Notes

Variation in Fork-to-Total Length Relationships of North American Lake Trout Populations

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Abstract

Length of fish species with forked tails, such as the Lake Trout Salvelinus namaycush, can be measured as total (TL), fork (FL), or standard (SL) length, although individual studies of such species often rely on only one measurement, which hinders comparisons among studies. To determine if variation in the relationship between FL and TL among Lake Trout populations affected estimates of FL from TL, we compared length relationships within Lake Trout populations sampled in multiple years, among multiple locations within lakes, among lakes, and from all samples from across the species’ range. Samples were from across the geographic range of the species and a wide range of lake sizes (1.31–82,100 km²) to represent the full range of variation in abiotic and biotic variables expected to influence the FL:TL relationship. The functional relationship for estimating FL (mm) from TL (mm) was \( FL = 0.91 \times TL - 8.28 \) and TL from FL was \( TL = 1.09 \times FL + 9.05 \). Error induced by length conversion was less when using a length relationship from a different year in the same lake than from a different area in the same lake or from a different lake. Estimation error was lowest when using an overall length conversion from across the species’ range, which suggests the overall relationship could be used whenever a more accurate length conversion is not available for a population of interest. Our findings should be useful for providing a standardized model for converting FL to TL (and TL to FL) for Lake Trout, such as comparing published findings of different measurement units, converting measurement units by agencies or institutions that change sampling methods over time, or programs that use different sampling methods among areas.

Keywords: Lake Trout; fork length; spatial and temporal variation; lakes; populations; morphology; total length

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Introduction

For fish species with forked tails, length can be measured as total (TL), fork (FL), or standard (SL) length (Carlander and Smith 1945; Jennings et al. 2012). All three metrics generally take a similar amount of time to measure, although FL and TL may be more repeatable than SL (Kahn et al. 2004). In the field, FL and TL may be preferable because the exact point of the body to measure is easier to locate (e.g., tip of the median caudal fin ray for FL, tip of the longest lobe of the caudal fin for TL, or end of the hypural plate for SL; Carlander and Smith, 1945; Kahn et al. 2004). Therefore, FL or TL are measured more often than SL for most fish species, although consistent use of one length measure is lacking for most species with forked tails, thereby making comparison among surveys, stocks, or populations difficult if an accurate conversion is not available (Pol et al. 2011). For some species, the relationship between length metrics varies among populations (Gaygusuz et al. 2006) or between sexes (Hossain et al. 2006), which hinders accurate conversions between length metrics when a conversion is not available for the same survey, stock, population, or sex (Pol et al. 2011). Agency fishery surveys also sometimes rely on length measured in one metric (e.g., FL) while fisheries managed by the same agency are regulated by length limits measured with another metric (e.g., TL; Joy et al. 2014).

Relationships between length metrics are remarkably precise within species, usually exceeding $r^2 \approx 0.99$, but even small errors in length relationships can cause large errors in population parameters used to regulate fisheries. For example, minimum landed sizes for commercial fisheries were 10% (4.5 cm) too low for Georges Bank haddock Melanogrammus aeglefinus and 5% (2.0 cm) too low for Gulf of Maine pollock Pollachius virens when converted to FL using inaccurate FL:TL conversions (Pol et al. 2011). These errors appear small but translate into important differences in commercial fishery harvests that exceed 750,000 metric tons annually of the two species combined (e.g., fishery-independent surveys measure both species in FL while harvest is regulated using TL; Pol et al. 2011). Similarly, when used to estimate yield potential of Lake Trout populations across the state of Alaska, use of a statewide FL:TL ratio (0.935; Burr 2006) overestimated mean weight of Lake Trout by 15% in Lake Louise, Alaska, compared with a lake-specific FL:TL ratio (0.915; Joy et al. 2014). This latter example illustrates how an inaccurate length conversion can be amplified into a much larger error in estimated weight because of the approximately cubic relationship between weight and length.

