North American Journal of Fisheries Management 24:939–951, 2004

Fish Total Length Measurement Error from Recreational Anglers: Causes and Contribution to Noncompliance for the Mille Lacs Walleye Fishery

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Abstract.—To estimate angler noncompliance with size limits due to measurement error by anglers, we used estimates of measurement error derived from (1) lengths of walleye *Sander vitreus* tagged and measured by biologists subsequently caught and voluntarily measured by anglers and (2) from dead walleyes of known length that anglers voluntarily measured during interviews at lake access sites. We also investigated the potential for postmortem changes in fish length. Monte Carlo simulations suggested that angler measurement error accounted for 41–100% of observed angler noncompliance with a 14-in to 16-in harvest slot limit for Mille Lacs lake, Minnesota. Simulations underestimated harvest (retention) rates for walleyes of lengths approaching the harvest slot boundaries compared with actual measures by anglers of the tagged fish they caught; this suggests greater attentiveness of anglers at measuring fish near the slot limits or angler intent to retain protected fish. When reporting total lengths of the tagged walleyes they caught, more anglers rounded measurements to 1-in or 1/2-in increments, whereas more anglers rounded to 1/4-in or 1/8-in increments when reporting lengths of tagged walleyes they retained or when measuring dead fish during interviews. Length measurement errors may be compounded by postmortem physical changes in harvested fish. Although postmortem changes will not influence angler retention of fish, temporal changes in the physical condition of fish may influence whether a creel clerk or conservation officer observes a fish as noncompliant. Understanding the level and characteristics of measurement error is important for understanding the factors influencing angler noncompliance with size limits.

Length is the most common measurement made by biologists and anglers to indicate fish size. Biologists measure fish length to characterize the size structure of fish populations and assess the quality and health of fisheries (Gabelhouse 1984; Anderson and Neumann 1996; Ney 1999). Anglers measure fish length to judge the quality of their catch and to determine whether captured fish are legally harvestable. Fisheries management programs, such as tagging studies (Green et al. 1983; Ferguson et al. 1984), often rely on anglers to supply length measurements of the fish they catch. Despite the importance of fish length data to fisheries management efforts and the increased prevalence of length-based regulations (Radomski et al. 2001), little attention has been given to error in measuring fish lengths.

Biologists and anglers vary in experience and the measuring techniques they employ. Fisheries biologists typically measure fish using prescribed protocols, such as using standardized fish measuring boards and compressing the caudal fin dorsoventrally when measuring fish total length (TL), and biologists typically generate length measurements with high precision (Gutreuter and Krzoska 1994). Conversely, anglers use a variety of measurement devices and techniques to measure fish, which may compromise precision and accuracy of length measurements.

The ability of anglers to accurately and precisely measure fish may have appreciable effects on the success of recreational fisheries management efforts. Modest levels of angler noncompliance can significantly impair management efforts (Paragamian 1982; Gigliotti and Taylor 1990; Pierce and Tomcko 1998). Typically, angler noncompliance of length-based fishing regulations has been primarily attributed to angler ignorance or indifference to regulations, even though anglers appear to measure individual fish with a high degree of variance (Green et al. 1983). Previous studies on measurement error by anglers have concentrated on

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Received August 15, 2003; accepted November 26, 2003

the potential bias between angler and biologist measurements in relation to estimates of fish population characteristics, such as length frequency distributions, growth, and length–weight regressions (Ferguson et al. 1984). To our knowledge, angler noncompliance, due to measurement error, with length-based fisheries regulations has not been studied. Angler measurement error, evaluated in terms of its influence on individual fish measurements and, consequently, on its relationship to angler noncompliance with fisheries regulations, should be investigated to develop a greater understanding of the components (i.e., measurement error, ignorance, or indifference) of angler noncompliance.

The goals of this study were to (1) quantify and characterize total length measurement error generated by anglers, (2) estimate levels of angler noncompliance associated with total length measurement errors by fishermen as related to length limits in a popular and intensively managed fishery for walleye *Sander vitreus*, (3) compare estimates of angler noncompliance due to total length measurement error with common direct measures of angler noncompliance in this fishery, and (4) investigate the potential for changes in postmortem length of fish over time.

Understanding the bias in length measurement data within a fishery, especially the influences of angler measurement error on levels of noncompliance, would be valuable information for managers when developing length-based regulations and predicting and setting harvest limits. In addition, knowledge of the factors influencing angler measurement error (i.e., preservation of fish, measurement device, and measurement technique employed) would help focus angler education efforts regarding effective measurement techniques and provide conservation officers with a basic inference of angler noncompliance due to length measurement error. Lastly, understanding temporal changes in the lengths of harvested fish would be useful for enforcement and for recognizing potential bias associated with using data taken by creel clerks and conservation officers.

Methods

Study site.—Mille Lacs, a 132,516-acre lake in central Minnesota, supports a popular recreational walleye fishery and an Ojibwe tribal subsistence fishery (Radomski 2003). The state of Minnesota regulates walleye harvests on Mille Lacs through annual harvest allocations. This has resulted in the implementation of restrictive length and bag limit regulations. During the 2002 fishing season in Mille Lacs, fishing was limited to a possession of four walleyes, of which walleyes 14–16 in long could not be retained (harvest slot limit) and only one walleye longer than 28 in could be retained.

Measurement error by anglers.—Between April 17 and May 7, 2002, before the opening of the walleye angling season, walleyes in Mille Lacs were captured, tagged, and released by biologists from the Minnesota Department of Natural Resources (MNDNR), Great Lakes Indian Fish and Wildlife Commission, Fond du Lac Band Department of Natural Resources, and the U.S. Fish and Wildlife Service. Walleyes were captured with trap nets set perpendicular to shore and pulsed DC electrofishing as they moved into shoal areas for spawning. Each captured walleye was examined for marks or tags, measured, and all unmarked walleyes exceeding 10 in were tagged with individually numbered 2-in T-bar anchor tags inserted between the dorsal pterygiophores. The total length of every walleye was measured on a measuring board to the nearest 0.1 in after compressing the caudal fin dorsoventrally.

