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Bridle herding efficiency of a survey bottom trawl with different bridle configurations

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ABSTRACT

An extensive field experiment was conducted to examine flatfish herding efficiency of the Northeast Fisheries Science Center survey bottom trawl gear. This experiment compared catches of six flatfish species from three different bridle length configurations with the assumption that increased catch is proportional to the increased area swept by the herding efficiency of the bridles. Underwater video observations were taken of the bridles and survey gear to observer gear performance and fish behavioral reactions to the survey gear.

RÉSUMÉ

INTRODUCTION

The fish capture process by bottom trawl is complex with species- and size-specific selectivity occurring well in front of the actual net. Behavioral responses to the approaching vessel and gear influence the horizontal and vertical distribution of some species and certain species react to the bottom trawl doors, bridles and sand clouds they generate (Main & Sangster, 1981a, 1981b; Wardle, 1993; Engas, 1994; Walsh, 1996). Some of these reacting fish move outwards and avoid capture while others move inwards towards the path of the approaching trawl, repeatedly encountering and reacting to the bridles while moving further inward toward the path of the trawl in a process termed herding (Hemmings, 1969; Wardle, 1993). Commercial trawls seek to exploit this herding response by extending the distance between the wing-ends and doors to increase the area swept by the gear and increase catch rates and often cover the cables with rubber discs to maximize bottom contact and visual stimuli (Dickson, 1974; Strange, 1984). Given the inherent variability in the capture process due to herding variability, some multispecies bottom trawl surveys utilize the shortest possible bridle lengths necessary to achieve the desired net mouth opening.

The degree of herding depends on many factors. Flatfish species tend to react to bottom trawl gear at shorter distances than roundfish and roundfish tend to have stronger burst and sustained swimming capabilities, suggesting differences in the herding or avoidance response mechanisms (Wardle, 1993; Winger et al., 1999; Winger et al., 2004; Ryer, 2008). Studies have shown that the length of the bridles are an influential factor for herding efficiency and that herding efficiency can be both size and species specific (Harden Jones et al., 1977; Engas & Godo, 1989a; Dickson, 1993a, 1993b; Ramm & Xiao, 1995; Somerton & Munro, 2001). However, herding efficiency is not well defined for species in the Northwest Atlantic, particularly for flatfish species. Engas & Godo (1989a) examined the effects of different bridle lengths on the length composition of survey trawl catches of Atlantic cod and haddock and found a general increase in both numbers and size of both species with increasing bridle length. Somerton & Munro (2001) estimate bridle efficiency of a survey trawl based on three different bridle lengths for seven species of flatfish in the Eastern Bering Sea. Their results showed significant herding effects for all species of flatfish with no length effect for five of the species and a significant decrease in bridle efficiency with increasing fish length for two species. The speed of the tow and the angle at which the bridle extends away from the wing-ends are thought to influence herding efficiency (Engas, 1994; Somerton & Munro, 2001). If the bridle angle is too wide or the tow speed too fast, iterative encounters with the bridle will occur too quickly and fish may be unable to react and thus be overtaken by the bridle and not captured. Once fish reach the mouth of the trawl they may react again in an attempt to avoid the gear. Some species are known to turn and swim in the mouth of the trawl or directly in front of the ground gear, at the same speed of the trawl until they become exhausted and fall back into the net or attempt to escape either over the headrope or dive under the ground gear (Hemmings, 1973; Wardle, 1993). Escapement under the ground gear is a function of the ground gear size and configuration and is also known to be species and size dependent (Engas & Godo, 1989b; Walsh, 1992; Munro & Somerton, 2002). Survey trawls typically utilize small mesh webbing and codend liners so escapement through the meshes is likely minimal for all but the smallest fish (Engas, 1994; Walsh, 1996). Vision is considered the primary sense used by fish for the avoidance of fishing gear (Glass & Wardle, 1989; Wardle, 1993). Herding and avoidance behaviors are therefore influenced by bottom light levels and studies have shown significant diel differences in catches of certain species as a result (Walsh, 1988; Walsh, 1991; Ryer & Barnett, 2006; Kotwicki et al., 2009).

The Northeast Fisheries Science Center (NEFSC) utilizes sampling gear designed by an advisory panel made up of regional fishing industry members and government and academic scientists. In an effort to minimize variability from herding the gear was designed to minimize the distance between the wing-ends and doors while maintaining the desired net mouth opening. This resulted in relatively short length bridles (36.5m) made of bare, uncovered wire. Several species assessed using these survey data potentially exhibit herding behavior, although the specific species, magnitude and length effects are unknown. If herding occurs, abundance estimates calculated based on the area swept by the net width would likely be an overestimate of true abundance due to the increased density in the net path from herding, whereas abundance estimates based on the area swept by the door width would likely be an underestimate, even for species exhibiting strong herding behavior, since some fish escape capture.

This study attempts to estimate species and length specific bridle efficiencies of the NEFSC standard survey bottom trawl as well as observe flatfish behavioral response along the survey trawl bridles using underwater video. An extensive field experiment in 2014, targeting Georges Bank flatfish, compared catches between varying bridle lengths with the assumption that increased catch is proportional to the increased area swept by the herding efficiency of the bridles.

METHODS

SAMPLING GEAR DESCRIPITON

The standard NEFSC survey bottom trawl gear is a 400 x 12cm trawl rigged with a rockhopper sweep. The trawl incorporates side panels, making it 4-seams, which requires a 3-bridle rigging configuration. The trawl is constructed of 6.0cm mesh webbing from the square aft to the codend and has a 2.54cm knotless mesh liner in the entire codend. The forward portion of the trawl (all jibs, upper and lower wings, 1st bottom belly and 1st and 2nd side panels) is constructed of 12.0cm mesh webbing. The headrope of the trawl is 20.58m long of 1.9cm (3/4in) combination wire rope and the 3-piece bolschline is 24.36m long of 1.6cm (5/8in) stainless steel wire covered with 6cm (2-3/8in) rubber discs. 60 Nokalon #508, 20cm (8in) center-hole floats are strung in two 30-float strings along the headrope. The 3-piece rockhopper sweep is 27m long and has 40.64cm (16in) diameter rubber rockhoppers in the center section and 35.56cm (14in) diameter rubber rockhoppers in each wing section. Rubber floppy discs (equal diameter to the rockhoppers) are between each rockhopper and 12.7cm diameter filler rubbers (cookies) tightly fill in all gaps between the rockhoppers and floppy discs. Lead weight is added to the center section (45.36kg) and wing ends (13.61kg each). The gear design utilizes a 27m long, 1.4cm (9/16in) galvanized wire traveler to attach the trawl to the rockhopper sweep.

The bottom legs are 36.6m of 1.9cm (3/4in) diameter, 6x19, galvanized, independent wire rope core (IWRC) wire. The upper legs are comprised of one 18.3m long, 1.4cm diameter, 6x36, IWRC wire connected to 2 additional 18.3m long, 1.4cm diameter wires connected to the top and middle wing-ends. Each wing-end has a wire extension coming from it that connects to the bridles. The bottom and middle wing end extensions are 124cm of 1.6cm diameter wire and the top wing end extensions are 174cm of 1.3cm diameter wire. The top wing end extensions are longer to increase the vertical opening and each have 3 trawl floats strung on them to minimize the weight of the wire. Please see Politis et al. (2014) for additional details and diagrams.

This study did not use the standard NEFSC survey trawl doors which are 2.2m², Poly-Ice Oval trawl doors and 550kg each. Rather, the 3.4m², Thyboron Type IV, 590kg, trawl doors of the contracted vessel, the F/V Karen Elizabeth, were used. Restrictor ropes attached between the trawl doors were used to define and hold door spread constant at each bridle configuration during the study. This minimized variability of trawl geometry and maintained a consistent bridle angle of approximately 12° between each of the configurations and between tows and depths. The restrictor ropes were made of buoyant, Samson Ultra Blue, polyolefin rope (Figure 1). Each rope had 1.8m of 1.3cm chain at each end so that the length could be adjusted to obtain the desired door spread.

FIELD EXPERIMENT

Data were collected during 19 sea-days in September-October 2014, aboard the F/V Karen Elizabeth, a 24m (78ft) stern trawler rigged with two aft net reels. Catches were compared of the standard survey bridle length, 36.6m, to two longer bridle lengths, 58.2m and 80.5m. Both the bridle angle and net width were held constant at approximately 12° and 13m, respectively, at each bridle length in an effort to maintain equal bridle efficiency, equal area swept by the net width and equal net efficiency for each length configuration (Figure 2). Increases in bridle lengths were equivalent so that the proportional increase in area swept by the door widths were equivalent. The 12° bridle angle was used since that is the designed target bridle angle for the NEFSC survey bottom trawl gear.

The experiment was conducted as a blocked sampling design which assumed physical parameters (temperature, light and bottom type) and fish abundance and distribution were homogenous within each block and that the efficiency of the net (escape under the footgear and through the trawl webbing) were equal between tows within a block. At each block, one tow was made with each bridle length following the NEFSC standard towing protocols of 20 minutes (on-bottom time measured by net mensuration equipment) at 3.0 knots, for a total of 3 tows per block (Politis et al., 2014). All 3 tows within a block were conducted during either daylight or darkness to control for differences in efficiency between light conditions. An archival light meter (TDR-MK9, Wildlife Computers, Redmond, WA) was attached to the trawl headrope to measure bottom light levels each tow. The towing order of each configuration was randomized within a block to reduce any bias. The experimental design attempted to offset tows within a block by approximately 0.25nm. In order to minimize the effects of bottom currents on the performance of the trawl gear all tows were conducted in the same direction relative to current direction. Horizontal spread between the doors and wings was measured and monitored each tow by Simrad ITI acoustic net mensuration equipment. Speed over ground was measured by GPS and depth was measured using a Simrad EK60 echo sounder.

All flatfish captured were weighed in aggregate and lengths were taken on individual fish to the nearest cm. Aggregate weights of mixed skates, goosefish, scallops and lobsters were taken beginning at block 33. Underwater video observations were made of the bottom bridles, groundgear and trawl doors using GoPro Hero 3 underwater cameras.

