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Improving Walleye Hooking Mortality Models for Lake Mille Lacs, Minnesota

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Abstract

Reliable estimates of hooking mortality are essential to estimating angler kill when large fractions of the recreational catch are released. From 2005-2016, hooking mortality rates in Lake Mille Lacs were estimated as a function of temperature and a quadratic fish length effect. However, re-examination of the data with Akaike and Bayesian information criteria comparisons showed conflicting support for the length effect. In 2016, we collected additional data to test the length effect model. Walleyes were caught by angling with live bait and artificial lures at water temperatures ranging from 11 °C to 24 °C and held in pens with survival recorded after 4 to 6 days. The original model did not reliably predict mortality rates in 2016, and prediction biases relative to length indicated some error was due to the quadratic length effect. We then used the 2016 data to compare the quadratic length effect model, a temperature-only model, and a mixed effect model of temperature plus a random holding pen effect. Information criteria favored the temperature-only model, though there was some evidence of pen effects on mortality rates. We recommend the temperature-only model and note that angler recall bias on both numbers and lengths of released fish may have a much larger effect on hooking mortality biomass estimates than uncertainty in the mortality rate model.

Introduction

Fishing mortality in recreational fisheries can lead to unacceptable declines in abundance and/or quality (Slipke et al. 2002, Ben-Hasan et al. 2021). Conservation-minded anglers have been voluntarily practicing catch-and-release for many species for at least 80 years (Wulff 1939), understanding that releasing fish should produce higher catch rates (Jones et al. 2022). In some fisheries, however, regulations requiring that some portion of the catch be released have been necessary to protect stocks (Webb and Ott 1991, Sánchez-Hernández et al. 2016). Released fish are subject to varying degrees of hooking mortality (Muoneke and Childress 1994), and if enough fish are released, hooking mortality can represent large fractions of total fishing mortality and should therefore be estimated. This becomes especially important in quota-based fisheries where mortality estimates can have political and legal ramifications.

Since 1997, the Walleye (*Sander vitreus*) population in Lake Mille Lacs in Minnesota has been managed as a combined State recreational fishery and Tribal subsistence fishery (Radomski 2003, Schmalz et al. 2011). Walleye quotas were assigned to each party and Minnesota estimated its Walleye kill through annual creel surveys. To account for total biomass of Walleye kill due to angling, the State included an estimate of Walleye hooking mortality to the estimated Walleye harvest. Initially, the hooking mortality rate was assigned as 10% for Walleyes less than 355 mm and 6% for larger Walleyes. These rates were derived from literature in which hooking mortality rates for Walleye ranged from 1% to 16% in shallow waters (< 7m) (Fletcher 1987, Payer et al. 1989, Schaefer 1989), although none of these studies supported the higher mortality rates for juvenile walleye.

As quotas were adjusted to account for changes in the Walleye population, the State applied increasingly more restrictive regulations to recreational angling. As a higher proportion of the Walleye were released, the importance of accurately estimating hooking mortality increased. Rather than use literature-based assumptions, a Mille Lacs specific hooking mortality model was developed through field experiments in 2003 and 2004 (Reeves and Bruesewitz 2007). Using logistic regression analysis, they developed a model of hooking mortality probability (P) containing a linear effect for temperature and a quadratic relationship for fish length:

$$\mathrm{logit}(P) = \mu + T + L + L^2 \qquad (1)$$

where $\mathrm{logit}(P) = \log_e(P/(1-P))$, μ was an intercept, T was temperature (°C), and L was fish length (mm). All parameter estimates in the 2007 temperature + quadratic length (T+QL) model were statistically significant ($p < .005$), and a likelihood ratio test (LRT) accepted the model over a nested temperature-only (TO) model ($p = 0.017$). In the fitted T+QL model, mortality rates increased with water temperature and were higher for larger and smaller Walleyes, with the minimum mortality rate occurring at approximately 450 mm (Figure 1). This T+QL model was applied to the observed length distribution of released Walleyes in the Mille Lacs creel survey data to estimate length-specific angler hooking mortality rates from 2005-2015. The biomass of killed walleye was then calculated from the length distribution using length-weight relationships.

