Estimation of bycatch in shrimp trawl fisheries: a comparison of estimation methods using field data and simulated data

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Abstract—Bycatch, or the incidental catch of nontarget organisms during fishing operations, is a major issue in U.S. shrimp trawl fisheries. Because bycatch is typically discarded at sea, total bycatch is usually estimated by extrapolating from an observed bycatch sample to the entire fleet with either mean-per-unit or ratio estimators. Using both field observations of commercial shrimp trawlers and computer simulations, I compared five methods for generating bycatch estimates that were used in past studies, a mean-per-unit estimator and four forms of the ratio estimator, respectively: 1) the mean fish catch per unit of effort, where unit effort was a proxy for sample size, 2) the mean of the individual fish to shrimp ratios, 3) the ratio of mean fish catch to mean shrimp catch, 4) the mean of the ratios of fish catch per time fished (a variable measure of effort), and 5) the ratio of mean fish catch per mean time fished. For field data, different methods used to estimate bycatch of Atlantic croaker, spot, and weakfish yielded extremely different results, with no discernible pattern in the estimates by method, geographic region, or species. Simulated fishing fleets were used to compare bycatch estimated by the five methods with "actual" (simulated) bycatch. Simulations were conducted by using both normal and delta lognormal distributions of fish and shrimp and employed a range of values for several parameters, including mean catches of fish and shrimp, variability in the catches of fish and shrimp, variability in fishing effort, number of observations, and correlations between fish and shrimp catches. Results indicated that only the mean per unit estimators provided statistically unbiased estimates, while all other methods overestimated bycatch. The mean of the individual fish to shrimp ratios, the method used in the South Atlantic Bight before the 1990s, gave the most biased estimates. Because of the statistically significant two- and 3-way interactions among parameters, it is unlikely that estimates generated by one method can be converted or corrected to estimates made by another method: therefore bycatch estimates obtained with different methods should not be compared directly.

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Bycatch, as used in the present study, is the incidental catch of nontarget organisms that occurs to some extent in almost all commercial fisheries (Alverson, 1994). Some of these incidentally caught organisms may be protected species—such as marine mammals, marine turtles, and seabirds—or they may be fish or invertebrates that are either harvested as target species by other fisheries, or species that fishermen call "trash fish" because they have little or no economic value. Bycatch in most commercial fisheries has only been a major issue since the 1980s—primarily because individuals caught as bycatch have historically been discarded at sea, leaving fishery managers and the general public unaware of the extent of bycatch mortality. For many organisms, bycatch may be a significant source of mortality, and inclusion of bycatch mortality in stock assessments or management plans may be critical for effective management.

Because bycatch species are not usually landed, quantifying bycatch poses a very different problem from that of quantifying the catch of a target species. Several methods of quantifying bycatch have been tried, including the requirement that fishermen record catch and bycatch in logbooks (Walsh and Kleiber, 2001), use of research vessel surveys to model commercial fishing (Nichols et al.[1]), and the placement of observers aboard fishing vessels (Julian and Beeson, 1998). Although direct observation is the most accurate method, unless observer coverage of the fleet is complete, estimation of bycatch from observation data requires sampling of the fleet and then extrapolating from the samples (the observations) to the entire fleet using statistical estimators. Two types of statistical estimators are used: mean-per-unit estimators and ratio estimators. In both types of estimators, the observed catch of the bycatch species (y) is linked to an auxiliary variable (x) for which the population total is known (Cochran, 1977). In mean-per-unit estimators, the auxiliary variable is a measure of fishing effort such as tow, day, trip, etc., where each unit of effort is the same as one observation. In ratio estimators, the auxiliary variable is a variable that is correlated with the catch of the bycatch species, such as the catch of the target species or the number of hours fished (Cochran, 1977). The major difference between these two types of estimators is that the auxiliary variable in the mean-per-unit estimator is a substitute for the number of observations rather than a mean value with a variance, while the auxiliary variable in the ratio estimator is the mean value of a quantity that varies from sample to sample. Although the statistical properties of these two types of estimators are well known, the choice of which estimator to use in bycatch research is often based on the ease of collecting fleet information on the auxiliary variable, and not on any inherent properties of the estimators themselves or on any specific information about the relationship between the catch of bycatch species and the auxiliary variable.

[1] Nichols, S., A. Shah, G. Pellegrin Jr., and K. Mullin. 1990. Updated estimates of shrimp fleet bycatch in the offshore waters of the US Gulf of Mexico, 22 p. Pascagoula Laboratory, Southeast Fisheries Science Center, NMFS, PO Drawer 1207, Pascagoula, MS 39568-1207.

Bycatch is a major issue in the shrimp trawl fisheries of the Gulf of Mexico and the South Atlantic Bight. These fisheries are the most valuable fisheries in the southeastern United States; almost 136,000 metric tons of shrimp, worth over $700 million, were landed in 2000 (NMFS[2]). It is estimated that 60–80% of the catch by weight in these fisheries is bycatch. Over 150 species have been reported in shrimp trawl bycatch, including marine turtles (Crouse et al., 1987) and juveniles of species that are highly valued as adults in other fisheries, such as weakfish (*Cynoscion regalis* [Vaughan et al.[3]]) and red snapper (*Lutjanus campechanus* [Goodyear[4]]).

Both types of statistical estimators have been used to estimate bycatch in shrimp trawl fisheries. In the South Atlantic, biologists have periodically participated as observers aboard commercial shrimp trawlers since at least the 1950s to characterize bycatch and estimate its magnitude (Fahy, 1966; Latham,[5] Lunz et al.,[6] Fahy,[7] Fahy,[8] Fahy,[9] Wolff,[10] Keiser,[11] Knowlton[12]). For most of the studies conducted between the 1950s and the 1980s, fisheries bycatch was estimated by using a ratio estimator, that is to say by calculating the observed ratio of fish (F) bycatch to shrimp (S) by weight and then multiplying by the total pounds of shrimp landed by the fleet (the F:S ratio estimator). The catch of shrimp was used as the auxiliary variable primarily because better records were kept of shrimp landings than of any measure of fleet effort. By the late 1980s, the problem of shrimp trawl bycatch in the United States was considered to be of such magnitude that in 1990 the Magnuson Fishery Conservation and Management Act (Magnuson Act) was amended to include bycatch research. Beginning in 1992, observers trained by the National Marine Fisheries Service (NMFS) to use a standardized sampling protocol (NMFS[13]) rode aboard paid volunteer commercial vessels in the South Atlantic and Gulf of Mexico. The 1992–94 observation data collected in the South Atlantic were used to estimate bycatch by species with a mean-per-unit estimator, which was the weight or number of fish caught per observed trip multiplied by the total number of trips taken by the fleet (the CPUE-mean-per-unit estimator). Trips were used as the auxiliary variable because fleet effort data were available at the trip level and this method was thought to be less variable than the F:S ratio method (SEAMAP[14]).

To date, there have been no detailed studies on how these different techniques compare to each other, or how accurately they estimate bycatch. Vaughan and Nance[15] in a draft paper compared the estimated bycatch of mackerels (*Scomberomorus* spp.) and cobia (*Rachycentron canadum*) using both methods and found much higher estimates with the F:S ratio estimator than with the CPUE-mean-per-unit estimator. Because of the wide range of estimation methods used over the years, the discrepancy in the estimates generated by the different methods, and the increasing importance of bycatch estimation for shrimp trawl fisheries

[2] NMFS (National Marine Fisheries Service). 2002. Unpubl. data Website: http://www.st.nmfs.gov/st1/commercial/index.html.

[3] Vaughan, D. S., R. J. Seagraves, and K. West. 1991. As assessment of the status of the Atlantic weakfish stock, 1982–1988. Special Report 21, 29 p. Atlantic States Marine Fisheries Commission, 1444 Eye Street, N.W., Sixth Floor, Washington, DC 20005.

[4] Goodyear, C. P. 1995. Red snapper in US waters of the Gulf of Mexico. Contribution MIA-95/96-05, 171 p. Miami Laboratory, Southeast Fisheries Science Center, NMFS,75 Virginia Beach Drive, Miami, Florida 33149-1099.

[5] Latham, F. F. 1951. Evidence of fish loss due to shrimping in Pamlico Sound. Appendix B *in* The destruction of small fish by the shrimp trawlers in Pamlico Sound, North Carolina (G. R. Lunz, J. L.,McHugh, E. W. Roelofs, R. E. Tiller, and C. E. Atkinson), p. 17–24. Committee Report to the Atlantic States Marine Fisheries Commission, 1 November 1951. Atlantic States Marine Fisheries Commission, 1444 Eye Street, N.W., Sixth Floor, Washington, DC 20005.

[6] Lunz, G. R., J. L. McHugh, E. W. Roelofs, R. E. Tiller, and C. E. Atkinson. 1951. The destruction of small fish by the shrimp trawlers in Pamlico Sound, North Carolina. Committee Report to Atlantic States Marine Fisheries Commission, 1 November 1951, 34 p. Atlantic States Marine Fisheries Commission, 1444 Eye Street, N.W., Sixth Floor, Washington, DC 20005.