After the opening of the walleye season on May 11, 2002, total length data of tagged walleyes captured in the recreational fishery were collected by MNDNR. Using the standard measurement techniques described above, creel clerks and interns measured all walleyes caught by charter boat anglers to the nearest 0.1 in. In addition, other anglers were encouraged to voluntarily report information on captured tagged walleyes to the MNDNR via e-mail, telephone, or postage paid post cards that were available at all public and most private access areas. These anglers were asked to report the total length, tag number, location of catch, and whether they had kept or released the fish. Anglers usually reported lengths in fractions of an inch; these lengths were rounded to the nearest 0.01 in (e.g., an angler measurement of 21 3/8 in was rounded to 21.38 in).

To determine whether measurement error changed over time (i.e., growth of fish influenced error measurements) and delineate an appropriate period for data evaluation, we regressed angler measurement error verses time at large (i.e., days between initial capture by biologists and recapture by anglers). We determined there was no significant relationship ($P = 0.32$) between the difference of angler and biologist measurements and time-at-large for walleyes recaptured within 45 d of tagging. Additionally, based on our scale analyses of

Mille Lacs walleyes, little or no growth occurs during this period (May 11 to June 25).

To determine whether there was bias in measurements by anglers and quantify the error in biologist and angler measurements, we performed the following calculations using individual walleye total length data collected during marking and recapture events on Mille Lacs:

$$\delta_{B_i} = B_{2i} - B_{1i}$$

and

$$\delta_{A_j} = A_j - B_{1j},$$

where δ_{B_i} is the difference between the biologist length measurement at marking (B_{1i}) and at recapture by biologists (B_{2i}) for fish $i = 1, \ldots, N_B$ (N_B being the number of walleyes recaptured by biologists). Similarly, δ_{A_j} is the difference between the biologist measurement at marking (B_{1j}) and the angler reported measurement at recapture (A_j) for fish $j = 1, \ldots, N_A$ (N_A being the number of fish recaptured by anglers). We assumed that biologists measured fish without bias and with error e_B, where e_B is an identically and independently distributed $N(0, \text{var}[B])$ with a standard deviation SD_B. The assumptions that biologist measurements were unbiased and had independent errors, negate any covariance between repeated biologist measurements of the same individual fish (i.e., $\text{cov}[B_1, B_2] = 0$). Then, $\delta_B = (\delta_{B_1}, \delta_{B_2}, \ldots, \delta_{\text{AN}_A})$ should have a mean of zero and variance $\text{var}(\delta_B)$, where

$$\begin{aligned} \text{var}\ \delta_B &= \text{var}(B_2 - B_1) \\ &= \text{var}(B_2) + \text{var}(B_1) - 2\ \text{cov}(B_1, B_2) \\ &= 2\ \text{var}_B \end{aligned}$$

such that

$$\text{var}_B = \text{var}\ \delta_B/2 \quad \text{and} \tag{1}$$

$$\text{SD}_B = \sqrt{\text{var}(\delta_B)/2}. \tag{2}$$

We assumed anglers measured fish with bias (BIAS_A) and error (e_A), where e_A is an identically and independently distributed $N(0, \text{var}[A])$ with standard deviation SD_A. We also assumed that measurement errors by biologists and anglers were independent and that $\text{cov}(A, B_1) = 0$. Then, $\delta_A = (\delta_{A_1}, \delta_{A_2}, \ldots, \delta_{\text{AN}_A})$ should have a mean equal to BIAS_A and variance $\text{var}(\delta_A)$, where

$$\begin{aligned} \text{var}\ \delta_A &= \text{var}(A - B_1) \\ &= \text{var}(A) + \text{var}(B_1) - 2\ \text{cov}(A, B_1) \\ &= \text{var}_A + \text{var}_B \end{aligned}$$

such that

$$\text{var}_A = \text{var}\ \delta_A - (\text{var}\ \delta_B/2) \quad \text{and} \tag{3}$$

$$\text{SD}_A = \sqrt{\text{var}(\delta_A) - [\text{var}(\delta_B)/2]} \tag{4}$$

We eliminated extreme values by deleting the δ_A and δ_B that exceeded three standard deviations of the mean. These calculations separate the variance introduced from biologist measurements from angler measurement errors, so that $\text{var}(A)$ is an unbiased measure of variance for angler measurement error. To determine if angler errors varied systematically with fish size, we regressed the difference between angler and biologist length measurements (δ_A) versus fish size (B_1) using least squares linear regression.

The proportion of anglers that rounded to whole, half, quarter, and eighth inches was estimated by comparing the distribution of angler measurements with an expected random distribution. A random sample of voluntary tag return postcards was inspected to obtain the distribution of measurements.

The proportion of anglers rounding to the nearest eighth inch (E) was computed as

$$E = 2(D/N), \tag{5}$$

where D is the number of measurements to 1/8, 3/8, 5/8, and 7/8 of an inch and N is the total number of measurements.

The proportion of anglers rounding to the nearest quarter (Q) inch was computed as

$$Q = 2(C/N) - 0.5E, \tag{6}$$

where C is the number of measurements to 1/4 and 3/4 of an inch.

The proportion of anglers rounding to the nearest half (H) inch was computed as

$$H = 2(B/N) - 0.5Q - 0.25E, \tag{7}$$

where B is the number of measurements to 1/2 of an inch.

Finally, the proportion of anglers rounding to the whole (W) inch was computed as

$$W = A/N - 0.5H - 0.25Q - 0.125E, \tag{8}$$

where A is the number of measurements to whole inches.