Incorrectly specified models can be a major source of error in science (Chatfield 1995), and several management concerns motivated a reexamination of the Reeves and Bruesewitz (2007) model. First, poor year-classes of Walleye from 2009-2012 resulted in a rapid tightening of angling regulations such that Walleye fishing in the open-water season of 2016 was limited to catch-and-release only. This greatly increased the importance of hooking mortality estimates, both in defensibility of the model and the reliability of its predictions. Second, few Walleyes were caught on artificial lures in the original study, especially in the warmer months. Public input suggested angler trolling with crankbaits had increased, so the model could be biased if hooking mortality rates were different with artificial lures relative to natural baits.

Finally, while both temperature and fish length were *a priori* hypotheses as factors affecting hooking mortality in the 2007 study, the quadratic length relationship found in the data was an unanticipated and novel result. The T+QL model predicted very different estimates of hooking mortality than a temperature-only model (Figure 1), especially at higher temperatures.

Ideally, the hooking mortality model for the Mille Lacs fishery would contain important factors that affect released Walleye mortality without any extraneous variables that decrease model interpretability, increase data requirements, or reduce prediction accuracy. Thus, we re-examined the 2007 models using scores from both Akaike Information Criteria (AIC, Akaike 1974) and Bayesian Information Criteria (BIC, Schwarz 1978). AIC is formulated for minimum prediction error (Shibata 1981), a desirable quality for a management model, but has a higher risk of including extraneous parameters, especially for very large sample sizes (Bhansali and Downham 1977, Bozdogan 1987, Taper 2004). BIC, on the other hand, is designed to select a consistent number of model parameters in the 'best' model regardless of sample size, but has a higher risk of excluding factors, especially those with relatively small effects (Dziak et al. 2020). In model comparisons for the 2007 data, AIC moderately favored inclusion of the length effects while BIC selected for the simpler TO model, indicating that although the T+QL may provide better predictions, there was evidence that including the length effects could be over-fitting the model. Since length information on released fish was already collected in creel surveys, the more complex model did not require additional data collection costs, so there was minimal downside to using the T+QL model at first. However, as regulations tightened and hooking mortality became the main source of Walleye fishing mortality, the lack of strong support for the T+QL model concerned managers due to the large effect of the quadratic length relationship on estimated mortality rates of larger and smaller Walleyes.

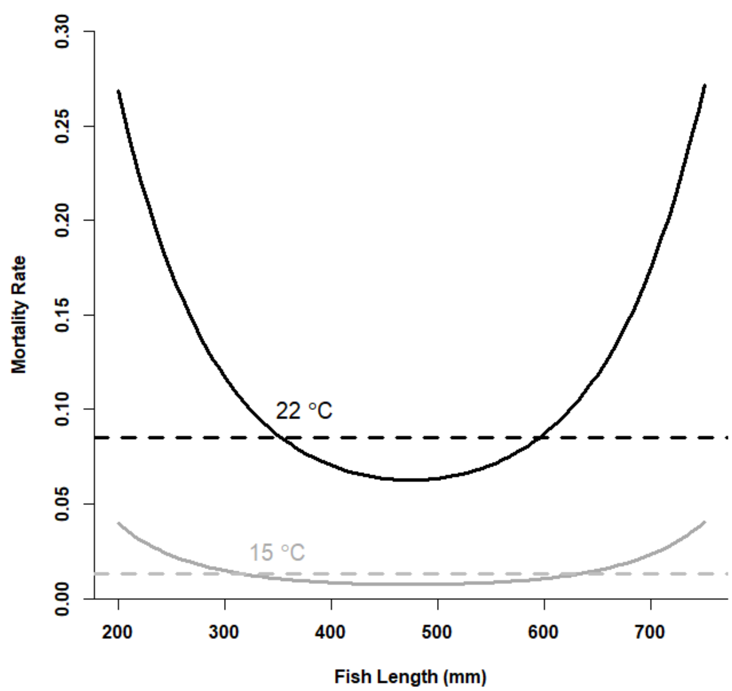

FIGURE 1. Predicted mortality rates versus fish length at 15 and 22 °C for the 2007 temperature + quadratic length model (solid lines) used for Lake Mille Lacs Walleye management in comparison to a temperature-only (dashed lines) model of the 2007 data.

