INTRODUCTION

Many fish species have large aggregations of calling fish [1], particularly during spawning periods. Among these species are members of Family Sciaenidae (Drums and Croakers) [2, 3] including weakfish *Cynoscion regalis*, spotted seatrout *Cynoscion nebulosus*, red drum *Sciaenops ocellatus*, and silver perch *Bairdiella chrysoura*.

One problem important to both scientists and managers is counting the number of fish of a given species present in an aggregation. Several tools are available to count fish, but each has specific drawbacks. Active sonar can be used to locate and count fish in an area, but it cannot be used to identify fish species. Single hydrophones are easy to deploy from a boat or can be attached to a remote data logger. Hydrophones can be used to record species-specific fish sounds that can be used to identify the species present and making sound, but single-hydrophone recordings cannot count the fish in an area. Hydrophone arrays can be used to isolate, identify, and count fish calls in an area, but they are difficult to deploy. Also, the analysis of hydrophone array data can be complicated. We would like to develop a technique for estimating the number of fish in an aggregation using single-hydrophone measurements. One way to do this is to use propagation modeling to identify relationships between patterns and properties of the aggregation sound such as sound level and the numbers and densities of calling fish in the aggregation.

This paper is a preliminary attempt at modeling the sound produced by an aggregation of weakfish. Weakfish are an important commercial and recreational fish in the estuaries and coastal waters of North Carolina (USA), where we are based. Male weakfish produce a sound known as a "purr" during spawning periods [1, 2] using sonic muscles and their swim bladders [4, 5]. These sounds have been used [6, 7, 3] to identify weakfish spawning areas and critical habitats for the species. MM 1 is an *in-situ* recording of an individual weakfish producing a purr. MM 2 is a recording of a weakfish producing a purr in captivity. MM 3 is an *in-situ* recording of an aggregation of purring weakfish. We will compare these sounds to sounds predicted by our modeled fish aggregations.

SOUND PROPAGATION CALCULATIONS

All sound propagation calculations were performed using the finite difference time domain (FDTD) model for sound propagation [8, 9, 10]. Our adaptation of the FDTD model [11] uses an impulsive pressure source [10] in a cylindrical geometry. We used the FDTD model to calculate the propagation of an impulsive pressure at the source position to the receiver (hydrophone) position to give an impulse response function at the receiver position. Then we performed a convolution of the source signal (in this case a weakfish purr sound) with the impulse response function to obtain the propagated signal at the receiver position.

In order to determine the propagation of sounds from any source position to the receiver position, we calculated a two-dimensional array of impulse response functions for sources at different horizontal ranges r from the receiver and depths z. Our array was a grid with spacing $\Delta r = \Delta z = 0.0768\,\mathrm{m}$, which corresponds to the grid spacing used in our FDTD calculations. We used a third order interpolation to estimate the impulse response functions for source positions between grid points.

All of our FDTD propagation calculations used a uniform water depth with uniform sound speed 1536 m/s and density 1024 kg/m^3. These values are consistent with the shallow water coastal inlets in North Carolina where we have recorded weakfish [6]. We assumed a sand bottom with effective sound speed 1700 m/s and density 2035 kg/m^3. We used a receiver depth of 1.92 m, which corresponds to 25 FDTD grid points below the surface, in our calculations. This depth is consistent with the depth at which we deploy a hydrophone from a boat in very shallow waters. We used three different water depths for our calculations: approximately 3 m, 5 m, and 10 m. (The actual water depths were the closest FDTD grid points to these depths: 2.9952 m, 4.9920 m, and 9.9840 m).

MM 1. An *in-situ* recording of an individual weakfish producing a purr.
See supplementary material at

MM 2. A recording of a captive individual weakfish producing a purr.

See supplementary material at

MM 3. An *in-situ* recording of an aggregation of weakfish producing purrs.

