A video method for quantifying size distribution, density, and three-dimensional spatial structure of reef fish spawning aggregations

Peter S. Rand
The Wild Salmon Center
The Natural Capital Center
721 NW 9th Avenue, Suite 280
Portland, OR 97209
E-mail address: prand@wildsalmoncenter.org

J. Christopher Taylor
Center for Marine Science and Technology
North Carolina State University
303 College Circle
Morehead City, NC 28557

David B. Eggleston
Department of Marine, Earth, and Atmospheric Sciences
North Carolina State University
Jordan Hall
Raleigh, NC 27695

Abstract—There is a clear need to develop fisheries independent methods to quantify individual sizes, density, and three dimensional characteristics of reef fish spawning aggregations for use in population assessments and to provide critical baseline data on reproductive life history of exploited populations. We designed, constructed, calibrated, and applied an underwater stereo-video system to estimate individual sizes and three dimensional (3D) positions of Nassau grouper (*Epinephelus striatus*) at a spawning aggregation site located on a reef promontory on the western edge of Little Cayman Island, Cayman Islands, BWI, on 23 January 2003. The system consists of two free-running camcorders mounted on a meter-long bar and supported by a SCUBA diver. Paired video "stills" were captured, and nose and tail of individual fish observed in the field of view of both cameras were digitized using image analysis software. Conversion of these two dimensional screen coordinates to 3D coordinates was achieved through a matrix inversion algorithm and calibration data. Our estimate of mean total length (58.5 cm, n = 29) was in close agreement with estimated lengths from a hydroacoustic survey and from direct measures of fish size using visual census techniques. We discovered a possible bias in length measures using the video method, most likely arising from some fish orientations that were not perpendicular with respect to the optical axis of the camera system. We observed 40 individuals occupying a volume of 33.3 m^3, resulting in a concentration of 1.2 individuals m^{-3} with a mean (SD) nearest neighbor distance of 70.0 (29.7) cm. We promote the use of roving diver stereo-videography as a method to assess the size distribution, density, and 3D spatial structure of fish spawning aggregations.

Introduction

There has been growing interest in measuring individual sizes of fishes at liberty and capturing three dimensional (3D) attributes of fish schools or aggregations in situ (Parrish and Hamner, 1997), particularly on exploited populations that have not been assessed using fisheries independent methods. There is a relatively long history of using ship-mounted sonar for quantifying attributes of fish schools and, with the recent introduction of split- and multi-beam echosounders, we have improved our capabilities of resolving bathymetry and water column targets in 3D (Simmonds and MacLennan, 1996; MacLennan, 2003). These methods suffer, however, from a lack of certainty in identifying targets. SCUBA divers have been employed to provide observations for species identification and to quantify density and spatial extent of fish schools and aggregations. Unless these surveys are designed to address observer bias, the approach is prone to generating imprecise data and can be difficult to replicate (Harvey et al., 2001). There is a clear need to develop methods that can reliably measure individual sizes, density, and 3D structure of known targets in situ to overcome the limitations of these other methods.

In field situations that permit it, the use of stereo photography and videography offers a straightforward method for generating data on individual sizes, density, and 3D positions of fish. In addition to providing species identification in most cases, it also allows for estimates of size and 3D positions of fish in the water column, measures that are often difficult using SCUBA observations. There has been a relatively short history of using stereo-pairs of underwater cameras in situ to quantify individual lengths and behaviors of fishes, particularly swimming speed. Klimley and Brown (1983) were the first to conduct such a study, relying on 35 mm still cameras to estimate lengths of hammerhead sharks (*Sphyrna* spp.). Since then, there have been a number of studies in freshwater and marine systems in-

volving stereovideography (Boisclair, 1992; Hughes and Kelly, 1996; Hinch and Rand, 2000; Harvey et al., 2001; Cocito et al., 2003; Harvey et al., 2003; Standen et al., 2004). All of these field efforts have focused on quantifying 3D positions and size of individuals, and, in some cases, estimating swimming speed and resolving swimming maneuvers. While some effort has been devoted to quantifying the structure of fish schools under laboratory conditions (Dill et al., 1981), we are not aware of any published work on combining 3D positioning and size estimation with spatial attributes of fish schools or aggregations in situ. Here we report on results of an application of stereo-videography for quantifying 3D positions, sizes, and spatial properties of a spawning aggregation of Nassau grouper (*Epinephelus striatus*).

