Atlantic States Marine Fisheries Commission

A Review of the modified Gonadal-Somatic Index (GSI) Monitoring System for Atlantic Herring Spawning Closures in US Waters

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Introduction

In 2015, the ASMFC adopted Amendment 3 to the Atlantic Herring FMP, which established a new model-based GSI monitoring program for herring spawning closures. This closure system, first implemented in 2016, replaced an earlier program that had operated for more than 15 years. The earlier system relied on monitoring the development of female herring (stages 3-5) within 2 size classes and compared the average observed GSI of each size class to its own threshold. Once three consecutive samples within a week showed that either size class exceeded their threshold, the fishery would close. If three consecutive samples were not available in the week prior, area-specific default closure dates would apply. Amendment 3 sought to critically evaluate the parameters and assumptions of this earlier system (size classes, GSI thresholds, default dates, closure duration) and implement modifications to improve performance.

Since the adoption of Amendment 3, there has been a concerted effort to collect GSI and maturity data from all sampled herring (not just stage 3-5 females) throughout the entire spawning season, including during the closure period. These new data provide an invaluable perspective from which to evaluate the performance of the current spawning closure program. The aim of this paper is to review the current spawning closure system in light of these new data, and evaluate the validity of the model's assumptions and whether the program in general is meeting its objectives.

Program Objectives

There are four main objectives of the ASMFC herring spawning closure program:

1) *Reduce interaction between fishing and spawning:*
From a management perspective, it is impractical to eliminate *all* fishery-spawning interaction and still allow full utilization of the annual quota. Consequently, there must be some acceptable low level of spawning fish present in the catch both before and after the spawning closure. A long-established rule allows the fishery to operate if a sample contains less than 25% spawning fish after the closure has been lifted (i.e., re-closure protocol). For the purpose of this review, we will mirror this logic and consider <25% spawning to be acceptable at the beginning of the season as well.

2) *Maximize coverage of the spawning season AND access to quota*:

To provide the greatest benefit with the least cost, the spawning closure should ideally cover the spawning season and no more. This requires understanding the timing and duration of spawning and aligning the closure system to the reproductive cycle. Closing the fishery too early or too late may unnecessarily restrict the fishery and provide inadequate protection for spawning herring.

3) *Account for interannual variation in spawning time*:

The onset of spawning in Atlantic herring can vary by several weeks from one year to the next. Measuring gonadal development via sequential GSI samples allows for predicting when spawning is likely to commence each year. Over-reliance on fixed closure dates (i.e., "default" dates) increases the possibility of a mismatch between the closure and spawning.

4) *Allow flexibility to extend closures, if necessary*:

Given the observation error inherent in small samples from a high-volume fishery, combined with the natural variability in reproductive biology, there may be instances when the timing and duration of the spawning closure is insufficiently matched to the actual spawning season. In these cases, a backup measure is needed to prevent the fishery from opening prematurely to significant spawning activity.

Current Closure Protocol

Samples are routinely collected from the directed herring fishery as it operates within the three defined spawning areas (EM = Eastern Maine; WM = Western Maine; MANH = Massachusetts/New Hampshire). Samples of 100+ fish are collected and the GSI of female herring in maturity stages 3-5 are recorded. To account for the effect of length on GSI, all values are standardized to that of a 30 cm fish (i.e., GSI_{30}), using a previously established formula. Once three samples from a given spawning area have been collected and processed, a linear model is fit to the mean GSI_{30} of stage 3-5 females, using sample date as the sole predictor variable. If a significant increase in GSI_{30} can be detected ($\alpha = 0.05$), the model is used to predict the closure date (i.e., when the threshold value of $GSI_{30} = 25$ will be reached). The model and predicted closure date are updated as additional samples are collected. Once the predicted closure date is five days away, the closure date is announced to the fishery (and thus 'fixed', regardless of subsequent samples). If an update to the model predicts that the threshold value will be reached in less than five days, the closure date will be set at five days from the model update date (i.e., a five day notice to the fishery will always be provided). If there are insufficient samples to predict a closure date, a default closure date, which represents the average date that the threshold value would have been reached in past sampling seasons, will apply.

Validity of Assumptions

Several assumptions underlie the current spawning closure program. The validity of each is evaluated here using recent full-season maturity and GSI data for the Massachusetts-New Hampshire (MANH) spawning area. Unfortunately, a lack of samples from the other spawning areas (Western Maine, Eastern Maine) prevents an equivalent analysis.

Assumption 1: Larger herring arrive and spawn earlier than smaller herring

It has long been noted that within a sample of fish, the GSI of smaller herring is less than that of larger herring. However, during the re-design of the spawning closure program, existing data suggested that this was due to larger herring maturing earlier, and that all sizes approached a similar maximum GSI prior to spawning. Consequently, the length effect on GSI was estimated from sample data and used to adjust all GSI values to that of a standard length (i.e., GSI_{30} = expected GSI of a 30 cm female herring).

Recent data confirm this assumption in that larger herring comprise a greater portion of fishery samples early in the season, and are replace by smaller fish as the spawning season progresses (Figure 1). In addition, the average size of fish decreases sequentially as the population moves through the maturity stages (Figure 2). This suggests that not only are larger fish present earlier; they are also maturing and likely spawning before smaller fish. The 30 cm standardization also appears to be having the desired effect of combining information from all sizes to achieve a more consistent measure of the maturation for the spawning population as a whole (Figure 3).

