Using underwater video to directly estimate gear selectivity: the retention probability for walleye (*Sander vitreus*) in gill nets

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Abstract: We developed a new approach for directly quantifying selection parameters for fishing gear using a dual underwater video camera apparatus and employed the method to estimate gill net retention probability for walleye (*Sander vitreus*). The method allows observation of fish behavior around fishing gear and estimation of the absolute probability of fish encountering, contacting, or being retained by the gear. We demonstrated the applicability of this method by quantifying the probability that walleye were retained in multifilament nylon gill nets after contacting the nets. Walleye with total lengths 2.49 times the perimeter of the mesh were most likely to be retained, and retention probability peaked at 0.60 (95% confidence interval 0.41–0.90), meaning 40% of walleye that were the ideal size for a given mesh escaped after contacting the net. Our empirically derived retention curve exhibited a steep ascending limb and strong positive skew because of walleye morphology and the tendency for larger walleye to be captured by tangling. Most walleye that avoided capture did not fully enter the mesh or backed out of the mesh after they became temporarily wedged or tangled.

Résumé : Nous avons mis au point une méthode nouvelle pour quantifier les paramètres de sélection d'engins de pêche qui utilise une paire de caméras vidéo sous-marines et nous l'avons appliquée à l'estimation de la rétention de dorés jaunes (*Sander vitreus*) dans un filet maillant. La méthode permet d'observer le comportement des poissons aux alentours du filet et d'estimer la probabilité absolue que les poissons rencontrent et touchent l'engin de pêche et soient retenus par lui. Nous démontrons l'efficacité de la méthode en calculant la probabilité que les dorés jaunes soient retenus par des filets maillants en multifilament de nylon une fois qu'ils sont entrés en contact avec eux. Les dorés dont la longueur totale représente 2,49 fois le périmètre de la maille sont les plus susceptibles d'être capturés et la probabilité de rétention atteint un sommet de 0,60 (intervalle de confiance de 95 %, 0,41–0,90), ce qui indique que 40 % des dorés de taille idéale pour une grandeur de maille donnée réussissent à s'échapper après avoir touché au filet. La courbe de rétention obtenue empiriquement possède une partie ascendante à forte pente et une asymétrie positive importante à cause de la morphologie des dorés et parce que les grands dorés ont tendance à se prendre par enchevêtrement. La plupart des dorés qui réussissent à éviter la capture n'entrent pas complètement dans le trou de la maille ou alors reculent après avoir été temporairement coincés ou enchevêtrés.

[Traduit par la Rédaction]

Introduction

Fishing gears typically catch some sizes and species of fish more efficiently than others. Selection is defined as any process that causes the probability of capture to vary with the characteristics of the fish (Lucas et al. 1960; Hamley 1975). A quantitative expression of selection is termed selectivity, which traditionally means selection by size (Lucas et al. 1960). Selection can occur at different stages of the capture process, and collectively these selective processes determine catchability, or the proportion of a stock removed with a given amount of fishing effort (Ricker 1975). If the catchability of the gear is known, population abundance can be estimated from catch data. Catchability of fishing gear, such as gill nets, has been estimated using both direct and indirect approaches. Direct estimates can be made when the number and sizes of fish in a population (or the number subjected to fishing) and the number of each size captured with a given amount of effort are known. Direct estimates of catchability have been produced using mark-and-recapture techniques to estimate population size (Hamley and Regier 1973) or by stocking known numbers of fish (Jensen 1995) and then subjecting the population to fishing. Indirect estimates of catchability can be made using a variety of statistical techniques that do not require the number of fish to be known, but rely on various assumptions about the relative shape and amplitude of selectivity curves.

Investigators have broken catchability of gill nets into various components to represent the sequence of events leading to capture and to define the selective processes occurring at each stage. A problem with breaking catchability into multiple components is that these components become con-

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founded and only relative probabilities for each component can be estimated. Rudstam et al. (1984) and Spangler and Collins (1992) assumed larger fish were more likely to encounter the gear because they have higher swimming speeds and thus cover more area per unit of time. These authors separated catchability into two selective processes: (1) the probability a fish would encounter the net, where they defined encounter as a fish contacting the net and (2) the probability the fish would be retained after encountering the net. Anderson (1998) separated catchability into three selective processes: (1) encounter — the probability a fish will approach the net close enough to detect it; (2) contact — the probability a fish that encounters the net will swim into it; and (3) retention — the probability a fish that contacts the net will be captured. We use Anderson's (1998) definitions of encounter, contact, and retention throughout this paper.