[7] Fahy, W. E. 1965a. Report of trash fish study in North Carolina in 1962. Division of Commercial and Sports Fisheries, NC Department of Conservation and Development, Special Scientific Report 5, 20 p. NC Division of Marine Fisheries, 3441 Arendell St., Morehead City, NC 28557.

[8] Fahy, W. E. 1965b. Report of trash fish study in North Carolina in 1964. Division of Commercial and Sports Fisheries, NC Department of Conservation and Development, Special Scientific Report 7, 13 p. NC Division of Marine Fisheries, 3441 Arendell St., Morehead City, NC 28557.

[9] Fahy, W. E. Unpubl. data cited in Brown, J., and E. McCoy. 1969. A review of the North Carolina scrap fishery. Division of Commercial and Sports Fisheries, NC Department of Conservation and Development, Information Series 1, 12 p. NC Division of Marine Fisheries, 3441 Arendell St., Morehead City, NC 28557.

[10] Wolff, M. 1972. A study of North Carolina scrap fishery. NC Department of Natural and Economic Resources, Special Scientific Report 20, 29 p. NC Division of Marine Fisheries, 3441 Arendell St., Morehead City, NC 28557.

[11] Keiser, R. K. 1977. The incidental catch from commercial shrimp trawlers of the South Atlantic states. Technical Report 26, 38 p. South Carolina Wildlife and Marine Resources Department, South Carolina Department of Natural Resources, Rembert C. Dennis Building, 1000 Assembly Street, Columbia, SC 29201.

[12] Knowlton, C. J. 1972. Fishes taken during commercial shrimping in Georgia's close inshore ocean waters. Contributed Series 21, 42 p. Georgia Department of Natural Resources, Coastal Resources Division, One Conservation Way, Suite 300, Brunswick, GA 31520.

[13] NMFS (National Marine Fisheries Service). 1992. Shrimp trawl bycatch characterization. Sampling Protocol Manual for Data Collection, 62 p. Galveston Laboratory, Southeast Fisheries Science Center, NMFS, 4700 Avenue U, Galveston, TX 77551-5997.

[14] SEAMAP (Southeast Area Monitoring and Assessment Program). 1996. Estimates of finfish bycatch in the South Atlantic Shrimp Fishery, July 24, 1995 (R. Peuser, ed.), 64 p. Final report of the Southeast Area Monitoring and Assessment Program (SEAMAP), SEAMAP-South Atlantic Committee, Shrimp Bycatch Work Group. Atlantic States Marine Fisheries Commission, 1444 Eye Street, N.W., Sixth Floor, Washington, DC 20005.

[15] Vaughan, D. and J. Nance. 1998. Estimates of bycatch of mackerel and cobia in US South Atlantic shrimp trawls. Report for Gulf of Mexico and South Atlantic Fishery Management Councils, February 16, 1998, 26 p. NMFS –SEFSC, Beaufort Laboratory, 101 Pivers Island Road, Beaufort NC 28516.

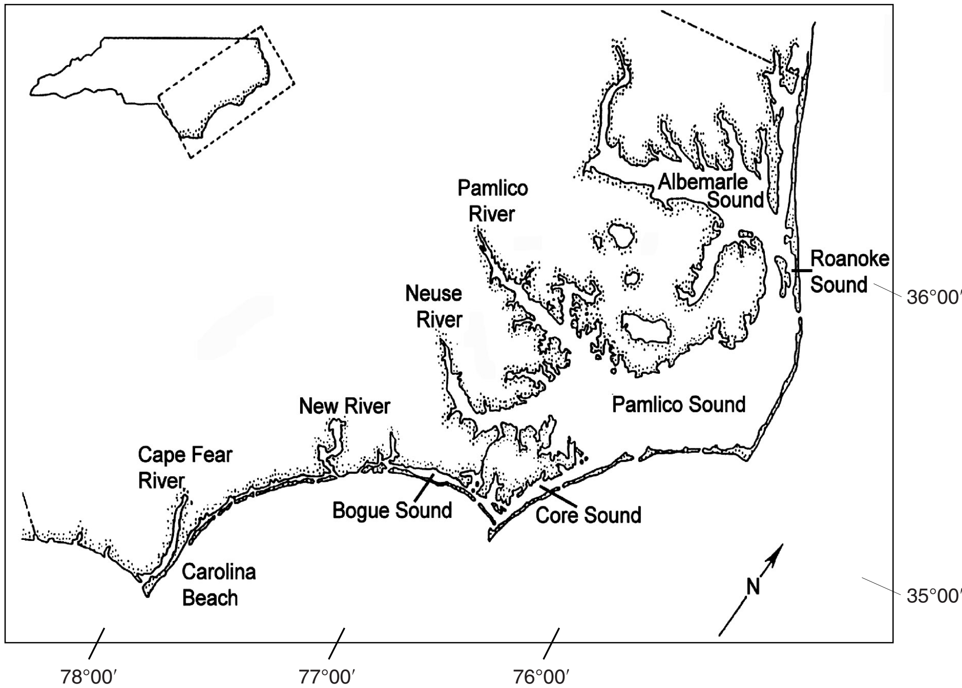

Figure 1

Map of North Carolina waters. Shrimping operations were observed in northern Pamlico Sound (between the mouth of the Pamlico River and southern Roanoke Sound) and the lower third of the Cape Fear River. For total bycatch, fleet shrimp landings and fleet shrimp effort, the northern region includes Pamlico Sound and its tributaries, and the southern region includes from the Cape Fear River to the New River.

and other fisheries, fishery biologists need clear guidance on which method to use to estimate bycatch and they need a definitive knowledge of which methods are best under the varying conditions that might be found in a field observer study.

In this article, I use both field data and computer simulations to compare the methods of bycatch estimation used in past studies. First, using field observations of Atlantic croaker (*Micropogonias undulatus*), spot (*Leiostomas xanthurus*), and weakfish bycatch from shrimp trawlers in North Carolina, I compare bycatch estimates generated by the CPUE-mean-per-unit estimator with two different forms of the F:S ratio estimator, the mean of the individual fish to shrimp ratios and the ratio of the mean catch of fish to the mean catch of shrimp. I then simulate fishing fleets with different catches of fish and shrimp, and estimate bycatch using the following five different estimators, a mean-per-unit estimator and four forms of the ratio estimator, respectively: 1) the mean fish catch per unit of effort, where unit effort is a proxy for sample size, 2) the mean of the individual fish to shrimp ratios, 3) the ratio of mean fish catch to mean shrimp catch, 4) the mean of the ratios of fish catch per time fished (a variable measure of effort), and 5) the ratio of mean fish catch per mean time fished. The simulations employ different mean catches of fish and shrimp, different levels of variability around the catches of fish and shrimp and around the variable measure of effort in the ratio estimator, and different levels of observer coverage, or the number of observations. I also investigate the effects on the bycatch estimates of different underlying distributions of fish and shrimp, including normal distributions of fish and shrimp with different levels of correlation between the catches of fish and shrimp, and delta lognormal distributions of both fish and shrimp, with differing probabilities of catching fish or shrimp.

Materials and methods

Field sampling

To compare the methods described in the literature using field data, I observed shrimping operations aboard commercial shrimp boats from July through October 1995 in Pamlico Sound, North Carolina, and from August through October 1995, in the Cape Fear River, North Carolina (Fig. 1). These two areas have different levels of fishing effort, different fish-to-shrimp ratios, and different probabilities of catching fish and shrimp. All fishermen cooperators were unpaid volunteers, and I did not direct them in any way regarding where or how to fish. Although sampled boats were not randomly chosen, the fishermen appeared to use gear and fishing methods similar to those of other shrimpers, and other shrimpers were often seen fishing in the area near the sampled boats.

Sampled shrimp boats towed one or two nets, and all nets contained some form of turtle excluder device (TED) and bycatch reduction device (BRD) required by regulation.

To sample the catch, I used the NMFS bycatch sampling protocol as described below. If the boat carried two nets and no try net (the small net towed in front of the main nets which is used to survey the catch at short time intervals), I randomly picked one net (the "selected net") by flipping a coin. If the boat had a try net, I picked the opposite net. I weighed the total catch of the selected net on a flat agricultural scale by emptying the net into a plastic tub placed on a scale. After having been weighed, the catch of the selected net was dumped onto the deck or into a culling tray that was divided so that the catch of the selected net was separated from the catch of the unselected net. Following the NMFS protocol, I mixed the selected net contents thoroughly with a shovel, then took a random sample and set it aside until after the rest of the net contents had been sorted. To sort the net contents, marketable shrimp, which are pink shrimp (*Farfantepenaeus duorarum*), brown shrimp (*Farfantepenaeus aztecus*), and white shrimp (*Litopenaeus setiferus*) larger than would comprise about a 70–80 count (i.e. 70–80 shrimp per pound) were separated from the rest of the contents of the selected net, weighed, and then returned to the fisherman. The unsampled bycatch from the selected net was discarded overboard. The random sample taken from the selected net was then weighed. Market shrimp in the sample were taken out, weighed and counted by species, and returned to the fisherman. The bycatch portion of the sample, including undersized market shrimp, mantis shrimp, and all other fish and invertebrates, was packaged in plastic bags and placed on ice for the remainder of the trip. Bycatch samples were brought back to the laboratory and frozen. Samples, including market shrimp, averaged 12% by weight of the total catch of the selected net, and ranged from 5% to 37% by weight.