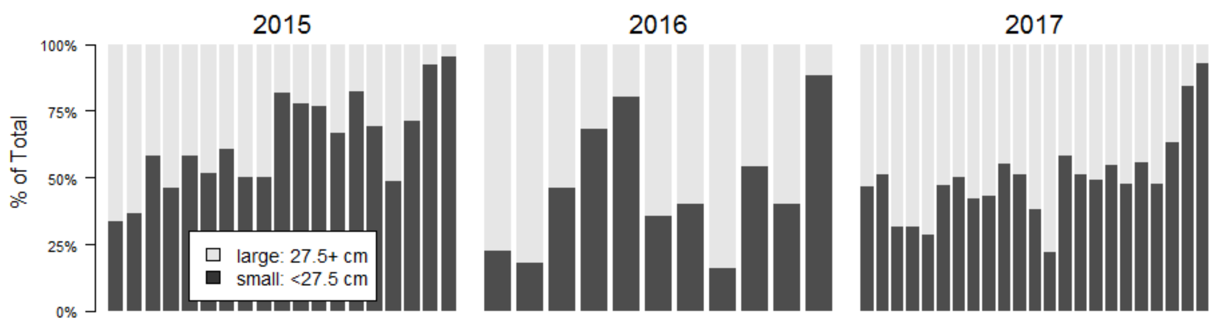

Figure 1. Fraction of herring in "large" or "small" size classes over the sequence of samples from the Massachusetts-New Hampshire spawning area, 2015-2017.

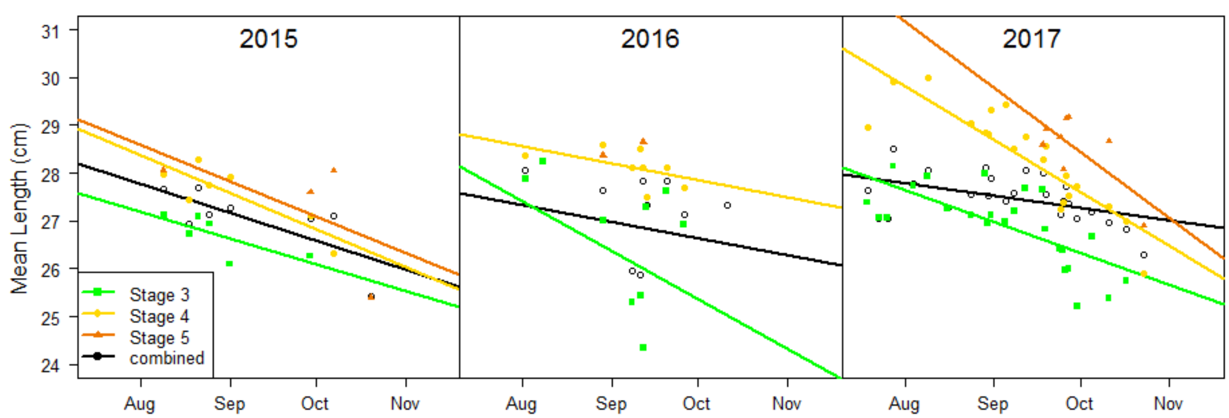

Figure 2. Mean length (cm) of female herring sampled for GSI, by maturity stage and sample date.

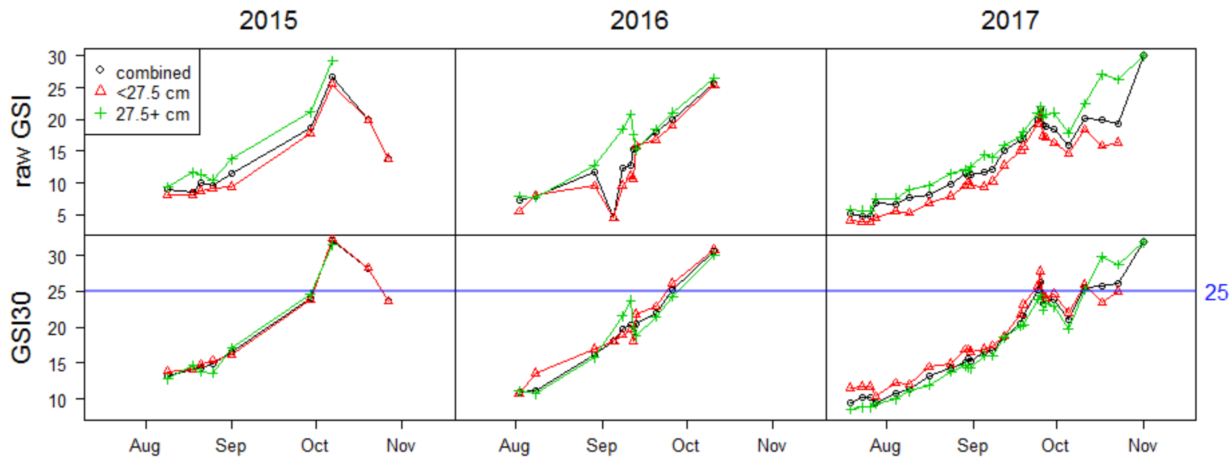

Figure 3. Mean GSI (top) and mean GSI_{30} (bottom) by sample year, date, and size class.

Assumption 2: Spawning commences near the closure threshold of GSI_{30} = 25

To adequately address this assumption, we need an objective measure of when spawning actually occurs. Prior to the collection of full-season maturity data, the only information available to us were pre-spawning GSI measurements from prior seasons. As such, the closure threshold was selected from a range of observed values at the high end of maturity stage 5, which is the last stage prior to spawning. While this approach is relevant for the maturation of an individual herring, the mean GSI of a sample (and the population) represents a mix of individuals with different developmental trajectories, even after accounting for the length effect. In other words, the peak GSI for the population may be less than that of individual fish due to this heterogeneity in spawning time.

Fortunately, by collecting maturity samples both during and after the spawning season, we can now quantitatively describe the timing and duration of the spawning season. Although more “noisy” than GSI data, we can clearly see a sequential progression of maturity stages in each of the last three years (Figure 4). The earliest samples are dominated by stage 3 (early maturing) fish, followed in sequence by later maturity stages and ending in post-season samples comprised primarily of spent (stage 7) and resting (stage 8) fish. Interestingly, the last sample in each year included some fish just entering the maturation cycle (stage 2), suggesting a portion of the population may spawn in the spring.