See supplementary material at

ENSEMBLE MODEL FOR FISH AGGREGATION SOUNDS

We created ensembles of 20 randomized instances of fish aggregations for statistical calculations for each water depth and aggregation population size. We made the following assumptions about the fish in the aggregations:

1. The fish in the aggregation have a uniform random horizontal distribution.
2. The fish in the aggregation are distributed vertically in a beta distribution [12] with average depth equal to 2/3 the water depth and standard deviation 0.45 m.
3. All fish in the aggregation are weakfish that make identical "calls."
4. All fish that contribute significantly to the maximum aggregation sound level are within 30 m of the hydrophone.
5. Each fish in the aggregation starts its call at a random time within a 1.15 s interval.

Assumptions 1 and 2 are based on *ad-hoc* observations of weakfish and other sciaenid aggregations. They have not been validated by a detailed study but serve as a useful starting point for these preliminary calculations. Assumption 1 is based on our recordings of weakfish and other sciaenid aggregations using towed arrays. The calling fish are not in a compact aggregation but distributed throughout an area. Holt [13] reported this same observation about calling aggregations of red drum. Assumption 2 is based on our observations that weakfish tend to be near the seafloor when calling. The beta distribution is useful because it has a well-defined mean and standard deviation and is bounded on two sides; hence, it does not produce fish above the water surface of below the seafloor.

Assumption 3 is based on our observations that calling fish species tend to partition the time/frequency bandwidth [6, 7, 3, 14]. Fish that produce calls within the same frequency band do not typically call at the same time in the same location. There are often situations where fish species that produce calls in different frequency bands will overlap in time and space. Since these overlapping calls have different frequency components, they are easy to separate using spectral analysis. For the purposes of this model, we have chosen to focus on a single species. These calculations could easily be expanded to include other species producing calls in other frequency bands.

Assumption 4 is based on attenuation calculations for the sound of an individual source. Our FDTD model gives the minimum attenuation of an individual source at horizontal range 30 m of 16.7 dB for in 3 m deep water, 19.4 dB in 5 m deep water, and 21.2 dB in 10 m deep water. We assume that sources at horizontal ranges greater than this distance do not contribute significantly to the maximum aggregation sound level. We are not arguing that fish at distances greater than 30 m cannot be detected, only that the much louder sounds of fish closer than 30 m dominate in contribution to the maximum sound level.

Assumption 5 is based on our *ad-hoc* observations that calling weakfish in our recordings tend to repeat their "purr" calls at an interval of approximately 1.15 s. We have assumed that the individuals in the aggregation do not synchronize their calls with each other. Rather, we have assumed that they simply repeat their calls over and over after a random starting time. This assumption is untested, but it serves as a useful starting point for these calculations.

SOUNDS PRODUCED BY VIRTUAL AGGREGATIONS

We produced graphs of fish distributions for typical instances of 10 fish (Figure 1), 20 fish (Figure 2), and 100 fish (Figure 3) in 3 m deep water. The sound predicted by the model for the 10 fish aggregation shown in Figure 1 is given

MM 4. Sound predicted by the model for the 10 fish aggregation in water of depth 3 m shown in Figure 1. The sound was calculated using the FDTD model with the assumptions detailed in this paper.

See supplementary material at

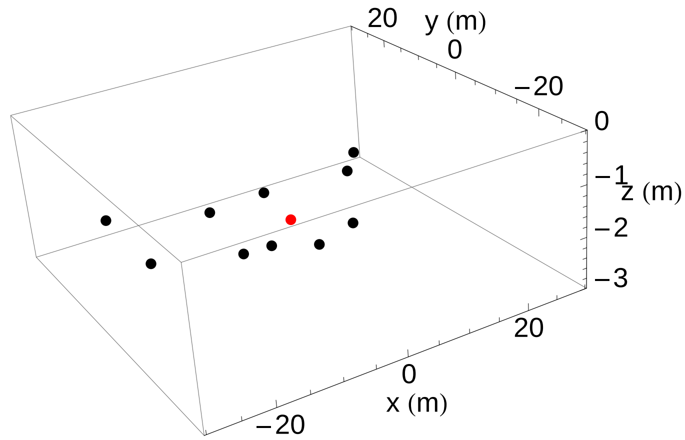

FIGURE 1. Distribution of a typical instance of an aggregation of 10 fish in 3 m deep water. The black circles represent the calling fish in the aggregation, and the red circle represents the hydrophone location. The Cartesian coordinates x and y are horizontal coordinates, and z is depth below the water surface.