DATA ANALYSIS

Bridle efficiency is estimated from the collected catch data following the logic of Dickson (1993a), Somerton & Munro (2001) and Somerton et al. (2007) who model the catch in a trawl as a function of the proportion of fish that are in the path of the net actually captured by the net plus the proportion of fish in the path of the bridle width that are captured. For a given species this is expressed as

$$N = En * D * An + En * D * Eb * Ab \qquad (1)$$

where N = number of fish captured

- En = Efficiency of the net; proportion of fish in the path of the net width retained
- D = Density of fish available to the gear
- An = Area swept by the net width
- Eb = Efficiency of the bridle; proportion of fish in the bridle path retained
- Ab = Area swept by the bridle width

The density of fish, D, and efficiency of the net, En, were assumed to be constant within a block but vary between blocks and were combined into one term, k, to reduce the number of parameters to be estimated in the model:

$$N = k * An + k * Eb * Ab \qquad (2)$$

Equation 2 was modified to be block specific, gear configuration specific, and fish length dependent as

$$N_{ijl} = k_{il} * Anij + k_{il} * Eb_l * Ab_{ij} + \varepsilon \qquad (3)$$

where i = block

- j = bridle length and angle configuration
- l = fish length class
- ε = error term

Parameters were estimated on a transformed scale, to avoid boundary issues, by non-linear least squares using R statistical software (R Core Team, 2016) for all blocks combined, day and night blocks separately and length specific.

The number of estimated parameters was reduced by conditioning on the total catch per block following the methods of Millar (1992). The numbers in each tow within a block are assumed to be multinomial distributed wth the expected proportion of catch for an individual gear configuration, given the total catch of all gear configurations in a block is expressed as

$$N_{ij}/N_i = \frac{En * D_i * An_{ij} + En * D_i * Eb * Ab_{ij}}{\sum(En * D_i * An_{ij} + En * D_i * Eb * Ab_{ij})} \qquad (4)$$

The net efficiency and fish density terms cancel out leaving

$$N_{ij}/N_i = \frac{An_{ij} + Eb * Ab_{ij}}{\sum(An_{ij} + Eb * Ab_{ij})} \qquad (5)$$

This model was also modified to allow for fish length dependency.

$$N_{ijl}/N_i = \frac{An_{ij} + Eb_l * Ab_{ij}}{\sum(An_{ij} + Eb_l * Ab_{ij})} \qquad (6)$$

Parameters were estimated on a transformed scale, to avoid boundary issues, by maximum likelihood using R statistical software (R Core Team, 2016) for all blocks combined, day and night blocks separately and length specific.

RESULTS

ESTIMATES OF BRIDLE EFFICIENCY

At total of 73 representative blocks (43 day, 32night) were sampled on eastern Georges Bank, Cultivator Shoals and south of Martha's Vineyard (Figure 3). On eastern Georges Bank fish were present only in a small area and tows within a block and between blocks overlapped. Due to strong bottom currents on eastern Georges Bank all tows were conducted in the same direction as the current. Fish distribution and bottom currents were less of an issue on Cultivator Shoals and south of Martha's Vineyard. Use of the restrictor ropes resulted in consistent trawl geometry and bridle angles between blocks, configurations and areas sampled (Table 1).

Catch data were obtained for 6 species of flatfish: yellowtail flounder (*Limanda ferruginea*), winter flounder (*Pseudopleuronectes americanus*), summer flounder (*Paralichthys dentatus*), fourspot flounder (*Hippoglossina*), windowpane flounder (*Scophthalmus aquosus*) and gulfstream flounder (*Citharichthys arctifrons*) (Table 2). Yellowtail flounder were captured in 51 (22 day, 29 night) of the 73 representative blocks. Mean catches per block were higher at night for each species of flatfish except yellowtail flounder, which had higher mean catches per day blocks than night blocks (Table 2). Analysis of variance (ANOVA) comparing the catch numbers between bridle length configurations, combined and separated by day and night, showed a significant difference for yellowtail flounder at night (p-value < 0.05), summer flounder combined (p-value < 0.01) and summer flounder at night (p-value < 0.01) (Table 3).

Comparing catch numbers between bridle length configurations, the proportion of yellowtail flounder captured increased with increasing bridle length both combined and when separated by night blocks, however, the proportional increase in catch with increasing bridle length was not observerd during the day blocks when extending from the standard length to the medium length bridle (Table 4) (Figure 4). For winter flounder, the largest proportion of fish were captured by the middle length bridle during day and night blocks and a higher number of small fish were captured during night blocks (Table 4) (Figure 5). Similarly, the proportion of summer flounder captured increased with increasing bridle length both when the data were combined and separated by night blocks, however, with the proportional catch did not increase during the day blocks when extending from the medium length bridle to the long bridle (Table 4). More small sized summer flounder were captured during the night blocks for all bridle configurations (Figure 6). The proportion of fourspot flounder captured increased with increasing bridle length for the day blocks, however, the medium length bridle configuration captured the largest proportion at night (Table 4). More small size fourspot flounder were captured at night by all bridle length configurations (Figure 7). Only a small number of windowpane flounder were captured during the day blocks and the proportion of fish increased with increasing bridle length at night (Table 4, Figure 8). Catches of gulfstream flounder were predominately in the night blocks with only 1% of the fish captured during day blocks and the proportion of fish increased slightly with increasing bridle length during the night blocks (Table 4) (Figure 9).

Estimates of bridle efficiency derived from both models were poor for all species (Table 5). Bridle efficiency, *Eb*, is estimated to be 0.15(0.02-0.62) for the combined day and night catch numbers, however, the model did not converge when *Eb* was estimated separately for the day and night blocks. Equation 4 provided a tighter estimate of *Eb* for the day and night blocks combined at 0.25(0.2-0.31), however, this model did not converge either when *Eb* was estimated for day and night blocks separately. Neither model provided valid estimates of *Eb* for any of the other species of flatfish. Each model estimated wide confidence intervals or did not converge when analyzed combined or separated by day and night blocks. Both models had similar issues with lack of convergence and wide confidence intervals when estimating length specific bridle efficiencies (Table 6).

Looking at the length specific catch ratios of yellowtail flounder, the largest proportional increase occurred at night when increasing from the standard bridle length to the medium bridle length, which is not the case during the day and shows less of an effect at the larger size class at night (Figure 10).

UNDERWATER VIDEO OBSERVATIONS

Video observations of the trawl gear and bridles were attempted during 20 tows, independent of the block sampling portion of this study. Unfortunately, water clarity and limited ambient light affected video quality and limited the underwater video opportunities to shallow water, <30m, inside Vineyard Sound and south of Martha's Vineyard where few fish were present and much of the video was unusable. Due to the water clarity and camera stabilization issues, species identification is problematic and the orientation of the camera when mounted on the middle bridle was difficult to determine. From the limited video of decent quality with the camera mounted on the middle bridle pointing downward towards the bottom bridle, it is apparent that bottom contact of the bottom bridle is light and intermittent (Figures 11). With the camera mounted approximately 2m forward of the bunt bobbin and pointed aft towards the bobbin and wing-end, it is clear that the lower bridle is not in contact with the bottom at this portion of the bridle (Figure 12). Despite the limited and intermittent bridle bottom contact, a few fish thought to be skates and summer flounder were observed reacting and moving away from the bridle inward toward the path of the approaching net (Figures 13 and 14).

DISCUSSION

Results from this study showed higher catch rates at night for each of the flatfish species other than yellowtail flounder. The reasons for this difference are unclear and may have been influenced by the high sampling intensity in a very small area on eastern Georges Bank. The increased number of small fish captured at night of all flatfish species by all bridle length configurations is likely due to the efficiency of the rockhopper rather than a result of the directed bridle efficiency study. Proportional increases in catch were greatest when increasing from the standard bridle length to the medium bridle length and the effect was most apparent in yellowtail flounder at night, winter flounder and fourspot flounder. Considering that vision is thought to be the primary sense used by fish when avoiding fishing gear, the increased proportion of yellowtail flounder captured at night with increasing bridle length but not during the day differs from other studies investigating diel differences in flatfish catch and suggests another influence on these results (Walsh, 1988; Glass & Wardle, 1989; Wardle, 1993). The lack of consistent bottom contact of the lower bridle is likely a significant factor limiting the daytime herding of flatfish. If fish react to the forward or middle portion of the bridles and are herded towards the net, the off-bottom portion of the lower bridle, forward of the wing-ends and bunt bobbins, provide an area of escapement more visible to fish during the day. This study was unable to determine the actual off-bottom distance of the lower bridle or actual length of bridle that remains completely off-bottom extending from the wing-ends. The NEFSC standard survey trawl uses 35.6cm (14in) rubber bunt bobbins on each wing-end which connect to the lower bridles, keeping the lower bridle off-bottom by approximately 17.8cm (7in, half of the bobbin diameter). Somerton and Munro (2001) directly observed and determined the actual length of bridle in contact with the bottom of their survey trawl to improve their estimates of bridle efficiency. This study was not able determine the actual off-bottom distance of the standard NEFSC survey trawl bridles, however, the off-bottom distance immediately in front of the wing-end is different from the bridles used by Somerton and Munro (2001) who concluded that the portion of bridle extending from the wing-ends of their survey trawl to be in full contact with the bottom.

Examination of wear and shine patterns on the wire bridles used during this field experiment further confirm that bottom contact of the lower bridles is limited. It is expected that the repeated towing of each bridle would result in wearing off of the grease along the wires if they were in contact with the bottom. Wear patterns were inconsistent along the length of the bridles, with minimal wear observed on the longest length bridle which still had a fair amount of grease along it's length (Figure 15). This suggests that the forward portion, toward the trawl door, of the standard bridle length has minimal bottom contact as well as the aft portion near the wing-end. Wear was observed on the medium length bridle and forward portions of the standard length bridle, suggesting that extending from the standard length to the medium length bridle increased the proportion of wire that was in contact with the bottom. Changing the proportion of bridle that is in contact with the bottom changes the actual proportional area swept by each of the bridle length configurations. The actual length of bridle in contact with the bottom of each of the three bridle configurations during this study is unknown and may explain the observed catch ratio differences between the medium and long bridle lengths configurations.

Several factors likely influenced that lack of valid bridle efficiency estimates from either of the models used. Actual on-bottom bridle distances likely did not reflect the measured area swept values used in the analyses. Attempts to correct for the effective bridle herding distances did not alter the results. Another factor may have been the lack of available fish. The distribution of fish was limited to a narrow area on eastern Georges Bank and several blocks and tows within a block sampled over the same bottom which may have altered the behavior and density of fish in that region.

In order to fully understand the bridle herding efficiency of the NEFSC survey bottom trawl it is critical to determine the actual length and region of the bridle in contact with the bottom. The portion of bridle extending from the wing-ends is thought to be an area of significant flatfish escapement minimizing the effective herding efficiency of the standard survey bridles. Further work should be done to observe and quantify escapement in the region of the survey trawl gear.

LITERATURE CITED

Dickson, W. 1974. A review of the efficiency of bottom trawls. Fiskeriteknologisk Forskningsinstittut, FTFI Report, Bergen, 14-17pp.

Dickson, W.
1993a. Estimation of the capture efficiency of trawl gear. I: Development of a theoretical
model. Fish. Res. 16: 239–253.