Angler measurement error was also evaluated by collecting angler total length measurements of dead walleyes that were measured by biologists just before and after the angler measurement. The anglers were selected from three lake access points along the western shore of Mille Lacs on May 11, 12, and 19, 2002. Eight walleyes (14 to 28 in TL) that were collected in trap nets before the angling season were frozen fresh and later thawed completely and individually tagged by biologists before being measured by anglers. Each day, anglers who had just completed their fishing trips were asked to measure two or three of these dead walleyes via the measuring device and technique they typically used while fishing. The same fish were used for only 1 d to eliminate potential bias in fish lengths that could result from deterioration due to repeated freezing, thawing, and handling. Walleyes were retained in cool water when not in use to avoid length changes from dehydration or daily temperature fluctuations. Biologists measured each walleye to the nearest 0.1 in, whereas angler measurements were usually made to the nearest fraction of an inch (i.e., 1/2 to 1/8 of an inch) and converted to the nearest 0.01 in.

For each angler, we recorded the type of measurement device, measuring technique, tag number, and lengths of each fish measured. Measurement devices were classified as either stick-on (adhesive-backed) tape measures, measuring boards, flexible tape measures, or rulers. Measurement devices classified as boards required a fixed, vertical headpiece designed to prevent fish from slipping during measurement, flexible tape measures included retractable metal tapes or cloth tapes, and rulers included plastic rulers or yardsticks. We also recorded whether or not the angler ''pinched'' the caudal fin (i.e., compressed the caudal fin dorsoventrally) while measuring each fish. Unusual techniques employed by anglers that may have influenced measurements were also noted.

We analyzed angler measurements of dead walleyes in the same manner as the voluntary angler tag return data to quantify biologist measurement error and angler bias and measurement error. Biologist measurements B_{1p} and B_{2p} were the before and after measurements, respectively, for walleye $p = 1, \ldots, N_C$ (N_C being the number of walleyes measured by biologists). Angler measurement A_{pq} was the measurement of walleye p by angler q, where $q = 1, \ldots, N_D$ (N_D being the number of anglers that measured walleyes). We calculated $\Delta_B = (\Delta_{B_1}, \Delta_{B_2}, \ldots, \Delta_{\mathrm{BN}_C})$, where $\Delta_{Bp} = B_{2p} - B_{1p}$, and $\Delta_A = (\Delta_{A_{11}}, \Delta_{\mathrm{A}_{12}}, \ldots, \Delta_{A_{21}}, \Delta_{A_{22}}, \ldots, \Delta_{\mathrm{AN}_C N_D})$, where $\Delta_{A_{PE}} = A_{pq} - B_{1p}$. The biologist measurement error and angler measurement bias and error were quantified as with the tagging data using equations (1)–(4), substituting Δ_A and Δ_B for δ_A and δ_B in the equations. The Δ_A were treated as independent samples, even though individual anglers measured several fish, because the error variance within anglers was almost identical to the error variance among anglers. To determine if method (pinched or unpinched), measuring device (board, stick-on tape, flexible tape, or ruler), or individual walleye measured had a significant effect on the Δ_A, we used multiple-factor analysis of variance (ANOVA). We expected measurement technique and device to have a significant effect on Δ_A. Because fish were dead and easily handled, we did not expect there to be any significant effect of fish size. We used least-squares linear regression to determine if there was a relationship between fish size and the difference between biologist and angler length measurements, Δ_A. Finally, we estimated the proportion of anglers that rounded to the nearest whole, half, quarter, and eighth of an inch in the same manner as for the voluntary angler tag return data.

Mille Lacs noncompliance simulation.—Noncompliance expected due to angler measurement error was estimated for walleye anglers on Mille Lacs via Monte Carlo simulations. After the opening of walleye season on May 11, 2002, MNDNR creel clerks acted as observers on sport fishing charter boats and measured, via the same technique used by biologists, all the walleyes caught. The lengths recorded by the charter boat observers we accepted as the true size distribution of angled walleyes during the 2002 fishing season (Figure 1). Monte Carlo simulations were performed by adding a random angler measurement error to the length of each individual fish in the distribution. We used two estimates of angler measurement error, one generated from the voluntary tag return data, and one generated from angler measurements of dead fish at lake accesses.

Two common estimates of noncompliance were estimated via the Monte Carlo technique. We modeled (1) the proportion of the total walleye harvest that was protected (not of legal or harvestable size, i.e., <14 in and >16 but <28 in) but that was measured by anglers as a legal or harvestable size and (2) the proportion of the protected catch that was measured by anglers as a legal size. To account for legal-sized fish released by anglers in the simulation, we assumed that anglers released 12% of all walleyes they measured to be of legal size,

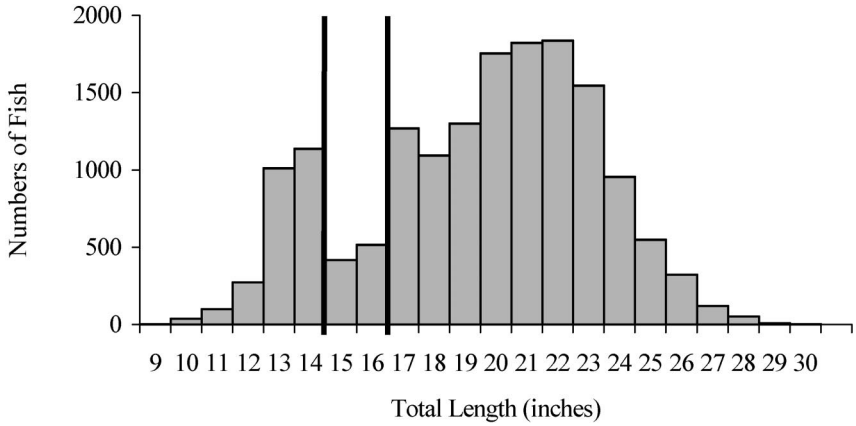

FIGURE 1.—Size frequency distribution of angled walleyes from Mille Lacs, as measured by creel clerks on sport fishing charter boats during the 2002 fishing season. The dark vertical lines indicate the protected slot limits.

which we based on the number of legal-sized walleyes that anglers reported they caught and released on Mille Lacs in 2002. To obtain estimates of the mean and standard deviation of noncompliance explained by measurement error, we repeated the simulation 10,000 times for both estimates of angler measurement error.