Expansion of observed bycatch to the entire tow In the laboratory, I thawed and rehydrated the bycatch sample in water. I sorted each sample by species and weighed each species as a group. All individuals of each species were then weighed and measured separately. To account for differences between the scales used on the boat and those used in the laboratory, and for weight loss due to freezing, I corrected the weight of the total catch of each net measured on the boat by the ratio of the sample weight from the laboratory to the sample weight from the boat as follows:

$$\textit{Corrected total weight}_j = \textit{boat total weight}_j \times \frac{\textit{lab sample weight}_j}{\textit{boat sample weight}_j}, \quad (1)$$

where $\textit{corrected total weight}_j$ = the corrected weight of the j^{th} selected net;

$\textit{boat total weight}_j$ = the weight of the entire catch of the j^{th} selected net measured on the boat;

$\textit{lab sample weight}_j$ = the weight of the bycatch sample of the j^{th} net measured in the laboratory plus the shrimp sample weight from the boat; and

$\textit{boat sample weight}_j$ = the weight of the entire sample (including shrimp) from the j^{th} net weighed on the boat.

This correction averaged less than 5% across all selected nets. To expand the catch in weight of each bycatch species from the sample to the entire selected net (called the "species net weight"), the total corrected weight of each selected net was multiplied by the fraction of the sample from the selected net that consisted of the bycatch species, as follows:

$$\textit{Species net weight}_{i,j} = \textit{corrected total weight}_j \times \frac{\textit{species sample weight}_{i,j}}{\textit{total sample weight}_j}, \quad (2)$$

where $\textit{species net weight}_{i,j}$ = the estimated catch in weight of the i^{th} species in the j^{th} net;

$\textit{corrected total weight}_j$ = the corrected weight of the total catch of the j^{th} net from Equation 1;

$\textit{species sample weight}_{i,j}$ = the weight of the i^{th} species in the sample from the j^{th} net; and

$\textit{total sample weight}_j$ = the weight of the bycatch sample from the j^{th} net measured in the laboratory plus the weight of the market shrimp in that sample measured on the boat.

Because the net contents were thoroughly mixed before sampling, I assumed, following the NMFS protocol, that there would be minimal variance among samples if more than one were taken.

Expanding the catch in numbers of each bycatch species from the sample to the entire selected net (called the "species net number") could not be done in the same way as the expansion for the species net weight because there were often organisms like sea lettuce or pieces of fish or crabs that were weighed but that could not be counted. The species net number was therefore calculated by dividing the species net weight by the average weight per whole individual:

$$\textit{Species net number}_{i,j} = \textit{species net weight}_{i,j} \div \frac{\textit{species sample weight}_{i,j}}{\textit{species sample number}_{i,j}}, \quad (3)$$

where $\textit{species net number}_{i,j}$ = the estimated number of individuals of the i^{th} species in the j^{th} net;

$\textit{species net weight}_{i,j}$ = the estimated total weight of the i^{th} species in the j^{th} net from Equation 2;

species sample weight$_{i,j}$ = the weight of the i^{th} species in the bycatch sample from the j^{th} net; and

species sample number$_{i,j}$ = the number of whole individuals of the i^{th} species in the bycatch sample from the j^{th} net.

To expand the observed bycatch from selected net to the entire tow, I multiplied either the species net weight or the species net number from each net by the number of nets towed concurrently.

Bycatch estimation To compare the methods of bycatch estimation used in past studies, I estimated the bycatch of Atlantic croaker, spot, and weakfish (three of the most commonly caught bycatch species) using two categories of statistical estimators: a mean-per-unit estimator using the mean observed bycatch per day expanded by the total number of days fished (the CPUE-mean-per-unit method) and a ratio estimator using the observed ratio of fish to shrimp expanded by the total shrimp landings (the F:S ratio method). Because my purpose was to compare bycatch estimation methods and not to generate bycatch estimates that could be used for management purposes, I estimated total bycatch of these three species only for certain months and geographic regions within North Carolina corresponding to the times and areas that I observed shrimp trawling. The term "shrimp fleet" in the following paragraphs therefore refers only to shrimpers operating in those times and areas. In the calculations, I used bycatch per day instead of the bycatch per tow or bycatch per trip. I could not use tow as the unit of effort because there was no information on the number of tows made by the fleet to use as an expansion factor. Although information on the number of trips made by the fleet was available, I could not use trip as the unit of effort because, although trips can last several days, all of the trips that I sampled were one-day trips. If my observations had also included a random sample of multiday trips, the unit of effort would have been trips instead of days.

The CPUE mean per unit method was based on the following equations:

$$\frac{\text{Mean observed bycatch}_i}{\text{day}} = \frac{1}{n}\sum_{d=1}^{n} F_{i,d}, \tag{4}$$

where *mean observed bycatch*$_i$ *per day* = the observed average bycatch in weight or number of the i^{th} species on the d^{th} day;

n = the number of days observed; and

$F_{i,d}$ = the sum of the expanded weight or number of the i^{th} bycatch species observed in all tows made on the d^{th} day; and

$$\text{Total bycatch}_{i,CPUE} = \frac{\text{mean observed bycatch}_i}{\text{day}} \times \text{total trips} \times \frac{\text{mean days}}{\text{trip}}, \tag{5}$$

where *total bycatch*$_{i,CPUE}$ = the total fleet bycatch of the i^{th} species estimated by the CPUE method;

mean observed bycatch$_i$ *per day* = the observed average bycatch of the i^{th} species per day from Equation 4;

total trips = the total number of trips taken by the shrimp fleet; and

mean days per trip = the average number of days that each fishing trip lasted based on the fleet.

The total trips and mean days per trip were calculated from the North Carolina Division of Marine Fisheries (NCDMF) trip ticket database, as follows. To obtain the total number of trips, I first collapsed the trip ticket database so that each fisherman could have only one ticket for shrimp on a single day. In the database, each trip ticket does not represent one trip, but the sale to one dealer. Fishermen could obtain more than one trip ticket per day by selling different size categories of shrimp (each size category commands a different price, and generates a separate trip ticket), or by selling their catch to more than one dealer. I then calculated the time (in days) between the first and last trips for each fisherman whose trips occurred between 1 July and 31 October in Pamlico Sound and its tributaries (called the northern region) and between 1 August and 31 October in the Cape Fear River and nearby waters (the southern region). Because inshore waters were closed to shrimping on weekends, I multiplied all time spans greater than 7 days by 5/7 (0.714) to obtain the number of days fished. The number of days fished was summed and then divided by the number of trips for each region to obtain the mean days per trip.

The F:S ratio estimator method was initially undertaken in two ways: by using the mean of the fish to shrimp ratios, called the mean of the ratios or the "basic" F:S ratio estimator method (Equation 6), and by using the ratio of the average catch of fish to the average catch of shrimp, called the ratio of the means or the "grand" F:S ratio estimator method (Equation 7). The two methods are shown mathematically as follows:

$$\text{Total bycatch}_{i,FSB} = \frac{1}{n}\sum_{d=1}^{n}\frac{F_{i,d}}{S_d} \times \text{total shrimp landed,} \tag{6}$$

$$\text{Total bycatch}_{i,FSG} = \frac{\sum_{d=1}^{n} F_{i,d}}{\sum_{d=1}^{n} S_d} \times \text{total shrimp landed,} \tag{7}$$

where *total bycatch*$_{i,FSB}$ = the total fleet bycatch of the i^{th} species estimated by the basic F:S method;

total bycatch$_{i,FSG}$ = the total fleet bycatch of the i^{th} species estimated by the grand F:S method;

$F_{i,d}$ = the sum of the expanded weight or number of the i^{th} species observed in all tows made on the d^{th} day;
S_d = the sum of the expanded weight of market shrimp observed in all tows made on the d^{th} day; and
n = the number of days observed.

Because of the small number of days observed in each area, I also used the basic F:S ratio estimator with the Hartley-Ross correction for biases caused by small sample size (Cochran, 1977):

$$Total\ bycatch_{i,HR} = total\ bycatch_{i,FSB} + \frac{n(N-1)}{n-1}(\bar{y}_i - \bar{r}\bar{x}), \quad (8)$$

where $total\ bycatch_{i,HR}$ = the total fleet bycatch of the i^{th} species estimated by the bias-corrected F:S ratio estimator;
$total\ bycatch_{i,FSB}$ = the total fleet bycatch of the i^{th} species estimated by the basic F:S ratio using Equation 6;
n = the number of days observed;
N = the total number of days fished from the trip ticket database;
$\bar{y}_i$ = the mean bycatch of of the i^{th} species observed per day in weight or numbers from Equation 4;
$\bar{r}$ = the mean of the F:S ratios from Equation 6; and
$\bar{x}$ = the mean catch of market shrimp observed per day in weight or numbers.