1993b. Estimation of the capture efficiency of trawl gear. II: Testing a theoretical model. Fish. Res. 16: 255–272.

Engas, A., 1994. The effects of trawl performance and fish behaviour on the catching efficiency of demersal sampling trawls. In: Ferno, A., Olsen, S. (Eds.), Marine Fish Behaviour. Blackwell Science Inc., Massachusetts, pp. 45–68.

Engas, A., and Godo, O.R.

1989a. The effect of different sweep lengths on the length composition of bottom-sampling trawl catches. J. Cons. Int. Explor. Mer. 45: 263-268.

1989b. Escape of fish under the fishing line of a Norwegian sampling trawl and its influence on survey results. J. Cons. Int. Explor. Mer. 45: 269-276.

Glass, C.W., and Wardle, C.S. 1989. Comparison of the reactions of fish to a trawl gear, at high and low light intensities. Fish. Res. 7: 249-266.

Harden Jones, F.R., Margetts, A.R., Walker, M.G., and Arnold, G.P. 1977. The efficiency of the Granton otter trawl determined by sector-scanning sonar and acoustic transponding tags. Rapp. P-v. Reun. Cons. Explor. Mer. 170: 45-51.

Hemmings, C.C. 1969. Observations on the behaviour of fish during capture by the Danish seine net and their relation to herding by the trawl bridles. FAO Fish. Rep. No. 62, 3: 645-655.

Hemmings, C.C. 1973. Direct observations of the behaviours of fish in relation to fishing gears. Helgol. Wiss. Meeresunters. 24: 348-360.

Kotwicki, S., De Robertis, A., von Szalay, P., and Towler, R. 2009. The effect of light intensity on the availability of walleye pollock (*Theragra chalcogramma*) to bottom trawl and acoustic surveys. Can. J. Fish. Aquat. Sci. 66: 983-994.

Main, J., and Sangster, G.I.

1981a. A study of the sand clouds produced by trawl boards and their possible effect on fish capture. Scott. Fish. Res. Rep. 20:1−20.

1981b. A study of the fish capture process in a bottom trawl by direct observations from towed underwater vehicle. Scott. Fish. Res. Rep. 23:1−23.

Millar, R.B. 1992. Estimating the size-selectivity of fishing gear by conditioning on the total catch. J. Amer. Statist. Assoc. 87(420): 962-968.

Munro, P.T., and Somerton, D.A. 2002. Estimating net efficiency of a survey trawl for flatfishes. Fish. Res. 55: 267-279.

Politis, P.J., Galbraith, J.K., Kostovick, P., and Brown, R.W. 2014. Northeast Fisheries Science Center bottom trawl survey protocols for the NOAA Ship Henry B. Bigelow. U.S. Dept. Commer., Northeast Fish. Sci. Cent. Ref. Doc. 14-06, 138p.

R Core Team. 2016. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Ramm, D. C., and Xiao, Y. 1995. Herding in groundfish and effective pathwidth of trawls. Fish. Res. 24:243−259.

Ryer, C.H. 2008. A review of flatfish behavior relative to trawls. Fish. Res. 90: 138-146.

Ryer, C.H., and Barnett, L.A.K. 2006. Influence of illumination and temperature upon flatfish reactivity and herding behavior: potential implications for trawl capture efficiency. Fish. Res. 81: 242-250.

Strange, E.S. 1984. Review of the fishing trials with Granton and Saro deep sea trawl gear 1963-1967. Scottish Fisheries Working Paper, 8-18: 1-59.

Somerton, D.A., and Munro, P. 2001. Bridle efficiency of a survey trawl for flatfish. Fish. Bull. 99: 641-652.

Somerton, D.A., Munro, P.T., and Weinberg, K.L. 2007. Whole gear efficiency of a benthic survey trawl for flatfish. Fish. Bull. 105:278-291.

Walsh, S.J. 1988. Diel variability in trawl catches of juvenile and adult yellowtail flounder on the Grand Banks and the effect on resource assessment. N. Am. J. Fish. Mgmt. 8: 373-381.

Walsh, S.J. 1991. Diel variation in availability and vulnerability of fish to a survey trawl. J. Appl. Icthyol. 7: 147-159.

Walsh, S.J. 1992. Size-dependent selection at the footgear of a groundfish survey trawl. N. Am. J. Fish. Mgmt. 12: 626-633.

Walsh, S.J. 1996. Efficiency of bottom sampling trawls in deriving survey abundance indices. NAFO Sci. Coun. Studies, 28: 9-24.

Wardle, C.S., 1993. Fish behaviour and fishing gear. In: Pitcher, T.J. (Ed.), Behavior of Teleost Fishes. Champman & Hall, London, pp. 609–643.

Winger, P.D., He, P., and Walsh, S.J., 1999. Swimming endurance of American plaice (*Hippoglossoides platessoides*) and its role in fish capture. ICES J. Mar. Sci. 56: 252–265.

Winger, P.D., Walsh, S.J., He, P., and Brown, J.A., 2004. Simulating trawl herding in flatfish: the role of fish length in behaviour and swimming characteristics. ICES J. Mar. Sci. 61: 1179–1185.

TABLES

Table 1. Summary of trawl geometry for each block sampled at each region.

AREA	Gear Configuration	Bridle Length(m)	Total Blocks	Day Blocks	Night Blocks	Mean Depth (m)	Door Spread (m)	Wing Spread (m)	Bridle Angle (deg)
Eastern Georges	Standard	46.6	37	23	14	68.7	33.1 ±0.3	12.8 ±0.3	12.6 ±0.3
	Medium	69	37	23	14	68.2	42.8 ±0.7	13.0 ±0.3	12.5 ±0.3
	Long	91	37	23	14	68.4	51.2 ±1.1	13.1 ±0.5	12.1 ±0.3
Cultivator Shoals	Standard	46.6	10	7	3	59.2	33.0 ±0.2	12.6 ±0.3	12.6 ±0.3
	Medium	69	10	7	3	59.4	42.6 ±0.5	13.3 ±0.3	12.2 ±0.2
	Long	91	10	7	3	59.8	51.5 ±0.6	13.4 ±0.4	12.1 ±0.2
South of Martha's	Standard	46.6	26	11	15	42.5	32.8 ±0.1	12.7 ±0.2	12.5 ±0.1
Vineyard	Medium	69	26	11	15	42.5	42.3 ±0.4	13.1 ±0.4	12.2 ±0.2
	Long	91	26	11	15	43.1	50.4 ±0.7	13.2 ±0.4	11.8 ±0.2

Table 2. Summary of flatfish catch per block.

SPECIES	Total Blocks	Number Day Blocks	Num Night Blocks	Num TotalFish	Mean Catch Per Block	Pct Caught Day	Pct Caught Night	Mean Catch Per Block Day	Mean Catch Per Block Night
YellowtailFlounder	51	22	29	4062	79.6	0.52	0.48	96.4	66.9
WinterFlounder	46	28	18	2834	61.6	0.43	0.57	43.5	89.7
SummerFlounder	36	18	18	2933	81.5	0.29	0.71	46.8	116.2
FourspotFlounder	63	31	32	3892	61.8	0.24	0.76	30.1	92.4
WindowpaneFlounder	28	13	15	2148	76.7	0.13	0.87	21.5	124.5
Gulfstream Flounder	20	5	15	14130	706.5	0.01	0.99	39.8	928.7

Table 3. ANOVA results comparing catch numbers with the bridle length configuration as the treatment.

Species	p-value
Yellowtail flounder	
All	0.25
Day Blocks	0.8
Night Blocks	0.03*
Winter flounder	
All	0.05
Day Blocks	0.4
Night Blocks	0.1
Summer flounder	
All	0.003*
Day Blocks	0.26
Night Blocks	0.002*
Fourspot flounder	
All	0.1
Day Blocks	0.1
Night Blocks	0.3
Windowpane flounder	
All	0.3
Day Blocks	0.6
Night Blocks	0.2
Gulfstream flounder	
All	0.8
Day Blocks	0.6
Night Blocks	0.8

Table 4. Numbers and proportions of flatfish captured by each bridle length configuration.

	TOTAL Num	STD	MED	LONG	PropSTD	PropMED	PropLNG
Yellowtail flounder							
All	4062	1194	1372	1496	0.29	0.34	0.37
Day	2121	754	665	702	0.36	0.31	0.33
Night	1941	440	707	794	0.23	0.36	0.41
Winter flounder							
All	2834	785	1128	921	0.28	0.40	0.32
Day	1219	378	466	375	0.31	0.38	0.31
Night	1615	407	662	546	0.25	0.41	0.34
Summer flounder							
All	2933	867	966	1100	0.30	0.33	0.38
Day	842	253	302	287	0.30	0.36	0.34
Night	2091	614	664	813	0.29	0.32	0.39
Fourspot flounder							
All	3892	1177	1382	1333	0.30	0.36	0.34
Day	934	255	326	353	0.27	0.35	0.38
Night	2958	922	1056	980	0.31	0.36	0.33
Windowpane flounder							
All	2148	670	728	750	0.31	0.34	0.35
Day	280	96	84	100	0.34	0.30	0.36
Night	1868	574	644	650	0.31	0.34	0.35
Gulfstream flounder							
All	14130	4436	4770	4924	0.31	0.34	0.35
Day	199	54	74	71	0.27	0.37	0.36
Night	13931	4382	4696	4853	0.31	0.34	0.35

Table 5. Flatfish bridle efficiency, Eb, estimated by two models with variance and 95% confidence intervals.

SPECIES	Model 1 Fit by NLS Nij = ki*Anij + ki*Eb*Abij				Model 2 Fit by NLL Nij = Anij + Eb*Abij/∑(Anij+Eb*Abij)			
	Eb	Variance	CI Low	CI Up	Eb	Variance	CI Low	CI Up
Yellowtail Fl All	0.15	1.26	0.02	0.62	0.25	0.15	0.2	0.31
Yellowtail Fl Day	NA	NA	NA	NA	0	1382.71	0	1
Yellowtail Fl Night	NA	NA	NA	NA	1	1055.16	0	1
Winter Fl All	0.11	2.28	0.01	0.7	0.16	0.3	0.06	0.36
Winter Fl Day	NA	NA	NA	NA	0	2275.69	0	1
Winter Fl Night	0.33	4.58	0.01	0.97	0.56	1.16	0.13	0.91
Summer Flounder All	0.48	0.4	0.21	0.76	0.25	0.22	0.12	0.46
Summer Flounder Day	0.09	1.8	0.01	0.58	0.07	1.9	0.01	0.53
Summer Floudner Night	0.58	1.04	0.16	0.91	0.37	0.38	0.15	0.67
Fourspot Fl All	0.15	0.44	0.05	0.39	0.11	0.24	0.07	0.17
Fourspot Fl Day	NA	NA	NA	NA	0.53	1.35	0.07	0.94
Fourspot Fl Night	0.09	1.23	0.01	0.47	0	Inf	0	1
Windowpane Fl All	0.09	0.71	0.02	0.34	0.08	0.64	0.03	0.24
Windowpane Fl Day	0.11	3.01	0	0.78	0	Inf	0	1
Windowpane Fl Night	0.09	1.28	0.01	0.47	0.1	0.61	0.03	0.27
Gulfstream Fl All	0.13	1.27	0.01	0.65	0.00	Inf	0	1
Gulfstream Fl Day	0.52	3.62	0.00	1.00	0.83	65.46	0	1
Gulfstream Fl Night	0.13	1.47	0.01	0.73	0.00	Inf	0	1

Table 6. Length specific flatfish bridle efficiency, Eb, estimated by two models with variance and 95% confidence intervals.