Noncompliance was directly estimated using five different data sets to compare with the Monte Carlo model estimates of noncompliance. Direct estimates were made from daytime access-point creel surveys, nighttime access-point creel surveys, and conservation officer contacts of anglers. Two direct estimates were also generated from voluntary angler reports of whether catches of tagged walleyes were retained or released. One noncompliance estimate was generated using the anglers' voluntarily reported total lengths of tagged walleyes captured, and one estimate was generated using the biologists' measure of total length of the same walleye at marking. For each data set, we calculated the proportion of the total walleye harvest consisting of protected fish and the proportion of the catch consisting of protected walleyes illegally harvested.

We were also interested in how angler measurement error affected noncompliance as fish lengths approached the edges of the 14–16-in harvest slot on Mille Lacs. Monte Carlo models were used to predict the proportion of walleyes that anglers would measure as harvestable as length increased from 12 to 18 in by 0.1-in increments. We assumed 10,000 walleyes were in each length category, applied a random angler measurement error to each fish length, and calculated the percentage of fish in each length-group that simulated anglers measured to be of legal size and therefore retainable. These simulation predictions were compared with the calculated walleye harvest rate by length from anglers' voluntary tag return reports and biologists' length measurements at marking.

Temporal changes in postmortem fish lengths.—To determine how walleye lengths might change during the period between capture and measurement by a conservation officer or creel clerk, we measured the total lengths of walleyes (nearest 0.05 in) before, immediately after being killed by a blow to the head, and after storage on ice for 3 and 24 h. These walleyes (12.9–20.1 in TL) were collected in September 2001 during annual gillnet and trawl surveys on Mille Lacs and tagged with numbered anchor tags for identification. With a few exceptions, all measurements made on a given fish were made by a single observer.

Because we did not expect to see equivalent changes in length for different sizes of walleyes, we expressed the change in length relative to body size by the equation

$$R = 100(L_t - L_{\text{Alive}})/ L_{\text{Alive}},$$

where R is the relative change in length, L_t is total length t hours after death, and L_{Alive} is the total length of live walleyes. Thus, negative values reflect smaller measurements after being killed, whereas positive values reflect larger measurements. Changes in size were quantified by determining mean change, standard deviation, and maximum increase and maximum decrease in length. The statistical significance of mean change was examined by means of two-sample Student's t-tests and determined at $\alpha = 0.05$. Dependency of rel-

TABLE 1.—Differences between concurrent biologist and angler measurements of dead walleyes used to characterize angler measurement error. Three factors were used in the analysis of variance, and each includes several or more categories. Number of observations, mean difference between biologist and angler measurements, and minimum (min.) and maximum (max.) differences are shown.

Factor	Category	*N*	Difference (in)			
			Mean	SD	Min.	Max.
Device	Stick-on tape	59	0.00	0.34	−0.55	1.25
	Board	36	−0.01	0.33	−0.75	1.00
	Flexible tape	29	0.12	0.48	−0.80	1.10
	Ruler	13	−0.08	0.23	−0.40	0.30
Technique	Pinched	84	0.01	0.33	−0.75	1.25
	Unpinched	53	0.02	0.41	−0.80	1.10
Fish	1 (14.6 in)	9	0.01	0.22	−0.35	0.40
	2 (16.3 in)	30	−0.24	0.23	−0.80	0.20
	3 (16.9 in)	12	0.04	0.25	−0.40	0.60
	4 (20.0 in)	29	0.00	0.30	−0.50	0.50
	5 (20.5 in)	29	0.28	0.40	−0.75	1.25
	6 (22.9 in)	11	−0.07	0.42	−0.40	1.10
	7 (24.2 in)	9	0.22	0.47	−0.45	1.05
	8 (27.4 in)	8	0.10	0.23	−0.40	0.10
Total	All fish	137	0.01	0.36	−0.80	1.25

ative change on absolute length was tested using linear regression techniques.

Results

A total of 20,318 walleyes were tagged and measured by biologists before the angling season. Of the 20,318 tagged walleyes, 1,554 were recaptured and remeasured by biologists before the walleye fishing season. The difference in those two measures (δ_B) was within 3 SDs of their initial mean length at tagging. The MNDNR received voluntary reports, including lengths, for 1,241 angled walleyes tagged by biologists before the fishing season. Of these, 998 walleyes were recaptured within 45 d of being tagged and had a δ_A (difference between initial length at tagging and length reported by the angler) within 3 SDs of their initial mean length at tagging; 25% of these fish were reported as harvested (retained) by anglers. A total of 137 angler length measurements of dead walleye were collected from 52 angler parties at lake access areas; these individual walleyes were measured 8–30 times (Table 1). Observers on charter boats recorded the lengths of 16,121 angled walleyes. The length-frequency distribution of walleyes captured by anglers and measured by observers suggests that the Mille Lacs walleye population was appreciably underrepresented within the 14–16-in harvest slot limit (Figure 1).

Measurement Error by Anglers

Measurement error by anglers (e_A) based on voluntary angler tag returns differed from the errors for dead walleyes (Figure 2). Angler measurement errors derived from voluntary tag returns were negatively biased (mean − 0.15 in), whereas errors for dead walleyes had a small positive bias (mean, 0.01 in). Measurement error for the voluntary tag return data (SD, 0.71 in) varied more than errors for dead walleyes (SD, 0.36 in). The number of tagged fish anglers incorrectly reported to be in the harvest slot was disproportionate to the number of fish incorrectly reported to be outside the harvest slot (ratio, 6.7:1), even after accounting for the fact that there were 2.4 times more walleyes caught that were within 1 in of the harvest slot (i.e., 13.0–13.9 in or 16.1–17.0 in) than were within the harvest slot (14.0–16.0 in). Of the walleye measurements voluntarily reported by anglers that differed from biologists' measurements, 69% were within 0.5 in of the biologists' initial measurements. By comparison, of anglers' measurements of dead walleyes that differed from biologists' measurements, 91% were within 0.5 in of the biologists' measurements.