A recent meta-analysis of life history metrics for Lake Trout required conversions between FL and TL (Hansen et al., In press), but unfortunately, all published length conversions for Lake Trout were either developed using methods of unknown reliability (e.g., Van Oosten and Deason 1938; Webster et al. 1959; Shuter et al. 1998; Joy et al. 2014) or were statistically biased (Hanson and Cordone 1967; Moshenko and Gillman 1983). For example, differences among length relationships that were provided without explanation of data or methods could be an artifact of methodological differences (Lake Michigan, Van Oosten and Deason 1938; Cayuga Lake, New York, Webster et al. 1959; Ontario lakes, Shuter et al. 1998; Lake Louise, Alaska, Joy et al. 2014; Alaska lakes, Burr 2006). For length relationships that were provided with descriptions of methods, most were developed using biased methods: (1) ratios of mean lengths do not allow for a nonzero intercept (Great Bear Lake and Great Slave Lake; Moshenko and Gillman 1983); and (2) simple linear regression does not account for measurement error of the independent variable (Lake Tahoe, California; Hanson and Cordone 1967). In summary, both issues related to previously published length conversion for Lake Trout resulted in questionable conversions that we sought to resolve.

Our objective was to determine if variation in the relationship between FL and TL among Lake Trout populations affected estimates of FL from TL (and FL from TL). Our study sought to remedy problems with previous published conversions that could cause small conversion errors to induce large errors in derived fishery regulations. Therefore, we compared FL:TL relationships between years for Lake Trout populations sampled in multiple years (i.e., temporal variation), among multiple locations sampled within lakes (i.e., local spatial variation), and among populations sampled in lakes from across the native range in North America (i.e., latitudinal spatial variation). We developed an overall relationship between FL and TL from all samples for general use when no other conversion was available. Length conversion relationships covered the range of morphological differences among populations and thereby represented a generalized FL:TL relationship for the species. Our findings should be useful for providing a standardized model for conversion of FL to TL (or TL from FL) for Lake Trout, such as for meta-analyses of the species, use by agencies or institutions that change sampling methods over time, or programs that use different sampling methods among areas.

Methods

Lake trout populations were sampled in 13 different years, 8 different lakes, and multiple locations in Great Bear Lake and Lake Superior (Table 1): Dease and McTavish Arms in Great Bear Lake, Northwest Territories (NWT); Great Slave Lake, NWT; Naknek and Skilak lakes, Alaska; Lake Mistassini, Quebec; six locations across Lake Superior; and Rush Lake, Michigan (Chavarie et al. 2017, 2018, 2019; Hansen et al. 2012, 2016a, 2016b, In press; Perreault-Payette et al. 2017). These samples were from across the geographic range of the species (Figure 1) and a wide range of lake sizes (from 1.31-km$^2$ Rush Lake to 82,100-km$^2$ Lake Superior), and therefore were assumed to represent a comprehensive range of variation in biotic and abiotic variables that could influence the FL:TL relationship.

Lake trout were collected using graded-mesh gillnets set within three depth strata (where available) to cover the anticipated depth distribution of the species (0–50
m, 50–100 m, and 100–150 m; Moore and Bronte 2001). Gill nets were 183 m long by 1.8 m high, and made of multifilament nylon twine, with 30.5-m panels of stretch mesh sizes ranging from 50.8 to 114.3 mm, in 12.7-mm increments. Based on girth–total length (TL) relationships for Lake Trout caught in similar gill nets in Lake Superior (Hansen et al. 1997), the range of mesh sizes used would enable wedging of Lake Trout ranging from small juveniles (222 mm TL) to large adults (827 mm TL). Nets were set on the lake bottom for ~24 h. Total length (TL = mm) of each fish was measured in the field for all samples, except Dease Arm in Great Bear Lake in 2015, when only fork length (FL = mm) was measured (Chavarie et al. 2018). Sampling in Dease Arm, Great Bear Lake, in 2015 (16 July to 2 August 2015) used monofilament multimesh gill nets (11 panels, 38–140-mm stretch mesh, 275 m long and 1.8 m wide) set for 24 h in three depth zones (0–20, 21–50, and 51–150 m) on bottom (0–20, 21–50, and 51–150 m), at mid-depth (21–50 and 51–150 m), and just below the surface (0–20 and 21–50 m; Chavarie et al. 2019).