To describe the start of the spawning season, we fit a logistic regression to the proportion of fish in each sample that had begun to spawn (stages 6+). Likewise, to describe the end of the spawning season, we fit a logistic regression to the proportion of fish that had completed spawning (stages 7+). In both cases, stages 1 (juveniles) and 2 (initial maturation) were omitted from this analysis because it is not likely they would have spawned in the current season. A threshold percentage value can then be selected, above which we consider the “spawning season” to be underway (Figure 5). As mentioned previously, there is a long-standing rule that accepts 25% spawning herring in a fishery sample; however, lower values could be selected if there is a desire to further minimize the potential for fishery-spawning interaction. Please keep in mind that a 25% threshold for defining for the spawning season refers to the expected value for the population, meaning that individual samples may contain greater than, or less than, 25% spawning herring.

The previous closure system was still in effect in 2015, yet for the first time we were able to collect maturity samples throughout the entire spawning season. The closure began on the default date of 9/21 in this year due to a lack of 3 consecutive GSI samples from either large or small herring above their respective thresholds. In retrospect, maturity data indicate that this resulted in closing the fishery nearly two weeks early (Figure 6). Consequently, when the initial four-week closure ended, additional samples contained more than 25% spawning fish, leading to an additional two-week closure. In total, the fishery was closed for six weeks, even though the spawning season (under the 25% definition) was only four weeks long. However, if the new model-based system had been in place in 2015, the closure would have achieved a better match to the spawning season, beginning 3 days after the 25% spawning point and likely without the need for a re-closure (Figure 7).

The progression of spawning appears to have occurred earlier and more rapidly in 2016 (Figure 8). However, with only one sample during the closure and one post-season sample, the description of the spawning season has the greatest uncertainty in this year. The newer model-based closure protocol was first implemented in this year, resulting in a closure 5 days after 25%[1]. A sample collected 10 days into the closure period contained 87% spent or resting herring, indicating the bulk of the population had already spawned. No additional samples were available until early December, when it was further confirmed that the spawning season had concluded. The logistic model fit to these data suggested the entire 2016 spawning season was only 2.3 weeks long; However, it should be emphasized that the scarcity of samples toward the end of the season adds significant uncertainty to this estimate. It's possible that the season was several weeks longer and we simply lacked the temporal resolution to measure it.

The 2017 season resulted in the most detailed and complete description of spawning to date, with 29 samples collected between July 19th and November 1st (Figure 9). In this year, the model-based system resulted in a closure that was slightly before 25% spawning (2 days). The accumulation of fish entering and passing through the spawning stage can clearly be seen in the sequence of maturity samples. These data suggest that the 2017 spawning season was 4.9 weeks long (34 days), making the initial 4-week closure period insufficient. Samples collected during the fourth closure week indicated that 50% had yet to finish spawning, resulting in an additional 2-week re-closure.

The current GSI_{30} threshold of 25 appears to result in a closure that starts within a few days of the point when 25% of the population is expected to be spawning, considered here to be the start of the spawning season. However, in years with few GSI samples (2015) or accelerated maturation (2016), the current threshold may result in greater than 25% spawners in the catch. Selecting a lower GSI_{30} threshold (i.e. 23 or 24) would reduce this possibility. Regardless, the current model-based system

[1] The model actually recommended closing on 10/1/16, four days after 25% spawning, but managers opted to wait an additional day.

achieves a far better match to the spawning season than the prior version, which tended to close the fishery several weeks early and rely more heavily on default dates.

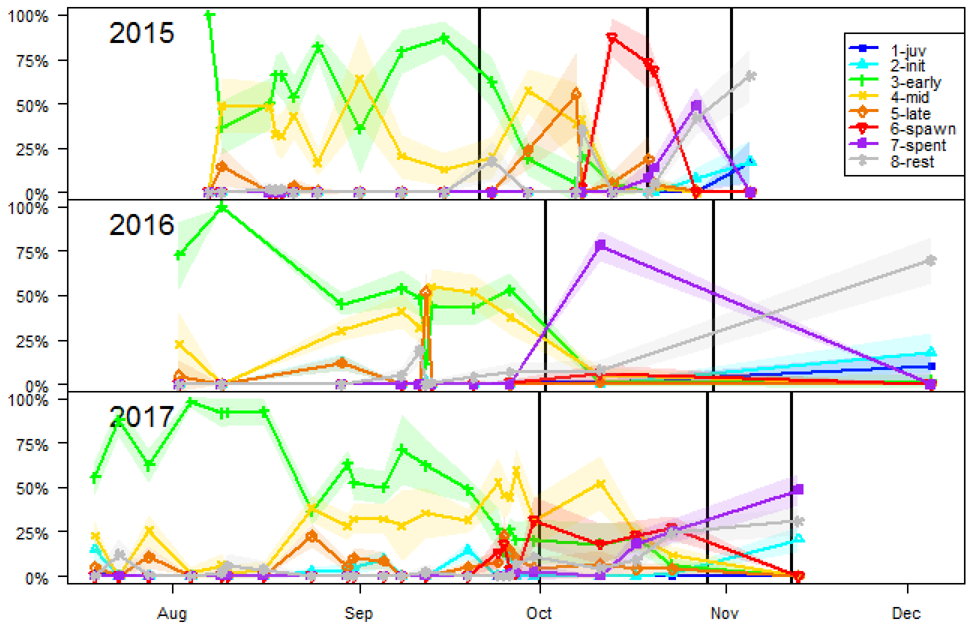

Figure 4. Fraction of MANH herring in each maturity stage by sample year and date. Black vertical lines indicate closures.