Because of the increased importance of hooking mortality estimates to Walleye management in Lake Mille Lacs, the 2007 hooking mortality study was replicated during the 2016 open-water season to evaluate the 2007 T+QL model. Specifically, the first objective was to test hooking mortality predictions from the 2007 T+QL model against observations of hooking mortality in 2016. Additionally, hooking mortality data from 2016 were used to refit a T+QL model and a temperature-only model, and model fits were evaluated with AIC and BIC. Finally, data from both the 2016 and the 2007 studies were pooled to develop a new hooking mortality prediction model.

Methods

Study Site

Lake Mille Lacs is a 53,650 ha lake located approximately 200 km north of the Minneapolis-St. Paul metropolitan area. It is the most intensely fished Walleye lake in Minnesota, with annual effort as high as 75 hrs/ha (Minnesota Department of Natural Resources, unpublished creel surveys). The lake has a maximum depth of 12.8 m and an average depth of 8.8 m. It is well known for self-sustaining fisheries for Walleye, Smallmouth Bass (*Micropterus dolomieu*), and Northern Pike (*Esox lucius*) as well as a fishery for trophy Muskellunge (*E. masquinongy*) that is partially maintained by stocking.

Walleye fishing runs from early to mid-May through late February. Open-water fishing seldom runs past October, and ice-fishing usually begins in December. Anglers usually fish from boats and favor live bait including minnows (Cyprinidae), nightcrawlers (Annelida), and especially leeches (Hirudinea). Crankbaits were historically trolled in the spring and fall when Walleye are in shallow water, but midsummer trolling has also become more popular in recent years.

Data Collection

Participating anglers caught Walleyes using angling techniques common to Lake Mille Lacs from May 17 through August 17, 2016. Anglers were mostly DNR staff but included some local volunteer anglers. Reeves and Bruesewitz (2007) relied more heavily on volunteer anglers encountered on the water but found that they frequently quit fishing or moved soon after receiving instructions (K. Reeves, Minnesota Department of Natural Resources, personal communication). Using paid anglers reduced instructing time and increased fishing time and catch. Collectively, anglers fished for 572 angler-days.

On most days, anglers were allowed to fish by whatever means they liked but occasionally were required to fish with artificial lures or plastics, including Gulp!Alive!® leeches, as there was concern low numbers of Walleye caught using artificial baits in the original study. Most anglers preferred live bait, but one boat was a designated trolling boat that fished almost exclusively with crankbaits trolled on leadcore lines or behind planer boards. The inclusion of soft plastic baits in this study was intended to reflect the large increase of smallmouth bass anglers and the subsequent observation of more walleyes caught on plastic baits (Minnesota Department of Natural Resources, unpublished creel surveys). Sampling goals were to have approximately equal numbers of fish caught on live and artificial baits during each half-month sampling period. Fishing took place within 400 meters of preset net pens. Participants caught Walleyes and unhooked them or cut lines as they normally would. Walleye were placed in tubs with fresh water and nearby "running boats" were summoned. The fish were transferred to the running boat, where staff measured each fish and applied a numbered t-bar anchor tag for identification, then released them into the holding pens. Additional data, including hooking location, bleeding, depth, and other factors were collected. However, our primary interest is in modeling hooking mortality from creel survey data, not identifying factors contributing to hooking mortality. We believe it is unrealistic to expect anglers to remember the details associated with each specific fish, and therefore these additional variables were not considered further.