Total shrimp landings used in Equations 6 and 7 were obtained from the NCDMF trip ticket database for the northern region from July to October and for the southern region from August to October. In the trip ticket database, some shrimp weights were reported as "heads-on" and others as "heads-off"; therefore I converted heads-off weight to heads-on weight with a conversion factor of 1.583, taken from the average of pink, brown, and white shrimp conversion information used by the National Marine Fisheries Service (Fisheries Statistics of the United States, 1977).

Bycatch simulations

For the bycatch simulations, I created different fishing fleets of 1000 "boats" in Matlab 5.0 (The Mathworks, Natick, MA). For the normally distributed catch data, the catch of fish, the catch of shrimp, and the hours fished for each boat in a fleet were generated by using multivariate random normal distributions with a mean and variance that was specific to that fleet. I simulated observer data for each fleet by taking a random sample of boats from the fleet, resampling the sample 1000 times, then using the mean of the bootstrapped observer data in the equations described below to estimate fleet bycatch. In the different fleets, the mean catches of fish and shrimp ranged from 0.01 to 1000, giving fish to shrimp ratios of 0.001 to 100,000. In some fleets, the catches of fish and shrimp were correlated, with correlation coefficients ranging from 0.5 to –0.5 (Table 1). Coefficients of variation (CVs) for fish catch and hours fished ranged from 20% to 80%, CVs for shrimp catch ranged from 20% to 120%, and the number of observations ranged from 20 to 500, giving observer coverages of 2% to 50% of the fleet. Although the range of mean catches I used in the simulations may seem fairly broad, they are within the range of the field data, depending on whether these were the mean catches per tow, per day, or per trip. The ranges of CVs for fish and shrimp catches were fairly narrow compared to those from the field data because CVs vary up to several hundred percent, particularly for patchy species. Observer coverage in the field is usually much less than 50%, but I picked 50% as the upper limit of the range to see if greater observer coverage (i.e., a greater sample size of observations per fleet) increased the accuracy of the bycatch estimates.

Bycatch estimates were calculated by using a mean per unit estimator and four forms of the ratio estimator, as described below. The CPUE mean per unit estimator was calculated by using the following equations, which are more general versions of Equations 4 and 5:

$$\frac{Mean\ observed\ bycatch_i}{UE} = \frac{1}{n}\sum_{UE=1}^{n} F_{i,UE} \quad (9)$$

$$Total\ bycatch_{i,CPUE} = \frac{Mean\ bycatch_i}{UE} \times total\ fleet\ effort, \quad (10)$$

where $mean\ observed\ bycatch_i\ per\ UE$ = the observed average bycatch of the i^{th} species per unit of effort (tow, day, or trip);
n = the number of observed tows, days, or trips;
$F_{i,UE}$ = the expanded weight or number of the i^{th} bycatch species observed on the UE^{th} tow, day, or trip;
$total\ bycatch_{i,CPUE}$ = the total fleet bycatch estimated by the CPUE method; and
$total\ fleet\ effort$ = the total number of tows, days, or trips fished by the fleet.

The four ratio estimators were as follows: 1) the mean of the individual F:S ratios, called the "basic F:S" ratio estimator (Eq. 11), 2) the ratio of the F:S means, called the "grand F:S" ratio estimator (Eq. 12), 3) the mean of the individual catch per effort ratios using a variable measure of effort such as hours fished as the auxiliary variable, called the "basic CPE" ratio estimator (Eq. 13), and 4) the ratio of the mean catch per mean effort using a variable measure of effort such as hours fished as the auxiliary variable, called the "grand CPE" ratio estimator (Eq. 14). Both F:S ratio estimators (Eqs. 11 and 12) are similar to the ones used in the field study (Eqs. 6 and 7), except that the observations could be from a tow, day, trip, or other measure of unit effort, rather than one day, as used in the field study.

$$Total\ bycatch_{i,FSB} = \frac{1}{n}\sum_{e=1}^{n}\frac{F_{i,e}}{S_e} \times total\ shrimp\ landed \quad (11)$$

$$Total\ bycatch_{i,FSG} = \frac{\sum_{e=1}^{n}F_{i,e}}{\sum_{e=1}^{n}S_e} \times total\ shrimp\ landed \quad (12)$$

where *total bycatch*$_{i,FSB}$ = the total fleet bycatch of the i^{th} species estimated by the basic F:S ratio estimator;
total bycatch$_{i,FSG}$ = the total fleet bycatch of the i^{th} species estimated by the grand F:S ratio estimator;
$F_{i,e}$ = the expanded weight or number of the i^{th} bycatch species observed in the e^{th} tow, day, or trip;
S_e = the expanded weight of market shrimp observed in the e^{th} tow, day, or trip;
n = the number of tows, days, or trips observed; and
total shrimp landed = the sum of the total weight of shrimp landed by the fleet.

$$Total\ bycatch_{i,CPEB} = \frac{1}{n}\sum_{e=1}^{n}\frac{F_{i,e}}{H_{i,e}} \times total\ hours\ fished \quad (13)$$

$$Total\ bycatch_{i,CPEG} = \frac{\sum_{e=1}^{n}F_{i,e}}{\sum_{e=1}^{n}H_e} \times total\ hours\ fished \quad (14)$$

where *total bycatch*$_{i,CPEB}$ = the total fleet bycatch of the i^{th} species estimated by the basic CPE ratio estimator;
total bycatch$_{i\ CPEG}$ = the total fleet bycatch of the i^{th} species estimated by the grand CPE ratio estimator;
$F_{i,e}$ = the expanded weight or number of the i^{th} bycatch species observed in the e^{th} tow, day, or trip;
H_e = the hours fished in the e^{th} tow, day, or trip;
n = the number of observed tows, days, or trips; and
total hours fished = the sum of all hours fished by the fleet.

To avoid confusion, it is important to note how fishing effort is used in the five estimators. All five estimators use a unit measure of fishing effort, such as a tow, day, or trip, as one sample, and the sample size for a fleet is the number of tows, days, or trips observed. In the CPUE mean-per-unit estimator, the estimate of total bycatch is a simple expansion of the observed bycatch per sample to the whole fleet. In the F:S ratio estimators, the unit effort appears in the calculations because the ratios of fish to shrimp are the amounts caught per tow, day, or trip (i.e. per sample). In the CPE ratio estimators, two measures of effort are used. As before, one measure of effort is the unit effort, such as a tow, day, or trip, that is equivalent to a sample, and the second measure of effort is the variable measure of effort, such as the hours fished, the distance towed, or the area covered, that is used as the auxiliary variable. The CPE ratio estimator is thus based on the amount of fish caught per hour fished (for example) in each tow, day, or trip.

The delta lognormal simulations were very similar to the normal simulations, except that I simulated the catch of fish and shrimp by using probabilities of catching fish or shrimp ranging from 0.05 to 0.95, multiplied by average catches of fish or shrimp generated from random lognormal distributions with means ranging from 0.01 to 1000. Lognormal functions have parameters of μ and σ^2, which are the mean and variance of the normally distributed variable before logarithmic transformation. To obtain values of μ and σ^2 from a lognormal distribution with a given mean and variance, I used an iterative procedure (the Solver procedure in Microsoft Excel, vers. 2000, Microsoft Corporation, Redmond, WA) to estimate μ and σ^2 based on the following equations:

$$mean = e^{\left(\mu + \frac{\sigma^2}{2}\right)} \quad (15)$$

$$\text{var} = e^{(2\mu + 2\sigma^2)} - e^{(2\mu + \sigma^2)}, \quad (16)$$

where *mean* = the mean of the lognormal distribution of the catch of fish or shrimp;
var = the variance of the lognormal distribution of the catch of fish or shrimp;
μ = the mean of the normally distributed catch of fish or shrimp before logarithmic transformation; and
σ^2 = the variance of the normally distributed catch of fish or shrimp before logarithmic transformation.

Levels of observer coverage and CVs for fish catch, shrimp catch, and effort and were the same as in the normally distributed data. In these simulations, sampled shrimp catch could be zero if the probability of catching shrimp was low and the number of observations was small, leading to F:S ratios of infinity. In these cases, for the basic F:S ratio estimator, the fish-to-shrimp ratio was the catch of fish divided by the expected catch of shrimp (probability of catching shrimp times the mean catch). For the grand F:S ratio estimator, if the average bootstrapped sample catch of shrimp was zero, Matlab substituted a value of 65535 to avoid division by zero. To avoid biases, these grand F:S simulations were left out of the subsequent analyses. In field sampling, tows that caught no shrimp at all were rare, but tows that caught only small unmarketable shrimp that were discarded as bycatch occurred occasionally early in the season and after big rainstorms.

Table 1

Parameters and their values used in the bycatch simulations for normal and delta lognormal distributions of fish and shrimp. Abbreviations for the parameters are shown in parentheses.