Underwater surveillance of deployed fishing gear can be used to directly quantify selective processes. Using underwater video cameras and recently developed video analysis techniques (Hughes and Kelly 1996), it is possible to count the number of fish that encounter, contact, and are ultimately captured in a gear or some portion of it and estimate their sizes. Underwater video has been used to observe reactions of Atlantic salmon (*Salmo salar*) and whitefish (*Coregonus lavaretus*) to modified trap nets (Toivonen and Hudd 1993). Matsuoka et al. (1997) used underwater video to observe the behavior of prawns and finfish in an ocean seine while quantifying selectivity with pocket and cover nets. To our knowledge, no studies have used video cameras to directly quantify size selectivity of fishing gear.

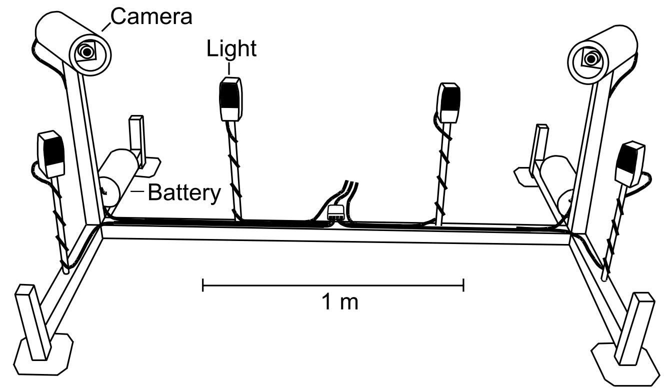
The purpose of this paper is to describe a new approach to directly quantify the selective processes for fishing gear and demonstrate its applicability by estimating the retention component for walleye (*Sander vitreus*) gill net selectivity models. Our primary goal is to develop a method to count absolute numbers and measure sizes of fish encountering a gear and (or) the probability that those fish will contact or be captured by the gear. Our second goal is to test the methodology by determining the probability that walleye are retained after contacting multifilament nylon gill nets and describe the methods of capture and behaviors that lead to escape from the nets. Finally, we demonstrate a potential use for this approach in testing indirectly estimated selectivity models by comparing the fit of our empirically derived retention curve to the retention function from Anderson's (1998) walleye gill net selectivity model.

Methods

General methodology

The general methodology requires two or more underwater video cameras to monitor deployed fishing gear and capture images of fish that approach, contact, and become captured by the gear. We developed a camera platform that was adjustable, yet could be transported and deployed next to fishing gear while maintaining the relative position of the two cameras. Our apparatus consisted of two high-resolution monochrome video cameras (M-370; Sony Corp., New York) in waterproof enclosures mounted on an aluminum frame along with four waterproof halogen lights (Ultra-Lights; ROS Inc., San Diego, Calif.) (Fig. 1). The lights were filtered with infrared glass (RG780; Schott Glass, Elmsford, N.Y.), allowing only infrared wavelengths (>780 nm) to pass. These wavelengths are outside the range detectable by the visual pigments of fish, but are detectable by monochrome video cameras. The video cameras were powered by 12-V batteries placed in waterproof housings that were mounted on the aluminum frame. The frame was adjusted so that the cameras were 1.8 m apart and 0.8 m from the bottom of the frame with their optical axes offset horizontally by approximately 90°. The camera platform was connected to a recording station on shore via a 300-m cable assembly consisting of two coaxial video cables (RG59U) that transmitted the video signals to video cassette recorders on shore and a 14-gauge power cable that carried electricity from a 1200-W generator on shore to the lights on the camera platform. Once the fishing gear was deployed, the camera platform was lowered into the water next to the gear and the cable assembly was unwound back to shore. Images were recorded on videotape using two high-density S-VHS recorders (Panasonic AG-6740; Matsushita Electric, Secaucus, N.J.), which allowed 8 h of real-time video (30 frames per second) to be recorded on a single tape. The video recorders' clocks were synchronized during recording to allow analysis of images taken simultaneously by the two cameras.

Fig. 1. Diagram of the camera and light apparatus used to observe walleye (*Sander vitreus*) that encounter gill nets and estimate their sizes.