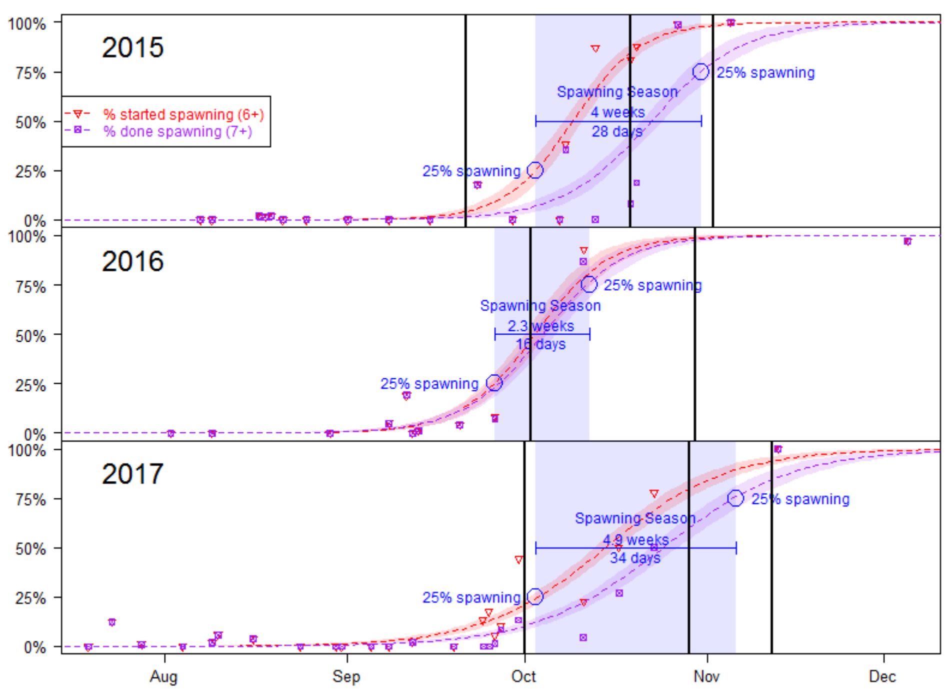

Figure 5. Observed fraction of sampled herring that had started spawning (red: stage 6+) and completed spawning (purple: stage 7+), with fitted logistic regression lines. The shaded blue region represents the

spawning season, as defined by the period between when 25% of fish had begun to spawn and when 25% of fish had yet to complete spawning. Vertical black lines represent spawning closures.

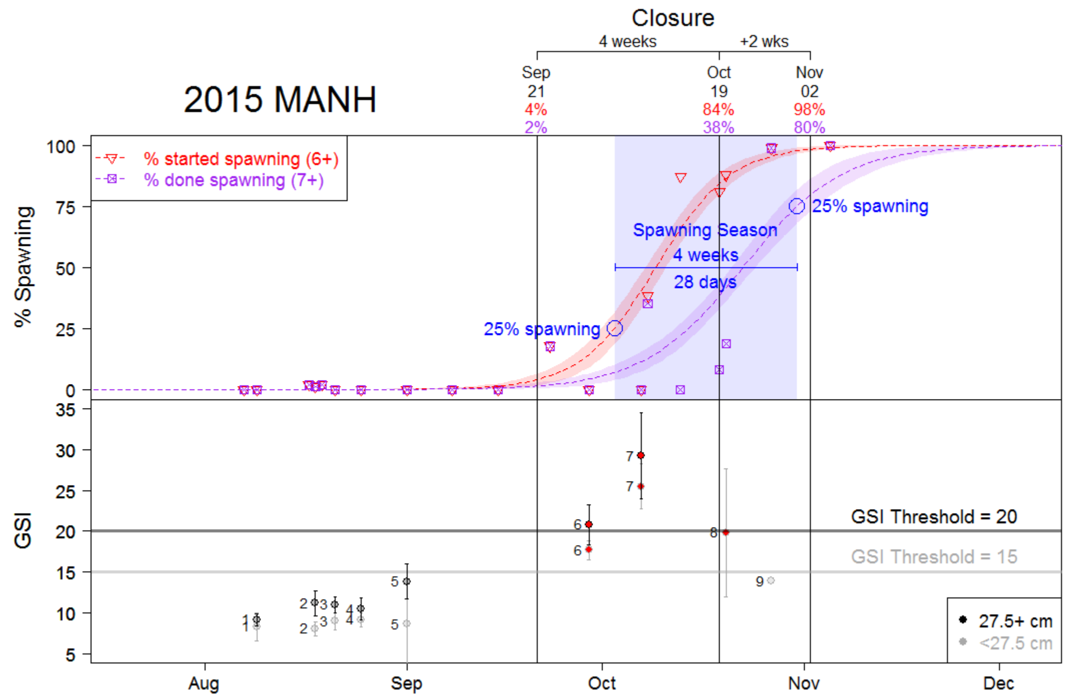

Figure 6. Estimated spawning season (top) and mean GSI (bottom) by sample date, for 2015 in the MANH spawning area. Closure dates refer to the actual closure dates under the old closure system.