Distribution	Parameter	Values
Normal	Mean fish catch (AvgF)	0.01, 0.1, 1, 10, 100, 1000, 10,000
	Fish CV (FCV)	20%, 50%, 80%, 120%
	Mean shrimp catch (AvgS)	0.01, 0.1, 1, 10, 100, 1000, 10,000
	Shrimp CV (SCV)	20%, 50%, 80%
	Mean hours fished	1.0
	Hours fished CV (ECV)	20%, 50%, 80%
	F:S ratio	0.001, 0.01, 0.1, 1, 10, 100, 1000, 10,000, 100,000
	Correlation coefficient (r)	–0.5, –0.25, 0, 0.25, 0.5
	Number of observations (n)	20,50,100,500
	Observer coverage	2%, 5%, 10%, 50%
Delta lognormal	Probability of catching fish (P(F))	0.05, 0.2, 0.5, 0.8, 0.95
	Mean fish catch (AvgF)	0.01, 0.1, 1, 10, 100, 1000, 10,000
	Fish CV (FCV)	20%, 50%, 80%
	Probability of catching shrimp (P(S))	0.05, 0.2, 0.5, 0.8, 0.95
	Mean shrimp catch (AvgS)	0.01, 0.1, 1, 10, 100, 1000, 10,000
	Shrimp CV (SCV)	20%, 50%, 80%, 120%
	Mean hours fished	1.0
	Hours fished CV (ECV)	20%, 50%, 80%
	F:S ratio	0.001, 0.01, 0.1, 1, 10, 100, 1000, 10,000, 100,000
	Number of observations (n)	20,50,100,500
	Observer coverage	2%, 5%, 10%, 50%

To statistically analyze the overall biases shown by each estimator regardless of fishing conditions (i.e. mean catches of fish or shrimp, CV, etc.), I first used paired sample t-tests (SAS v. 8, The SAS Institute, Cary, NC) to separately compare each of the five estimates of fleet bycatch with the "actual" bycatch for that fleet, based on the following equation:

$$\%\ bias_{m,b} = \frac{estimated\ bycatch_{i,m,b} - \text{“}actual\text{”}\ bycatch_{i,b} \times 100}{\text{“}actual\text{”}\ bycatch_{i,b}} \quad (17)$$

where $\%\ bias_{m,b}$ = the bias in the m^{th} estimator for the b^{th} fleet;
$estimated\ bycatch_{i,m,b}$ = the bycatch of the i^{th} species by the m^{th} estimator for the b^{th} fleet; and
"$actual$" $bycatch_{i,b}$ = the simulated actual bycatch of the i^{th} species by the b^{th} fleet.

For these statistical tests, all fleets with normal distributions of fish and shrimp were combined and analyzed separately from the fleets with delta lognormal distributions of fish and shrimp, giving sample sizes of 21,600 fleets for the normal distribution and 118,810 fleets for the delta lognormal distribution (Table 1). To look for significant factors influencing the bycatch estimates for each of the five estimation methods, I used ANOVAs on all main effects and all 2-way and 3-way interactions of the main effects for each estimator. Although 7-way interactions were possible in the normally distributed simulations and 8-way interactions were possible in the delta lognormal simulations (Table 1), I stopped the analysis at 3-way interactions because of the difficulty in interpreting higher level interactions. Main effects were the following: mean catches of fish and shrimp, CVs of fish catches, CVs of shrimp catches, CVs of hours fished, number of observations or observer coverage, correlation coefficient in the normally distributed simulations, and the probabilities of catching fish and shrimp in the delta lognormal simulations. In these ANOVAs, the response variable was the percent bias for each method, as calculated above.

Results

Field sampling

I observed 16 tows from five trips in Pamlico Sound between July and October 1995 and 24 tows from five trips in the Cape Fear River between August and October 1995 (Table 2). According to the 1995 trip tickets, these months comprised the peak of the summer brown shrimp and fall white-pink shrimp seasons; 77% of the total shrimp catch and 75% of the total trips in the northern region and 63% of the total shrimp catch and 54% of the total trips in the southern region occurred during those months. All observed tows were daytime tows, which is when fishing generally occurs in these areas. All nets sampled in July were 2-seam or 4-seam flat trawls, designed to catch brown shrimp, and

Table 2

Characteristics of boats and fishing operations observed in North Carolina waters in 1995. All boats were commercial shrimp trawlers operating using their standard operating procedures. Each entry represents one observed fishing trip. Each observed fishing trip lasted one day. Avg. h/tow = mean hours per tow.

Area	Month	Boat name	Boat length (m)	No. of tows	No. of nets	Headrope length (m)	Avg. h/tow
Pamlico Sound	Jul	*Last Toy*	8.3	5	2	9.8	1.2
	Aug	*Islander*	8.9	2	1	18.4	1.1
	Aug	*Last Toy*	8.3	2	1	13.1	1.3
	Sep	*Islander*	8.9	5	1	18.4	1.1
	Oct	*Islander*	8.9	2	1	18.4	1.2
Average			8.7	3.2	1.2	15.6	1.2
Cape Fear River	Aug	*Cajun Lady*	16.0	9	2	18.0	0.9
	Aug	*Cajun Lady*	16.0	2	2	18.0	0.7
	Sep	*Sea Mullet*	14.2	4	2	14.8	1.3
	Sep	*Cajun Lady*	16.0	5	2	18.0	1.0
	Oct	*Dorothy Glen*	11.4	4	1	19.7	1.9
Average			14.7	5	1.8	17.7	1.2

Table 3

Landed and observed shrimp catch (heads-on kg landed), effort (total number of trips and days/trip), and catch per unit of effort (CPUE, kg /trip and kg/day) for regions within North Carolina. Information on fleet totals was obtained from the North Carolina Department of Marine Fisheries trip ticket database for vessels fishing during July through October 1995 in the Northern region (Pamlico Sound and tributaries), and during August through October 1995 in the Southern region (the Cape Fear River and nearby waters). Observations were conducted during these same months in Pamlico Sound and the Cape Fear River.

Region or location	Shrimp catch (kg landed)	No. of trips	Mean days/trip	CPUE (kg/trip)	Days fished[1]	CPUE (kg/day)
Fleet totals						
Northern	2,018,612	3196	3.64	631.6	11,633	173.5
Southern	122,893	1716	3.48	71.5	5972	20.6
Observations						
Pamlico Sound	278	5	1	55.6	5	55.6
Cape Fear River	867	5	1	173.4	5	173.4

[1] This value represents the maximum days fished because the calculations are based on the assumption that fishing takes place every allowable day between landings.

both tongue trawls and flat trawls were sampled in August through October. Tongue trawls are modified mongoose trawls that have a higher vertical profile for catching white shrimp. In addition, the tongue trawls had a greater headrope length than the flat trawls; therefore many of the fishermen switched from pulling two flat trawls to pulling one larger tongue trawl. Tows typically lasted around one hour. The observed catch of shrimp per day in the Cape Fear River was almost three times higher than the observed catch of shrimp per day in Pamlico Sound (Table 3).

Total shrimp landings and total shrimp trips during the observed months from the 1995 trip ticket database were used as the expansion factors in the estimates. Over half of the total shrimp landings, or 2,018,622 kg, were caught in the northern region between July and October and only 122,893 kg came from the southern region between August and October, the months that corresponded to the observations. Although there were about twice the number of trips and days fished the northern region, the average catch per trip (kg/trip) from the northern region was almost nine times higher than the catch per trip from the southern region (Table 3).

The different estimation methods made a tremendous difference in the estimates of bycatch, but the differences were exactly opposite in the two geographic regions and varied somewhat by species. Total bycatch estimates derived with the basic F:S ratio estimator (mean of the ratios) by both weight and number were two to seven times higher than those based on the CPUE-mean-per-unit method for all species in the northern region, and about two to five times lower by both weight and number for all species in the southern region (Table 4). For Atlantic croaker and

Table 4

Total bycatch in weight and numbers estimated from observation data using different estimation methods. The CPUE-mean-per-unit estimator (CPUE=catch per unit of effort), which is based on the catch per day, uses day as a proxy for sample size. The basic F:S ratio estimator is the mean of individual fish (F) to shrimp (S) ratios, and the grand F:S ratio estimator is the ratio of the mean catch of fish to the mean catch of shrimp. The Hartley-Ross method is the basic F:S ratio estimator corrected for small sample sizes. AC = Atlantic croaker, SP = spot, and WF = weakfish. The northern region includes Pamlico Sound and its tributaries, and the southern region includes from the Cape Fear River to the New River. Estimates are for July through October 1995 in the northern region and August through October 1995 in the southern region. See text for calculations. Equations for the 95% CL are from Cochran (1977), Equations 2.24, 6.12, and 6.14.