Videotapes were reviewed to determine the number of fish that encountered, contacted, or become captured by the gear and to estimate the sizes of those fish. We used a video analysis technique developed by Hughes and Kelly (1996) that requires at least two views of the scene and a calibration quadrat, or object of known dimensions, to determine the three-dimensional (3-D) location of objects in the field of view of the cameras. Our calibration quadrat consisted of a 1-m^3 aluminum frame with 10-cm^2 grids on four sides, which was lowered into the field of view of the cameras and oriented so that two of the four sides were perpendicular to the optical axis of each camera. We recorded the images of the calibration quadrat from both cameras for 1 min and then removed the quadrat from the water. We used the methods of Hughes and Kelly (1996), with slight modification, to estimate fish size. Video images were digitized using an IBM-compatible computer with a video capture card. We used NIH Image software, a JAVA program, and two Excel macros to calibrate the video images and calculate 3-D locations of a fish's snout and tail locations from the two views. The JAVA program and Excel macros were provided by L.H. Kelly (Bureau of Land Management, Northern Field Office, 1150 University Avenue, Fairbanks, AK 99709-3844, U.S.A., personal communication; available for download at http://aurora.ak.blm.gov/science/).

Walleye observations

To illustrate the methods, we estimated the probability that walleye would be retained after contacting multifilament nylon gill nets. We observed walleye encountering gill nets in Moody Lake using the camera apparatus during open water on five nights in October 1999, 31 nights from late April to October 2000, and 12 nights from May to August 2001. Moody Lake is a small (17 ha), clear lake in central Minnesota with a maximum depth of 3.7 m and a Secchi depth usually exceeding the maximum depth. Moody Lake was used to extensively raise walleye fingerlings in the 1980s, but was later abandoned because of lack of winterkill. The fish community was dominated by walleye surviving from the original stockings. Walleye in Moody Lake were limited in their size range, most being between 270 and 350 mm fork length (FL) in 2000, and exhibited poor condition and slow growth because of lack of forage fish. To increase the size range of fish in Moody Lake, we introduced 22 walleye between 424 and 582 mm total length (TL) in 2000 and 275 walleye between 384 and 636 mm TL in 2001. Walleye introduced in 2000 were from Whitefish Lake and did not differ significantly in their length–girth relationship from Mille Lacs Lake walleye (G. Grant, unpublished data), whereas walleye introduced in 2001 were from Mille Lacs Lake.

We modified standard Minnesota experimental gill nets (Minnesota Department of Natural Resources 1993) to reduce the number of walleye killed outside the field of view of the cameras. Each night we used one 3-m-long panel consisting of 25-, 32-, or 38-mm bar mesh, the three mesh sizes we calculated would be most effective at capturing the size of walleye present in Moody Lake. Each panel was centered on 15.5-m lead and float lines to simulate a longer net because we noticed our standard nets were often set loose and bowed both horizontally and vertically because of wind-induced water currents. We set the gill net in the late afternoon and then lowered the camera apparatus next to the net approximately in the center of the panel. The cameras were inspected by SCUBA diving to ensure that they were close enough to the net and that the net had not been tangled and to remove any vegetation between the cameras and the net. Finally, we set a 3-m-high × 50-m-long, 6-mm bar mesh beach seine perpendicular to the gill net panel with one end anchored between the two cameras to lead fish towards the gill net. Within each year, we set the gill net and cameras in the same general location within Moody Lake. In 1999 and 2000, the gill net and cameras were set in the deepest part of Moody Lake (~3.7 m deep), where there was little vegetation, and the seine used to lead walleye into the gill net did not extend to shore. In 2001, we set the gill net and cameras in vegetation in shallower water (~3 m deep) and extended the lead seine to the shore. Once deployed, the lights were activated and the video recorders were started. The nets and camera apparatus were removed the following morning. We measured the FL and girth of all captured fish and noted the method by which they were captured (tangled or wedged) and the point on the body where the mesh was wedged or tangled.

We estimated the FL of each walleye observed to contact the nets using simultaneous estimates of the fish's snout and tail locations. Each walleye observed to touch the net was defined as a single contact regardless of the number of times it touched the net, as long as it remained in the field of view of the cameras. The snout and tail locations were estimated from still images taken when the snout and tail of the fish were visible from both cameras and when the fish was not flexing its tail or body (i.e., was approximately straight). We attempted to obtain at least three sets of simultaneous images for each fish, with each set separated by at least 1 s. However, in some cases we could only obtain one or two sets of images from each fish, and in some cases the images were separated by less than 1 s. FL was calculated as the straight-line distance between the estimated snout and tail fork locations for each set of images, and length of each fish was estimated as the mean FL calculated from the images rounded to the nearest millimetre. We compared the estimated and actual FL of fish that were retained in the nets to calculate errors in the length estimates.

