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Determining minimum ultimate size, setting size limits, and developing trophy standards and indices of comparable size for maintaining quality muskellunge (*Esox masquinongy*) populations and sports fisheries

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Abstract Growth and ultimate size can provide important population insights and a sound biological basis for setting length limits, which can be the best single regulation for preventing overexploitation of muskellunge (*Esox masquinongy*) populations. A system was developed, using cleithral age and total length at age confidence limits (CL) data, to determine reproductive and growth potential (ultimate size) for calculating and setting increased size limits based on minimum reproductive size (upper 99% CL at age at first maturity + 2 year) and minimum ultimate size (MUS) calculated from the lower 99% CL—minimum ultimate size limit (MUSL). MUS also provides a trophy standard and an index of relative size for comparing trophy potential of individuals within and among populations. Guidelines are provided for determining minimum sample size (mean ± 95% confidence interval = 12 ± 4) and minimum age (8–10 ± 2.0 year) required to produce valid von Bertalanffy growth trajectories. MUS, MUSL, and trophy standards for both length and estimated weight are provided for female and male muskellunge from 14 Ontario sources. Mean MUS, or trophy standard, for females was 115 ± 10.3 cm (MUSL range 75–135) and 11.1 ± 2.6 kg (2.5–17.5) and for males was 95 ± 7.5 cm (66–110) and 6.1 ± 1.3 kg (1.9–9.2). These indices can precisely define growth and growth potential for muskellunge populations and individuals and can be used to better manage and maintain or improve the quality of muskellunge populations and fisheries.

Keywords Muskellunge · Size limit · Trophy standard · Minimum ultimate size · Growth index · Length · Weight · Age · Growth potential · L-infinity · 99% confidence limits

Dedicated to the late Dr. E.J. Crossman.

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Introduction

Growth of muskellunge, *Esox masquinongy*, varies widely across the range of the species. This has been well documented in recent years because accurate, validated age assessment has been developed for the species (Casselman et al. 1999). Differences in growth potential and ultimate size are well known to muskellunge anglers. In recent years, populations with high growth potential, producing large-bodied fish, have been heavily fished and are increasingly the focus of intense sport fisheries.

With the increasing practice of voluntary catch-and-release and its promotion by organized muskellunge angling groups (such as Muskies Inc. and Muskies Canada), there has been a substantial increase in size of fish caught and angling success. This has, to some extent, been facilitated by increasing length limits (commonly referred to as size limits) to restrict harvest and by more favourable environmental conditions (Robinson 2005) associated with warmer temperatures in the Great Lakes Basin (Casselman 2002).

In order to better manage populations and to provide diverse fishing opportunities, some agencies have implemented a range of size limits across their jurisdictions, depending upon whether the water body can produce small-, medium-, or large-bodied muskellunge (Casselman et al. 1999). In Ontario, more diverse growth-based size limits were implemented widely in the late 1980s (Ontario Ministry of Natural Resources 1986). Indeed, Hunt (1970) emphasized that a size limit, if appropriately applied, is the best single regulation for preventing overexploitation of fish populations.

Encouragement by organized muskellunge anglers to increase length limits necessitated a science-based method for determining desirable size, based on growth. Although age at first maturity seems to be quite consistent across the range of the species, growth and ultimate size seem much more variable (Casselman et al. 1999). This is probably related to productivity of the environment, abundance and size of available prey, and even size of the water body.

Genetics can also affect growth and growth potential of muskellunge. Koppleman and Philipp (1986) confirmed that there are distinct genetic stocks of muskellunge and emphasized that this should be taken into consideration when managing the species. Minnesota conducted performance evaluation of four muskellunge strains in two Minnesota lakes and confirmed that the Mississippi strain grew fastest and reached the largest size (Younk and Strand 1992). Margenau and Hanson (1996) documented that genetics affected fish size and growth of stocked muskellunge. This is strong evidence that genetics can affect growth potential and requires special consideration when stocking and managing for quality fisheries and overall trophy potential.