Region and species	Bycatch estimate by weight (millions of kg)							
	CPUE-mean-per-unit estimator		F:S ratio estimator					
			Basic		Grand		Hartley-Ross	
	Total wt.	±95% CL	Total wt.	±95% CL	Total wt.	±95% CL	Total wt.	±95% CL
Northern								
AC	0.6	0.5	2.1	4.1	1.7	0.1	2.6	0.1
SP	0.5	0.8	2.9	5.6	1.5	0.3	2.3	0.3
WF	0.6	1.2	1.5	1.5	1.9	0.4	1.7	0.4
Southern								
AC	0.1	0.2	0.03	0.05	0.02	0.09	N/A[1]	N/A
SP	0.02	0.05	0.006	0.01	0.003	0.03	N/A	N/A
WF	0.2	0.2	0.03	0.04	0.2	0.1	N/A	N/A

Region and species	Bycatch estimate by number (millions)							
	CPUE-mean-per-unit estimator		F:S ratio estimator					
			Basic		Grand		Hartley-Ross	
	Total no.	±95% CL	Total no.	±95% CL	Total no.	±95% CL	Total no.	±95% CL
Northern								
AC	28.1	23.7	186.0	263.8	84.8	8.4	144.1	8.4
SP	18.7	27.2	146.5	305.5	56.5	11.7	109.2	11.7
WF	11.8	20.8	36.2	34.8	35.7	6.4	35.9	6.4
Southern								
AC	13.7	20.9	4.1	7.1	1.7	12.7	N/A	N/A
SP	1.5	3.4	0.4	0.6	0.2	1.8	N/A	N/A
WF	19.1	29.2	3.5	4.9	2.3	16.3	N/A	N/A

[1] The estimator gave negative estimates for bycatch.

spot, the grand F:S ratio estimate (ratio of the means) was intermediate between the basic F:S ratio estimate and the CPUE-mean-per-unit estimate in the northern region, but was lower than either of the other estimates in the southern region. The grand F:S ratio estimate for weakfish was larger by both weight and number than either of the other two estimates in the northern region and was the smallest in the southern region. The Hartley-Ross bias-corrected F:S ratio estimator gave estimates for the northern region that fell between the basic and grand F:S methods but gave negative estimates for the southern region (Table 4). CVs of the catch rates were generally larger for the basic F:S ratio estimator method than for CPUE-mean-per-unit estimator for spot in the northern region and Atlantic croaker in both regions, and smaller for spot in the southern region and weakfish in both regions. CVs estimated by the grand F:S ratio method were much smaller than those for either of the other methods for the northern region and much larger than the others for the southern region (Table 5). The variance of the catch rates with both methods was usually much larger than the mean (sometimes by an order of magnitude), indicating that catches were aggregated (Table 5). The confidence intervals around the bycatch estimates were huge regardless of method because of the small number of observed fishing days and the large variability in catch rates (Table 4).

Table 5

Observed catch rates in weight and numbers for selected species obtained with different estimation methods from field data. Observations in Pamlico Sound took place in July through October 1995 and observations in the Cape Fear River took place in August through October 1995. The CPUE-mean-per-unit estimator (CPUE=catch per unit of effort), which is based on the catch per day, uses day as a substitute for sample size. The basic F:S ratio estimator is the mean of the individual fish (F) to shrimp (S) ratios, and the grand F:S ratio estimator is the ratio of the mean catch of fish to mean catch of shrimp. AC = Atlantic croaker, SP = spot, and WF = weakfish. See text for calculations. Equations for the standard deviations are taken from Cochran (1977), Equations 2.20 and 2.45.

	Observed catch rate by weight								
				F:S ratio estimator					
	CPUE-mean-per-unit estimator			Basic			Grand		
Location and species	Avg. kg/day	SD	CV (%)	kg fish/kg shrimp	SD	CV (%)	kg fish/kg shrimp	SD	CV (%)
Pamlico Sound									
AC	49.64	34.79	70	1.62	1.05	154	0.86	0.05	6
SP	41.57	52.40	126	1.46	2.21	152	0.72	0.17	16
WF	53.04	79.90	151	0.75	0.60	80	0.92	0.15	16
Cape Fear River									
AC	24.01	21.56	90	0.27	0.31	116	0.14	0.61	438
SP	4.14	6.71	162	0.05	0.06	129	0.02	0.18	757
WF	31.80	30.10	95	0.25	0.24	94	0.18	0.81	443

	Observed catch rate by number								
				F:S ratio estimator					
	CPUE-mean-per-unit estimator			Basic			Grand		
Location and species	Avg. no./day	SD	CV (%)	no. fish/kg shrimp	SD	CV (%)	no. fish/kg shrimp	SD	CV (%)
Pamlico Sound									
AC	2418	1639	68	92.15	105.29	114	42.02	3.37	8
SP	1610	1885	117	72.56	121.92	168	27.97	4.69	17
WF	1014	1438	142	17.92	13.89	77	17.62	2.54	14
Cape Fear River									
AC	2287	2826	124	33.70	46.90	139	13.20	83.35	632
SP	257	464	181	3.05	4.16	136	1.48	12.10	816
WF	3198	3941	123	28.09	32.14	114	18.45	106.75	579

Bycatch simulations

For the normally distributed data, the CPUE-mean-per-unit estimator was the only estimator whose estimated bycatch was not significantly different than the actual simulated bycatch (% bias=0.006, P=0.94). All four of the ratio estimators significantly overestimated bycatch (Table 6), although the average bias was less than a 1% overestimate for the grand F:S and grand CPE ratio estimators. The basic F:S ratio estimator and the basic CPE ratio estimator both overestimated bycatch by 300–400% (Table 6). Using a model that included all main effects and all 2-way and 3-way interactions in the ANOVA, I found that the CV of the auxiliary variable (either shrimp catch or hours fished) was a significant main effect for all four of the ratio estimators, but there were no significant main effects for the CPUE mean-per-unit estimator (Table 7). Observer coverage was also a significant main effect for the F:S and CPE grand ratio estimators, but was not significant for the basic F:S or CPE ratio methods. The grand F:S ratio estimator, the grand CPE ratio estimator, and the basic F:S ratio estimator all showed several significant 2-way and 3-way interactions (Fig. 2), whereas the basic CPE ratio estimator had no significant 2-way or 3-way interactions. The CPUE-mean-per-unit estimator showed only two significant 3-way interactions among variables, and observer coverage occurred in both. The correlation between fish catches and shrimp catches was a significant main effect for the basic

Table 6

Mean percent bias of each of the estimators with normal and delta lognormal distributions of fish (F) and shrimp (S) from simulated data. Percent bias (Eq. 17) was calculated separately for each simulated fleet. N = the number of fleets in each analysis. The * indicates that the mean estimated bycatch is significantly different than the mean actual bycatch in a paired sample t-test (P<0.05). The CPUE-mean-per-unit estimator (CPUE=catch per unit of effort) uses unit effort as a proxy for sample size. The basic F:S ratio estimator is the mean of the individual fish to shrimp ratios, and the grand F:S ratio estimator is the ratio of the mean catch of fish to the mean catch of shrimp. The basic CPE ratio estimator is the mean of the ratios of catch per effort, where effort is a variable measure such as hours fished, and the grand CPE estimator is the ratio of the mean catch of fish to the mean estimate of effort.

	Mean % bias	
Estimator	Normal distribution N = 21,600	Delta lognormal distribution N = 118,810
CPUE mean-per-unit	0.006	0.09
Basic F:S ratio	427.80*	9.98*
Grand F:S ratio	0.65*	12.23*
Basic CPE ratio	336.13*	30.75*
Grand CPE ratio	0.46*	0.47*

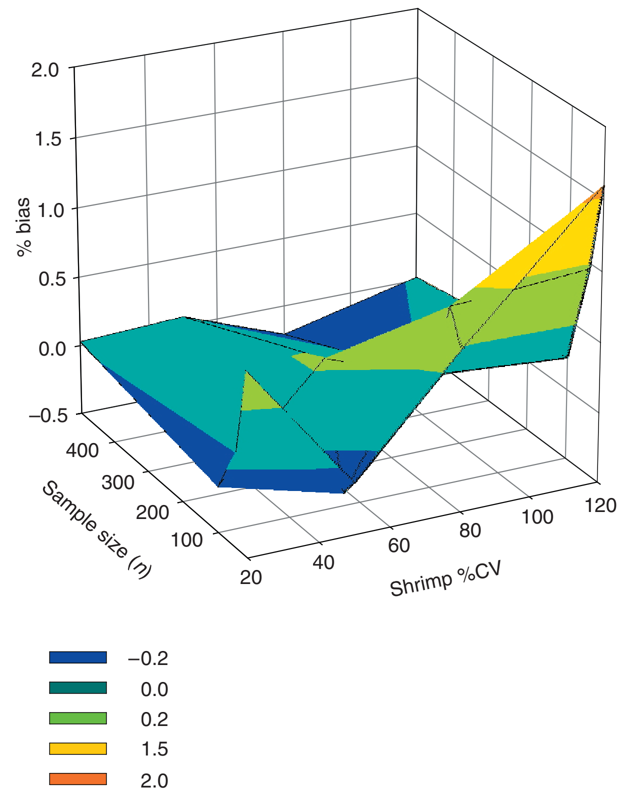

Figure 2

An example of a significant 3-way interaction among parameters in the bycatch simulations. This interaction is between shrimp CV and observer coverage (n) for the grand F:S ratio estimator with a correlation coefficient (r) of 0.5 between the catches of fish and shrimp. The simulated fish and shrimp catches were normally distributed. The lack of pattern in the % bias due to the interactions among various parameters was a common feature of all the estimators.