To correct for bias caused by the smaller girth of walleye in Moody Lake, we converted the estimated FL of Moody Lake walleye into estimated TL of walleye from Mille Lacs Lake with equivalent girths. We developed a FL–girth regression for Moody Lake walleye that were captured by angling or in study nets during 2001, where both girth and FL were measured in millimetres.

$$\text{(1)}\quad \ln(\text{girth}) = 0.4545 + 0.7926\ \ln(\text{FL}),\qquad \text{df} = 44,\ R^2 = 0.85$$

For Moody Lake walleye (≤380-mm FL) that we observed to contact the nets, we used this FL–girth regression to calculate an estimated girth from either the actual FL of walleye that were captured or the estimated FL for fish that were not retained. We then estimated the TL of walleye in Mille Lacs Lake that would have equivalent girths using a regression provided by R.E. Bruesewitz (Minnesota Department of Natural Resources, 1200 S. Minnesota Avenue, Aitkin, MN 56431, U.S.A., personal communication), where both TL and girth were measured in millimetres.

$$\text{(2)}\quad \ln(\text{TL}) = [\ln(\text{girth}) + 1.6678]/1.1662,\qquad \text{df} = 677,\ R^2 = 0.98$$

Because we never captured any Moody Lake walleye >380-mm FL, fish that were longer than 380 mm were assumed to be stocked, and their estimated FL was converted to TL using equations from Carlander (1997).

Retention curve estimation

For each mesh size, we computed the number of walleye in each 25-mm TL size category that contacted the net and (1) swam through the mesh, (2) were blocked by the mesh but not retained, and (3) were retained by the mesh. We also calculated the ratio of TL to mesh perimeter, x_i, for each i =

1, 2, …, n walleye observed to contact the nets. We followed Anderson's (1998) assumption that retention probability depended only on the ratio of fish size to mesh size. To understand the relationship between the method of capture and ratio of TL to mesh perimeter, we plotted the proportion of fish that were captured by wedging and tangling in each 0.2-unit-wide x_i category (i.e., $2.0 \le x_i < 2.2$, $2.2 \le x_i < 2.4$, $2.4 \le x_i < 2.6$, etc.).

To better understand the shape of the retention curve (i.e., skewness), we used our data on captured walleye to determine if there were trends between TL–mesh perimeter ratios and the point on the body that the mesh became wedged or tangled. We calculated the mean TL–mesh perimeter ratio for fish that were wedged to their maxillaries, opercula, pectoral fins, pelvic fins, and dorsal fins. We also noted the range of TL–mesh perimeter ratios of walleye captured by tangling.

Comparison with indirect estimates

We used our empirical data to test Anderson's (1998) relative retention curve for Mille Lacs Lake walleye by comparing the deviances for three models: (1) $P(R) = G$, (2) $P(R) = aG$, and (3) $P(R) = aG(lm^{-1})^c$, where $P(R)$ is the probability of retention, G represents Anderson's (1998) relative retention function for Mille Lacs Lake walleye, a is a proportionality constant that controls the amplitude of the retention curve (i.e., fewer than 100% of fish are caught at the optimal TL–mesh perimeter ratio), c is a rotational constant that adjusts the shape of the curve (i.e., the TL–mesh perimeter ratio where retention is maximized), l represents fish total length, and m represents mesh size. We calculated the deviance, D, for model 1 following the formulas of Hosmer and Lemeshow (1989).