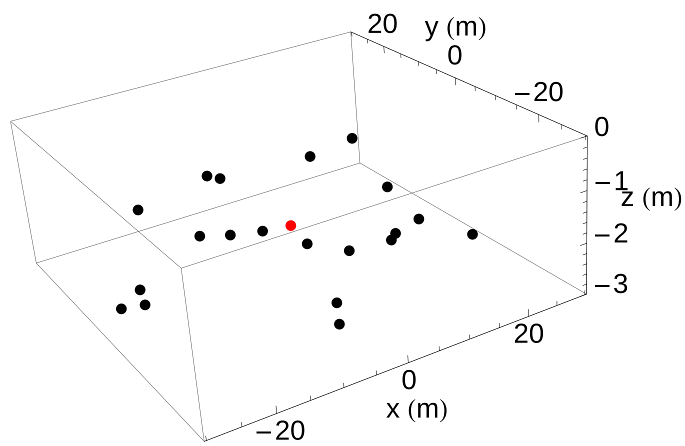

FIGURE 2. Distribution of a typical instance of an aggregation of 20 fish in 3 m deep water. The black circles represent the calling fish in the aggregation, and the red circle represents the hydrophone location. The Cartesian coordinates x and y are horizontal coordinates, and z is depth below the water surface.

MM 5. Sound predicted by the model for the 20 fish aggregation in water of depth 3 m shown in Figure 2. The sound was calculated using the FDTD model with the assumptions detailed in this paper.

See supplementary material at

MM 6. Sound predicted by the model for the 100 fish aggregation in water of depth 3 m shown in Figure 1. The sound was calculated using the FDTD model with the assumptions detailed in this paper.

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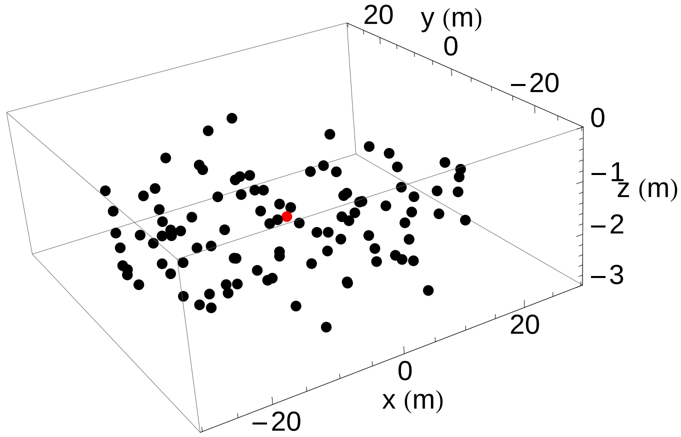

FIGURE 3. Distribution of a typical instance of an aggregation of 100 fish in 3 m deep water. The black circles represent the calling fish in the aggregation, and the red circle represents the hydrophone location. The Cartesian coordinates x and y are horizontal coordinates, and z is depth below the water surface.

in MM 4. The sound predicted for the 20 fish aggregation shown in Figure 2 is given in MM 5. The sound predicted for the 100 fish aggregation shown in Figure 3 is given in MM 6. Each of these three sounds is similar to *in-situ* recordings of weakfish aggregations that we have made. The 100 fish aggregation sound in MM 6 is remarkably similar to the *in-situ* recording of the aggregation in MM 3.