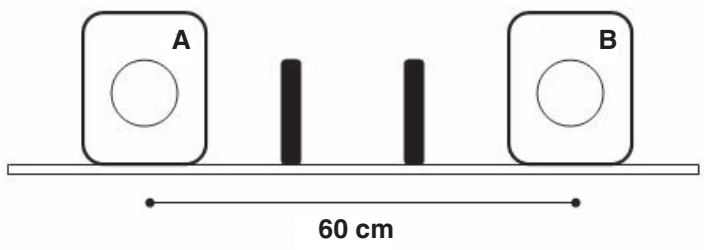

Figure 1

Schematic diagram of a 3D underwater stereo-video system. Two housings containing digital video recorders were fastened on either end of a 1 m steel bar. The cameras were positioned on the bar to achieve a 60 cm optical axis separation. The filled upright bars in the figure are the handles used by diver to support the system during a survey.

Methods

We assembled an underwater stereo-video system for use in resolving 3D attributes of grouper aggregations. The system consisted of two underwater housings (Ikelite Model #6035.36) fitted with dome ports and mounted on opposite ends of a stainless steel bar (see Fig. 1). The weight in air of the bar support was 1.2 kg. This weight was sufficient to achieve slight positive buoyancy of the entire video assembly at the depths where grouper typically aggregate during the spawning period (ca. 30 m depth). The video cameras were SONY Model TRV-11 (single 1.4 type CCD, 680,000 pixel resolution). The cameras were mounted to achieve an optical axis separation of 60 cm (Fig. 1). The zoom lens was fixed at wide angle (3.3 mm focal length), and the cameras were set on auto-focus. Video records were archived on 60 min DV tape format. A single diver operated the camera system and supported the system while underwater using handles placed between the two housings (Fig. 1).

The stereo-video system was calibrated with a 50 cm × 50 cm × 30 cm quadrat consisting of 6.4 mm diameter welded aluminum pipe (Fig. 2). The pipe was welded in a regular grid pattern on each face of the quadrat such that the nodes of adjoining pipe were 10 cm apart. Images of the quadrat were captured in digital format. We conducted the full calibration analysis with the quadrat placed 2 m from the camera assembly (measured from the center point of the steel bar support). The calibration was conducted in approximately 1 m water depth in a swimming pool located at the Southern Cross Club on Little Cayman (see Fig. 2). Still images of the quadrat were captured as JPEG format and analyzed using ImagePro (v. 4.5, Media Cybernetics, Silver Spring, MD). Nodes (n = 36 for each face) were digitized using the Manual Tag method in ImagePro. Pixel coordinates (360 by 270 image resolution) for each node were saved. We used a new program, Mathematica (v. 4.0, Wolfram Research, Champaign, IL), adapted from the approach of Hughes and Kelly (1996), that uses a transformation matrix to convert pixel screen coordinates to view coordinates as a means to estimate 3D positions. This approach can significantly reduce errors in determining positions that are not within the calibration area (Hughes[1]).

We synchronized the two free-running cameras in the field. Frame synchronization was achieved using an underwater laser pointer (Model MBSL, Class IIIA, maximum output <5mW, wavelength 635 nm) directed onto a light background. The diver operating the camera pointed the camera assembly either at another diver or on the reef, and repeatedly illuminated an area with the laser pointer such that both cameras would record the point simultaneously. To assure that we had proper frame synchronization for a particular pair of images captured during a dive, we relied on additional unique visual or auditory clues during playback (e.g. diver movements, taps on housing or sounds from regulator, and recognizable distinct fish behaviors captured in the field of view).

We estimated 3D positions of fish within the spawning aggregation during a dawn dive on 23 January 2003. For all these periods, the anterior- and posterior-most points of each fish clearly identified in both paired camera images were digitized. Pixel coordinates were then read into the transformation matrix program for conversion

[1] Hughes, N. 2004. Personal commun. University of Alaska Fairbanks, School of Fisheries and Ocean Sciences, 204 Arctic Health, P.O. Box 757220, Fairbanks, AK 99775-7220.