$$(3) \qquad D = \sum_{i=1}^{N} d(r_i, \hat{\pi}_i)^2$$

where

$$(4) \qquad d(r_i, \hat{\pi}_i) = -\sqrt{2|\ln(1 - \hat{\pi}_i)|}$$

when $r_i = 0$, and

$$(5) \qquad d(r_i, \hat{\pi}_i) = \sqrt{2|\ln(\hat{\pi}_i)|}$$

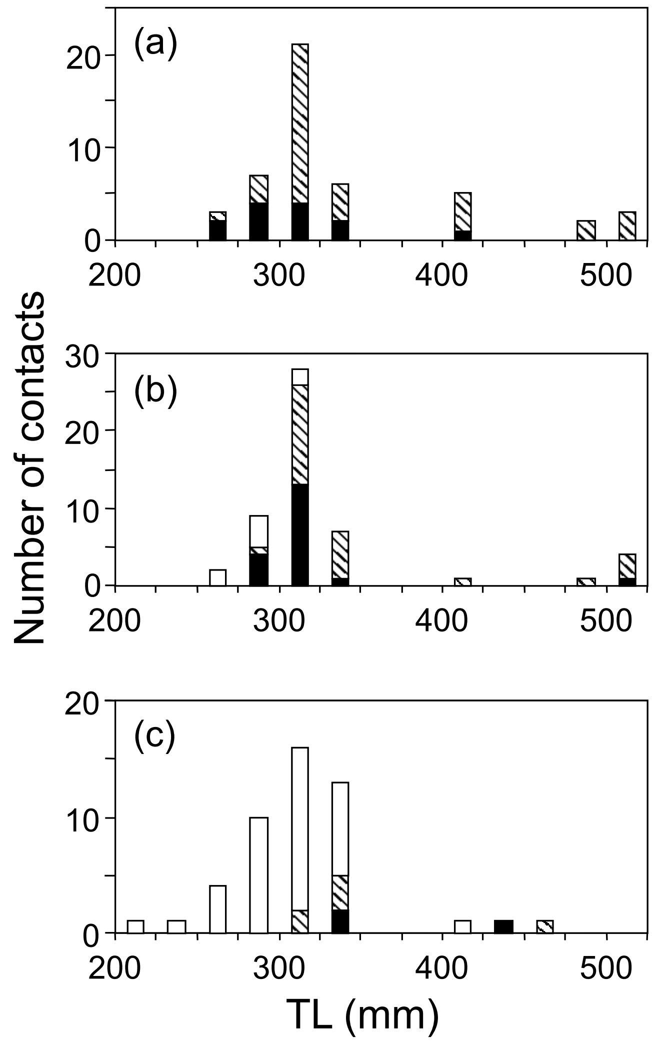
when $r_i = 1$ and where $\hat{\pi}_i$ is the predicted retention probability from Anderson's (1998) retention function (G) for Mille Lacs Lake walleye based on x_i. Estimates of parameters a and c in models 2 and 3, as well as deviance values for models 2 and 3, were calculated by maximum likelihood estimation using the General Linear Model function in S-Plus. We used an analysis of deviance to determine whether additional parameters significantly improved model fit using a χ^2 probability distribution (Hosmer and Lemeshow 1989).

Results

Walleye observations

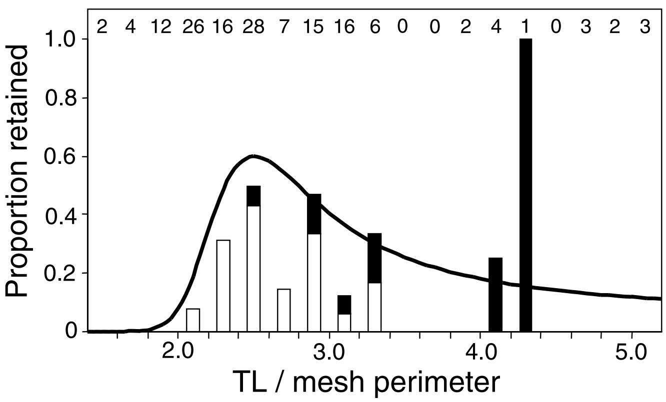
During 48 net-nights, we observed 153 walleye contact the gill nets, and FL was estimated for 147 of these fish. Of the 147 walleye that contacted the nets for which length could be estimated, 35 were retained, 46 swam through the nets, 29 escaped after being temporarily wedged or tangled, and 37 never became wedged or tangled. The number of walleye that passed through the gill nets and the number retained varied with mesh size (Fig. 2). No walleye swam through the 25-mm mesh, whereas eight walleye swam through the 32-mm mesh and 39 walleye swam through the 38-mm mesh. Thirteen, nineteen, and three walleye were retained in the 25-, 32-, and 38-mm mesh sizes, respectively. Of the 35 walleye that were retained, 27 were wedged in the net and eight were tangled (Fig. 3). The 3-D analysis software produced accurate length estimates; the difference between estimated and actual walleye lengths was not significantly different from zero (t test: $p = 0.218$; actual–estimated: range –12 to 18 mm).