Angled Walleyes were in held in the pens for 4 to 6 days. Angling generally occurred on

Tuesdays, Wednesdays, and Thursdays, and pens were recovered the following Monday. Net pens were 2m X 2m in area, and ran from the surface to the lake bottom, at depths of up to 11 m. Polyvinyl chloride (PVC) rings every 2 m kept the pen from collapsing, allowing fish access to all depths. The netting itself was 6 mm bar knotless nylon and was small enough to avoid entanglement. Fish were introduced into the pen through an 8-inch PVC tube fixed through a zippered top. A powered lifting device retrieved the pen and held it above the boat deck, where fish could be removed through a zippered slot on the bottom of the net. Live Walleye were released back into the lake. Tags were collected from dead Walleye, and the tag numbers were used to look up their lengths when caught.

Initially there were no concerns about fish density within a pen; water temperatures were low and mortalities were limited even when the number of Walleye in a pen approached 100. However, on June 21, water temperature exceeded 20 °C and fishing was exceptionally good, resulting in 107 Walleyes being placed into a single pen. Mortality in this pen was 25%, and surviving Walleyes appeared pale and lethargic. Consequently, Walleyes from this pen were excluded from the analyses. Afterwards, pen density was limited to 60 Walleyes per pen until temperatures reached 23 °C, and 40 Walleyes per pen after that, and no other incidences of apparent overcrowding were visibly observed.

Statistical Analyses

Following Reeves and Bruesewitz (2007), we used the 2007 data to fit the T+QL model (eq. 1) and a temperature-only (TO) model. A generalized linear mixed effect (Breslow & Clayton 1993) T+Pen model was also fit to 2007 data; the pen effect, assumed to be distributed Normal($0,\sigma_{Pen}$), accounted for correlations in mortality for fish within the same holding pen. All three models in addition to a Null model, logit(P) ~ μ, were compared with both AIC and BIC scores.

After data collection in 2016, we used the 2007 TO and T+QL models to predict mortality probabilities for Walleye captured in 2016. Predictions were evaluated with a Hosmer-Lemeshow goodness-of-fit test (Hosmer and Lemeshow 2000). The 2016 data were further used to evaluate model structure with comparisons of the four models described above using AIC and BIC model selection approaches to evaluate for selection of consistent model structure between the two studies. When pen effects were present, estimates of pen effects on mortality rates were regressed against walleye numbers in the pens to examine for overcrowding effects.

While determining the validity of the T+QL model over a TO model for management use was the primary objective of the study, there was also interest in how artificial vs. natural bait affected mortality rates. Thus, after the preferred model structure was determined for the 2016 data, IC were used to compare bait type to two additional models, both of which included the random pen effect: 1) temperature plus an additive bait type effect, and 2) bait type*temperature interaction.

The preferred 2016 model was then applied to predict mortalities of Walleye sampled in the 2007 study, and these predictions were tested with a Hosmer-Lemeshow goodness-of-fit test (Hosmer and Lemeshow 2000).

Finally, data from both the 2007 study and this study were pooled, and temperature only and temperature plus quadratic length models were developed for the combined data set. Model selection was evaluated for the combined model using both AIC and BIC scores.

All analyses were performed in the statistical program R (R Core Team 2022), and the glmer() function in the lme4 package (Bates et al. 2015) was used to fit the generalized mixed effect models.

Results

In the 2016 open-water season, anglers caught a total of 1,704 Walleyes at temperatures ranging from 10.7 °C to 24.1 °C. Numbers were approximately equal by bait type, with 862 caught on live bait and 842 caught on artificial lures. A total of 43 net pens were employed, with a mean density of 41.6 Walleyes per pen (range of 2 to 96). Walleye length varied from 206 mm to 714 mm (mean = 381 mm). The range of lengths in 2016 was similar to that from the 2007 study, but a very strong 2013 year class dominated the catch in 2016, producing a strong mode between 300 and 400 mm (Figure 2). Overall, 111 Walleye (6.5%) died in the holding pens.

The goodness-of-fit test indicated that neither the 2007 TO model nor the 2007 T+QL model performed well at predicting 2016 hooking mortality. However, the 2016 TO model and the 2016 T+Pen model both adequately described predicted mortalities for the 2007 data set (Table 1).