F:S estimator, and showed significant interactions with other parameters in both the grand F:S and grand CPE ratio estimators.

For the delta lognormally distributed data, the CPUE-mean-per-unit estimator was the only estimator whose estimated bycatch was not significantly different than the actual simulated bycatch (% bias=0.087%, P=0.64). All four of the ratio estimators significantly overestimated bycatch (Table 6), with estimates ranging from a less than 1% overestimate using the grand CPE ratio estimator to a 30% overestimate with the basic CPE ratio estimator (Table 6). Using all 2-way and 3-way interactions in the ANOVA, I found that significant main effects for both the basic and grand F:S ratio estimators were the probability of catching shrimp and the CV of the shrimp catch. The CV of the fish catch and observer coverage were also main effects in the grand F:S ratio method. The probability of catching fish was an additional main effect in the basic F:S ratio method. The only significant main effect in both CPE ratio estimators was the CV of effort, and the only significant main effect in the CPUE-mean-per-unit method was the CV of the fish catch. All five methods exhibited several statistically significant 2-way and 3-way interactions (Table 7).

Discussion

The differences in bycatch estimates generated from the field data show how confusing bycatch estimation can be and how difficult it is to compare bycatch estimates from past and recent studies. There was tremendous variability in the bycatch estimates generated by the different methods in the field study; for example, the estimate of Atlantic croaker bycatch in the northern region of North Carolina was either 28 million (±24 million), 84 million (±264 million), 144 million (±8.4 million), or 186 million (±8.4 million) fish depending on the estimator used. In addition, each method could give estimates that were higher or lower than the other methods without any consistent pattern by region or species; for example, in the northern region, the basic F:S ratio estimate was the highest estimate for spot, but it was one of the lowest for weakfish.

Based on the simulation results, the CPUE-mean-per-unit estimator was the best estimator, both because it showed less bias than the ratio estimators and because it was less influenced than the ratio estimators by parameters such as the mean or variance of the catch, observer coverage, or the correlation between the catches of fish and

Table 7

Significant parameters and interactions among parameters influencing bycatch estimates from simulated data. Significance was tested by using ANOVAs. *** = $P < 0.001$, ** = $0.001 \le P < 0.02$, * = $0.02 \le P \le 0.05$. AvgF = the mean catch of fish; AvgS = the mean catch of shrimp; FCV = fish CV; SCV = shrimp CV; ECV = Effort CV; r = the correlation coefficient between the catch of fish and the catch of shrimp, n = observer coverage; P(S) = probability of catching shrimp; and P(F) = probability of catching fish. The ranges of values for all parameters are shown in Table 1. The CPUE-mean-per-unit estimator (CPUE=catch per unit of effort) uses unit effort as a proxy for sample size. The basic F:S ratio estimator is the mean of the individual fish to shrimp ratios, and the grand F:S ratio estimator is the ratio of the mean catches of fish and shrimp. The basic CPE ratio estimator is the mean of the ratios of catch per effort, where effort is a variable measure of effort, and the grand CPE estimator is the ratio of the mean catch of fish to the mean estimate of effort.

		Ratio estimators			
Normal distribution	CPUE Mean-per-unit	Basic F:S	Grand F:S	Basic CPE	Grand CPE
Main effects					
SCV		***	***		
ECV		**		***	***
r		**			
n			***		***
Two-way interactions					
AvgS × AvgF			**		
SCV × n			***		
FCV × n			**		
ECV × n					***
ECV × r		**			
Three-way interactions					
AvgS × AvgF × FCV		**			
AvgS × FCV × n	**				
AvgS × n × r			*		
AvgF × SCV × ECV					*
AvgF × FCV × n					**
AvgF × ECV × n					**
SCV × FCV × ECV		**			
SCV × n × r	**				
FCV × ECV × r			**		
FCV × n × r					*

continued

shrimp. In fact, only the mean-per-unit estimators gave overall bycatch estimates that were statistically unbiased for both the normally distributed and delta lognormally distributed data. Three other estimators, the grand F:S and the grand CPE ratio estimators for the normally distributed data and the grand CPE ratio estimator for the delta lognormally distributed data, gave bycatch estimates that differed by less than 1% on average from the actual simulated bycatch, although these differences were statistically significant. In these simulations, the reason that a bias of less than 1% was statistically significant was probably due to the large number of fleets included in the paired-sample t-tests for each distribution, which made the standard errors and confidence intervals very small. Both the F:S and CPE basic ratio estimators (mean of the ratios) performed poorly in terms of bias in both normally distributed and delta lognormally distributed data, overestimating bycatch by between 10% and 427%, regardless of whether shrimp catch or hours fished was used as the auxiliary variable.

The ANOVAs performed on the simulated data indicated why the different estimates are so variable, and showed the complexities of the interactions among the parameters. The CPUE-mean-per-unit estimators displayed the fewest main effects and showed the fewest higher-level interactions among parameters. In the normally distributed data, there were no significant main effects or 2-way interactions for the CPUE-mean-per-unit estimator although observer coverage, (the sample size for each fleet) was a factor in both significant 3-way interactions. For the delta lognormally distributed data, the CV of the catch of fish was a significant main effect for the CPUE-mean-per-unit estimator, and observer coverage was a factor in three of the four significant 3-way interactions. The probability of catching fish and the CV of the fish catch were also fac-

Table 7 (continued)

Delta lognormal distribution	CPUE Mean-per-unit	Ratio estimators			
		Basic F:S	Grand F:S	Basic CPE	Grand CPE
Main effects					
P(S)		***	***		
P(F)		*			
SCV		***	***		
FCV	**		*		
ECV				***	***
n			***		
Two-way interactions					
P(S)×SCV		***	***		
P(S)×FCV			***		
P(S)×*n*			***		
P(F)×FCV	***				
P(F)×*n*			**		*
Avg(S)×FCV			*		
Avg(S)×ECV					*
Avg(F)×ECV					**
SCV×*n*			***		
ECV×*n*					***
Three-way interactions					
P(S)×AvgS×SCV		*			
P(S)×AvgS×ECV			**		
P(S)×AvgS×*n*	*				
P(S)×SCV×ECV		**			
P(S)×SCV×*n*			***		
P(F)×AvgS×AvgF		**	*		
P(F)×AvgS×SCV		**			
P(F)×AvgS×ECV				**	**
P(F)×AvgF×ECV					*
P(F)×SCV×*n*	**				
P(F)×FCV×ECV				***	
P(F)×FCV×*n*	**	**			**
AvgS×SCV×FCV	*				
AvgS×FCV×ECV			**		
SCV×FCV×*n*				***	**
FCV×ECV×*n*				**	

tors in several significant 2-way and 3-way interactions for the CPUE mean-per-unit estimator with delta lognormally distributed catches of fish and shrimp. All four of the ratio estimators were extremely sensitive to variance in the auxiliary variable, which was either shrimp catch or a variable measure of effort such as hours fished. Often in field data, the variance in the catch of shrimp will be much greater than the variance in the measure of effort; therefore the basic F:S ratio method has both the greatest bias and the highest variance in the auxiliary variable, making it the least desirable of the five methods tested. Both of the grand ratio methods were very sensitive to observer coverage for normally distributed data, although because of interactions with other parameters, it was hard to discern how increasing the number of observations changed the bias of the estimates (Fig. 2). Surprisingly, the correlation between the catch of shrimp and the catch of fish in the normally distributed simulations was only a significant main effect for the basic F:S ratio estimator, and even for that estimator the CV of shrimp catch had a much more profound effect. In the grand F:S ratio estimator, there were two 3-way interactions between the correlation coefficient and other parameters, but the other variables seemed to exert much more influence on the bycatch estimate than the correlation between the catches of fish and shrimp.

Comparisons of bycatch estimators between the normally distributed data and delta lognormally distributed data suggested that the basic ratio methods (mean of the ratios) might actually be less biased for lognormally distributed data than for normally distributed data. Both the CPE and F:S basic ratio estimators showed only about 10% of the bias with the delta lognormal data that they had with normally distributed data. The change in underlying distribution made very little difference to the bias shown by the grand CPE ratio method and increased the bias in the grand F:S method. For the CPUE-mean-per-unit method, the normally distributed data had less bias by an order of magnitude than the delta lognormal data, but neither of the biases was statistically significant, and both were much less than a 1% overestimate.

Cochran (1977) stated that the ratio estimator is the best linear unbiased estimate if the relationship between y_i, which is the catch of the bycatch species, and x_i, which is the auxiliary variable, is a straight line through the origin (indicating that the ratio of bycatch to shrimp or the catch of bycatch per hour fished is constant over all observations) and if the variance of y_i about this line is proportional to x_i. In practice, these conditions rarely hold true. The ratio of fish to shrimp catches and the bycatch per hour fished from field data often vary considerably among observations because of the patchy spatial distributions of fish and shrimp, seasonal differences in the relative abundances of fish and shrimp, movements associated with development through different life stages, and environmental factors. In addition, the bias of a ratio estimator is on the order of $1/n$, indicating that the bias will be small if n is large (Cochran, 1977). In practice, n, or the number of onboard bycatch observations, is often very small, particularly if the data are stratified by season or area, leading to large biases in ratio estimators.