	Model 1 Fit by NLS Nij = ki*Anij + ki*Eb*Abij				Model 2 Fit by NLL Nij = Anij + Eb*Abij/∑(Anij+Eb*Abij)			
Size Class (cm)	Eb	Variance	CI Low	CI Up	Eb	Variance	CI Low	CI Up
Yellowtail Fl All								
16-32	NA	NA	NA	NA	0.2	0.86	0.04	0.57
32-36	0.35	0.94	0.07	0.78	0.31	0.49	0.15	0.54
36-40	0.1	1.29	0.01	0.51	0.46	0.86	0.14	0.82
40-52	0.04	3.66	0	0.64	0.07	1.79	0	0.71
Yellowtail Fl Day								
16-32	NA	NA	NA	NA	NA	NA	0	1
32-36	NA	NA	NA	NA	NA	NA	0	1
36-40	NA	NA	NA	NA	NA	NA	0	1
40-52	NA	NA	NA	NA	NA	NA	0	1
Yellowtail Fl Night								
16-32	NA	NA	NA	NA	NA	NA	0	1
32-36	NA	NA	NA	NA	NA	NA	0	1
36-40	NA	NA	NA	NA	NA	NA	0	1
40-52	0.12	1.5	0.01	0.61	0.34	2.08	0.01	0.97
Winter Fl All								
18-30	NA	NA	NA	NA	0.31	1.14	0.05	0.81
30-36	NA	NA	NA	NA	0.48	1.39	0.06	0.93
36-41	NA	NA	NA	NA	0.15	1.1	0.02	0.6
41-56	NA	NA	NA	NA	NA	NA	0	1
Winter Fl Day								
18-30	NA	NA	NA	NA	NA	NA	0	1
30-36	NA	NA	NA	NA	0.26	2.04	0.01	0.95
36-41	0.62	2.82	0.06	0.98	NA	NA	0	1
41-56	NA	NA	NA	NA	NA	NA	0	1
Winter Fl Night								
18-30	NA	NA	NA	NA	0.46	2.24	0.01	0.99
30-36	NA	NA	NA	NA	NA	NA	0	1
36-41	NA	NA	NA	NA	NA	NA	0	1
41-56	NA	NA	NA	NA	NA	NA	0	1

Table 6. Continued.

Size Class (cm)	Model 1 Fit by NLS Nij = ki*Anij + ki*Eb*Abij Eb	Variance	CI Low	CI Up	Model 2 Fit by NLL Nij = Anij + Eb*Abij/∑(Anij+Eb*Abij) Eb	Variance	CI Low	CI Up
Summer Fl All								
28-40	0.66	1.53	0.14	0.96	NA	NA	0	1
40-44	0.12	0.69	0.03	0.41	NA	NA	0	1
44-48	0.62	1.6	0.12	0.95	0.25	0.99	0.05	0.69
48-52	0.03	3.34	0	0.56	NA	NA	0	1
52-58	0.28	0.68	0.07	0.66	0.35	1.88	0.01	0.96
58-80	NA	NA	NA	NA	NA	NA	0	1
Summer Fl Day								
28-40	NA	NA	NA	NA	NA	NA	0	1
40-44	0.2	1.22	0.03	0.69	NA	NA	0	1
44-48	0.06	3.22	0	0.69	NA	NA	0	1
48-52	0.45	1.09	0.1	0.87	NA	NA	0	1
52-58	0.13	1.96	0.01	0.69	NA	NA	0	1
58-80	0.05	5.2	0	0.81	NA	NA	0	1
Summer Fl Night								
28-40	0.54	1.27	0.11	0.92	NA	NA	0	1
40-44	0.11	1.46	0.01	0.58	NA	NA	0	1
44-48	0.8	12.85	0	1	NA	NA	0	1
48-52	NA	NA	NA	NA	NA	NA	0	1
52-58	0.38	1.56	0.05	0.88	NA	NA	0	1
58-80	NA	NA	NA	NA	NA	NA	0	1
Fourspot Fl All								
4-16	NA	NA	NA	NA	NA	NA	0	1
16-24	NA	NA	NA	NA	NA	NA	0	1
24-28	0.64	0.69	0.26	0.9	0.26	0.45	0.12	0.46
28-32	0.18	0.38	0.06	0.42	0.1	0.95	0.02	0.41
32-42	NA	NA	NA	NA	NA	NA	0	1
Fourspot Fl Day								
4-16	NA	NA	NA	NA	NA	NA	0	1
16-24	NA	NA	NA	NA	NA	NA	0	1
24-28	NA	NA	NA	NA	NA	NA	0	1
28-32	0.12	1.14	0.02	0.53	0.29	1.71	0.01	0.92
32-42	NA	NA	NA	NA	NA	NA	0	1
Fourspot Fl Night								
4-16	NA	NA	NA	NA	NA	NA	0	1
16-24	NA	NA	NA	NA	NA	NA	0	1
24-28	0.44	0.34	0.2	0.71	NA	NA	0	1
28-32	0.19	0.7	0.04	0.55	NA	NA	0	1
32-42	NA	NA	NA	NA	NA	NA	0	1

Table 6. Continued.

Size Class (cm)	Model 1 Fit by NLS Nij = ki*Anij + ki*Eb*Abij				Model 2 Fit by NLL Nij = Anij + Eb*Abij/∑(Anij+Eb*Abij)			
	Eb	Variance	CI Low	CI Up	Eb	Variance	CI Low	CI Up
Windowpane Fl All								
6-22	0.21	0.41	0.07	0.49	0.26	1.04	0.04	0.73
22-26	0.17	0.62	0.04	0.49	0.11	1.36	0.01	0.65
26-36	0.04	2.1	0	0.43	NA	NA	0	1
Windowpane Fl Day								
6-22	NA	NA	NA	NA	NA	NA	0	1
22-26	NA	NA	NA	NA	NA	NA	0	1
26-36	NA	NA	NA	NA	NA	NA	0	1
Windowpane Fl Night								
6-22	0.22	0.69	0.05	0.59	0.24	1.14	0.03	0.75
22-26	0.18	1.09	0.03	0.63	0.17	1.16	0.02	0.66
26-36	0.04	4.78	0	0.75	NA	NA	0	1

FIGURES

Figure 1. Photograph of the buoyant restrictor rope used during the field experiments just prior to shooting the trawl doors.

- 1 – Standard Length, 12°
  - DS=32m WS=13m
  - Area door=59264m²
  - Area wing=24076m²
- 2 – Medium Length, 12°
  - DS=41m WS=13m
  - Area door=75932m²
  - Area wing=24076m²
- 3 – Long Length, 12°
  - DS=50m WS=13m
  - Area door=92600m²
  - Area wing=24076m²

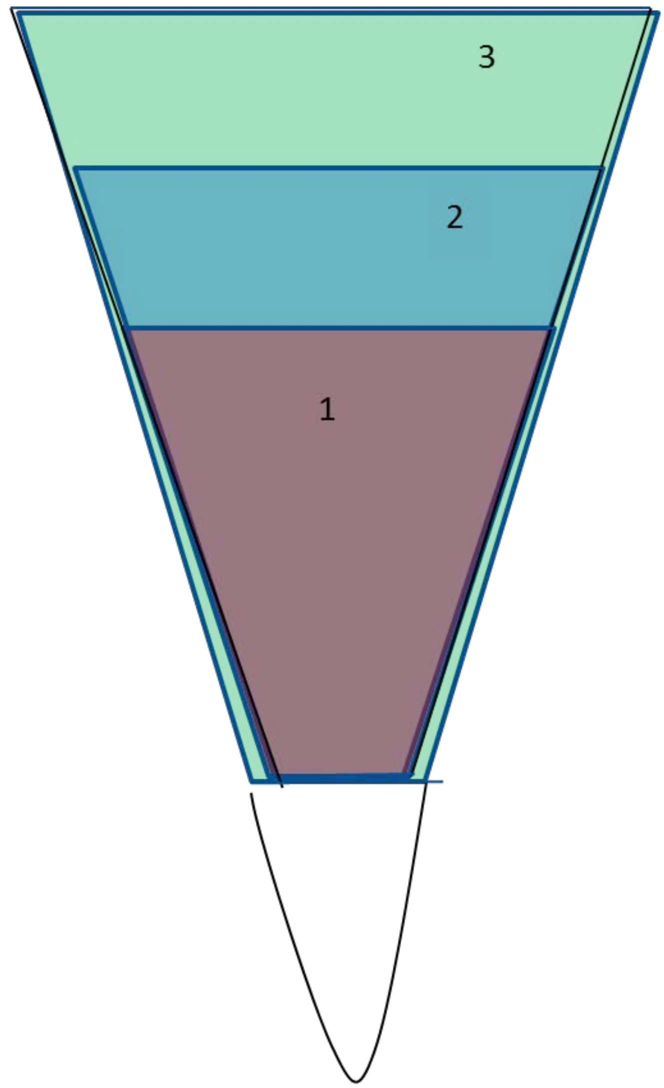


Figure 2. Diamgram of the three bridle length configurations and associated target spreads and areas swept. Diagram is not too scale.