Digital full-body images of each specimen were captured in the field using methods described by Muir et al. (2012). Each fish was photographed with a ruler in the image for use in scaling digital measurements. Because TL was measured in the field, we did not also measure it from digital images, except for the sample from Great Bear Lake in 2015 for which only FL was measured in the field. We measured the length of each fish (FL or TL) and the ruler in pixels on each image (SPOT Image Analysis Software, Diagnostic Instruments, Inc.), and then converted it into mm using the number of pixels per mm measured on the ruler. We confirmed accuracy of length measurements from images (FL and TL) in Table 1.

### Table 1. Lakes and locations within lakes, surface area, latitude, longitude, years sampled (see Table 2), number of gillnets lifted, and number of Lake Trout *Salvelinus namaycush* measured in total length and fork length (Great Bear and Superior = sum of locations) in three depth strata in North America during 2001–2015. Latitude and longitude reflect mean locations of all gill nets lifted at each location. Lakes and locations within lakes are sorted from north to south. Surface area estimates were not available for locations (reef complexes) in Lake Superior.

| Lake and location | Surface area (km²) | Latitude | Longitude | Years | Lifts | Fish |
|-------------------|-------------------|----------|-----------|-------|-------|------|
| Great Bear        | 31,790            | 66°33′06″N | 119°24′61″W | 3     | 62    | 591  |
| Dease Arm         | 3,007             | 66°45′29″N | 120°17′77″W | 2     | 23    | 278  |
| McTavish Arm      | 4,553             | 66°12′32″N | 117°54′47″W | 2     | 39    | 313  |
| Great Slave       | 28,568            | 62°32′12″N | 110°50′36″W | 3     | 43    | 392  |
| Skilak            | 99                | 60°25′77″N | 150°19′76″W | 1     | 9     | 132  |
| Naknek            | 610               | 58°40′63″N | 155°53′65″W | 1     | 4     | 36   |
| Mistassini        | 2,164             | 51°00′83″N | 73°32′33″W | 1     | 12    | 123  |
| Superior          | 82,100            | 47°09′64″N | 87°12′18″W | 7     | 89    | 1,999|
| Isle Royale       | 47°58′55″N        | 88°54′38″W | 2         | 20    | 736  |
| Superior Shoal    | 47°12′55″N        | 87°11′77″W | 1         | 12    | 394  |
| Stannard Rock     | 47°11′74″N        | 87°12′44″W | 2         | 21    | 370  |
| Klondike Reef      | 47°05′29″N        | 85°51′27″W | 1         | 2     | 93   |
| Grand Marais       | 46°46′64″N       | 85°57′37″W | 2         | 10    | 121  |
| Big Reef           | 46°35′54″N        | 86°24′89″W | 2         | 24    | 285  |
| Rush              | 1.31              | 46°53′31″N | 87°54′60″W | 2     | 19    | 138  |
interaction was significant, we compared lakes pairwise using Tukey’s honestly significant differences. Fourth, to develop an overall model for estimating FL from TL, we estimated parameters of an overall FL:TL relationship across all samples using a linear mixed-effects model with TL as covariate and year(location(lake)) as a nested random effect. For estimating FL from TL (and TL from FL), we estimated the functional relationship from model parameters (Ricker 1975), so slopes of FL against TL relationships were reciprocals of those for TL against FL. We defined bias as the difference between observed FL (measured directly in the field or from an image) and estimated FL (estimated from TL using a linear equation). To determine if relative bias was greater for large fish than small fish, we tested linear trends in bias with TL in linear mixed-effects models with bias as the dependent variable and other factors as described above for testing FL:TL relationships.

**Results**

Measured lengths of 3,411 Lake Trout ranged from 92 to 1,194 mm FL (median = 442 mm; mean = 453 mm; SD = 121 mm) and 104 to 1,278 mm TL (median = 494 mm; mean = 504 mm; SD = 132 mm; Figure 2; Table S2, Supplemental Material). For the 2004 sample from Great Bear Lake, field and image measurements were similar, with field measurements averaging 1.3 mm longer than image measurements for FL (SD = 5.2 mm; range = −22 to +13 mm) and 0.6 mm shorter for TL (SD = 5.2 mm; range = −57 to +13 mm). Across all samples, differences between field and image measurements (outliers >2 × SD) were all associated with errors in field measurements or records (47 of 3,411 fish = 1.4%). Across all samples, a functional linear relationship explained 99.6% of the variation between fork length (mm) and total length (mm):

\[
\text{FL} = -8.2772 + 0.9143 \times \text{TL}
\]

The functional linear relationship for estimating TL from FL was

\[
\text{TL} = +9.0533 + 1.0938 \times \text{FL}
\]

Standard errors were 0.9322 for intercepts and 0.0008348 for slopes. Parameters varied widely among samples (Table 2). For FL:TL relationships, intercepts ranged from −19.846 to +11.198 and slopes ranged from 0.871 to 0.937. For TL:FL relationships, intercepts ranged from −12.851 to +21.459 and slopes ranged from 1.067 to 1.148.