All of this emphasizes the need for a biologically based growth method for setting specific size limits. Initial discussions in the mid-1990s that led to new length-limit regulations for the province of Ontario in the late 1990s (Ontario Ministry of Natural Resources 1999) were initiated with a discussion of "favourite" length limits. This resulted in considerable debate that seemed irresolvable and fraught with controversy. It was apparent that what was needed was a universally applicable growth-based method for calculating length limits that would take into consideration population-specific growth potential.

Considerable data had been collected on size at age, mainly as a result of the success of The Cleithrum Project in assembling and archiving a large quantity of muskellunge data and cleithral samples from numerous water bodies throughout Ontario (Crossman and Casselman 1996). A grant from Muskies Inc. made it possible to extract a considerable amount of data from this archive (Robinson 2005). Detailed growth of muskellunge populations from 17 Ontario water bodies was assembled and analyzed (Casselman et al. 1999).

Detailed age and growth data that were available made it possible to examine size at age and growth rate quite precisely and to categorize specific populations, based on growth potential, producing small-, medium-, or large-bodied fish (Casselman et al. 1999). Size limits in the mid-1980s were grouped according to growth but did not take into consideration ultimate growth potential. These limits were initially set around age at first maturity + 2 years. It was generally assumed that reproduction was not totally successful at first maturity but that fish required several years to reach full reproductive potential. Early analyses of growth resulted in an increase in size limits but did not truly address the broad range of ultimate sizes, or growth potentials, that existed for populations across Ontario.

To develop a more refined set of length limits, it was necessary to examine growth rate and growth potential in more detail. Ideally, because of differential growth of the sexes, different limits would be needed for males and females. However, this required a level of complexity that anglers did not appear ready to accept at that time, even though external sex determination of live muskellunge was possible (LeBeau and Pageau 1989), using a method that had been developed for northern pike, *Esox lucius* (Casselman 1974). If female growth was used to set size limits, slower-growing males would be underexploited. Nevertheless, it seems appropriate to focus on female size limits since the reproductive capacity of the population is strongly influenced by egg production.

The general purpose of the present study was to develop a method and criteria for setting size limits based on linear growth potential, using growth trajectories and ultimate size, or L-infinity. The new upper size limit developed here uses $L\infty$, or ultimate length, calculated from the lower 99% confidence limit (CL) and is referred to as minimum ultimate size (MUS). MUS is a mathematical projection of the length that 99% of the fish would reach if they lived indefinitely. A number of other ultimate-size values could be considered; for example, maximum ultimate size (upper 99% CL) would be of interest to anglers seeking the largest possible individuals, but this is an extreme size that is rarely seen or reached. MUS is a more realistic size frequently seen and exceeded and is a better lower-level upper-length benchmark; theoretically, only one fish in 100 would not reach this MUS.

MUS has both a genetic (Koppleman and Philipp 1986; Margenau and Hanson 1996) and an environmental (Casselman et al. 1999; Robinson 2005) component, depending upon population and water body. It is best assessed empirically from actual growth data assembled for the population. It can also define trophy potential, or status, and not only categorizes the fish, the population, and the water body but can also be used to assess relative size of an individual within and among populations in terms of a trophy standard. This trophy standard can be used to describe a quite specific ultimate size (length or estimated weight) that could be defined as being equal to one trophy unit, and any fish could be compared to it on a proportional basis.

The specific purpose of this study was to analyze growth to determine MUS for both sexes and set a minimum ultimate trophy size limit (MUSL) and to develop trophy standards and indices for examining trophy size and status, using muskellunge populations in Ontario as examples. Muskellunge are rare fish and sample sizes are often small, so it would also be useful to determine just how few samples are required and how old the fish would need to be to calculate ultimate size accurately and consistently.