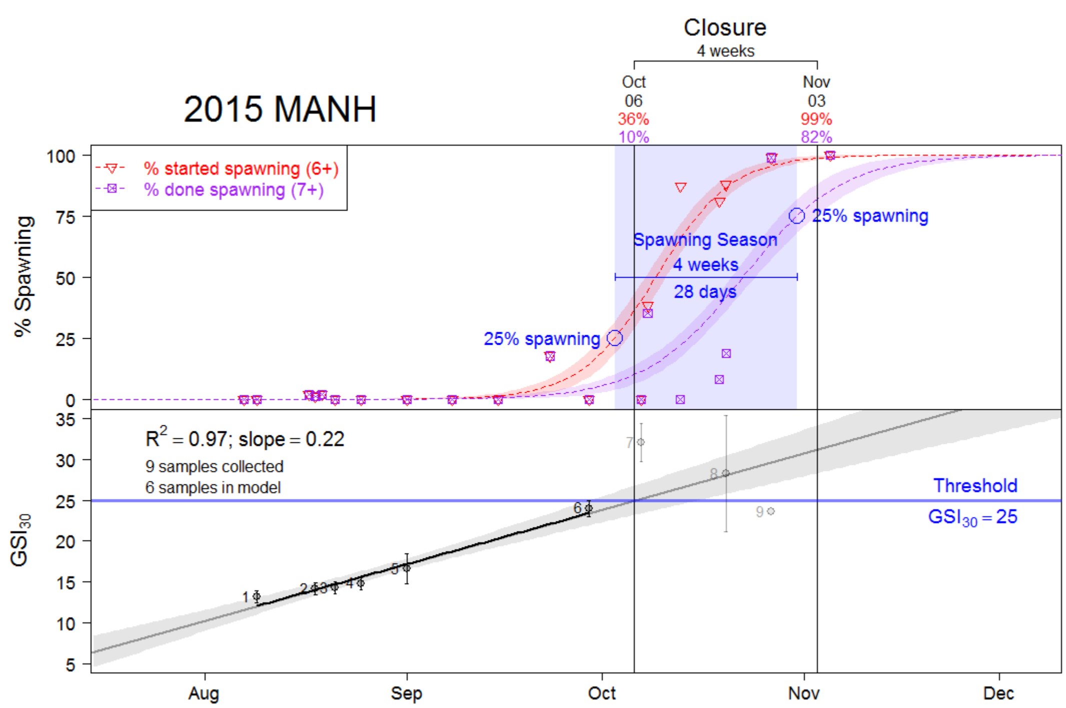

Figure 7. Estimated spawning season (top) and mean GSI_{30} (bottom) for 2015 in the MANH spawning area. Closure dates refer to what would have occurred under the current model-based system.

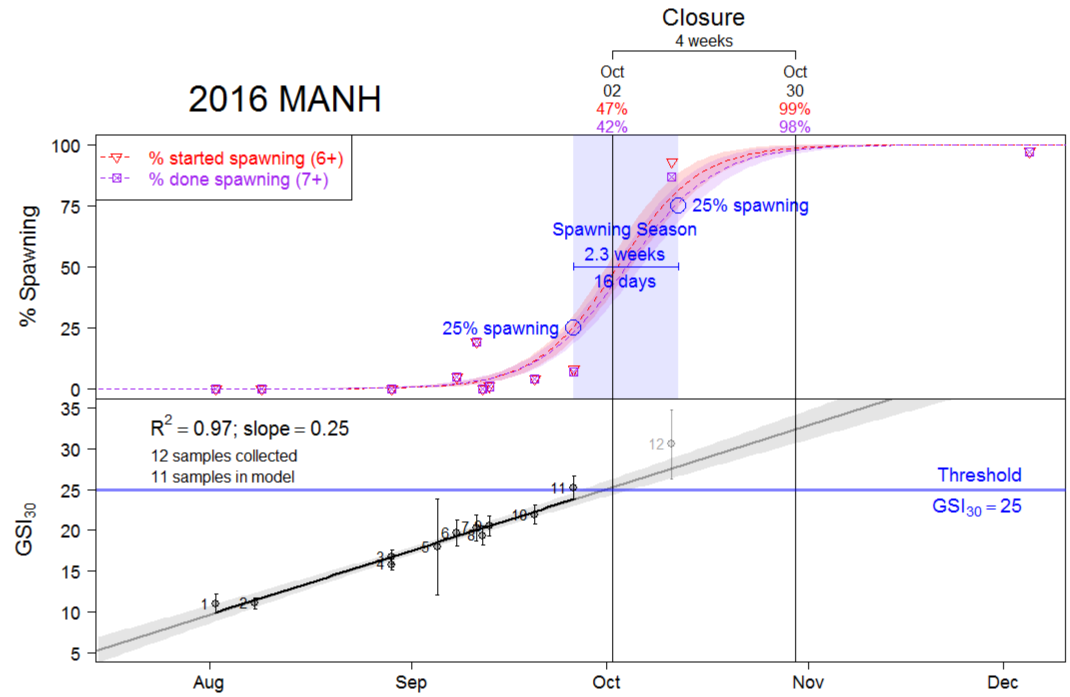

Figure 8. Estimated spawning season (top) and mean GSI (bottom) for 2016 in the MANH spawning area. Closure dates refer to the actual closure dates under the current closure system.