Anglers had a propensity to round walleye measurements to the nearest whole inch or 1/2-in when reporting lengths of released fish but tended to round to smaller units (i.e., 1/4-in or 1/8-in increments) if the walleye measurement was monitored by biologists (i.e., the dead walleyes that were measured). From the voluntary angler tag return data, we estimated that 30% of reported lengths of released fish were rounded to the nearest whole inch, 51% to the nearest 1/2 in, 13% to the nearest 1/4 in, and 6% to the nearest 1/8 in. For harvested (retained) fish, we estimated that 6% of reported

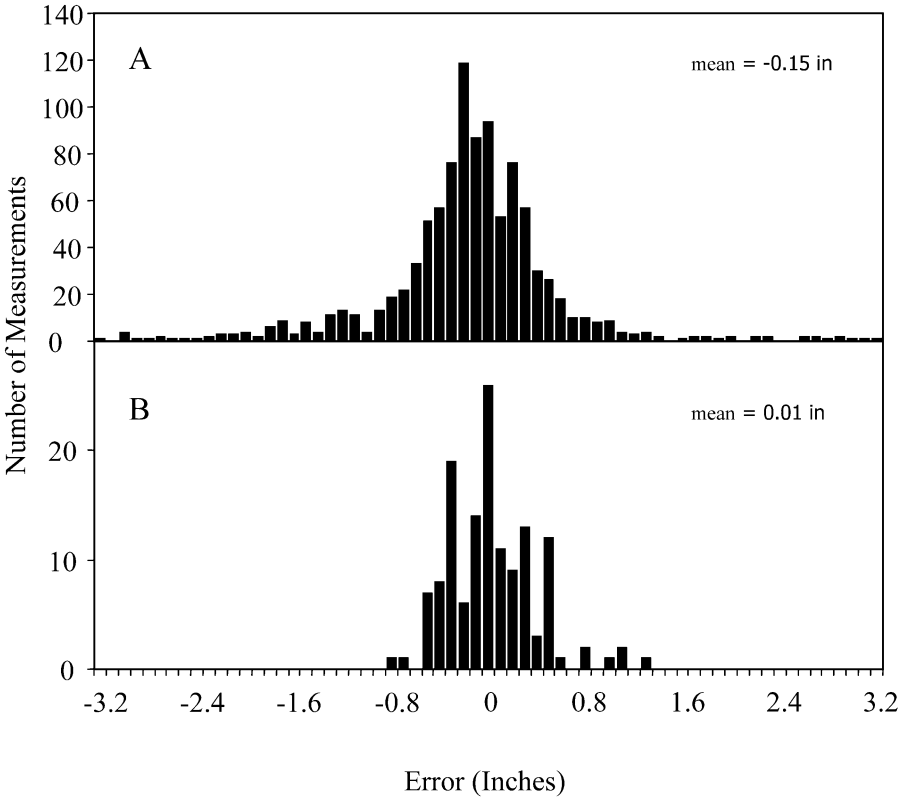

FIGURE 2.—Frequencies of differences in walleye total lengths (Mille Lacs, Minnesota), as measured by biologists and anglers in 2002: **(A)** differences as measured by biologists at tagging and as reported by anglers upon recapture (998 walleyes) and **(B)** differences in dead walleyes (frozen and later thawed at measuring), as concurrently measured by biologists and anglers at access sites.

lengths were rounded to the nearest whole inch, 46% to the nearest 1/2 in, 26% to the nearest 1/4 in, and 22% to the nearest 1/8 in. Of the angler measurements of dead walleyes, we estimated 9% were rounded to the nearest whole inch, 26% to the nearest 1/2 in, 48% to the nearest 1/4 in, and 17% to the nearest 1/8 inch.

The type of measuring device and technique (e.g., pinched or unpinched) did not have significant effects on Δ_A or on differences between angler measurement and the initial biologist measurement of dead walleyes measured at access sites (Tables 1, 2). Only the fish factor × fish technique interaction had significant effects on Δ_A, suggest-

TABLE 2.—Multiple-factor analysis of variance relating the effects of measuring device, technique, and individual fish (as described in Table 1) on the difference between angler and biologist measurements of dead walleyes from Mille Lacs, Minnesota. The following abbreviations are used: SS = sum of squares, MS = mean square; *P*-values in bold italics indicate significant factors.

Factor	df	SS	MS	*F*	*P*
Constant	1	0.024445	0.024445	0.27036	0.604
Device	3	0.45243	0.15081	1.66799	0.179
Technique	1	0.0083149	0.0083149	0.09196	0.762
Device × technique	3	0.034534	0.011511	0.12732	0.944
Fish	7	4.4688	0.6384	7.06078	***<0.001***
Device × fish	20	2.1114	0.10557	1.16761	0.300
Technique × fish	6	1.9212	0.32019	3.54138	***0.003***
Device × technique × fish	5	0.66109	0.13222	1.46236	0.210
Error	91	8.2277	0.090415		

TABLE 3.—Estimates of angler noncompliance with length regulations for the Mille Lacs walleye fishery by (1) Monte Carlo simulations (mean of 10,000) based on angler measurement errors quantified from voluntary angler tag return data and angler measurements of dead walleyes, (2) direct estimates of noncompliance from creel clerk interviews and conservation officer contacts with anglers, and (3) voluntary angler returns using either angler reported length measurement at capture or biologist length measurement at marking. Noncompliance includes (1) the percentage of the total harvest that was of nonlegal size and (2) the percentage of protected fish captured that were noncompliant.