Temporal variation in the relationship between FL and TL was evident for only three of eight lakes or locations within lakes sampled in multiple years. The relationship between FL and TL differed among years for Great Slave Lake (\(F_{3,384} = 6.31; P < 0.0004\)), Isle Royale, Lake Superior (\(F_{1,732} = 8.49; P < 0.01\)), and Big Reef, Lake Superior (\(F_{1,281} = 11.9; P < 0.01\)), but not for Dease Arm, Great Bear Lake (\(F_{1,274} = 0.56; P = 0.45\)), McTavish Arm Great Bear Lake (\(F_{1,309} = 0.82; P = 0.37\)), Grand Marais, Lake Superior (\(F_{1,117} = 1.98; P = 0.16\)), Stannard Rock, Lake Superior (\(F_{1,366} = 0.0004; P = 0.98\)), or Rush Lake (\(F_{1,134} = 0.0004; P = 0.98\)).
Table 2. Intercepts ($b_0$) and slopes ($b_1$) of linear relationships between fork length (FL) and total length (TL) of Lake Trout Salvelinus namaycush populations sampled in North America during 2001–2015. Parameters of the FL:TL relationship for each location or lake sampled in multiple years were estimated from a linear mixed-effects model with TL as covariate and year as a random effect. We estimated the parameters of the FL:TL relationship for Great Bear Lake and Lake Superior using a linear mixed-effects model with TL as covariate and year(location) as a nested random effect. We estimated the parameters of the overall FL:TL relationship across all years, locations, and lakes using a linear mixed-effects model with TL as covariate and year(location) as a nested random effect. Lakes and locations within lakes are sorted from north to south. See Table 1 for surface area, latitude, and longitude of all locations.

| Lake and location | Year | $n$  | $r^2$ | Mean TL | FL | $b_0$ | SE | $b_1$ | SE | $F_{1,587}$ | $p$ | $F_{5,1987}$ | $p$ |
|------------------|------|------|------|---------|----|-------|----|-------|----|------------|----|------------|----|
| Great Bear       | 2003 | 159  | 0.998 | 555   | 501 | 13.67 | 3.17 | 10.35 | 0.01 | 6.76;         | 0.01 | 13.67;      | 0.01 |
| Dease Arm        | 2004 | 260  | 0.995 | 516   | 459 | 10.11 | 2.37 | 10.76 | 0.005 | 14.0;        | 0.003 | 17.85;      | 0.001 |
| Rush             | 2005 | 133  | 0.995 | 566   | 510 | 11.70 | 3.06 | 10.35 | 0.01 | 13.67;       | 0.01 | 13.67;      | 0.01 |
| Skilak           | 2006 | 132  | 0.998 | 565   | 504 | 7.24  | 2.37 | 9.72  | 0.005 | 13.67;       | 0.01 | 13.67;      | 0.01 |
| Naknek           | 2007 | 159  | 0.998 | 506   | 459 | 9.38  | 2.37 | 9.72  | 0.005 | 13.67;       | 0.01 | 13.67;      | 0.01 |
| Mistassini       | 2008 | 132  | 0.996 | 506   | 459 | 8.21  | 2.37 | 9.72  | 0.005 | 13.67;       | 0.01 | 13.67;      | 0.01 |
| Superior        | 2009 | 132  | 0.995 | 506   | 459 | 7.07  | 2.37 | 9.72  | 0.005 | 13.67;       | 0.01 | 13.67;      | 0.01 |
| Isle Royale     | 2010 | 140  | 0.997 | 506   | 459 | 5.81  | 2.37 | 9.72  | 0.005 | 13.67;       | 0.01 | 13.67;      | 0.01 |
| Superior Shoal  | 2011 | 159  | 0.998 | 506   | 459 | 4.63  | 2.37 | 9.72  | 0.005 | 13.67;       | 0.01 | 13.67;      | 0.01 |
| Stannard Rock   | 2012 | 159  | 0.998 | 506   | 459 | 3.42  | 2.37 | 9.72  | 0.005 | 13.67;       | 0.01 | 13.67;      | 0.01 |
| Klondike Reef    | 2013 | 159  | 0.998 | 506   | 459 | 2.21  | 2.37 | 9.72  | 0.005 | 13.67;       | 0.01 | 13.67;      | 0.01 |
| Grand Marais    | 2014 | 159  | 0.998 | 506   | 459 | 1.00  | 2.37 | 9.72  | 0.005 | 13.67;       | 0.01 | 13.67;      | 0.01 |
| Big Reef        | 2015 | 159  | 0.998 | 506   | 459 | 0.00  | 2.37 | 9.72  | 0.005 | 13.67;       | 0.01 | 13.67;      | 0.01 |