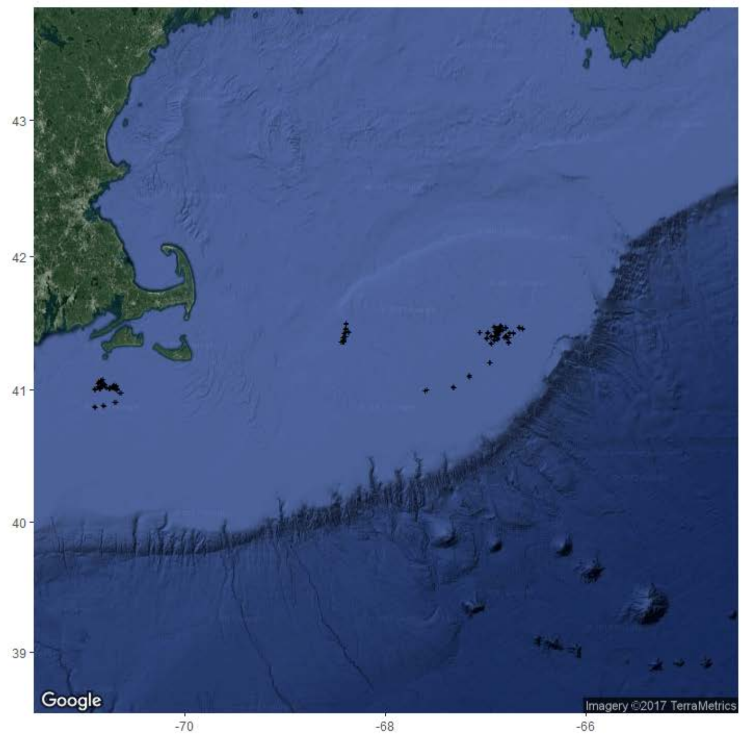
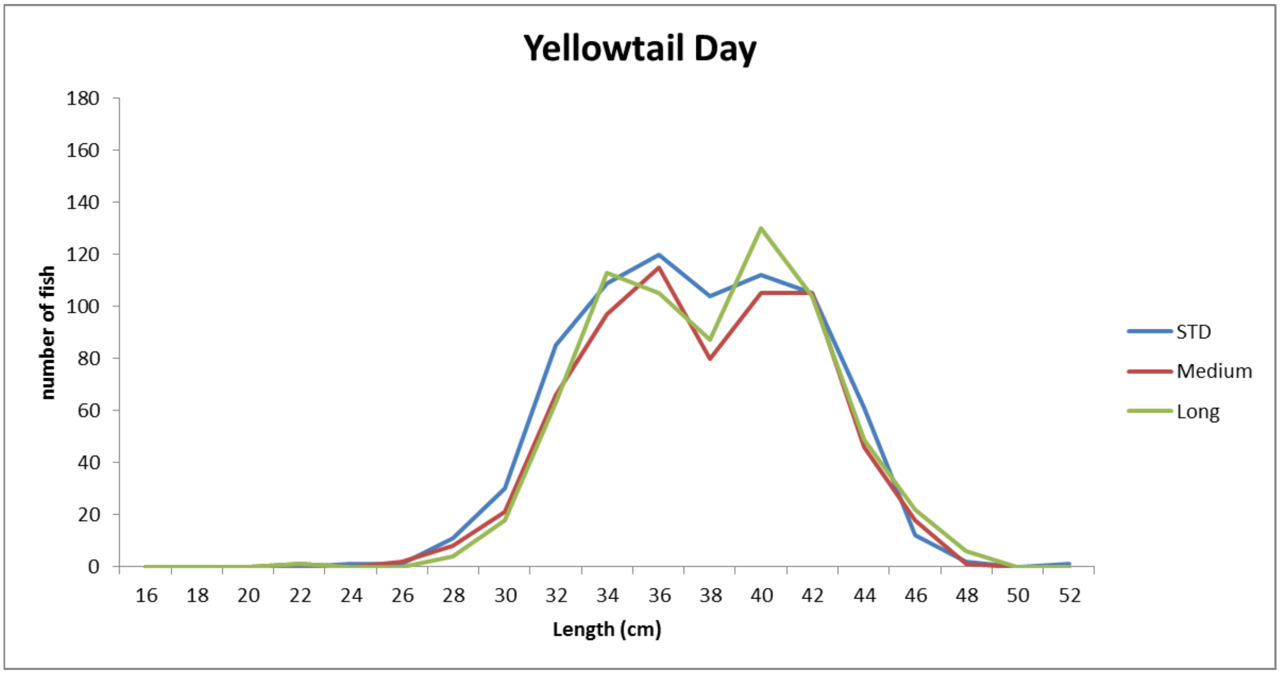


Figure 3. Locations of blocks sampled during the field experiments.

a)



b)

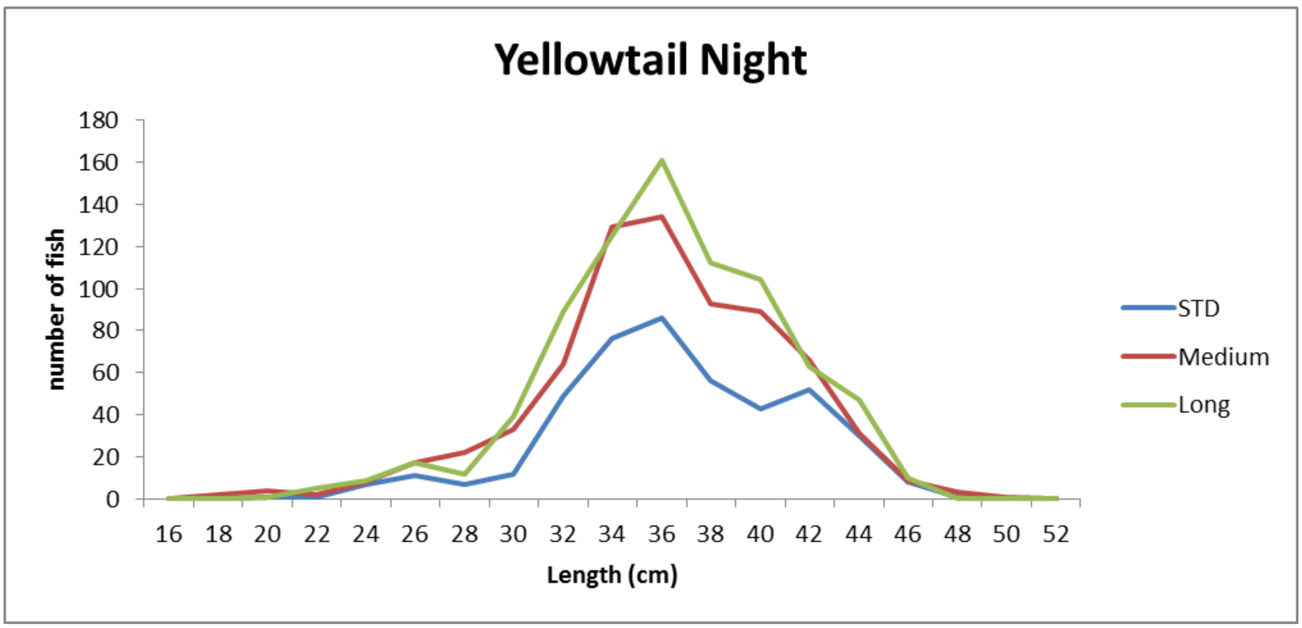
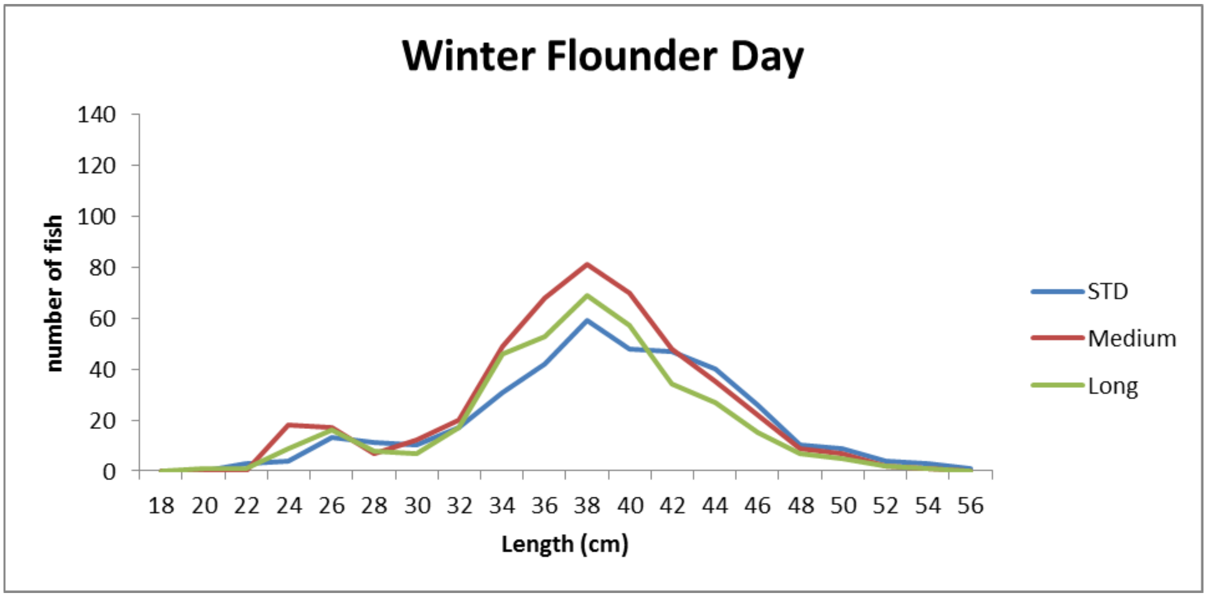


Figure 4. Plots of yellowtail flounder length frequencies captured during the a) day blocks and b) night blocks.

a)



b)