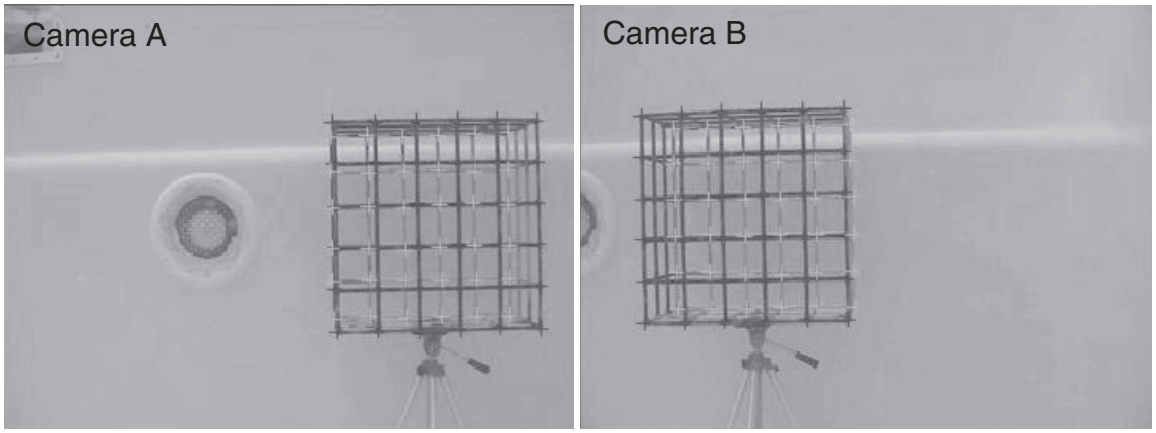

Figure 2

Paired digital images of the calibration quadrat captured with the stereo video system. The calibration was conducted in a swimming pool at the Southern Cross Club, Little Cayman Island, Cayman Islands, BWI. The camera was placed 2 m from the near face of the quadrat. Nodes on the near and far face of the quadrat were digitized.

to a view coordinate system oriented relative to the position of the camera. The origin of the view coordinate system was positioned at 2 m range from the camera system and was located at the point in space occupied by the left bottom corner node of the near face of the calibration quadrat at the time the system was calibrated. In the view coordinate system, the positive x-axis points to the right, the y-axis points away from the camera, and the z-axis points upward.

The resulting 3D positions of each individual fish were plotted as a 3D scatter plot with dropline in SPlus 2000 (Insightful, Inc., Seattle, WA). A convex 3D hull was computed using qhull (Barber et al., 1996). A convex hull of a set of points is the smallest convex set containing the points. The resulting coordinates defining each of the polygons that comprised the hull were uploaded to Mathematica and plotted using the Graphics3D function. This allowed us to define a volume occupied by the fish within the view coordinate system to estimate volumetric density.

We computed a matrix of linear distances separating all members of the fish visible in the image pair. We computed straight line distance between the 3D position of each fish by taking the square root of the sum of the squared distances, using the view coordinates determined for the anterior point on each fish. We computed the mean and standard deviation of the nearest neighbor distances. Finally, we selected a subset of fish that were clear in the image and appeared to be oriented perpendicular to the optical axis of our cameras. We estimated their length by taking the square root of the sum of the squared differences, using the view coordinates of the nose and tail of each fish in the aggregation.

Results

We captured a pair of images of the aggregation at approximately 0725 hr on 23 January 2003 (Fig. 3). Fish were swimming relatively close to the bottom and exhibited polarized swimming behavior. We digitized the nose of 40 individual fish in the field of view and estimated the aggregation in the field of view occupied 33.3 m^3, resulting in a volumetric density of 1.2 grouper m^{-3} (Fig. 4). Nearest neighbor distances ranged from 22.1 to 139.3 cm, with a mean of 70 cm and a standard deviation of 29.7 cm (Fig 5A). This equates to a mean interindividual spacing within the aggregation of 1.2 body lengths. We digitized the nose and tail of a subset of these individuals and computed an average size of 58.5 cm TL (n = 29), with a range from 32 to 107 cm TL (Fig. 5B). The aggregation was located between 5 and 10 m from the camera system.

Discussion

Our video estimate of fish length is in good agreement with the TL ranges reported on the same aggregation using diver visual methods (45–75 cm TL) and acoustic methods (60–90 cm TL) as reported in Taylor et al. (this volume). Size ranges observed for both of these methods were more constricted than estimated using the