0.56; $P = 0.46$). The largest within-lake temporal difference in the FL:TL relationship was between 2002 and 2010 in Great Slave Lake, with an average bias of $-8.7$ mm (SD = 7.5 mm) in estimated FL for the 2002 sample using the 2010 relationship and $+8.4$ mm (SD = 8.8 mm) in estimated FL for the 2010 sample using the 2002 relationship (Figure 3a). Bias of estimated FL was related to TL for both samples, and TL explained 29–35% of the variation in estimated FL (Figure 3a).

Spatial variation in the relationship between FL and TL was evident among locations within Lake Superior, but not within Great Bear Lake. In Lake Superior, the relationship between FL and TL differed among six locations ($F_{5,1987} = 13.67; P < 0.01$), with Isle Royale differing from three of five other areas, Superior Shoal differing from four of five other areas, Stannard Rock differing from three of five other areas, Klondike Reef differing from one of five other areas, Grand Marais differing from two of five other areas, and Big Reef differing from all other areas (Table 3). In contrast, in Great Bear Lake, the relationship between FL and TL did not differ between Dease and McTavish arms ($F_{1,587} = 0.94; P = 0.33$). The largest within-lake spatial difference in the FL:TL relationship was between Big Reef and Superior Shoal in Lake Superior, with an average bias of $-11.3$ mm (SD = 7.9 mm) in estimated FL for the Superior Shoal sample using the Big Reef relationship and $+14.0$ mm (SD = 6.9 mm) in estimated FL for the Big Reef sample using the Superior Shoal relationship (Figure 3b). Bias of estimated FL was related to TL for both samples, and TL explained 15–31% of the variation in estimated FL bias (Figure 3b).

Relationships between FL and TL differed among Lake Trout lakes in North America. The relationship between FL and TL differed among lakes ($F_{6,3397} = 7.85; P < 0.01$), with Great Bear Lake differing from three of six other
lakes, Great Slave Lake differing from three of six other lakes, Lake Mistassini differing from two of six other lakes, Lake Superior differing from four of six other lakes, Naknek Lake differing from one of six other lakes, Rush Lake differing from five of six other lakes. The largest among-lake spatial difference in the FL:TL relationship was between Naknek and Skilak lakes in Alaska, with an average bias of \(-12.3\) mm (SD = 9.5 mm) in estimated FL for the Naknek Lake sample using the Skilak Lake relationship and +0.9 mm (SD = 4.4 mm) in estimated FL for the Skilak Lake sample using the Naknek Lake relationship (Figure 3c). Bias of estimated FL was related to TL for both samples, and TL explained 46–49% of the variation in estimated FL bias (Figure 3c).

An overall FL:TL relationship across all samples caused less average bias in estimated FL than when using length conversions from another year in the same lake, another location in the same lake, or another lake. The largest average bias for individual samples caused by using an overall length conversion ranged from \(-8.5\) mm for Superior Shoal in 2013 to +7.0 mm for Big Reef in 2006.