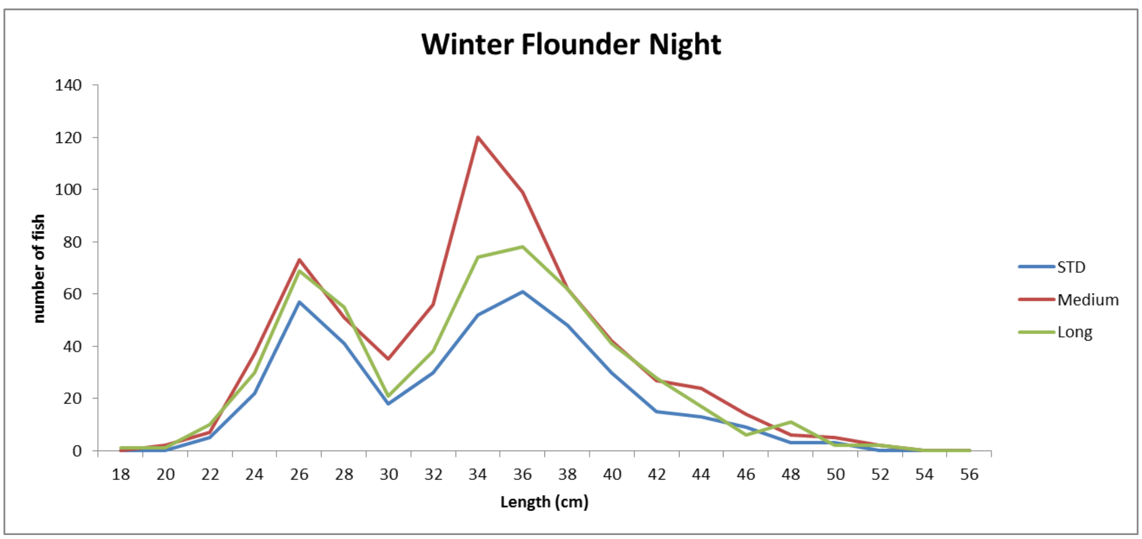
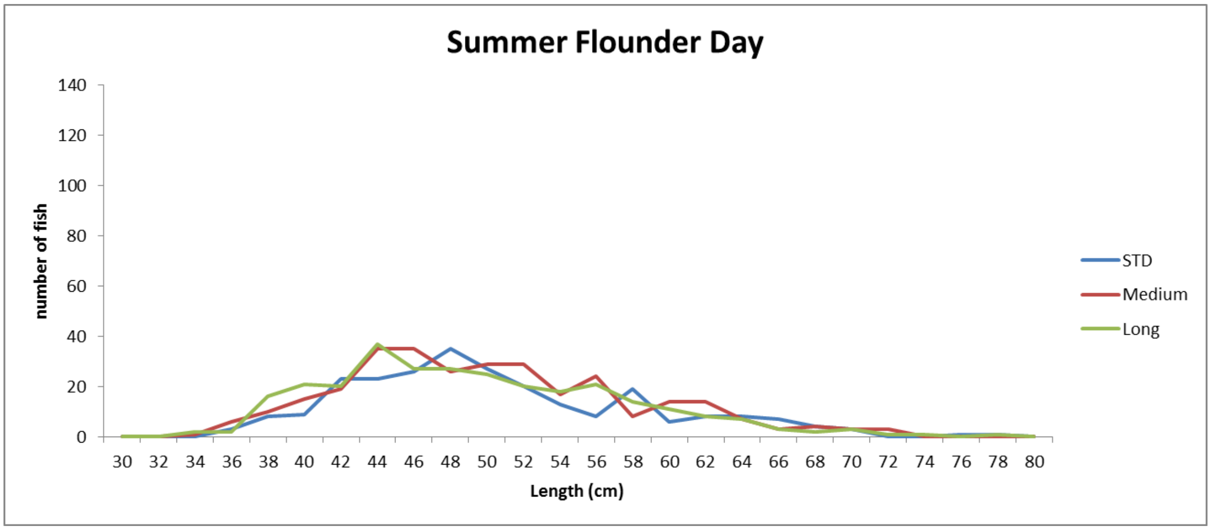


Figure 5. Plots of winter flounder length frequencies captured during the a) day blocks and b) night blocks.

a)



b)

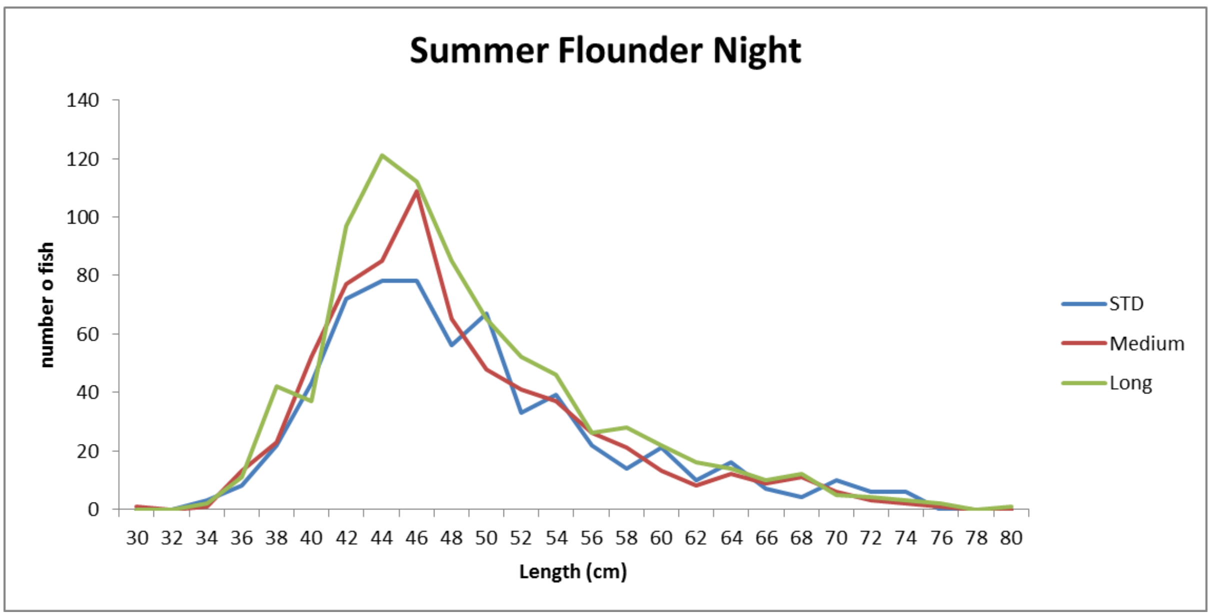
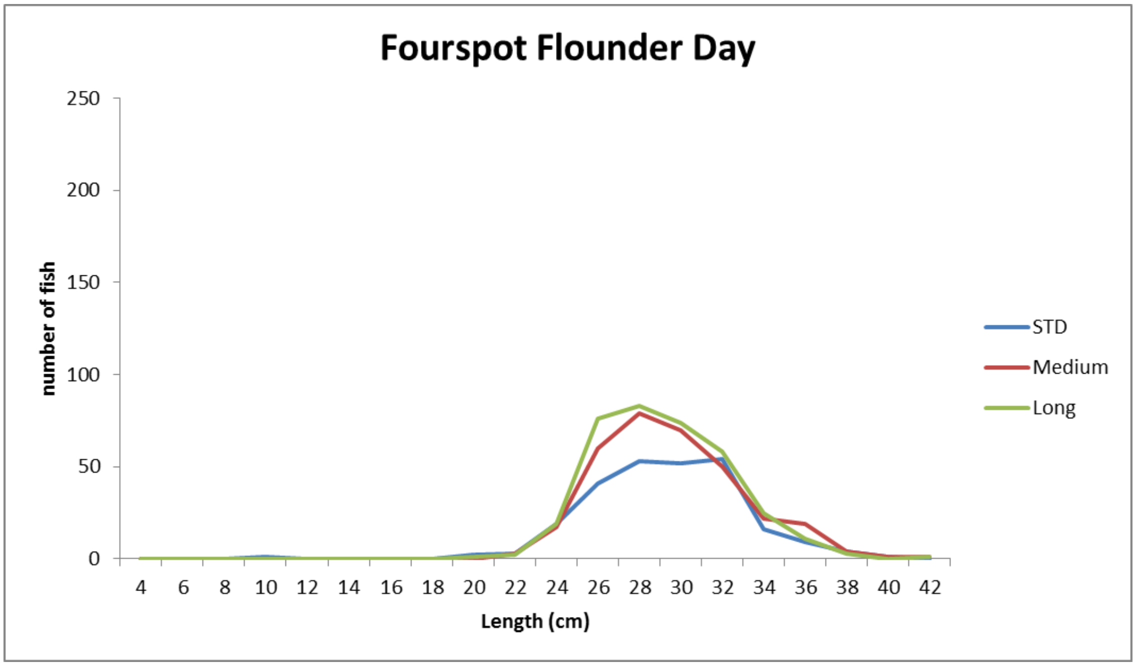


Figure 6. Plots of summer flounder length frequencies captured during the a) day blocks and b) night blocks.

a)



b)

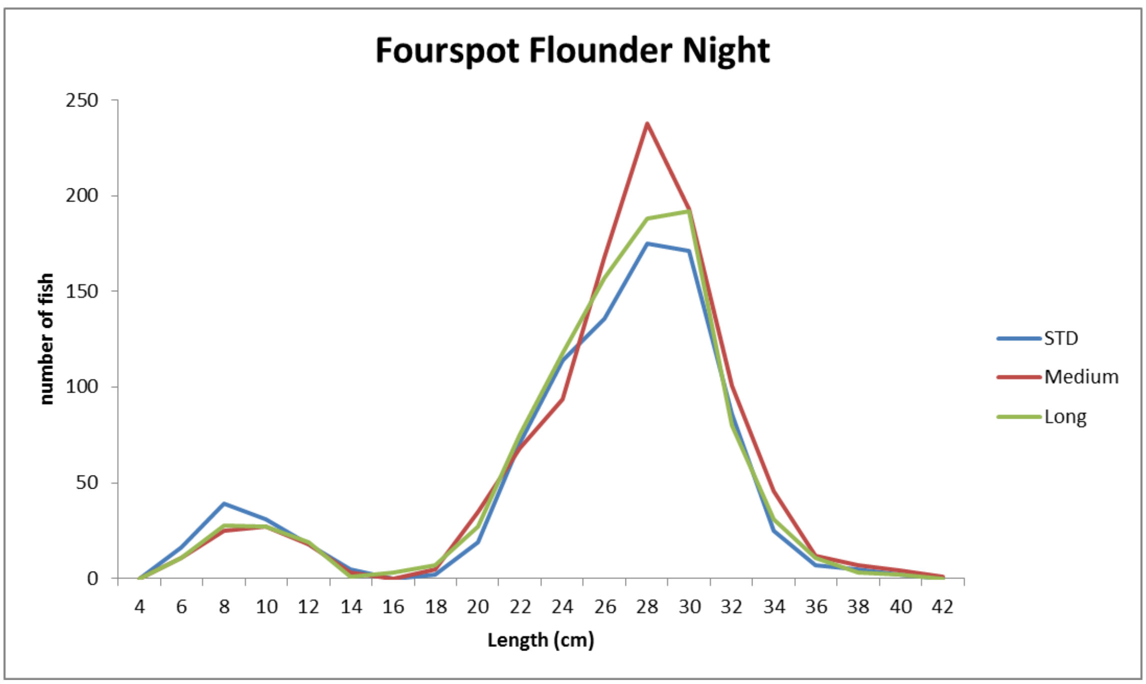
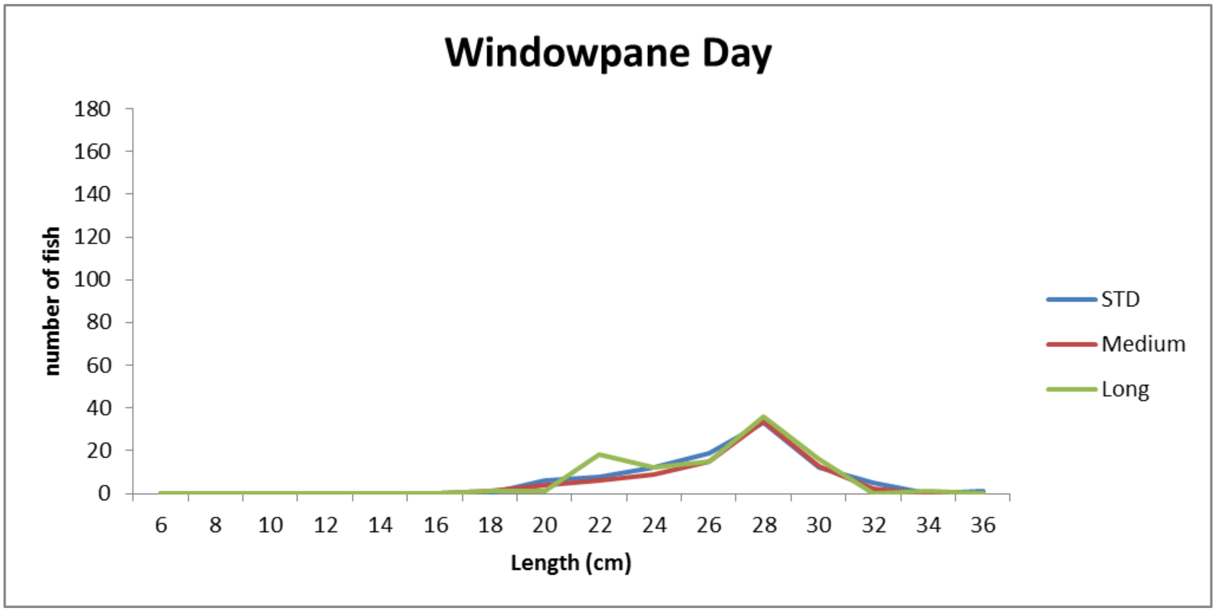