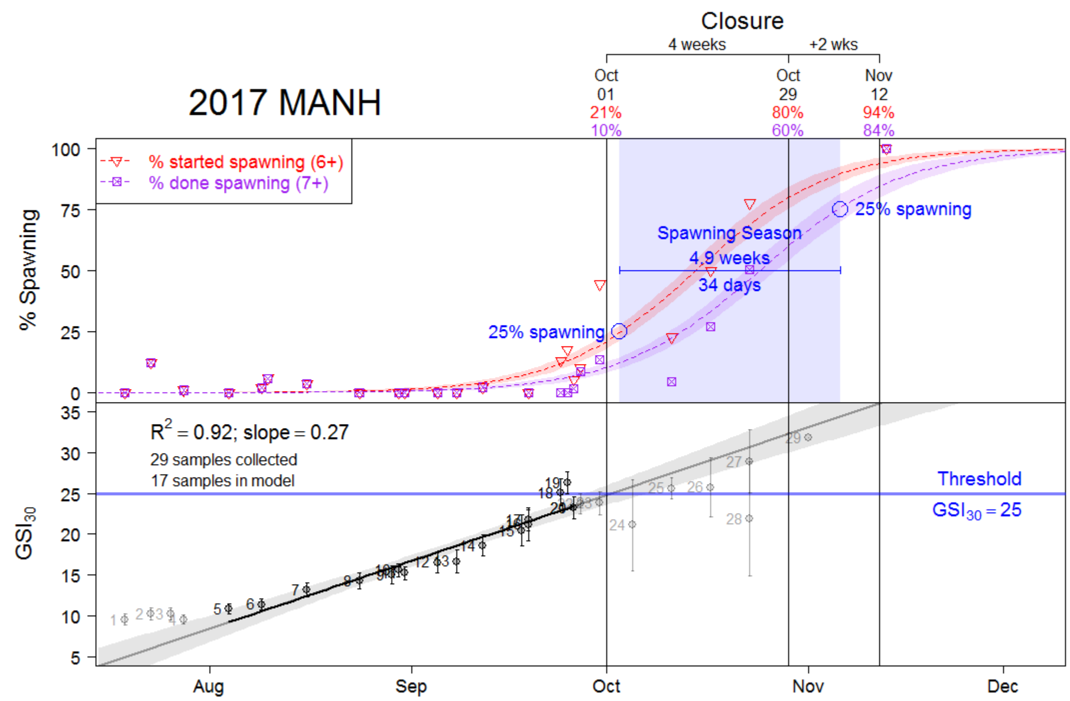

Figure 9. Estimated spawning season (top) and mean GSI (bottom) for 2015 in the MANH spawning area. Closure dates refer to the actual closure dates under the current closure system.

Assumption 3: Four weeks is a sufficient to cover the typical spawning season

The appropriate closure duration largely depends upon the percent of spawning fish deemed to be acceptable in fishery catches. Under the assumption that 25% spawning is acceptable, the spawning seasons of 2015-2017 were estimated to be between 2.3 to 4.9 weeks long; although, there is far greater confidence in the longer season estimates (2015 and 2017) than with the shorter (2016) due to a low number of samples from during/after the closure in that year. Consequently, an initial closure period of 4 weeks is likely to result in frequent use of the re-closure protocol to extend the closure. If the uncertainty inherent in frequent use of the re-closure protocol is deemed undesirable, the initial closure period could be lengthened (e.g., to 5 or 6 weeks). Furthermore, if 25% is considered an unacceptable level of spawners in the fishery, alternative values could be selected. However, it should be noted that lowering the management target for maximum acceptable % spawning will increase the defined spawning season (Figure 10) and therefore require a longer initial closure period, a lower GSI_{30} threshold (Figure 11) and an earlier default date (Table 1).

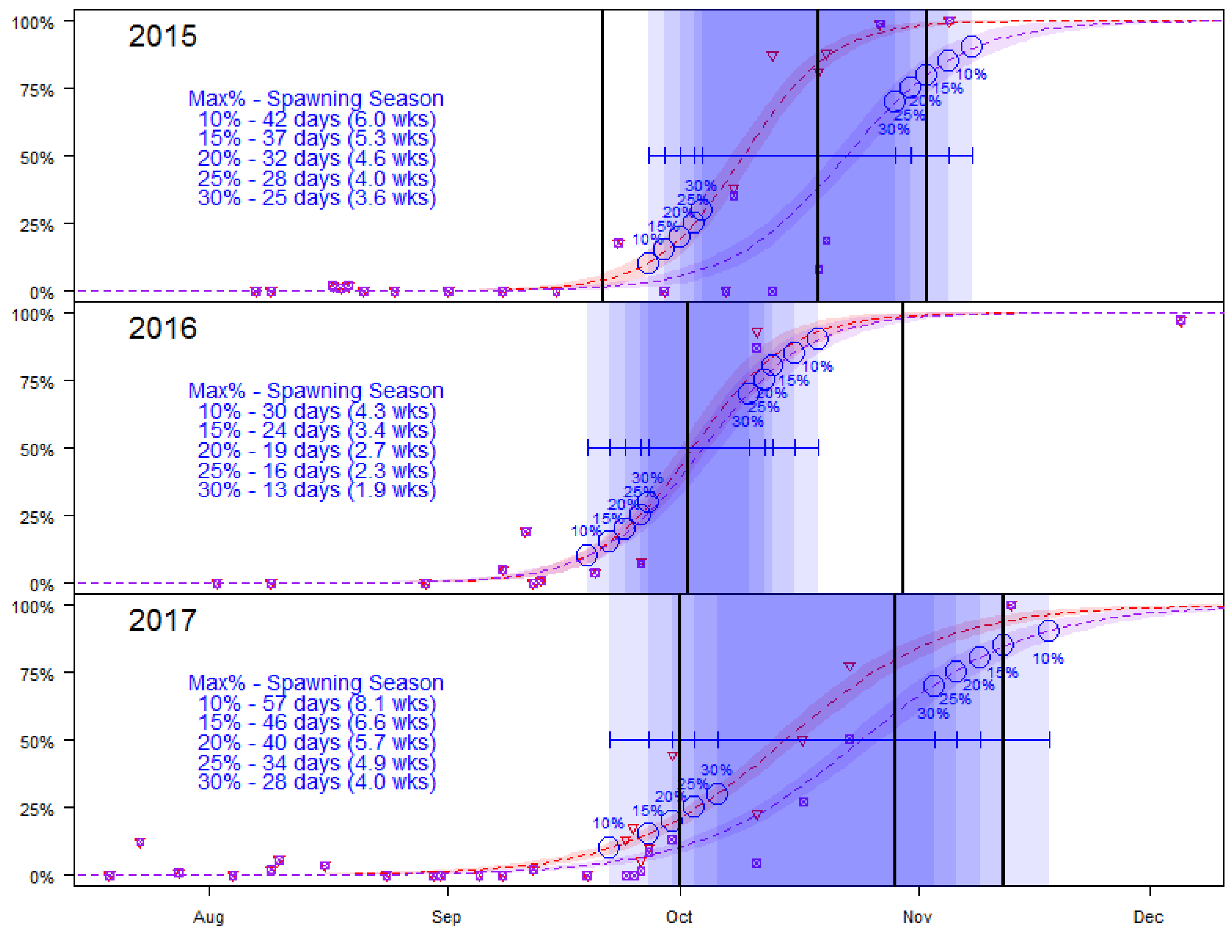

Figure 10. Effect of choice of maximum allowable % spawning in the catch on duration of the spawning season.