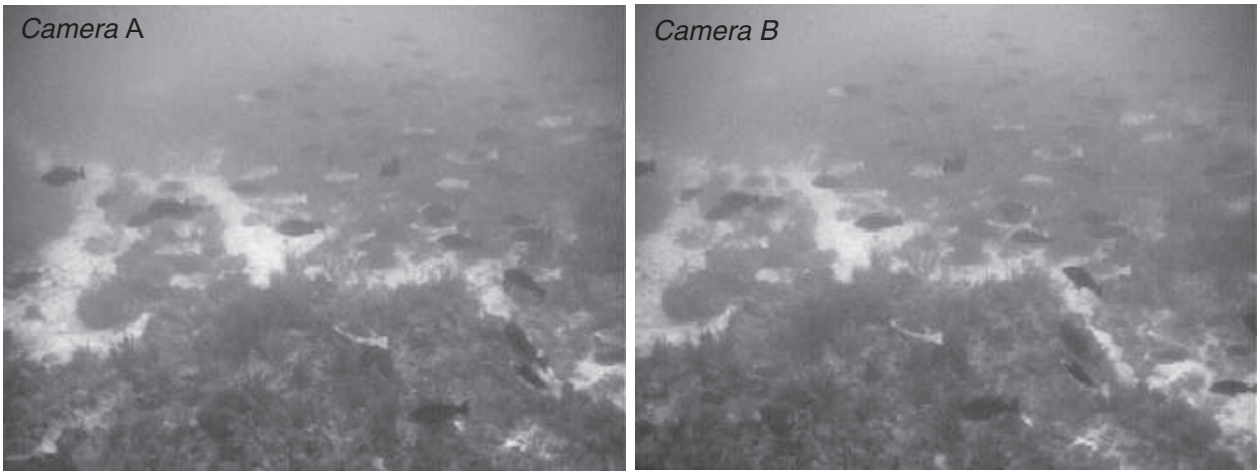

Figure 3

Stereo paired images of a Nassau grouper aggregation. Images were captured on digital video at 0725 hr on 23 January 2003 at Little Cayman Island, Cayman Islands, BWI.

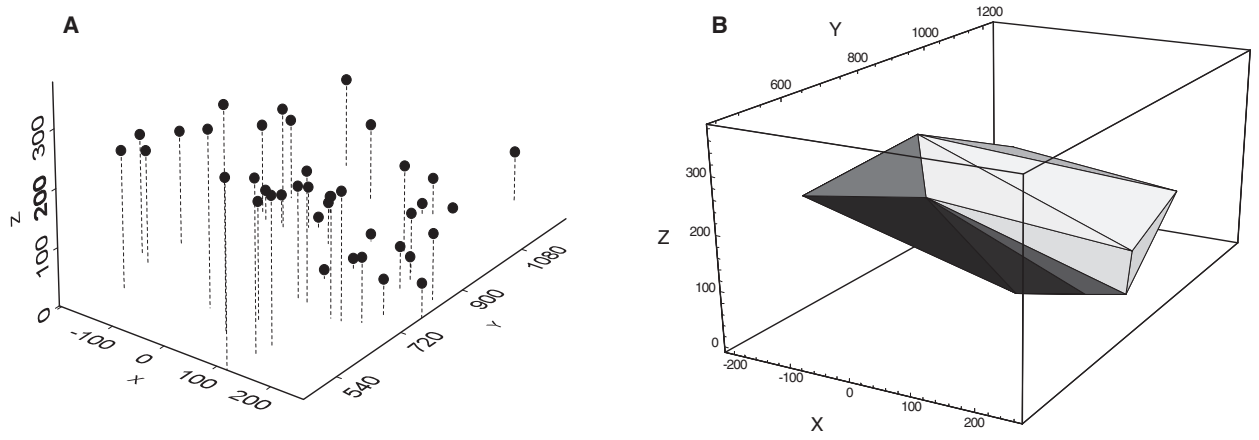

Figure 4

Results of three dimensional analyses depicted as a 3D scatter plot with drop line of individual fish (A) and a 3D rendering of a complex hull surrounding the aggregation (B). A total of 40 individuals were identified in the view of both cameras occupying a total volume of 33.3 m^3 and a volumetric density of 1.2 grouper m^{-3}. Scales on axes in (A) and (B) are in cm.

stereovideography method describe herein. Harvey et al. (2001) reported greater statistical power in resolving changes in mean lengths reported using a stereovideo method, compared to visual surveys performed by divers. We do, however, identify some limitations in estimating total length of grouper using the stereo-video approach described here. The most important source of error likely arises from an alignment of the main axis of the body of the fish that is askew relative to the optical axis of the cameras, resulting in estimated lengths that may be biased low. This is evident in the shape of the distribution of fish lengths generated from images captured during our 23 January 2003 dawn dive. We made an effort to select fish that appeared to be oriented perpendicular to the optical axis of the cameras, but this was relatively difficult to determine, particularly if the fish were at a distance away from the cameras. In past work we have obtained reasonable estimates of fish length by opportunistically targeting small groups of individuals at relatively close range, helping to assure