TABLE 1. Hosmer-Lemeshow goodness-of-fit tests. Models fitted to 2007 data did not predict 2016 observed mortalities, while 2016 models adequately predicted 2007 results. Models are temperature only (TO), temperature plus a quadratic length effect (T+QL), and temperature-only with pen effects (T+Pen)

Model	**Year of Data**	**G^2_{HL}**	***p***
2007 TO	2016	43.4	<0.0001
2007 T+QL	2016	29.3	0.0002
2016 TO	2007	8.6	0.38
2016 T+Pen	2007	7.2	0.51

In the 2016 data, both AIC and BIC showed strong evidence against the null model. Additionally, neither IC supported the T+QL model (Table 2). There was conflicting evidence for holding pen effects on mortality as AIC selection found moderate evidence supporting the T+Pen model, while BIC selection marginally favored the TO model without pen effects (Table 2).

There was no relationship between estimated pen effects and pen density (p = 0.93), but densities were much higher in 2016 (mean 41/pen, 75% of pens had ≥ 21 Walleyes) than in the 2007 data set (median 5.5/pen, 95% had ≤ 21 Walleyes). Pen effects may have contributed to some of the prediction error from the 2007 models applied to the 2016 data.

Although bait type is not a practical component of determining hooking mortality associated with our creel surveys, models

TABLE 2. AIC and BIC scores for model selection on 2016 data. The ΔAIC and ΔBIC scores are set relative to the model with the minimum score for each Information Criterion. Models are temperature only (TO), temperature plus a quadratic length effect (T+QL), and temperature-only with pen effects (T+Pen)

Model	***df***	**ΔAIC**	**ΔBIC**
Null	1	50.1	39.7
TO	2	5.0	0
T+QL	4	8.0	13.9
T+Pen	3	0	0.5

including bait type were evaluated to quantify their effects (Table 3). For the temperature*bait type interaction model, mortality rates for Walleye caught on live bait were higher than that for artificial bait at cooler temperatures (Figure 3A), although confidence intervals overlapped over the entire range of temperatures and the BIC comparison favored the model without bait type (Table 3).

TABLE 3. Model comparison for additive and interactive effects of bait type on hooking mortality relative to a temperature-only model. The ΔAIC and ΔBIC values were set relative to the temperature + pen effect (T+Pen) model, thus negative values indicate better model fit relative to the T+Pen model. Other models include temperature + bait type + pen effect (T+Bait+Pen) and a temperature cross bait interaction term with pen effect (T*Bait+Pen).

Model	***df***	**ΔAIC**	**ΔBIC**
Null	1	50.1	39.2
T+Pen	3	0	0
T+Bait+Pen	4	-1.5	3.9
T*Bait+Pen	5	-4.6	6.2

Additionally, the interaction model only moderately reduced the AIC score compared to the T+Pen model, so there is no strong evidence that including bait type improved the models.

Finally, data from the 2007 and 2016 studies were pooled and fit to TO, T+Pen, and T+QL models. Both AIC and BIC scores favored the T+Pen model (Table 4). Predicted mortality rates from the T+Pen model fit to a combined 2007/2016 dataset were similar to the 2007 TO model predictions and those of the 2016 GLMER TO model fit separately, and the 95% confidence bounds for the joint 2007/2016 predicted mortality rate encompassed the predicted

TABLE 4. Model comparisons for a temperature only model (TO), temperature + pen effects model (T+Pen), and temperature plus quadratic length model (T+QL) using pooled data from 2003, 2004, and 2016

Model	***df***	**ΔAIC**	**ΔBIC**
TO	2	7.0	1.1
T+Pen	3	0	0
T+QL	4	5.4	11.3

mortality rates for both datasets fit individually (Figure 4). For the combined 2007/2016 T+Pen model, hooking mortality probability based on temperature, T(˚C), was