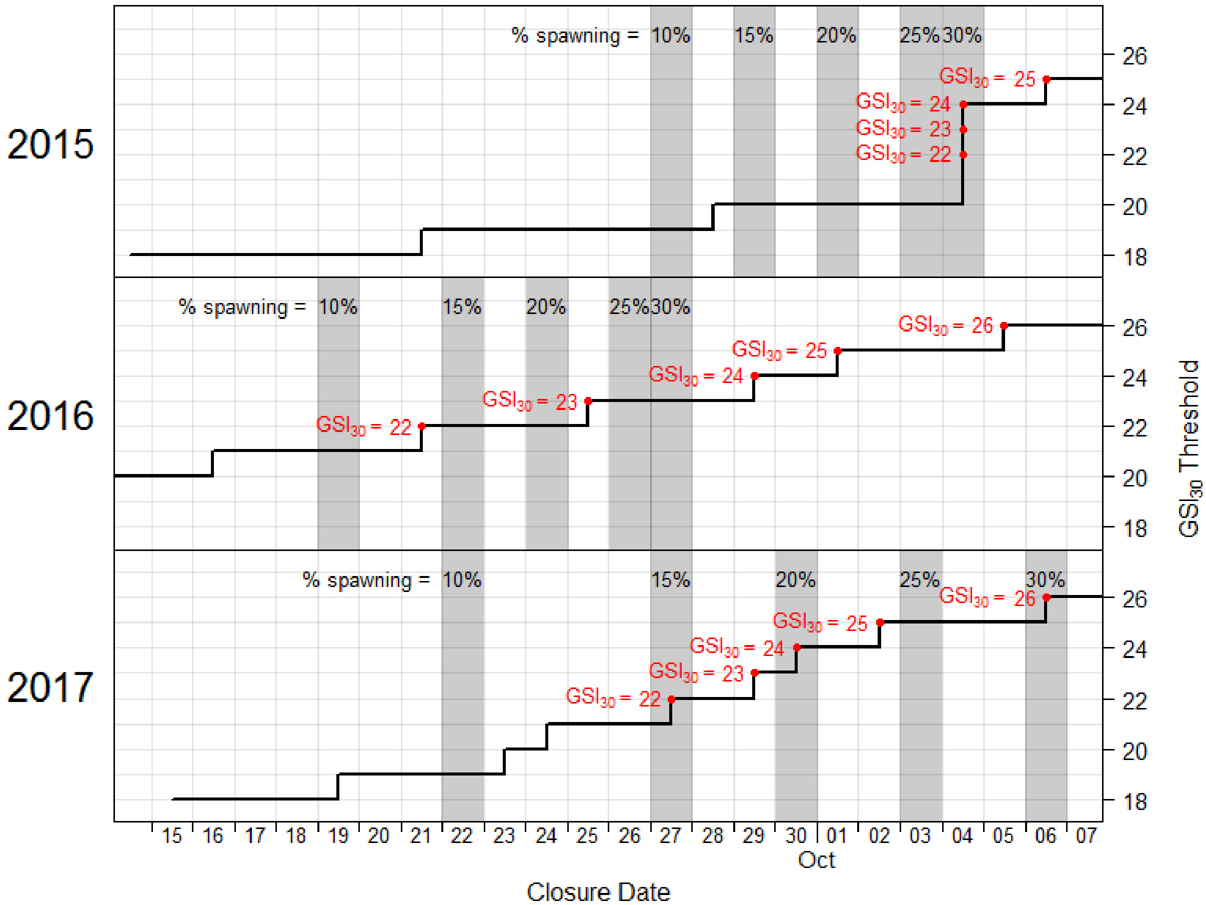

Figure 11. Date when the MANH spawning closure would have started, under different GSI_{30} thresholds. The vertical gray bands indicate the percent of the population expected to be spawning.

Table 1. Updated default dates for different GSI_{30} thresholds and spawning areas, using GSI observations from 2005-2017. As with the original analysis conducted under Amendment 3, sample data from the WM and MANH spawning areas were combined due to a lack of detectable difference in spawning time. There are insufficient samples from which to estimate a default date for the EM area. As such, the previous default date would remain (based on historical observations of herring eggs on lobster traps).

	Default Date		
GSI_{30} Threshold	MANH	WM	EM
26	Oct-6	Oct-6	Aug-28
25	Oct-1	Oct-1	Aug-28
24	Sep-27	Sep-27	Aug-28
23	Sep-23	Sep-23	Aug-28
22	Sep-19	Sep-19	Aug-28

Assumption 4: GSI increases linearly during the last 2 months prior to spawning

During the development of Amendment 3, a review of 15 years of sample data suggested that a linear model could adequately represent the increase in GSI during the pre-spawning period (i.e., ~2 months preceding spawning), despite an expected exponential relationship over the full course of gonadal development. The recent effort to sample the population over the full season now provides us with a longer time series of GSI observations to evaluate the conditions under which this assumption remains valid.

Data from the most recent 3 sampling seasons indicate that the rate of change in mean GSI_{30} (i.e., slope of the linear model) does increase slightly as the population approaches spawning (Figure 12). This results in a trend toward earlier forecasted closure dates with the addition of subsequent samples. However, the linear model continued to explain more than 90% of the variation in mean GSI_{30} (i.e., R^2) prior to the spawning closure in all years. In 2017 (the year with the best sampling coverage), it appears that GSI_{30} increased linearly over most of the pre-spawning period, and only departed from linearity in the days immediately preceding spawning (at the GSI_{30} threshold of 25). Subsequent samples during the closure period showed that mean GSI became more variable as fish moved out of the spawning stage, leaving behind a smaller pool of pre-spawning (stage 3-5) females to sample from. Although four GSI samples were collected from the MANH spawning area in July of 2017, the Herring PDT decided to omit these samples from the model due to concerns that further extending the period of observation could increase non-linearity, and because July samples were never included in the original analysis from which the system was developed.