Materials and methods

Age and growth determination

Samples and data used in this study came from The Cleithrum Project (Crossman and Casselman 1996) and were primarily from fish provided by anglers and taxidermists. Age and growth were extracted from cleithra, using validated age-interpretation procedures (Casselman 1996; Casselman et al. 1999). The majority of the samples were from relatively large trophy muskellunge, defined by Casselman and Crossman (1986) as angled fish mounted or considered worthy of being mounted. Some samples from the Niagara River and Georgian Bay came from Ontario Ministry of Natural Resources (OMNR) assessment sampling but were from large fish that were of trophy size. The Nogies Creek sample came from a sanctuary population in central Ontario provided from research studies conducted by the late Dr. E. J. Crossman and was used to encompass the range in growth potential of the species. Additional samples were used from the French River, which flows into Georgian Bay. Recent samples submitted to The Cleithrum Project made it possible to include this new source. It included 17 females, maximum age 22 years, and five males, maximum age 11 years. Only samples for which sex was provided were used in the analyses. Total length, weight, and age of muskellunge used in this study are provided in Casselman et al. (1999).

To reconstruct growth, annual increments in cleithra were measured, using the Calcified Structure Age-Growth data Extraction Software

(CSAGES) (Casselman and Scott 2000) modified to incorporate electronic calipers for measuring and enumerating annuli (Robinson 2005). Cleithral length was converted to body length by using the body-cleithrum relationship in Casselman et al. (1986). For all populations, von Bertalanffy relationships were constructed for the mean and also for the upper and lower 99% CL. $L\infty$ for von Bertalanffy relationships for upper and lower 99% CL were used to estimate mathematically the maximum and minimum ultimate lengths. To provide a more complete comparison when too few samples were available to calculate an accurate von Bertalanffy relationship, the relationship for the population with the most similar size at age was selected, using concordance sum of squares (Casselman et al. 1999). When unrealistic maximum or minimum ultimate lengths were estimated, equal confidence intervals were used to provide more realistic estimates. This most frequently occurred in the case of upper 99% CL. No males were available for Lake of the Woods and Tweed water bodies, so for comparative purposes, male means and confidence limits were estimated from regressions of the average relationship between male and female growth (Casselman et al. 1999). All growth analyses were conducted on length, and weights, when presented, were estimated from length, using a standard length-weight relationship (Casselman and Crossman 1986).

Minimum sample size and age

Growth potential was estimated by using ultimate length calculated from the von Bertalanffy relationship. Estimates of $L\infty$ are greatly influenced by maximum age of the sample (Ontario Ministry of Natural Resources 1983), so additional analyses involving 10 populations were conducted to determine how old muskellunge needed to be in order to provide an $L\infty$ that fell within the confidence limits for the population. This provided the minimum age required to produce a statistically reliable mean von Bertalanffy growth curve. The age at which this mean ultimate size was reached was calculated and compared with minimum age. For this analysis, as was shown in a previous study (Casselman et al. 1999), at least six individuals were required at each age to calculate an accurate von Bertalanffy relationship.

In addition to age, the minimum number of samples required was considered an important variable in estimating an appropriate L∞. A set of six different sequential removals was conducted for three populations (Indian Lake, Lake of the Woods, and Lake St. Clair) to determine the minimum number of samples needed. This also provided an estimate of the minimum age required to estimate $L\infty$ accurately.

Setting minimum ultimate size limits

A method was developed to determine minimum ultimate size limits based on female linear growth potential but also considering minimum reproductive length limit at the upper 99% CL at age seven (Fig. 1). Since the late 1980s in Ontario, reproductive minimum size limit has always been set at the age at which the majority of females were first mature (age five plus 2 years) to ensure experienced spawning before harvest. In females, this is age seven, and in males, it is age six, since males usually mature one year younger than females. The upper 99% CL at this age was chosen rather than mean size because it would reduce selective removal of faster-growing, young, mature muskellunge.

MUSL was MUS rounded down to the nearest cm (if limits were in inches, the same unit rounding was performed); this was done to make sure that rounding did not exclude more individuals. For a similar reason, reproductive size limit was rounded up to the nearest cm. Depending upon growth rate of the population, if reproductive size limit was greater than MUSL, then reproductive size was selected as the upper size limit. This occurred only in populations that had very rapid early growth and reached an asymptotic length early in life. If MUSL was greater than reproductive size, and this was usually the case, then MUSL remained the minimum upper size limit.