$$P = \frac{e^x}{1+ e^x} \ , \qquad (3)$$

where

$$x = 0.25 * T - 7.9. \qquad (4)$$

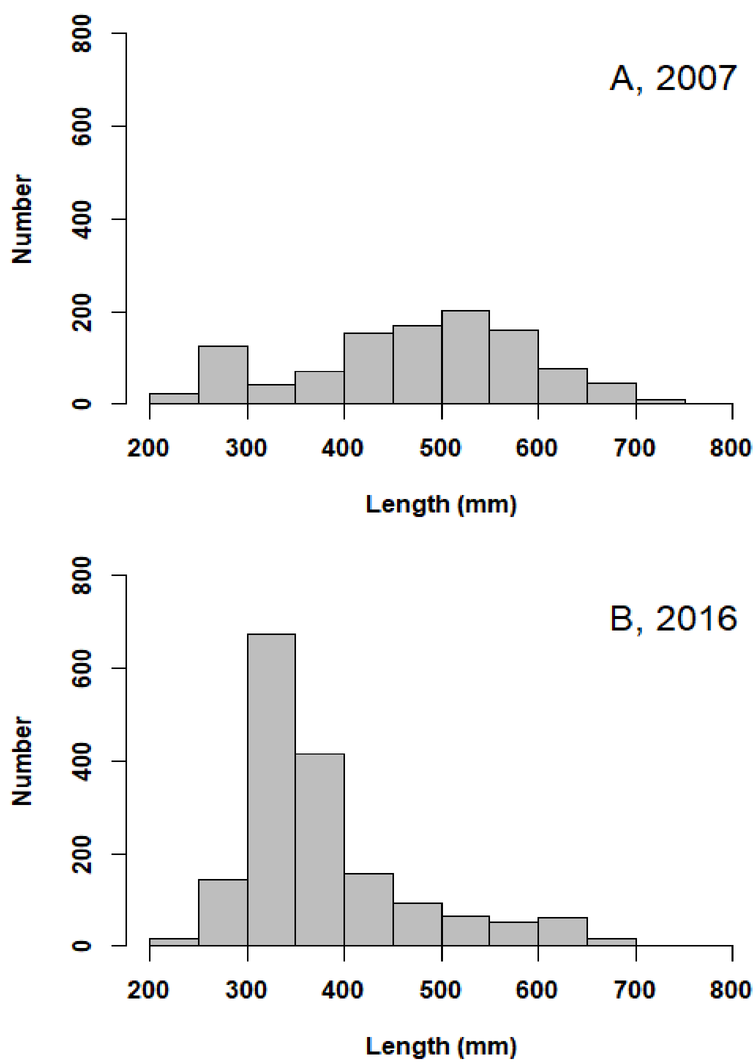

FIGURE 2. Length distributions of walleyes captured in hooking mortality studies in Reeves and Bruesewitz (2007) (panel A) and this study in 2016 (panel B).

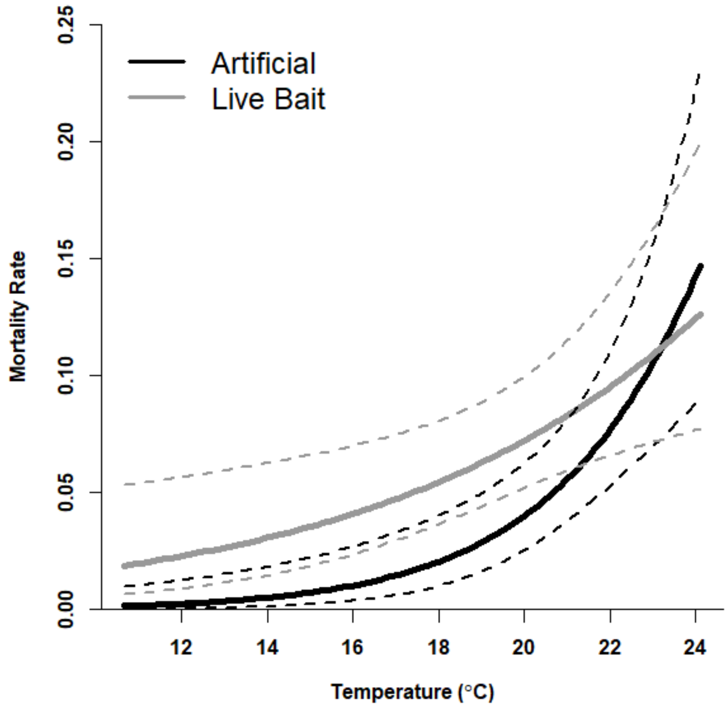

FIGURE 3. Interactive effects of temperature and bait type on 2016 study mortality rates. Dashed lines represent 95% confidence intervals for model predictions.

