	85	47/52	12,153	I	(0/0)	NW 600	108	On grid
1083	F (B/R/FE)	99	46/52	18,041	I	(0/0)	N 100	50	On grid[14]
1084	M	89	40/52	19,758	I	(0/0)	NE 500	106	On grid[15]

[1]Made one detected trip to the fore reef from 6/21 to 6/29 (full moon).
[2]Made one detected trip to the fore reef on 6/6 (between full and last quarter).
[3]Most likely scenarios for loss of signal are that the tag fell of the lobster into a hole or we tagged this female with brown eggs while she was transiting to the fore reef and she returned to her home patch reef area which was an area outside our sonic receiver grid.

[4]Made two detected trips to the fore reef, the first on 6/22 (between full and last quarter); the second on 7/15 (between last quarter and new)

(Table 1 cont.)
[5]This tag probably came off the lobster at some time on or after 7/15 as this tag continued to ping the same fore reef receiver to the end of the project
[6]This female may have ventured to the fore reef approximately 6/12 returning about three days later.
[7]Tag probably dropped on June 24th.
[8]Made two detected trips to fore reef, the first on 6/28 (near full moon) and the second on 7/23 (near first quarter).
[9]This female arrived on the fore reef on 7/12 and likely lost her tag near the fore reef shortly after 7/12.
[10]This male, tagged in the northern part of the grid was only "heard" by the south-east most sonic receiver occasionally by the last two weeks of the project. This male likely established a new home range south and/or east of the grid by the end of the project.
[11]This female may have been en-route to the fore reef when we tagged her. She left the grid to the south east by the following day then we detected her tag at the fore reef. A month later, we detected her tag again at the fore reef. This second arrival could have signaled a second clutch. Her primary Hawk Channel patch reef was likely outside our grid.
[12]This female was tagged near the western edge of the grid. By 6/20, this lobster was only "heard" by the westernmost receivers. We may have tagged her by chance on the eastern-most part of her home range.
[13]There are two "gaps" in the sonic record of this female. She left the grid to the south on 6/16 and returned by 6/22. The second gap appears from 7/9 to 7/13. None of the fore reef sonic receivers picked up her tag. The gaps most likely represent egg bearing trips to the fore reef to the south. If true, then she spawned outside the Ecological Reserve.
[14]Tag probably fell of on 7/16 when "movement" of the tag stopped
[15]Tag probably fell off on 7/15 when "movement" of the tag stopped

Table 2. Size of home range and habitat utilization of lobsters and the amount of habitat available in the grid. Only lobsters remaining on the grid through most of the project are included in this table. The relatively small number of female lobsters is due the large percentage that migrated to the fore reef to spawn.

Tag#	Sex	Size	Home Range (m^2)	Grass	Octo-corals	Patch reef	Rock	Sand/ Mud
1060	M	98	88,557	23.2%	0.0%	0.0%	6.7%	70.1%
1071	M	134	145,691	66.1%	0.0%	0.0%	3.7%	30.2%
1047	M	84	176,785	47.0%	1.6%	0.0%	0.0%	51.4%
1058	M	117	185,376	24.4%	7.6%	3.4%	0.0%	64.6%
1063	M	80	202,114	8.3%	5.7%	3.8%	0.0%	82.2%
1083	F	99	263,257	71.2%	0.0%	0.0%	3.7%	25.1%
1052	F	70	292,155	7.6%	10.1%	3.8%	0.0%	78.5%
1074	M	84	441,100	30.7%	2.5%	1.2%	0.0%	65.6%
1029	M	88	447,227	34.1%	3.0%	3.0%	0.0%	59.9%
1048	M	108	469,077	44.5%	2.5%	1.2%	2.4%	49.3%
1082	M	85	516,600	8.8%	6.0%	2.8%	0.0%	82.4%
1075	M	113	679,170	26.2%	3.2%	2.3%	1.3%	67.1%
1069	M	79	715,847	14.3%	9.4%	6.0%	0.0%	70.3%
1067	M	127	715,847	14.3%	9.4%	6.0%	0.0%	70.3%
1049	M	109	762,151	21.5%	4.3%	2.1%	0.6%	71.5%
1057	F	71	781,756	16.2%	5.7%	2.2%	0.6%	75.3%
1062	F	74	795,738	21.0%	4.0%	3.0%	0.7%	71.3%
1044	M	112	877,674	17.4%	3.9%	2.3%	1.3%	75.0%
1065	M	66	886,325	16.3%	5.4%	3.2%	1.2%	73.9%
1035	M	81	924,301	3.0%	5.8%	4.3%	0.1%	86.8%
1084	M	89	998,156	24.2%	3.3%	2.5%	1.1%	68.9%
		means	541,186	25.7%	4.4%	2.5%	1.1%	66.2%
		Total habitat available	3,091,616	664,216	162,026	91,084	13,906	2,160,385
				21.5%	5.2%	2.9%	0.4%	69.9%