Figure 7. Plots of fourspot flounder length frequencies captured during the a) day blocks and b) night blocks.

a)



b)

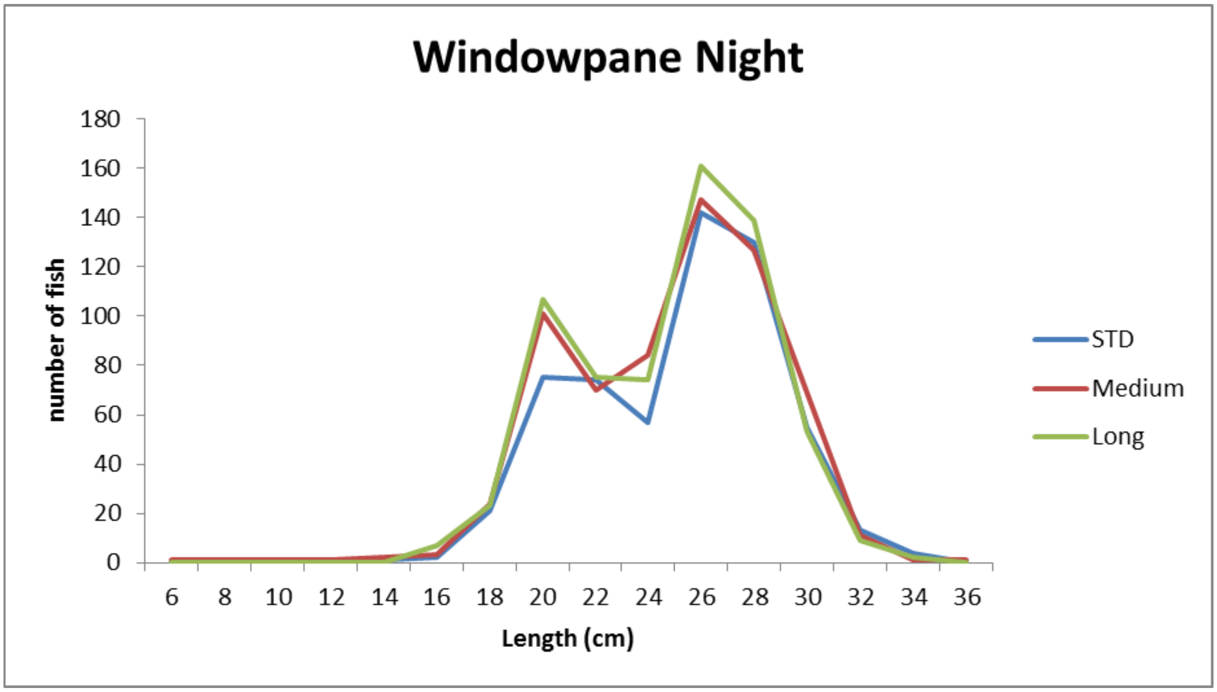
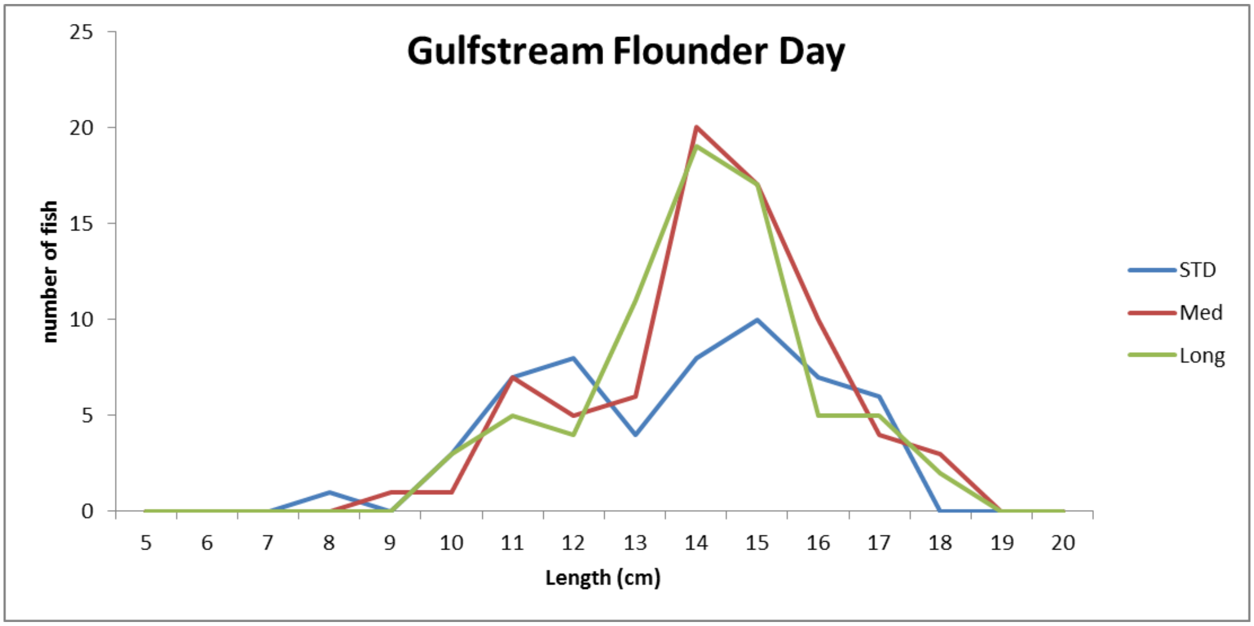


Figure 8. Plots of windowpane flounder length frequencies captured during the a) day blocks and b) night blocks.

a)



b)

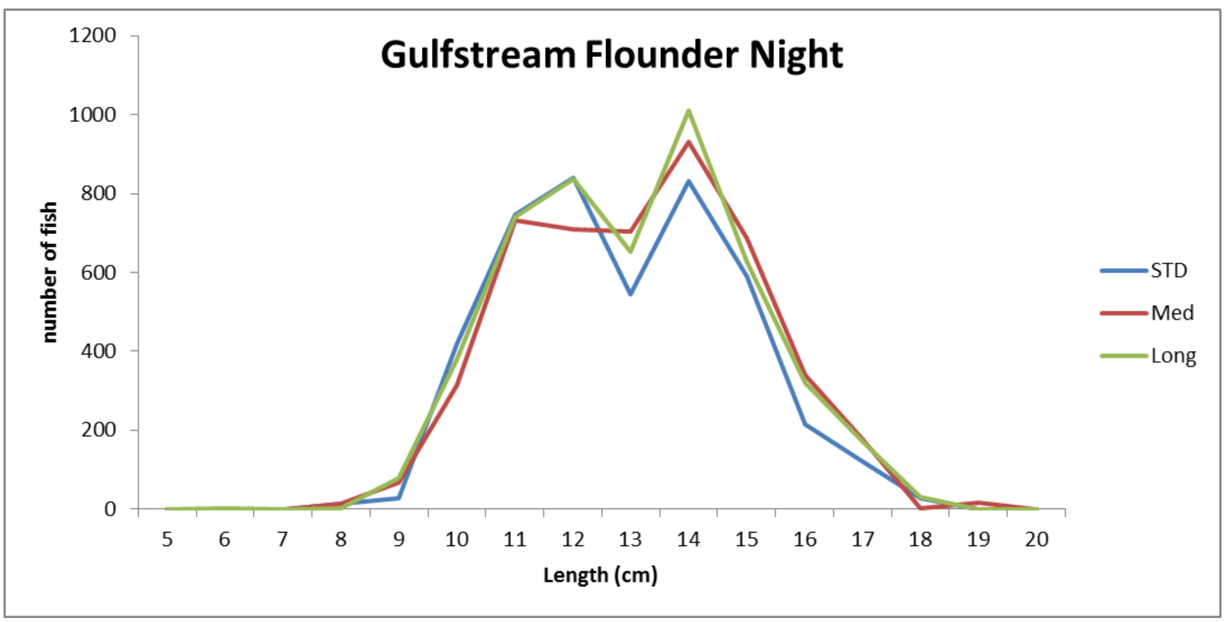
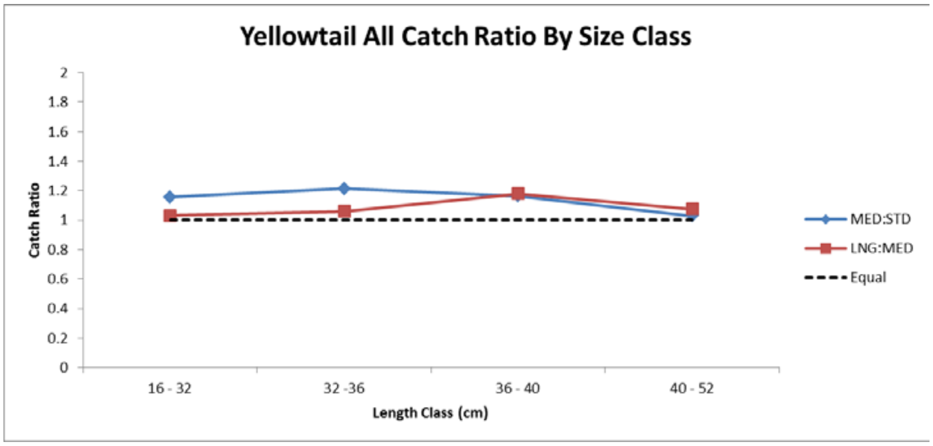
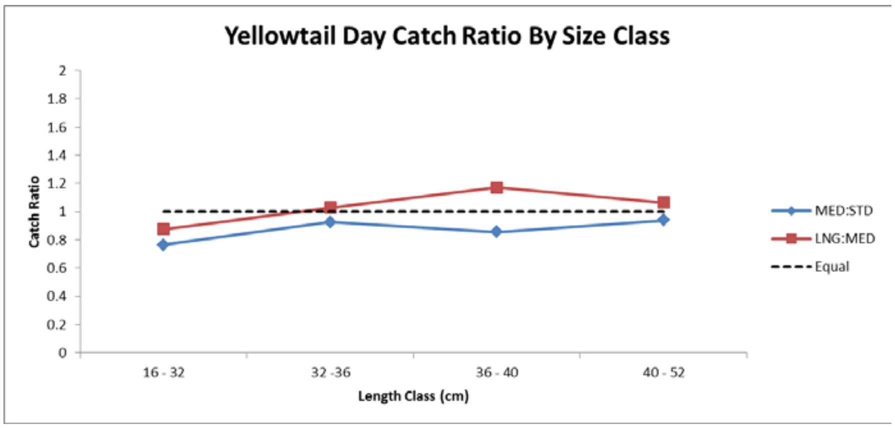