Table 3. Results of pairwise comparisons of slopes of linear relationships between fork length (FL) and total length (TL) of Lake Trout *Salvelinus namaycush* sampled at six locations in Lake Superior during 2002–2014. For each comparison, the value shown is the \(P\)-value (bold font if \(P < 0.05\)) for the interaction between TL and subareas from a general linear model. See Table 1 for locations and numbers of Lake Trout sampled.

|               | Isle Royale | Superior Shoal | Stannard Rock | Klondike Reef | Grand Marais |
|---------------|-------------|----------------|---------------|--------------|--------------|
| Superior Shoal| 0.003       |                |               |              |              |
| Stannard Rock | 0.047       | <0.001         |               |              |              |
| Klondike Reef | 0.497       | 0.436          | 0.095         |              |              |
| Grand Marais  | 0.185       | 0.007          | 0.753         | 0.125        |              |
| Big Reef      | <0.001      | <0.001         | <0.001        | <0.001       | 0.014        |
Table 4. Tests of length-related trends in bias between fork length (FL) estimated from (TL; Est) using the overall equation from Table 3 and measured in the field (Obs) for Lake Trout Salvelinus namaycush populations in North America during 2001–2015. Lakes and locations within lakes are sorted from north to south. See Table 1 for surface area, latitude, and longitude of all locations. A table-wide P-value of 0.05 with Bonferroni correction is P = 0.0015 for judging significance of each test (denoted in bold font).

| Lake and location | Year | N | r² (%) | b₀ | SE (b₀) | b₁ | SE (b₁) | P | Mean | SE |
|------------------|------|---|--------|----|---------|----|---------|---|------|----|
| Great Bear       | 2011 | 480 | 0.290  | -1.04 | 0.06    | 0.60 | 0.08    | 0.001 | 1.754 | 0.446 |
|                  | 2010 | 70  | 0.939  | 4.01  | 0.32    | 0.03 | 0.005   | 0.001 | 4.785 | 1.386 |
|                  | 2009 | 270 | 0.550  | -1.49 | 0.08    | 0.02 | 0.007   | 0.001 | 2.378 | 0.778 |
|                  | 2008 | 210 | 0.700  | 0.94  | 0.06    | 0.01 | 0.004   | 0.001 | 2.530 | 0.787 |
|                  | 2007 | 150 | 0.849  | 1.18  | 0.08    | 0.02 | 0.007   | 0.001 | 2.460 | 0.767 |
|                  | 2006 | 100 | 0.950  | 3.96  | 0.31    | 0.03 | 0.008   | 0.001 | 3.475 | 1.065 |
|                  | 2005 | 50  | 0.999  | 5.03  | 0.35    | 0.04 | 0.009   | 0.001 | 4.120 | 1.330 |
|                  | 2004 | 25  | 0.999  | 8.07  | 0.67    | 0.10 | 0.016   | 0.001 | 6.690 | 2.010 |
|                  | 2003 | 10  | 0.999  | 14.35 | 1.19    | 0.15 | 0.024   | 0.001 | 12.35 | 3.645 |
|                  | 2002 | 5   | 0.999  | 28.88 | 2.28    | 0.25 | 0.038   | 0.001 | 26.49 | 7.944 |
|                  | 2001 | 2   | 0.999  | 72.73 | 3.12    | 0.30 | 0.051   | 0.001 | 69.71 | 20.36 |

but the average bias of all other samples ranged between -4.7 mm and +3.9 mm (Table 4; Figure 3d). Bias was related to TL for 15 of 33 samples, but TL explained <10% of bias for 27 samples, 10–15% for 15% for only for 3 samples (26% for Rush Lake 2018, 27% for Great Slave Lake 2001; Table 4).

Discussion

For Lake Trout, published estimates of length relationships or ratios were lacking in methodological descriptions or were developed using statistically less reliable methods. For example, conversions between SL and TL were provided as text or table footnotes without descriptions of methods or disclosure of data for Lake Trout in Lake Michigan and in Ontario, Canada, inland lakes (Table 5). Further, conversions developed as means of ratios or ratios of means fail to account for a nonzero intercept, such as those for Lake Trout in Great Bear Lake and Great Slave Lake that were computed as ratios of mean lengths (Table 5). For samples in our Table 2, ratios of mean lengths were biased low for FL:TL and high for TL:FL for 31 of 34 samples. In contrast, linear regression allows for a nonzero intercept (e.g., Lake Tahoe, California, and Cayuga Lake, New York; Table 5), but should account for measurement error of the independent variable that attenuates the slope and thereby biases estimates of the dependent variable (Ricker 1975). As in our study, inaccurate or insufficiently documented TL:FL conversions for pollock from the Gulf of Maine and haddock from Georges Bank prompted development of more accurate conversions from large samples using functional linear regression for use in developing minimum landing size for commercial fisheries that harvest >750,000 metric tons annually of the two species combined (Pol et al. 2011).