STATISTICAL CALCULATIONS

We produced ensembles of 20 instances of randomized fish aggregations using the assumptions given above for aggregation population sizes of 5, 10, 20, 50, 100, 200, 500, and 1000 fish within a 30 m radius horizontal range from the receiver for each of the water depths 3 m, 5 m, and 10 m. For each instance of a randomized aggregation, we calculated the aggregation sound and determined the maximum RMS pressure and sound level of the aggregation sound using a time constant of 0.125 s, which is characteristic of a fast-response sound level meter similar to the meter we have used [2, 3, 6, 7] when making *in situ* recordings from a boat. We calculated the ensemble mean $\overline{p}_{\max}$ and standard deviation $\sigma_{p_{\max}}$ of the maximum RMS pressure of the virtual aggregations for each population/water depth combination. The ensemble mean maximum sound pressure levels $\overline{SPL}_{\max}$ were computed from $\overline{p}_{\max}$ using the maximum RMS pressure of an individual weakfish 1 m from the hydrophone p_1 as the reference pressure,

$$\overline{SPL}_{\max} = 20\log_{10}\left(\frac{\overline{p}_{\max}}{p_1}\right). \tag{1}$$

An $\overline{SPL}_{\max}$ of 0 dB would mean that the average aggregation in the ensemble has the same sound pressure level as one fish calling at a distance of 1 m from the hydrophone. Uncertainties in the ensemble sound pressure level were determined using the sound pressure level of the RMS pressure one standard deviation above and one standard deviation below $\overline{p}_{\max}$.

$$SPL_{\max,\text{high}} = 20\log_{10}\left[\frac{\overline{p}_{\max}+\sigma_{p_{\max}}}{p_1}\right], \tag{2}$$

and

$$SPL_{\max,\text{low}} = 20\log_{10}\left[\frac{\overline{p}_{\max}-\sigma_{p_{\max}}}{p_1}\right]. \tag{3}$$

We could normalize the sound pressure levels predicted by our model to a reference pressure of 1 µPa by adding SPL_1(re 1 µPa) the maximum sound pressure level of an individual 1 m fro the hydrophone with reference 1 µPa,

$$\overline{SPL}_{\max}(\text{re } 1\,\mu\text{Pa}) = \overline{SPL}_{\max} + SPL_1(\text{re } 1\,\mu\text{Pa}). \tag{4}$$

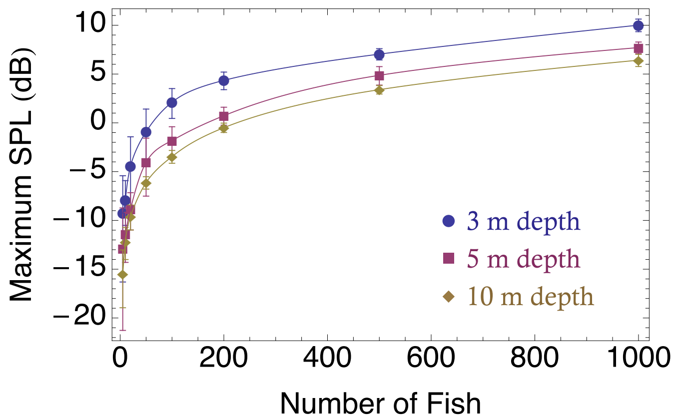

FIGURE 4. Ensemble maximum sound pressure level vs. fish population size for geometries with water depths 3 m, 5 m, and 10 m. The symbols represent the ensemble mean $\overline{SPL}_{\max}$ for the aggregation population size, and the error bars represent the $SPL_{\max,\text{high}}$ and $SPL_{\max,\text{low}}$ calculated with Eqs. (2) and (3).

RESULTS AND DISCUSSION

As the number of fish in the virtual aggregations increased, the ensemble mean of the maximum sound pressure level increased at all three depths we modeled (Figure 4). The negative values in maximum sound pressure level observable in Figure 4 occurred because some fish in our virtual aggregation are more than 1 m from our modeled hydrophone resulting in an aggregation sound pressure levels less than that of a single fish 1 m from the hydrophone.