Fig. 2. Number of walleye (*Sander vitreus*) in 25-mm size groups that contacted gill nets that passed through (open bars), were blocked (i.e., did not pass through and were not retained; hatched bars), or were retained (solid bars) in (*a*) 25-mm, (*b*) 32-mm, and (*c*) 38-mm bar mesh gill nets. TL, total length.



Walleye typically escaped from gill nets by backing out of the mesh and then turning and swimming parallel to or away from the net. Twenty-three of the walleye that were tempo-

Fig. 3. Proportion of walleye (*Sander vitreus*) in each total length (TL)–mesh perimeter category that were retained after contacting the gill net. The number of contacts observed in each TL–mesh perimeter category is indicated along top of graph. Open bars represent fish that were wedged, whereas solid bars represent fish that were tangled. The solid line represents 0.6*G*, where *G* is the retention probability of Anderson's (1998) gill net selectivity model for Mille Lacs Lake walleye.



rarily retained swam into the mesh but could not swim through. Upon backing out of the mesh, the twine hooked on the maxillary or opercular bones of these fish, and they escaped by turning and swimming away from the net or thrashing their head from side to side to dislodge the twine. Three other fish did not enter the mesh, but were temporarily tangled by their teeth or maxillaries before escaping, whereas two fish turned after contact and became wrapped in the net before escaping. Only one walleye that was temporarily retained was observed to pass through the net upon escaping. Nineteen of the 29 fish that were temporarily retained escaped in less than 1 min, whereas two walleye were retained for >1 h before escaping (maximum 5 h 34 min).

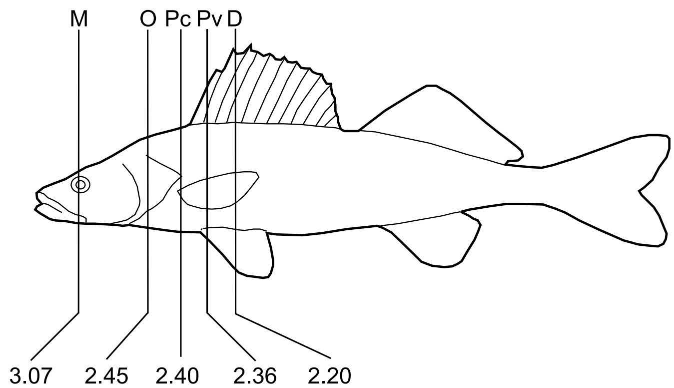
We observed a walleye swim into the net multiple times on 21 occasions; however, each encounter in which the walleye touched the net was considered to be a single contact regardless of the number of times the walleye touched the net. Sixteen walleye that repeatedly swam into the net were never retained, either permanently or temporarily, despite contacting the mesh up to nine times. Three walleye contacted the mesh more than once before being temporarily retained, one walleye contacted the mesh twice before swimming through, and another contacted it twice before being captured.

Retention curve estimation

The retention probability increased rapidly at TL–mesh perimeter ratios between 2.0 and 2.5, then decreased gradually at ratios above 2.5, exhibiting a strong positive skew. A second peak in retention was observed at TL–mesh perimeter ratios between 4 and 4.4 because of larger fish tangling in the net (Fig. 3).

Walleye with larger TL–mesh perimeter ratios were wedged closer to their snout, whereas fish with smaller ratios progressed farther into the mesh before becoming wedged (Fig. 4). The eight walleye that were captured by tangling had TL–mesh perimeter ratios ranging from 2.53 to 4.23 (mean 3.20).

Fig. 4. Mean total length (TL)–mesh perimeter ratios for walleye (*Sander vitreus*) wedged at different points on their body in gill nets. Lines represent the location on the body that the mesh encircled, indicated by the letter above the line. M, maxillary; O, operculum; Pc, pectoral fin; Pv, pelvic fin; D, dorsal fin.



Comparison with indirect estimates

Comparing our empirical data with Anderson's (1998) retention function for Mille Lacs walleye, we found that adding a proportionality constant of 0.60 significantly decreased model deviance, whereas adding a rotational constant did not improve model fit significantly. Our empirical data fit model 2 with a proportionality constant $a = 0.60$ (95% confidence interval, 0.41–0.90) significantly better than model 1 (Table 1). The addition of a rotational constant, c, in model 3 did not significantly reduce the deviance residuals, so we lacked the evidence to refute the shape and modality of Anderson's (1998) relative retention curve (Table 1).