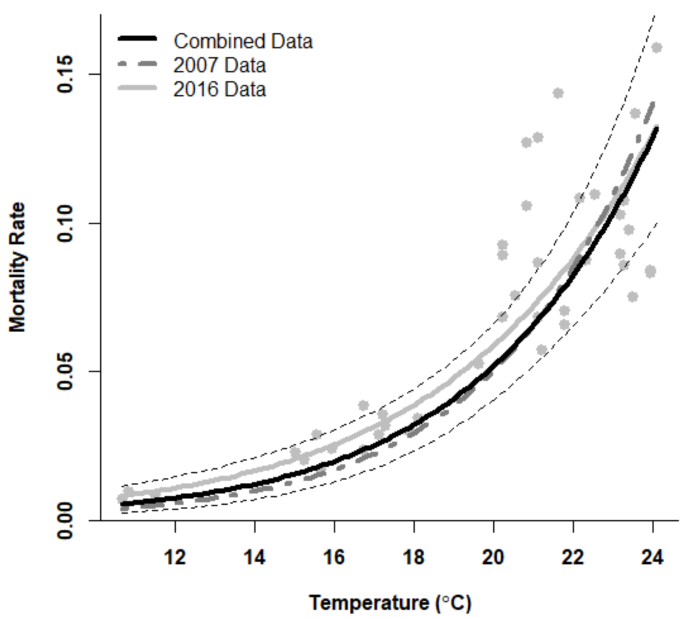

FIGURE 4. Predictions of hooking mortality rates for the 2007 temperature only model, the 2016 temperature + pen model, and the combined data temperature + pen model. Light dashed lines are 95% confidence intervals for the combined data model, gray dots represent observed pen-specific mortality rates in the 2016 study

Discussion

Replicated studies are rare but fundamental to science (Ritchie 2020), and they are especially important for confirming models used for critical management questions. Repeating the hooking mortality study to test the 2007 T+QL model with new data showed that the quadratic length effect was likely a spurious effect in the data and could bias mortality rate estimates. Temperature has been shown to have strong effects on mortality of released fish (Gale et al. 2013), while length has not been consistently found to be strongly related to hooking mortality (Goeman 1991, Stunz and McKee 2006, Talmage and Staples 2011). Here, the difference in AIC comparisons only marginally supported the T+QL model for just the 2007 data, and the BIC comparisons strongly favored the TO model for both data sets, thus we believe that the temperature only model as parameterized using pooled data from both studies is the most appropriate model for estimating Walleye hooking mortality rates in Mille Lacs Lake (equations 3 and 4).

Both AIC and BIC favored the inclusion of a pen effect in the combined data set, suggesting that extraneous factors could have affected mortality rates in holding pens. Reeves and Bruesewitz (2007) found no evidence of pen density affecting mortality rates in the 2007 data, and our mixed-effect model re-analysis showed no evidence of pen effects. While there was evidence in the 2016 data for pen effects, there was no evidence that they were related to walleye density in the holding pens. However, pen effects are a catch-all for many factors that could influence mortality on a given day. For example, some anglers may be better or worse at handling Walleye, resulting in unequal stresses between crews. Handling was an important component of hooking mortality for Walleyes taken from deep water on Rainy Lake (Talmage and Staples 2011) but was not related to mortality rates in the 2007 study on Lake Mille Lacs (Reeves and Bruesewitz 2007). Other study factors, such water temperatures in temporary holding tubs or pen placement may have also affected mortality rates, but no data were collected to evaluate causes of the observed pen effects. Our inability to partition pen effects into random differences in handling between anglers (a part of ordinary angling) and experimentally induced stress from transferring fish and holding them in pens (not a normal part of angling) allows for the possibility that our model overestimates short-term hooking mortality rates. Higher fish densities in the pens in the 2016 study may have made pen effects easier to detect, while the lack of observed pen effects in our analysis of the 2007 data may have been the result of low sample sizes for most of the pens. On the other hand, we were not able to account for delayed mortality after 5 days, which could lead to underestimates of total hooking mortality rates. For these reasons, the true accuracy of our model is unknown.