The Hartley-Ross ratio estimator, which is a form of the basic ratio estimator method, may in some cases be an unbiased or less biased ratio estimator for small samples (Cochran, 1977). However, the Hartley-Ross method was not effective for the field data in the present study, giving nonsensical negative estimates of bycatch for all species in the southern region, although the estimates in the northern region were generally (but not always) somewhere between the basic and grand F:S ratio methods. The problems with the Hartley-Ross ratio estimator in the southern region may have been due to two factors: 1) the very low value for total shrimp landings from trip tickets in the southern region, and 2) discrepancies between the observed average catch of shrimp per day and the fleet shrimp catch per day from the trip ticket database. The Hartley-Ross equation starts with the mean of the individual fish to shrimp ratios expanded by the total shrimp landings (the basic F:S ratio estimator) and corrects the estimate based on the sampling fraction multiplied by a quantity that includes the average observed catch of shrimp per day (Eq. 8). The total shrimp landings recorded on trip tickets for the southern region were extremely low, about 16 times lower than the total shrimp landings in the northern region, although the number of days fished was about half as many in the southern region. In addition, the average shrimp catch per day on vessels that I observed in the southern region was much greater than the average reported on trip tickets (173.4 kg per day observed vs. 20.6 kg per day from trip tickets), whereas the average shrimp catch per day of shrimp that I observed in the northern region was much lower than the catch per day shown on trip tickets (55.6 kg per day observed vs. 173.5 kg per day from trip tickets). The result of this combination of factors was that the estimated total bycatch before correction in the southern region was very small due to the low amount of total shrimp landings, whereas the correction factor was very large because of the high observed average catch of shrimp, leading to negative estimates of total bycatch. These problems did not occur in the northern region. Low shrimp landings in the southern region compared to the northern region may have been due to an actual difference in the abundance of shrimp or differences in fishing habits such as a smaller number of nets per boat, tows per day, or tow times per tow in the southern region. However, it is also possible that more fishermen in the southern region than the northern region keep their catch or sell part of their catch independently without generating a trip ticket, which would reduce the total landings of shrimp in the trip ticket database. The differences in the average observed catch of shrimp per day were probably due to a combination of factors, most of them based on the problem of nonrandom or nonrepresentative sampling of boats. Because I depended on volunteer fishermen, the observed shrimp boats and captains were not randomly selected. In addition, because no records are kept of the boat size, gear used, fishing habits, or effort history of fishermen in the fleet, sampled boats could not be compared to unsampled boats for these factors. However, most of the fishermen whose boats I observed in the Cape Fear River (the southern region) owned large boats and made an average of 5 tows per day, whereas the fishermen I observed in Pamlico Sound (the northern region) generally had smaller boats and made an average of 3.2 tows per day. If the fishermen whose boats I observed in the Cape Fear River fished more than the average number of tows per day and the observed fishermen in Pamlico Sound fished fewer than the average number of tows per day, then the catch per day values would show these discrepancies. Other factors could have been differences between observed boats and average boats in the number of nets per boat, or tow times.

All of the methods that I used for bycatch estimation for the field data were based on the summed catches over all tows on a single day, because in this study the variance of catches among tows within days was much less than the variance among days. The use of tows as the basic unit of effort would therefore have underestimated the total variance. Sampling only day-trips probably contributed to the covariance among tows because tows spread over several days (and probably several locations) in a multiday trip would probably vary more among tows within a trip than tows in a single day. For randomly sampled multiday trips, estimation methods based on tows rather than days or trips may be preferred to those based on a trip as the unit of effort because the sample size of tows increases faster than the sample size of days or trips, which would tighten the confidence intervals around the estimates. However, the use of tows as the unit of effort could be considered pseudoreplication (Hurlbert, 1984) and could lead to erroneous variance estimates if the tows in a trip are not independent samples (Cochran, 1977). The choice of whether to use trips or tows as the unit of effort is dependent on two factors: 1) whether there is a high degree of covariance among tows in a trip, and 2) whether there is an independent estimate of the average number of tows per trip to use as an expansion factor.

Confidence intervals around the bycatch estimates are not symmetrical, although they are shown in Table 4 as symmetrical to allow for easier comparisons between the methods in the field study. Because of the small numbers of observations, most of the confidence intervals in the field study were larger than the means, with the general exceptions of the grand ratio estimators for all species in the northern region, which were surprisingly small. Most grand ratio estimators underestimate the true catch rate and are positively skewed unless the sample size is greater than 30 and the CVs of both the observed fish catch and the auxiliary variable are less than 10% (Cochran, 1977). As seen in Table 5, CVs of the observed fish catch from field data are rarely as low as 10%, and many are over 100%. The very small confidence intervals for all species in the northern region, and the very large confidence intervals for all species in the southern region generated by the grand ratio estimators are due to the nonrandom sampling of boats for the average catch of shrimp in both areas. This nonrandom sampling affects the confidence intervals because the average catch per day is a term in the denominator of the equation used to estimate the variance of the grand ratio estimator (Eq. 2.45 in Cochran, 1977). A very large value for the average catch per day from trip tickets compared to the value from observations as in the northern region causes an underestimate in the variance and reduces the confidence intervals, whereas a small value for the average catch per day from trip tickets compared to the value from observations as in the southern region causes an overestimate in the variance and increases the confidence intervals.

The field data shown here indicate some of the problems that are peculiar to observing and estimating bycatch in shrimp trawl fisheries in comparison to other fisheries. First, there are several hierarchical levels of variability that are ignored because of the logistical difficulties of sampling shrimp trawls. If the National Marine Fisheries Service (NMFS) protocol for shrimp trawl bycatch is followed, only one sample of the catch is taken from a net because of the large numbers of organisms caught in a typical tow. The NMFS protocol depends on the observer thoroughly mixing the catch so that a single sample characterizes the entire catch without variance, but mixing the catch to obtain a random sample is sometimes difficult because of the weight of the catch, the position of the culling tray, the size of the boat, or weather conditions. In addition, some species such as crabs may redistribute themselves after the catch is mixed by simply walking away. Stender and Barans (1994) found differences in fish-to-shrimp ratios when sampling the net compared with enumerating everything in the net. However this source of variability is not measured when following the NMFS protocol and not included in the bycatch estimates. Second, only one net is generally sampled per tow, although the boat may tow two, four, or more nets. There is therefore an expansion from the sampled net to the number of nets per tow so that variance among nets is ignored, and this process also adds error. Third, the expansion term, regardless of whether the total shrimp landings or the total shrimp effort is used, is assumed known without error. To include the error in the expansion term further widens the confidence intervals around the final estimates (Diamond and Hanan[16]).

One of the most interesting findings from the simulations was that all the methods tended to overestimate bycatch. None of the overall bycatch estimates, and relatively few of the individual fleet simulations, generated underestimates of the actual values. Although the mean-per-unit and grand ratio estimates overestimated bycatch by less than 1%, if the bycatch is large enough, these estimators could erroneously add hundreds of thousands of fish to the catch-at-age matrices used in stock assessments. Inaccurate stock assessments could have consequences for the management of fisheries, particularly for species like red snapper that are managed by quotas on the directed fisheries that are based on the level of bycatch or that have target levels set for rebuilding fish stocks. One method that might be used to "correct" bycatch estimates for the mean-per-unit estimator would be to use the estimator to calculate the catch of the target species from the observations, and then to compare the estimated target species catch with the total landings. Although this correction method assumes that the total landings of the target species are accurate (which is rarely a valid assumption), comparison of the estimated total catch of the target species to the actual landed catch might help to pinpoint biases and to adjust the estimated bycatch.

Because of the differences in estimates generated by the different methods of estimating bycatch, interpretations of bycatch estimates and comparisons of bycatch studies should be made very cautiously. It is often difficult to tell in past studies whether estimates were generated by basic F:S or grand F:S methods, but basic F:S methods overestimate bycatch to a much greater degree. Because of the statistically significant 2-way and 3-way interactions among parameters, it is unlikely that estimates generated by one method can be converted or corrected to other methods, so bycatch estimates made over time using different methods should not be directly compared. In addition, any bycatch estimate should include some indication of the variance around either the estimate or the catch rate, although variance estimates can be misleading if samples are not random. Finally, estimates of the weight or number of species taken as bycatch, no matter how large or small, are meaningless without an estimate of population abundance. Small populations could be harmed by relatively small amounts of bycatch, whereas large populations

[16] Diamond, S. L., and D. Hanan. 1986. An estimate of harbor porpoise mortality in California set net fisheries April 1, 1983 through March 31, 1984. National Marine Fisheries Service Admin. Report SWR-86-15, 40 p.

could be able to withstand even large amounts of bycatch. For this reason, the consequences of bycatch can only be evaluated if examined in conjunction with some estimate of stock size.

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