Data source	Noncompliance (%)	
	Harvest	Protected
Monte Carlo simulations		
Voluntary angler tag return	47.3	3.6
Measurements of dead walleyes	23.2	1.1
Direct estimates		
Creel clerk daytime interviews	18.4	1.3
Creel clerk nighttime interviews	20.6	1.1
Conservation officers	22.0	2.7
Voluntary angler tag return data		
Angler length measures	1.2	0.4
Biologist length measures	22.9	0.4
	22.9	7.5

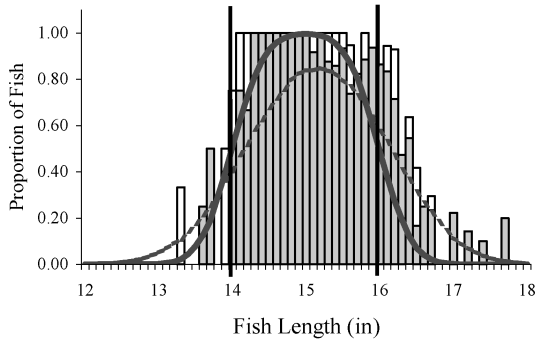

FIGURE 3.—Comparisons of simulated and actual proportions of walleyes in Mille Lacs, Minnesota, that anglers harvested (retained) in 2002, by length category. The curves represent Monte Carlo simulation estimates of the proportion of walleyes in each size-category that would be measured in the harvest slot (dark vertical lines) because of angler measurement error: the solid line was generated from error values from angler measurements of dead walleyes at access sites, the dashed line from errors in angler measurements of tagged, recaptured walleyes. Bars represent the actual proportion of the angler catch of walleyes that were measured by biologists at tagging and subsequently measured and reported by anglers as being within the slot limit boundaries, whereas shaded areas within bars represent the proportion of walleyes that anglers harvested.

ing that walleye size differences affected the difference between angler and biologist measurements and these differences may be compounded by the measuring technique. For angler measurements of dead walleyes, there was a significant positive linear relationship between fish size (B_1) and Δ_A, such that lengths of smaller walleyes were underestimated and lengths of larger walleye were overestimated ($\Delta_A = -0.38 + 0.02 \cdot B_1$, df = 135, $R^2 = 0.033$, $F_{1,135} = 4.63$, $P = 0.033$). However, a significant relationship between fish size (B_1) and δ_A was not observed for the voluntary angler tag return data ($\delta_A = -0.004 - 0.008 \cdot B_1$, df = 996, $R^2 = 0.000$, $F_{1,\,996} = 1.12$, $P = 0.291$).

Mille Lacs Noncompliance Simulation

Monte Carlo simulations of noncompliance suggest that measurement error by anglers accounts for the majority of noncompliance within the Mille Lacs walleye fishery (Table 3). Based on angler measurement errors of dead walleyes, the Monte Carlo model predicted that the percentage of harvest that would be illegal was greater but similar to direct estimates from creel surveys and conservation officers. The model also explained 41–100% of direct noncompliance estimates of protected fish captured that were illegally harvested. Simulations based on angler measurement error from voluntary tag returns predicted noncompliance would be 2–3 times greater than direct estimates.

Direct estimates of noncompliance calculated from voluntary angler reports differed greatly depending on whether we used the measurements by biologists or anglers (Table 3). Noncompliance estimates based on the voluntary angler reports of captured and harvested fish were much lower than other direct estimates. However, direct noncompliance estimates based on biologist-measured fish at marking versus angler reports of harvest and release were similar to other direct estimates for total harvest, but they were higher than other direct estimates for catch of protected fish.

The Monte Carlo simulation underestimated the proportion of fish near the 14-in and 16-in slot boundaries that would be measured within the slot limit and subsequently underestimated the probability of harvest compared with voluntary angler reports (Figure 3). Anglers retained more walleyes within the harvest slot and retained more protected walleyes greater than 16 in than the simulations predicted. The larger variance in the voluntary angler tag return data caused the Monte Carlo model to predict that more legal-size walleyes would be measured as protected and that more protected fish

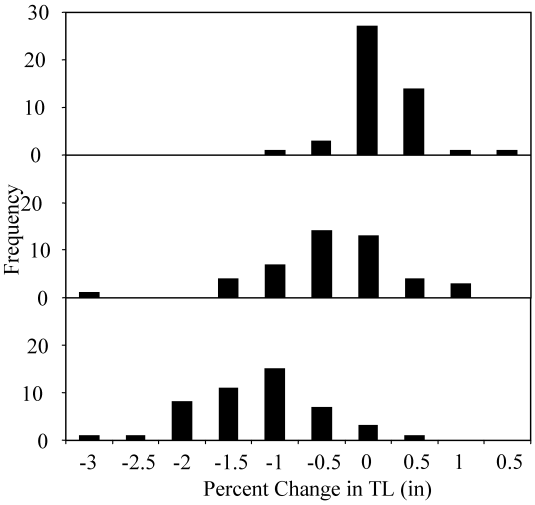

FIGURE 4.—Frequency distribution of changes in total lengths of individual walleyes from biologist measures just before euthanasia to measures just after euthanasia and after being stored on ice for 3 and 24 h.

would be measured as legal compared with the simulations based on the error variance from dead walleye measurements (Table 2). Directional bias existed for protected fish incorrectly reported as legal (i.e., within the slot) over legal fish incorrectly reported as protected for simulations using both dead fish measurement errors (ratio, 1.2:1) and voluntary angler return measurement errors (ratio, 1.9:1).

The majority of protected fish predicted to be measured as legal were within 0.5 in of the harvest slot limits for both sets of measurement error estimates. However, the simulation based on angler measurement error from tag returns predicted that a small proportion of protected fish up to 2 in from the harvest slot would be measured as harvestable. Similarly, based on angler error generated from measurements of dead walleyes, a small proportion of protected fish up to 1.3 in from the harvest slot would be measured as harvestable.

Temporal Changes in Postmortem Fish Lengths

Analysis of postmortem changes in length showed that walleye lengths increased significantly immediately after death and then decreased significantly between 3 and 24 h postmortem (Figure 4). The mean change in relative length between live and freshly killed walleyes was 0.14 in (SE = 0.06, range = −0.94 to 1.42; df = 46, t = 2.44, P = 0.019); that between live walleyes and those stored on ice for 3 h was −0.36 in (SE = 0.12, range = −3.07 to 1.19, df = 45, t = −3.12, P = 0.003); and that between live walleyes and those stored on ice for 24 h was −1.17 (SE = 0.10, range = −2.76 to 0.44, df = 46, t = −12.22, $P < 0.001$). Relative changes in measurement were not dependent on absolute fish length after 3 h (P = 0.73) or 24 h (P = 0.36).