Ranges of slopes for FL:TL relationships (0.872–0.937) and TL:FL relationships (1.067–1.146) from our study were generally consistent with previously published values (Table 5), although some previously published conversions would result in large errors in estimated FL or TL.
example, the TL:FL conversion for Lake Trout populations in Alaska (0.935, Burr 2006, cited by Joy et al. 2014) was near the upper limit of those we found that induced large errors when used to estimate FL from TL (Figure 3). The range of TL estimated from FL (maximum − minimum) based on previously published studies (Table 5) was 9 mm at 200 mm FL, 24 mm at 500 mm FL, and 47 mm at 1000 mm FL, which confirms a potentially large magnitude of error when using a length conversion from a published compilation (e.g., Carlander and Smith 1945; Carlander 1969, 1977, 1997; Morato et al. 2001; Moutopoulos and Stergiou 2002; Gaygusuz et al. 2006). For Lake Trout, our compilation of length conversions would induce a similar magnitude of error when using a length conversion from a different year within the same lake, a different area within the same lake, a different lake, or an overall conversion from across the species’ range. This magnitude of error could substantially alter estimates of length at maturity, yield per recruit, or length at age that are often intermediate calculations toward setting harvest regulations (e.g., length limits or harvest quotas based on sustainable yield estimates; Ricker 1975). Despite the risk of such errors, few published length conversions caution against using a conversion from one area or population for use elsewhere, as in Ramseyer (1995) for Coho Salmon Oncorhynchus kisutch and Chinook Salmon O. tshawytscha.

Relationships between FL and TL are remarkably precise (e.g., \( r^2 = 0.990-0.999 \); this study), but even small errors in these relationships can cause large errors in fishery regulations derived from an incorrect length conversion. For example, use of an inaccurate length conversion can cause important errors in harvest of large-scale commercial fisheries when minimum length limits are prescribed in TL and fishery-independent surveys are measured in FL (Pol et al. 2011). Similarly, use of an inaccurate length conversion can lead to large errors in sustainable yield because length is converted into weight using a power function that translates small errors in length into much larger errors in weight (e.g., Joy et al. 2014). Surprisingly, we found that estimation error was least when using a length conversion developed from populations across the species’ range. The overall length conversion we developed likely performed better than sample-specific length conversions because the overall conversion dampened effects of variability among sample-specific relationships caused by small samples or narrow ranges of length. In the absence of standardization within and among all agencies and institutions studying or managing Lake Trout populations (e.g., Bonar et al. 2009), we therefore suggest using the overall length conversion developed herein whenever a more accurate length conversion is not available for a population of interest (e.g., from a subsample of the same population in the same year).

### Supplemental Material

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Table S1. Results of tests for homogeneity of slopes among linear relationships between fork length (FL) and total length (TL) for Lake Trout Salvelinus namaycush morphs in North America sampled during 2002–2015, including number of fish captured, number of morphs identified, F-ratio of the Morph × TL interaction (as described in the Methods for testing year effects), \( P \)-value of the F-ratio for the Morph × TL interaction, \( r^2 \) for a full model with different intercepts and slopes for each morph, \( r^2 \) for a reduced model without morphs, percent of the residual variation (%) from the reduced model explained by separate morphs in the full model, and source of morph assignments. Lakes and locations within lakes are sorted from north to south. See Table 1 for surface area, latitude, and longitude of all locations. A table-wide \( P \)-value of 0.05 with Bonferroni correction is \( P = 0.045 \) for judging significance of each test.

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Table S2. Data table of fork length (FL) and total length (TL) for Lake Trout Salvelinus namaycush populations in North America sampled during 2001–2015. See Table 1 for surface area, latitude, and longitude of all lakes and locations within lakes.

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