Trophy standards and indices of relative size and status

MUS also provides a trophy standard and index that is the mathematical projection of minimum

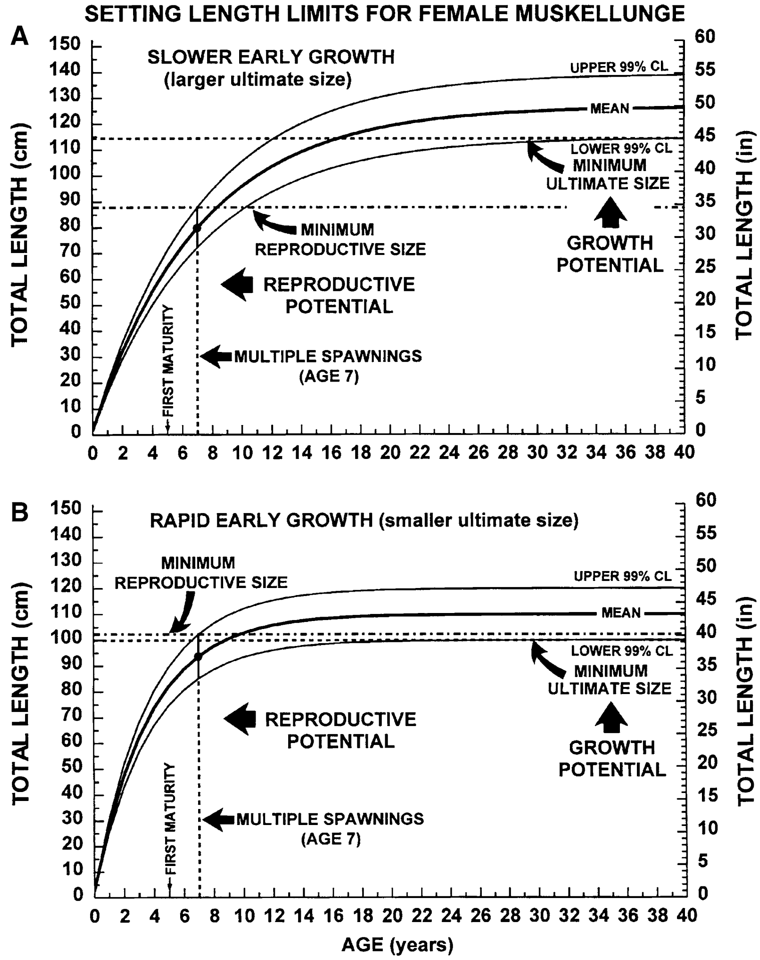

Fig. 1 Illustration of generalized size-at-age growth trajectories for female muskellunge with (**A**) slow early growth and large ultimate length and (**B**) rapid early growth and small ultimate length, indicating age and growth data important for setting size limits for muskellunge based on reproductive potential involving first maturity plus 2 years and growth potential involving ultimate length, calculated on the mean and 99% confidence limits, emphasizing the lower or minimum ultimate size

growth potential of the population, the theoretical size that 99% of individuals would reach if they lived indefinitely. MUS provides a trophy standard precisely equal to one trophy that other muskellunge can be compared with, using an index of relative size expressed as per cent, based on either length or weight, depending upon which criterion is chosen to define trophy. Mean or maximum ultimate length can also be expressed as a per cent of this minimum, or trophy, standard. Size varies considerably in relation to sex of a fish, so male and female standards were developed. If fish are released, external sex determination is necessary. However, if sex is unknown or not determined, then a sex-independent standard that equally weights males and females was developed and can be used. This eliminates the necessity to sex fish but is far less precise because it underestimates for females and overestimates for males.