Discussion

Angler noncompliance with sized-based regulations can have an appreciable effect on the success of fishery management programs. Theoretical evidence suggests that success of sized-based regulations can be impaired by moderate levels of noncompliance (Gigliotti and Taylor 1990). Gabelhouse (1980) reported that noncompliance in fisheries for largemouth bass *Micropterus salmoides* in Kansas ranged from 0% to 90% of harvest, and angler noncompliance with a 14-in minimum for a largemouth bass fishery in Oklahoma ranged from 8% to 67% of harvest (Glass and Maughan 1984). Angler noncompliance with a slot limit in fisheries for northern pike *Esox lucius* in northern Minnesota was as high as 29% of harvest (Pierce and Tomcko 1998). Average illegal harvest by anglers among walleye fisheries in Alberta, Canada, was 18.4% of protected fish caught (range, 0.2–68.8%; Sullivan 2002).

Angler noncompliance with size limits has generally been attributed to ignorance or indifference of anglers to fishing regulations. Some studies have suggested that noncompliance may be partially attributable to measurement error, but measurement error has been generally regarded as inconsequential compared with cheating and ignorance (Glass and Maughan 1984; Pierce and Tomcko 1998; Sullivan 2002). Although angler ignorance or indifference to length-based regulations may constitute a large component of observed noncompliance, the contribution of measurement error to noncompliance may be of greater importance than previously believed.

This study suggests that measurement error by anglers accounts for a substantial component of angler noncompliance, which we found to be 41–100% for one lake in Minnesota. We found large proportions of angler measurements of walleye total lengths (69% of tagged fish measurements and 91% of dead walleye measurements) differed from measurements by biologists by up to 0.5 in. Other studies have found that appreciable proportions of illegally harvested fish were close to size limit boundaries. Pierce and Tomcko (1998) found 35% of illegally harvested northern pike were within

0.5 in of protected slot limits. Paragamian (1982) and Novinger (1987) found 35–65% of illegally harvested largemouth bass were within 0.5 in of minimum size limits boundaries. Sullivan (2002) found that for fisheries exhibiting low catch rates nearly 60% of illegally harvested walleyes were within 0.4 in of minimum size limits and that 46% of illegally harvested walleyes were within 0.4 in of protected slot limits. Sullivan attributed the greater rates of noncompliance for walleye slot limits compared with minimum size limits (twice the rate) to increased cheating of anglers; however, we suggest that the disparity Sullivan observed may also reflect increased opportunities for measurement error associated with more complex size-limit regulations. Therefore, measurement error appears to be of significance in the harvest of protected fish.

We believe that the measurement error estimated from angler measurements of dead walleyes at access sites better reflects true angler measurement error than the error estimated from voluntary tag return data. Length measurements of tagged fish reported by anglers were less accurate and precise than measurements of the dead fish. Although difficulties associated with measuring live fish may have contributed to greater measurement error, anglers at access sites were encouraged to measure fish of all sizes as accurately as possible, whereas no guidelines were given to anglers when measuring the live angled walleyes. We also documented that anglers that voluntarily reported lengths of harvested walleyes or that measured dead fish for biologists tended to round more to quarters and eighths of an inch, whereas anglers voluntarily reporting lengths of released fish tended to round more to whole or half inches, suggesting that anglers measure fish with greater accuracy when deemed important. Therefore, differences between biologist and angler estimates of individual fish lengths may be a function of unequal attention to accuracy among different fish lengths. If anglers measured fish that are close to the size limit more carefully than fish that are clearly of legal or illegal size for harvest, then our estimates of noncompliance attributable to measurement error would be inflated for simulations using errors from voluntary returns.

Idiosyncrasies in how anglers handled fish may have contributed to the observed measurement error. We observed that most anglers affixed measurement devices to the top of the gunwale or floor of the boat, allowing fish to be measured in a horizontal position, similar to standard measurement protocols employed by biologists. However, some anglers secured measurement devices along the inside wall of the boat, which required anglers to continually hold sample fish up to the tape while visually aligning the fish with the measurement device. This approach appeared to create difficulties in measuring fish, such as effectively maintaining alignment of the fish snout with the edge of the tape while pinching the tail. In addition, the act of holding fish up to an affixed tape typically resulted in the contortion of the shape of larger fish. Large fish were observed to distend downward between the hands of angler who secured fish at the head and tail, or to arc appreciably upwards when held within the midsections. In addition, a number of anglers were observed measuring the curvature of the body of fish with flexible plastic or metal retractable tape measures, which may increase error for larger fish. These idiosyncrasies in measuring techniques may account for the significant influences of fish size and fish size × technique (pinched versus unpinched tail) interaction on the measurement error documented in this study (Table 1) and also the unexpected nonsignificant influences documented for the device and technique factors.

Surprisingly, whether the pinched or unpinched technique was used to measure fish was not by itself a significant influence on measurement error (Table 1). We believe that this may be related to the fact that caudal fins of the dead walleyes were already slightly pinched due to being wrapped and frozen within plastic bags during storage. As a result, measurement errors associated with anglers that did not pinch the caudal fin may be less than what would be expected when measuring a live or freshly killed fish.