Discussion

The application of underwater video to quantify size selectivity of fishing gear has several advantages over more traditional direct and indirect approaches. Underwater surveillance allows direct estimation of the absolute probability of individual selectivity components, such as the probability that fish encounter, contact, or become retained in the gear. Direct approaches used in the past allow estimation of catchability (i.e., the combination of all selective processes) but not the selectivity occurring at different stages leading up to capture. Indirect approaches can be used to estimate the selectivity occurring at different stages of the capture process, but only on a relative rather than on an absolute scale. Indirectly estimated probabilities inherently depend on model assumptions, whereas the underwater video approach produces empirically derived probabilities that can be used to directly estimate selectivity patterns and validate indirectly derived selectivity models. The technique also allows observation of fish behavior, which leads to a refined understanding of the process of capture in, and escape from, fishing gear. The use of infrared lights allows observation of fish behavior at night without disturbing the fish or altering behavior.

The general approach should be widely applicable to size and species selectivity for a wide variety of fishing gear, including trap nets, trammel nets, baited hooks, and trawls.

Table 1. Analysis of deviance table for the fit of our binomial data to three models.

			Difference		
Model	Residual df	Residual deviance	df	Deviance	P
(1) $P(R) = G$	147	321.868			
(2) $P(R) = aG$	146	138.920	1	182.948	<0.0001
(3) $P(R) = aG(lm^{-1})^c$	145	138.797	1	0.123	0.726

Note: The retention probability $P(R)$ is equal to the following for each model: (1) Anderson's (1998) retention function G; (2) Anderson's retention function with a proportionality constant a; and (3) Anderson's retention function with a proportionality constant a and a rotational constant c; l is fish total length and m is mesh size. Probability values were calculated using a χ^2 probability function.

Hughes and Kelly's (1996) video analysis technique is very flexible in allowing the two cameras to be in any orientation; therefore, the camera platform may be altered based on the size of fish and type of gear being monitored. A camera platform could also be deployed alone to estimate the probability that fish would encounter a gear at a given location.

The primary disadvantages of this technique are that it is limited to environments with high water transparency and only a limited space can be monitored at any time, which may require many nights of observation or high fish densities to collect an adequate sample. Sample size may not be an issue if the entire gear can be monitored (e.g., trap net throat, hook, etc.) and sample sizes can be increased by using multiple camera platforms or increasing deployment time.

By quantifying the absolute retention probability for walleye after contacting gill nets, we were able to estimate the amplitude of the retention curve from Anderson's (1998) gill net selectivity model for Mille Lacs Lake walleye and confirm that it's main mode occurs at TL–mesh perimeter ratios of 2.5. Anderson's (1998) model was generated by assuming the number of walleye of different sizes in Mille Lacs Lake was equal to virtual population analysis estimates, which were based on harvest estimates and tuned with gill net and trawl surveys. Using the virtual population analysis population estimates and catches from annual gill net surveys, Anderson (1998) applied maximum likelihood methods to infer the amplitude and shape of the encounter, contact, and retention selectivity functions. Because the encounter, contact, and retention functions were confounded, the amplitude of the contact and retention functions were normalized to one, suggesting that 100% of walleye that contacted the gill net and were the ideal size for the mesh were retained. We found the probability of retention for walleye in gill nets peaked at 0.60, meaning 40% of walleye that were the ideal size for a given mesh escaped after contacting the net. However, our results confirm that Anderson's (1998) retention function accurately predicted that the optimum TL–mesh perimeter ratio for walleye in gill nets was 2.5.

The shape of Anderson's statistically derived retention curve closely resembled our empirically derived retention data; therefore, we did not have the evidence necessary to refute the shape of Anderson's (1998) retention curve. Because the length distribution of fish observed was limited and the response was binary, the sample size (n = 147) was not adequate to decide whether the shape of the curve should be unimodal or multimodal. Although model 2 has a good fit, the visual impression from Fig. 3 is that the model overestimates $P(R)$ at the left end of the curve, which represents walleye that are wedged in the net.

Thus, modifying Anderson's (1998) retention function to be more realistic only requires adding a proportionality constant of 0.60, indicating the product of the encounter and contact probabilities must be underestimated by a factor of 1.667 (= 0.60^{-1}). Because Anderson's (1998) contact function was also relative (contact probability for the largest mesh size was set to one), it is likely that absolute contact probability is lower than the model predicts, and encounter probability is underestimated by a factor >1.667.