Results

Minimum sample size and age

Calculation of the minimum age required to produce a mean von Bertalanffy curve and an $L\infty$ that fell within the 95% CL of the $L\infty$, using all ages, was examined for females from 10 water bodies (Table 1). Samples were fairly large (mean $N = 33.9$ fish) with a broad range of ages, producing a reliable overall $L\infty$. Mean minimum age required was 8.2 years, with 95% CL ranging from 6.2 to 10.2 years (Table 1). Mean age when overall $L\infty$ was reached was 29.5 years, and

Table 1 Minimum age required to calculate a mean von Bertalanffy growth curve that produces an ultimate length ($L\infty$) that fell within the 95% confidence limits (CL) of the $L\infty$ for female muskellunge from 10 Ontario sources. Approximate ultimate age at the ultimate length and minimum age relative to this ultimate age are also provided. Overall means and 95% CL are given. An *N* of at least six was required at each age

Source	*N*	Minimum age	Ultimate age—when $L\infty$ reached	Minimum age relative to ultimate age (%)
Tweed water bodies	22	4	19.7	20.3
Lake St. Clair	31	11	21.2	51.9
Georgian bay	42	7	22.8	30.7
St. Lawrence river	15	6	24.6	24.4
Lake of the woods	27	8	26.6	30.1
Indian lake	38	5	26.6	18.8
Maskinonge lake	34	10	29.0	34.5
Eagle–Wabigoon lakes	46	8	31.9	25.1
Lac Seul	11	10	39.5	25.3
Kawartha lakes	73	13	53.1	24.5
Mean	33.9	8.2	29.5	28.6
95% CL—lower	21.2	6.2	22.3	21.8
95% CL—upper	46.6	10.2	36.7	35.3

minimum age was only 28.6% of overall ultimate age, with 95% CL ranging from 21.8 to 35.3%.

Minimum number of samples required to produce an $L\infty$ that fell within the 95% CL for female muskellunge was examined for three Ontario sources used to examine the various confidence limits. An average of 32 samples was available; an adequate number to determine from six different sequential random removals the minimum number of samples required (Table 2). These samples and analyses indicated that the mean minimum number of samples required was 11.6, with 95% CL ranging from 7.6 to 15.6, rounded to 12 ± 4 (Table 2). Mean minimum age, which was also estimated in this analysis, was 10.1 years, ranging from 7.9 to 12.3, rounded to 10 ± 2 years (Table 2).

Mean and extreme ultimate sizes and ages

Ultimate length was calculated for female (Table 3) and male (Table 4) muskellunge from 14 Ontario sources for the mean, as well as extremes, using 99% CL. Appendices A and B present these data in inches and pounds. For a few sources, samples were inadequate to determine ultimate length directly, and estimates had to be made using concordance sum of squares (Casselman et al. 1999). For females, overall mean ultimate length was 123.0 ± 11.0 cm (Table 3), compared with 104.4 ± 7.6 cm for males (Table 4), 15.1% smaller. Also, mean maximum ultimate length for females was 134.1 ± 12.8 cm, compared with 116.0 ± 9.2 for males, 13.5% smaller. Mean minimum ultimate length for

Table 2 Minimum sample required to produce an ultimate length ($L\infty$) that fell within the 95% confidence limits (CL) for female muskellunge from three Ontario sources. Determined from six different sequential random removals. The ages of these subsamples are also provided. An *N* of at least six was required at each age

Source	*N*	Number			Age		
		Mean minimum	95% CL		Mean minimum	95% CL	
			Lower	Upper		Lower	Upper
Indian lake	38	10.5	4.5.	16.5	7.3	5.6	9.0
Lake of the woods	27	8.2	5.9	10.4	10.7	8.0	13.4
Lake St. Clair	31	16.0	12.3	19.8	12.3	10.2	14.5
Mean	32	11.6	7.6	15.6	10.1	7.9	12.3

Table 3 Growth and age data important for setting length limits (cm) based on reproductive size and growth potential for female muskellunge from 14 Ontario sources. Ultimate length (cm) provides a measure of growth potential, whereas reproductive potential is indicated by the upper 99% confidence limits (CL) at age seven (2 years after first maturity, age five). Minimum ultimate size limits with estimates of weight (kg) and predictions of age (youngest and oldest) are provided. The oldest observed age is given. Overall means and 95% confidence intervals (CI) are provided