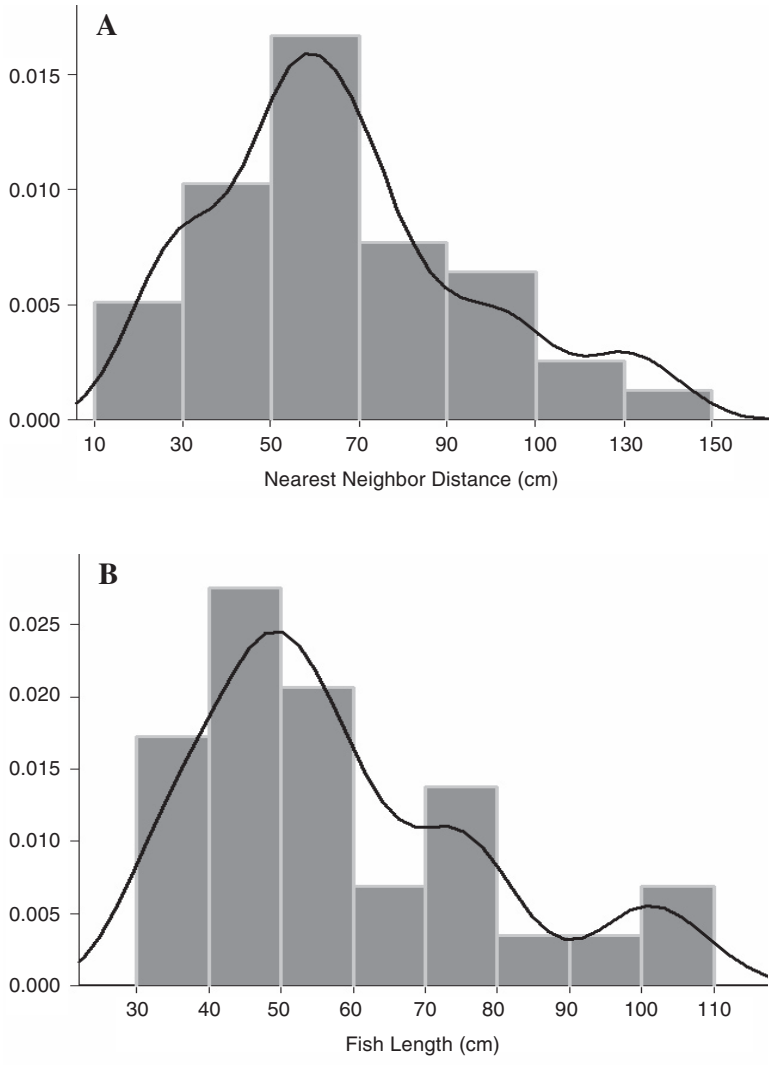

Figure 5

Nearest neighbor distances separating Nassau grouper (A) and size frequency histogram of Nassau grouper (B) measured using stereo-video methods. Average nearest neighbor distance was 70.0 (29.7 SD) cm. Average total length of individuals was 58.5 cm. Measurements were made during 23 January 2003 at a spawning aggregation site off Little Cayman Island, Cayman Islands, BWI. Bold line is density.

that the fish are oriented near perpendicular to the optical axis of the camera (Rand, unpubl. data). The error in estimated size described here is analogous to that introduced from variation in tilt angle exhibited by fish measured using vertical incidence sonar (MacLennan and Simmonds, 1992).

Our stereo-video estimate of volumetric density is within the range reported by Taylor et al. (this volume) on echo-integrated densities. Taylor et al. (this volume) reported maximum volumetric densities of 1.05 and 0.74 grouper m^{-3} during two surveys of the aggregation site, which compare favorably with the estimate of 1.2 grouper m^{-3} reported here. These estimates, however, are not directly comparable because the samples were not collected at the same time of day (stereovideo sampling was conducted during morning of 23 January, and the acoustic sampling was conducted during the afternoon). The stereovideo sampling focused at the center of the main aggregation determined visually during a dive, so it is most appropriate to compare our estimate with that of the maximum recorded during the acoustic sampling. Our average nearest-neighbor

estimate of 0.7 m is the first reported for Nassau grouper within a spawning aggregation. Shapiro et al. (1993) reported nearest neighbor distances greater than 3.2 m for a spawning aggregation of red hind *Epinephelus guttatus*. Their visual observations were made from above the aggregation and in two dimensions; therefore, they may not represent true nearest-neighbor distances (Dill et al., 1981).