In order to compare our modeling results with *in-situ* recordings of weakfish aggregations, we must know the sound pressure level of single fish [i.e. the maximum sound pressure level of an individual 1 m from the hydrophone, SPL_1(re 1 µPa) in Eq. (4)]. The highest sound pressure level we have recorded *in situ* for an individual weakfish was 127 dB re 1 µPa [6]. If we use this source level in our model for SPL_1(re 1 µPa), 127 dB re 1 µPa would correspond to the 0 dB value in Figure 4. The resulting transformed data (assuming this source level measurement) rises to 137 dB re 1 µPa (which is 10 dB plus the measured source level) for an aggregation of 1000 fish in 3 m water depth. A similar approach can be used to predict maximum sound pressure level at other fish aggregation sizes and water depths. We have recorded mixed-species aggregation sounds *in situ* with a sound pressure level of 147 dB re 1 µPa. This may indicate that the aggregations *in situ* are larger than 1000 fish, that our assumption that fish occurring beyond a 30 m radius from the hydrophone make no contribution to the sound level is incorrect, or that the actual weakfish source level is greater than 127 dB. Also, the 147 dB recording has contributions to the maximum sound pressure level from other species (e.g., silver perch), which also have pulsed calls, but we did not include such sound sources in our model here. Further models of mixed species aggregations and measurements from enclosures with known fish species combinations and in known densities in experimental situations are needed to determine if our modeling result is correct.

We also converted the fish density (reported as number of fish) to a volume-specific density (Figure 5). The three curves from the different water depths overlay one another here, increasing to a maximum SPL of 10 dB at a fish density of $0.12\,\text{m}^{-3}$. This result suggests that fish density, and not depth, is the dominant factor in determining the aggregation sound level measured with a single hydrophone. The measured density of fish using an echosounder in Pamlico Sound (North Carolina, USA) is often as high as $0.5\,\text{m}^{-3}$.

CONCLUSIONS

We can model fish aggregation sounds measured at a single hydrophone using pulsed fish calls from *in-situ* recordings and an FDTD sound propagation model. It may be possible to use this ensemble model to estimate fish counts and densities using single hydrophone recordings. Although these findings are preliminary, we feel they are worthy of further investigation. We need more confirmatory experiments to verify our fish distribution assumptions. We would like to simultaneously measure sounds from varying sizes of aggregations of weakfish using echosounders to estimate

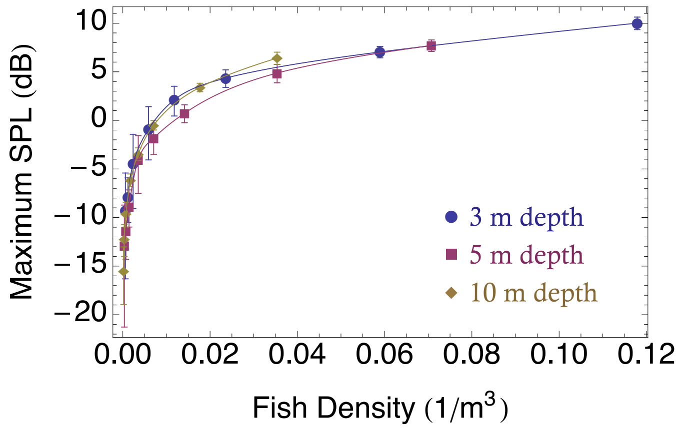

FIGURE 5. Ensemble maximum sound pressure level vs. fish population density for geometries with water depths 3 m, 5 m, and 10 m. The symbols represent the ensemble mean $\overline{SPL}_{\max}$ for the aggregation population size, and the error bars represent the $SPL_{\max,\mathrm{high}}$ and $SPL_{\max,\mathrm{low}}$ calculated with Eqs. (2) and (3).

fish density and distribution.

ACKNOWLEDGMENTS

Thanks to Jasdeep Maggo for running computer programs and doing statistical calculations that were used in this paper.

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