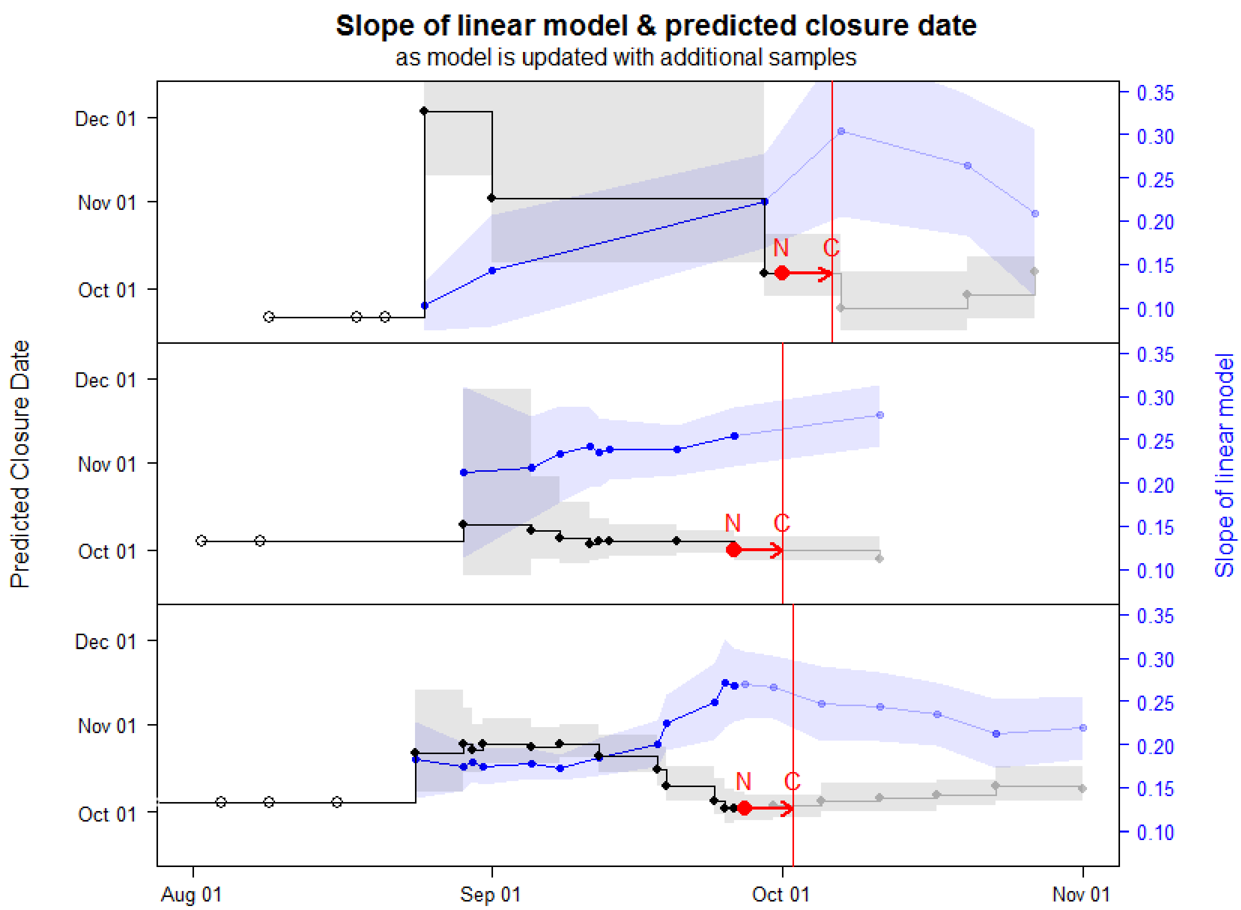

Figure 12. Slope of linear model GSI_{30}~DATE (blue, right y-axis) and predicted closure date (black, left y-axis) as the model is updated with additional samples. Open black circles show where the default closure date would apply: when <3 samples have been collected and/or the model fails to detect a significant increase in GSI_{30}. The red point labeled "N" indicates when the closure date is finally selected and the fishery notified. The red vertical line labeled "C" indicates the final selected closure date (5 days after the notify date). Darker points and lines indicate samples used in the model, whereas lighter points and lines indicate samples collected after the final closure date was selected.

Conclusions and Considerations for the Section

The current model-based spawning closure system appears to be meeting all of the Section's main objectives. The assumptions regarding length effects and spawning time appear sound, which allows the new system to be far better aligned with the reproductive biology of the population. Overall, this represents a clear improvement over the previous system.

If managers want to further minimize the risk of spawning herring in the catch, the TC notes two changes for consideration by the Section.

1) The TC found that in the two years with the most comprehensive maturity data (2015, 2017), the spawning season lasted 28 days and 34 days, respectively. This suggests that 2 week re-closures may occur frequently in the herring fishery, given that the initial closure period is currently set at 4 weeks. To simplify the herring closure protocol, provide greater predictability to industry, and provide greater protection during the spawning season, the Section could consider a longer closure of 5 or 6 weeks, reducing the need for a 2-week re-closure.

2) To further minimize the risk of spawning herring at the beginning of the season, a lower GSI_{30} threshold could be selected. As a reminder, the current threshold is 25; however, analysis suggests that a GSI_{30} threshold of 23 or 24 would reduce the probability of greater than 25% spawners in the catch. In addition, this change would have the added benefit of shortening the monitoring period by restricting it to the portion of the season when GSI increases most linearly. This may result in more consistent closure forecast dates from one sample to the next. However, please note that lowering the GSI_{30} threshold will require an earlier default date (Table 1) and will further increase the likelihood for re-closures, if the initial closure period remains at 4 weeks.

Finally, the TC highlights the need for fishery independent sampling during the spawning closures, especially in eastern and western Maine where there has are fewer fishery-dependent samples available. The information that these samples provide will be critical for our ability to further evaluate and improve the performance of this system.