Figure 9. Plots of gulfstream flounder length frequencies captured during the a) day blocks and b) night blocks.

a)



b)



c)

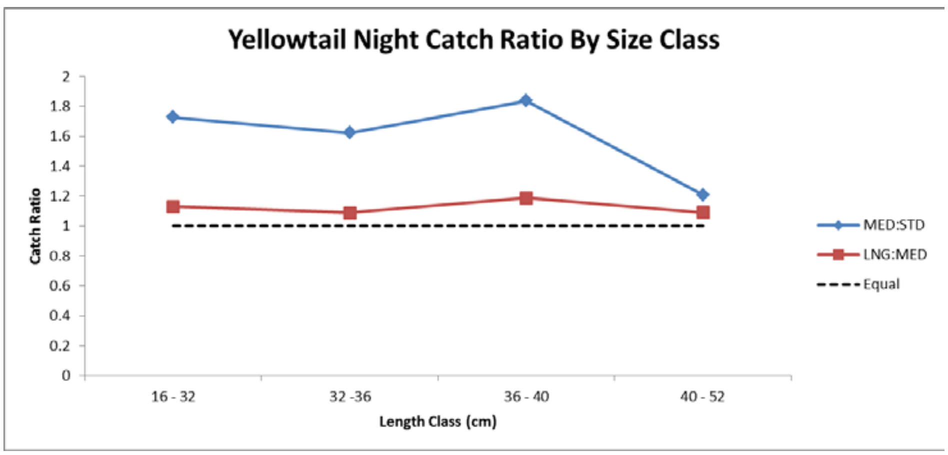


Figure 10. Ratios of yellowtail flounder catch by size class for a) all blocks combined, b) day blocks and c) night blocks, when extending from the standard to the medium bridle length (MED:STD, blue line) and when extending from the medium to the long bridle length (LNG:MED, red line). The dashed line represents equal catches between bridle length configurations.

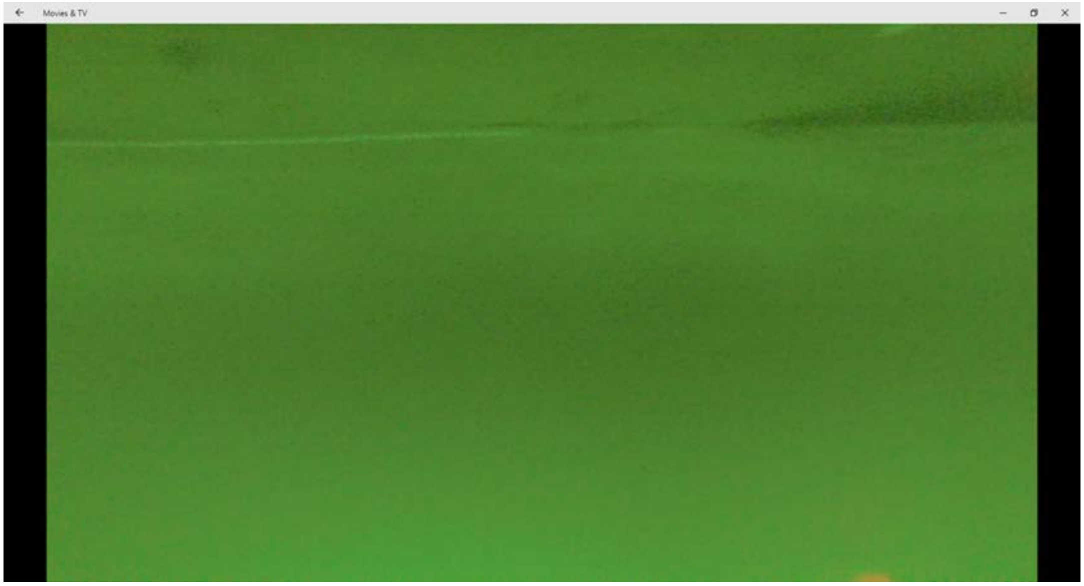


Figure 11. Video image of the starboard lower bridle showing intermittent bottom contact. The camera was mounted on the middle bridle bridle pointing downwards.

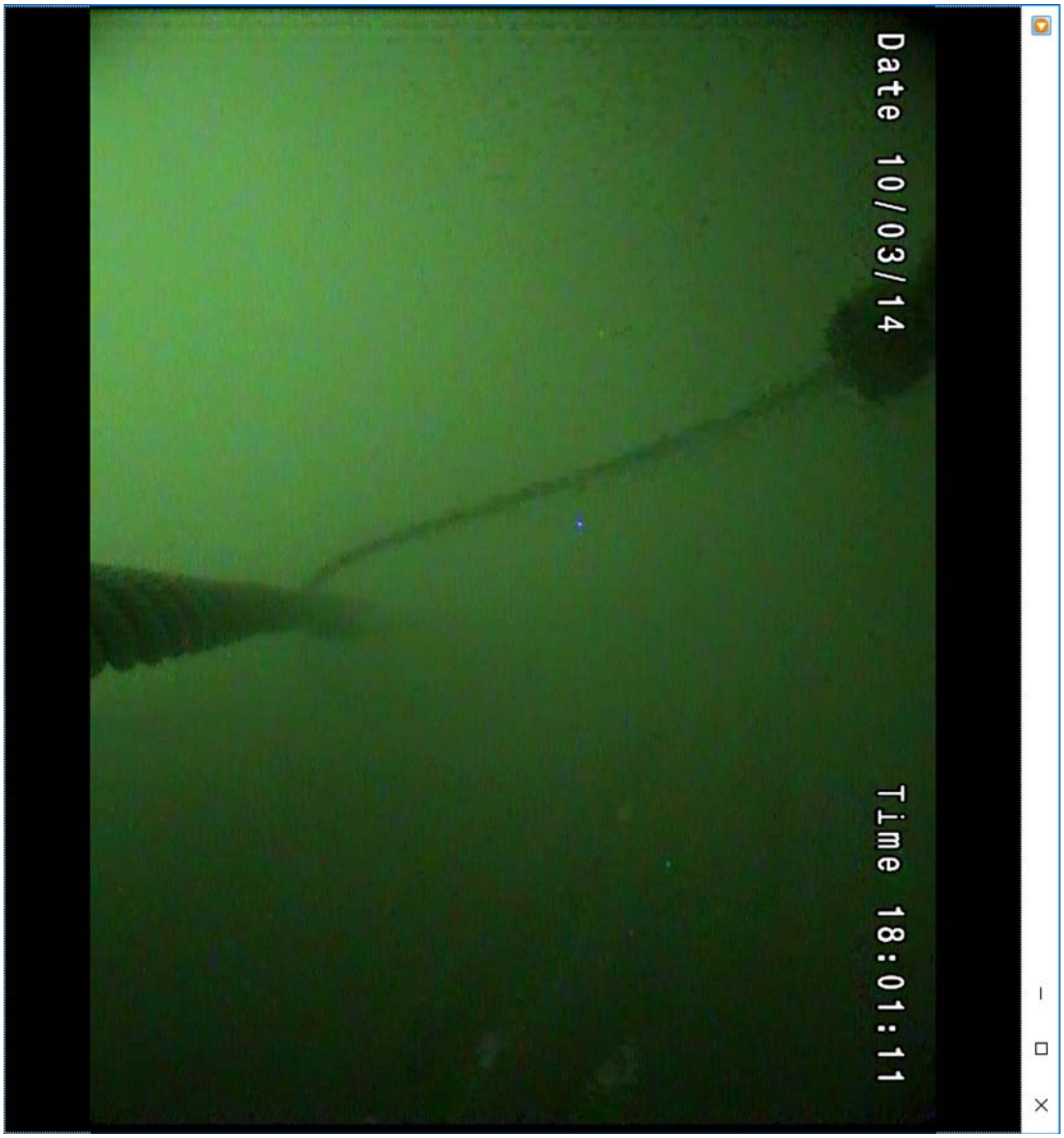


Figure 12. Video image of the starboard lower bridle showing lack of bottom contact. The camera was mounted approximately 2m forward of the bunt bobbin on the lower bridle pointing aft towards the wing-end. Due to the orientation of the camera the image is rotated so that the sea floor is at the bottom of the image.

Figure 13. Video image from the camera mounted on the starboard middle bridle pointed downward toward the lower bridle. The lower bridle is not visible and located to the bottom of the image. In the lower left of this image is thought to be a skate reacting and moving away from the lower bridle inward towards the path of the net.

Figure 14. Video image from the camera mounted on the starboard middle bridle pointed downward toward the lower bridle. The lower bridle is not visible and located to the bottom of the image. In the lower left of this image is thought to be a summer flounder reacting and moving away from the lower bridle inward towards the path of the net.

Figure 15. Photograph showing the difference in wear and shine patterns of the wires used during the field experiments.