Anglers measured a greater proportion of walleyes to be within the harvest slot than our models predicted. The number of protected walleyes measured as legal was 3.5 times or more than expected. The fact that walleyes near the slot limit boundaries were harvested at a greater rate than expected, suggests this is not just a result of more accurate measuring, but that anglers must be making conscious decisions to carefully measure and harvest fish close to the size limit. Rounding of measurements by anglers could have resulted in the differences observed between expected and realized proportions of fish measured in the slot; however, simple acts of rounding would not result in the concomitantly high rates of harvest observed for protected sized fish (Figure 3). We would expect that if the differences between predicted and

actual levels of measurement error were mostly related to rounding the release rates of protected fish reported as being in the slot would be greater than those we observed. In addition, it is not likely that rounding would explain the greater-than-expected proportions of large fish (≥17 in) measured in the slot and subsequently harvested. Furthermore, noncompliance rates based on voluntary angler return data were substantially low compared with rates based on biologist estimates of tagged walleyes at marking, creel clerk, and conservation officer interviews, suggesting anglers misreported protected sized fish (Table 3). Therefore, the greater-than-expected proportions of fish measured in the slot limit could be attributed to increased measurement accuracy by anglers and anglers knowingly reporting protected fish to be in the slot.

The characteristics of angler-reported fish length data were consistent with those of other studies reporting similar data. Our estimate of the measurement error derived from angler measures of tagged fish (mean, −0.15 in) was nearly identical to the angler measurement error documented for tag reports from a marine fishery (mean, −0.16 in; Green et al. 1983). Similarly, the rounding of length measurements of tagged walleyes (half or whole inches) was similar to that in the findings of Ferguson et al. (1984) for a fishery for red drum *Sciaenops ocellatus*. We also found no significant difference between frequency distributions of walleye length measurements generated by biologists versus anglers, which supports previous studies finding no significant bias related to total length measurements of fish measured by biologists and anglers (e.g., Green et al. 1983). Because angler measurements of total length were characteristic of the overall fish population size distribution, angler-reported lengths of tagged fish would probably not bias estimates that use group or categorical data (e.g., number of fish per length-group) to estimate fish population parameters. However, high variability in individual fish measurements, as reported by anglers, may bias estimates that use individual fish data (e.g., growth rates; Ferguson et al. 1984).

Factors associated with temporal changes in the physical condition of harvested fish other than angler measurement error of fish length, may contribute substantially to incongruous estimates of fish length estimates between anglers, creel clerks, and conservation officers. Studies have shown evidence of length changes in juvenile and adult fish resulting from icing (Halliday and Roscoe 1969; Gordon 1994), freezing (Halliday and Roscoe 1969; Engel 1974; Treasurer 1990; Armstrong and Stewart 1997), and rigor mortis (Schetter 1936; Halliday and Roscoe 1969). Blackwell et al. (2003) also found that walleyes held on ice decreased in total length: a 0.7% average decrease at 5 h and a 1.0% decrease at 10-h. We found an average decrease in total length of 0.4% at 3 h and 1.2% at 24 h. Leslie and Moore (1986) found that temporal changes in lengths before and after preservation of fish were predominantly a consequence of postmortem effects (i.e., rigor mortis), but they also cited measurement error as a factor, especially in fish of smaller sizes. Similarly, we documented changes in postmortem total lengths of fish, apparently as a result of temporal changes in physical condition of fish (e.g., change in shape and bending).

Temporal changes in lengths of harvested fish can create a potential problem for fisheries managers (e.g., fish population dynamics, harvest and noncompliance studies) that would complicate enforcement efforts. Because creel clerks and conservation officers typically measure fish harvested by anglers well after fish are initially captured, changes in fish length related to postmortem effects or preservation techniques may influence whether fish are observed as compliant with size regulations. Conservation officers may have to consider compensating for changes in lengths of postmortem walleyes stored on ice. Conservation officers may also need to reevaluate under what circumstances (e.g., physical condition of fish) allowances for noncompliant fish will be granted. In addition, noncompliance studies using creel clerk or conservation officer estimates of harvested fish lengths should recognize the potential bias associated with temporal changes in lengths of harvested fish.

Our study showed that measurement error contributes substantially to noncompliance within the Mille Lacs walleye fishery. However our study focused on one lake during one fishing season, and therefore, contribution of measurement error to noncompliance within other fisheries may differ, depending on the characteristics of the fishery. For example, measurement error as a component of angler noncompliance will probably depend on the size structure of a fish population around the size limits. The size distribution of walleye in Mille Lacs is substantially truncated within the harvest slot limit (Figure 1), which in part, accounts for the disproportionate number of protected fish measured as being in the slot compared with legal fish measured outside the slot, as predicted in our sim-

ulations. If the number of fish on either side of a limit was equal, and measurement error was unbiased, then equivalent numbers of fish would be incorrectly measured on either side of a size limit. Measurement error as a proportion of noncompliance may also be influenced by the propensity of anglers to knowingly harvest illegal fish, which has been shown to be dependent on catch rates among fisheries (i.e., lower catch rates increases cheating; Sullivan 2002). Catch rates for the Mille Lacs walleye fishery in 2002 were high (0.750 fish/h in the daytime, 0.912 fish/h at nigh), which possibly reduced angler willingness to cheat and increased the proportional contribution of measurement error to overall noncompliance. Therefore, responses by anglers to the characteristics of a fishery should be recognized as a potential influence on the relative levels of factors contributing to noncompliance (i.e., indifference, ignorance, and measurement error).

Because of angler measurement error, protected walleye sizes may have accounted for an appreciable component of the recreational walleye harvest on Mille Lacs in 2002. If angler measurement error explained 41–100% of the illegal harvest of protected fish, then noncompliance due to measurement error may have accounted for 8–20% of the recreational angler harvest quota for 2002. This is important because the recreational walleye harvest on Mille Lacs exceeded the harvest quota in 4 of the last 7 years (Radomski 2003). Understanding the relative contributions of angler measurement error, ignorance, and indifference to angler noncompliance may be helpful in directing efforts to reduce angler noncompliance (e.g., increased education or enforcement) and control harvests within the quota limits. In addition, understanding measurement error as it relates to overall noncompliance could be important as a component for creating sociological models predicting recreational harvests related to various regulation strategies and catch rates. Further, information on measurement error could be useful for enforcement officers judging potential violations in fish size regulations.

Acknowledgments

We thank Charles Anderson for statistical advice and D. Periera and P. J. Wingate for reviewing earlier drafts of the manuscript.

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