This effort underscores the need to conduct more rigorous cross-calibration involving independent measures of abundance, density, distribution, and individual sizes of fish within schools or aggregations. As in most cases involving population estimation and biological sampling, there are a variety of approaches that can be applied. It is clear from our work that there is not one clearly superior sampling method to quantify attributes of spawning aggregations of reef fishes; rather, we support a sampling approach involving two or more methods that will likely provide more rigorous and defensible results. Emerging technologies involving acoustic and video techniques will undoubtedly assume a more prominent role in efforts directed toward assessing status and trends of reef fishes in the tropical Atlantic Ocean and Caribbean Sea.

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Literature cited

Barber, C. B., D. P. Dobkin, and H. T. Huhdanpaa.
1996. The Quickhull algorithm for convex hulls, ACM Trans. on Mathematical Software 22(4):469–483.

Boisclair, D.
1992. An evaluation of the stereocinematographic method to estimate fish swimming speed. Can. J. Fish. Aquat. Sci. 49:523–531

Cocito, S., S. Sgorbini, A. Peirano, and M. Valle.
2003. 3-D reconstruction of biological objects using underwater video technique and image processing. J. Exp. Mar. Biol. Ecol. 297:57–70.

Dill, L. M., R. L. Dunbrack, and P. F. Major.
1981. A new stereophotographic technique for analyzing the three-dimensional structure of fish schools. Environ. Biol. Fish 6:7–13.

Harvey, E., D. Fletcher, and M. Shortis.
2001. Improving the statistical power of length estimates of reef fish: a comparison of estimates determined visually by divers with estimates produced by a stereo-video system. Fish. Bull. 99:72–80.

Harvey, E., M. Cappo, M. Shortis, S. Robson, J. Buchanan, and P. Speare.
2003. The accuracy and precision of underwater measurements of length and maximum body depth of southern bluefin tuna (*Thunnus maccoyii*) with a stereo-video camera system. Fish. Res. 63:315–326.

Hinch, S. G., and P. S. Rand.
2000. Optimal swimming speeds and forward-assisted propulsion: energy-conserving behaviours of upriver-migrating adult salmon. Can. J. Fish. Aquat. Sci. 57:2470–2478.

Hughes, N. F., and L. H. Kelly.
1996. New techniques for 3-D video tracking of fish swimming movements in still or flowing water. Can. J. Fish. Aquat. Sci. 53:2473–2483.

Klimley, A. P., and S. T. Brown.
1983. Stereophotography for the field biologist: measurement of lengths and three-dimensional positions of free-swimming sharks. Mar. Biol. 74:175–185.

MacLennan, D. N. (ed.).
2003. Acoustics in fisheries and aquatic ecology. Part 1. Proceedings of an ICES Symposium held in Montpellier, France, 10–14 June 2002. ICES Marine Science Symposia, 218,706 p.

MacLennan, D. N., and E. J. Simmonds.
1992. Fisheries acoustics. Fish and Fisheries Series 5. Chapman and Hall, New York, 325 p.

Parrish, J. K., and W. H. Hamner (eds.).
1997. Animal groups in three dimensions. Cambridge University Press, New York, 378 p.

Shapiro, D. Y., Y. Sadovy, and M. A. McGehee.
1993. Size, composition, and spatial structure of the annual spawning aggregation of the red hind, *Epinephelus guttatus*. Copeia 1993(2):399–406.

Simmonds, E. J., and D. N. MacLennan (eds.).
1996. Fisheries and plankton acoustics. Proceedings of an ICES International Symposium held in Aberdeen, Scotland, 12–16 June 1995. ICES Marine Science Symposia, 202.

Standen, E. M., S. G. Hinch, and P. S. Rand.
2004. Influence of river speed on path selection by migrating adult sockeye salmon (*Oncorhynchus nerka*). Can. J. Fish. Aquat. Sci. 61:905–912.

Taylor, J. C., D. B. Eggleston, and P. S. Rand.
2006. Nassau grouper (*Epinephelus striatus*) spawning aggregations: hydroacoustic surveys and geostatistical analysis. *In* Emerging technologies for reef fisheries research and management (J. C. Taylor, ed.), p. 18–25. NOAA Prof. Paper NMFS 5.