The shape of the retention curve appears to be a function of both walleye morphology and method of capture. Retention due to wedging alone appeared to be unimodal and positively skewed, with the modal TL–mesh perimeter ratio of 2.5 corresponding to walleye that were gilled (i.e., wedged with the twine hooked behind their opercula). The left edge of the retention curve is defined by the threshold of TL–mesh perimeter ratio at which smaller fish can pass through the net, approximately 2.1 for walleye. The ascending limb of the retention curve represents fish with TL–mesh perimeter ratios between 2.1 and 2.5 that can progress into the mesh past their opercula before becoming wedged, whereas the descending limb represents fish that are wedged closer to their snout. Walleye with TL–mesh perimeter ratios >2.5 are typically wedged between their opercula and maxillaries, the maxillary being the most anterior structure that can hook the twine during wedging, preventing fish from backing out of the mesh. The positive skew in retention probability due to wedging may be partly explained by walleye body morphology. The difference between girth at the operculum and maximum girth is less than the difference between girth at the operculum and girth at the maxillary, which results in retention of a narrower size range of fish to the left of the mode and a wider size range to the right of the mode.

Tangling of walleye with larger TL–mesh perimeter ratios caused the retention curve to be positively skewed or possibly bimodal. Our data support Hamley and Regier's (1973) finding that little tangling occurs at TL–mesh perimeter ratios below the optimal value for wedging, presumably because smaller fish eventually swim forward and can pass through the net. Because we observed few walleye with large TL–mesh perimeter ratios contact the nets, it is impossible to determine whether tangling results in a bimodal retention probability curve using our data. Although we stocked larger walleye in Moody Lake, they were much less numerous than the naturalized walleye and were rarely observed. There are also discrepancies in the literature as to whether tangling and wedging result in bimodal selectivity curves for walleye. Hamley and Regier (1973) found that catchability for walleye was bimodal for a given mesh size, caused by a combination of unimodal selectivity curves for wedging and tangling, with tangling relatively more important for large mesh sizes. Henderson and Wong (1991) assumed tangling and wedging were dependent processes and did not distinguish between them in their selectivity model for walleye. Walleye selectivity models derived indirectly, where no shape was assumed for the retention curve, have produced both unimodal and bimodal selectivity curves for a given mesh size (Anderson 1998).

Catchability may be bimodal or multimodal for walleye even if retention probability is unimodal, because larger fish may have a higher probability of encountering the nets (Rudstam et al. 1984; Spangler and Collins 1992). When selectivity is computed for a gang of meshes, catchability may be multimodal because of the combination of net sizes and because larger mesh sizes may be harder for fish to detect and avoid (Anderson 1998). Baranov (1914) postulated that all mesh sizes had selectivity curves of the same height, assuming that the thickness of the twine was proportional to mesh size. For Minnesota gill nets, twine size is held constant as mesh size decreases, which should make smaller mesh nets easier to detect and avoid (Hamley 1975).

We did not use our data on encounters and contacts to test the corresponding components of Anderson's (1998) model, although the technique could be applied to any component of selectivity. We assumed that altering the dimensions of the gill net and adding a seine as a lead net biased the number of walleye that encountered the nets. A longer gill net might have led more fish towards the cameras and increased the encounter rate, whereas the lead net probably increased the number of fish that encountered the nets near the cameras. We also assumed that the high transparency of Moody Lake made the nets easier to detect than in more turbid water. However, we assumed that once a walleye contacted a gill net, the overall dimensions of the net and water transparency did not affect the retention probability.

Underwater video has become popular with recreational anglers, but the potential of this tool has not been realized in fisheries research. We believe surveillance of deployed fishing gear to quantify aspects of gear selectivity is one potential use for this tool that can lead to more refined selectivity models and a greater understanding of reaction of fish to gear. We are making further refinements to multiple underwater video camera platforms. Refinements include reducing power requirements by using monochromatic LED (light emitting diode) illuminators, allowing the camera module to be battery-powered and self-contained. Wireless transmission systems are being employed to eliminate cable assemblies, thereby increasing portability and decreasing deployment time. Finally, we are experimenting with camera–light configurations for use in various habitats or with different types of gear, including downward-looking cameras to provide dorsal aspects and improve accuracy of fish size estimates by accounting for flexing during swimming.

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