A control group of Walleye introduced into the holding pens would be useful to directly estimate pen effects and their potential effects on mortality rate estimates. However, there is no way to collect walleye throughout the summer that would not have its own set of confounding stressors. Future studies should carefully consider study factors that could artificially inflate mortality rates in pens and evaluate whether mortality rates are correlated within holding pens.

Although lower mortality rates were observed over most temperatures when Walleye were caught on artificial baits, the IC comparisons found no clear evidence that bait type was significantly influencing modeled mortality rates. Other studies have found lower rates of mortality for Walleyes caught on artificial lures. Fletcher (1987) fished with jigs and plastics or nightcrawlers on bare hooks and reported total mortality of 1.1%; however, water temperature in that study was only 11 °C. Schaeffer (1989) lost only one of 120 Walleyes caught on artificial lures at temperatures less than 20 °C. Reeves and Bruesewitz (2007) also found mortality less than 1% for Walleyes caught on artificial lures, but did not use artificials at temperatures above 20 °C. In a pond study, Payer et al (1989) observed zero mortality on

Walleyes caught on casted crankbaits, even though some sampling occurred at temperatures as high as 28 °C. In our study there was a very large year class of age 3 Walleye that ranged in size from 11 to 14 inches that were sometimes hooked on baits behind planer boards without being detected. These fish were dragged for unknown amounts of time, and the dragging may have increased levels of stress in the fish, especially at warmer temperatures. However, the failure to detect strikes from smaller Walleyes when using planer boards is not outside the realm of normal fishing activity. Strikes from smaller fish were easier to detect on the leadcore rods. Since we do not have data on the proportion of fish caught trolling with planer boards, leadcore lines, and with in-line weights, we assumed that the hooking mortality rates for Walleye caught on artificial lures in this study were representative of those for recreational anglers on Mille Lacs.

We ignored depth of fishing in this study because we believed we could not reliably obtain estimates from creel surveys. In a similar study on Rainy Lake, Minnesota, Talmage and Staples (2011) found that epilimnetic water temperature was not related to hooking mortality rates, but that capture depth had the strongest effect on mortality. This was likely because Walleye angling in Rainy Lake mainly occurs below the thermocline at depths greater than 10 m, while fish in Mille Lacs were typically caught from depths less than 10m. Reeves and Bruesewitz (2007) investigated the effect of depth on hooking mortality in Mille Lacs and concluded that depth of capture was not related to hooking mortality in the shallower system.

Management Implications

We believe that our temperature-only model of hooking mortality produces improved estimates of hooking mortality in Lake Mille Lacs than the T+QL model, though it is uncertain how generally our model may be applied to other Walleye fisheries. It is most applicable for approximating Walleye hooking mortality in other shallow, holomictic lakes with similar temperature regimes. In the absence of any other information, managers may cautiously choose to use this model. However, for stratified lakes with waters deeper than 10 m, Talmage and Staples (2011) demonstrated that factors other than temperature become more important, and the results from our model would not apply.

The purpose of estimating the hooking mortality rate is ultimately to estimate the biomass of Walleyes that die after being caught and released in order to estimate total fishing mortality from angling. The biomass that dies after being released is not just a function of the hooking mortality rate but is also dependent on numbers and lengths of released fish reported by anglers to creel clerks. However, Walleye anglers may over-report their catch (Sullivan 2003), which would lead to an overestimate of kill even if the hooking mortality rate were known exactly. Furthermore, estimated weights of released Walleyes, which are roughly proportional to length cubed, are very sensitive to recall bias when anglers report lengths of released Walleyes during creel survey interviews. Thus, the biases resulting from angler reporting are likely to introduce error in estimates of Walleye kill that are much more serious than inaccuracies in the hooking mortality rate. Future work directed at quantifying angler biases would be helpful.

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