Females		Ultimate length (cm)			Upper 99% CL at age seven (cm)	Minimum ultimate size limit				
		Mean	99% CL			Length (cm)	Estimated weight (kg)	Predicted age		Oldest observed
Source	*N*		Upper	Lower				Youngest	Oldest	
Lac Seul	11	140.0	148.6	135.6	88.9	135	17.5	16	31	23
Lake of the woods	27	136.4	148.8	130.3	97.5	130	15.7	14	30	24
Eagle-Wabigoon lakes	46	133.1	141.2	128.0	93.2	128	14.8	16	30	23
St. Lawrence River	15	139.2	156.7	126.7	101.3	126	13.9	10	19	20
Ottawa river[a]	4	133.9	140.7	128.7	96.3	128	13.9	14	26	17
Georgian bay	30	134.1	148.6	126.0	95.8	126	13.9	13	24	30
Lake St. Clair	31	124.2	130.8	119.1	97.3	119	11.4	12	20	19
Kawartha lakes	74	129.8	143.0[b]	116.6	89.9	116	10.7	11	20	22
French river	17	132.6	149.4[b]	115.8	101.3	115	10.7	9	20	22
Niagara river[a]	6	116.6	130.6	114.3	108.2	114	10.7	11	33	15
Tweed water bodies	20	121.9	134.6	111.3	100.3	111	9.3	8	19	19
Indian lake	38	116.6	135.1[b]	98.0	80.3	98	6.3	9	22	14
Nogies creek	21	81.8	81.8	83.6	73.9	83[c]	3.7	15	15	10
Maskinonge lake	39	81.3	88.1	75.7	68.1	75	2.5	8	14	14
Mean ± 95% CI		123.0 ± 11.0	134.1 ± 12.8	115.0 ± 10.3	85.9 ± 14.6	115	11.1 ± 2.6	11.9 ± 1.7	23.1 ± 3.5	19.4 ± 3.0

[a] Data were calculated from concordance sum of square comparisons (Casselman et al. 1999)

[b] Values were adjusted to an equal confidence interval because original values were unrealistically large

[c] Minimum length limit was suspect because mean ultimate length was less than the lower 99% CL

Table 4 Growth and age data important for setting length limits (cm) on a biological basis, considering reproductive size and growth potential for male muskellunge from 14 Ontario sources. Ultimate length (cm) provides a measure of growth potential, whereas reproductive potential is indicated by the upper 99% confidence limits (CL) at age six (2 years after first maturity, age four). Minimum ultimate size limits with estimates of weight (kg) and predictions of age (youngest and oldest) are provided. The oldest observed age is given. Overall means and 95% confidence intervals (CI) are provided

Males		Ultimate length (cm)			Upper 99% CL at age six (cm)	Minimum ultimate size limit				
		Mean	99% CL			Length (cm)	Estimated weight (kg)	Predicted age		Oldest observed
Source	*N*		Upper	Lower				Youngest	Oldest	
Lake of the woods[a]		114.3	122.9	110.0	82.6	110	9.2	8	22	
St. Lawrence river[b]	6	114.3	125.5	106.2	84.6	106	8.0	9	18	17
French river[b]	5	114.3	125.5	106.2	84.6	106	8.0	9	18	11
Lac Seul[b]	5	115.1	125.9	104.4	79.0	104	8.0	11	30	25
Eagle-Wabigoon lakes	17	115.1	125.9	104.4	79.0	104	8.0	11	30	18
Ottawa river[b]	3	106.7	111.8[c]	101.6	85.6	101	7.4	8	31	17
Georgian bay[b]	6	110.5	123.4	100.6	86.6	100	6.9	9	17	20
Lake St. Clair	25	107.2	118.6	96.8	82.8	96	6.3	8	26	17
Tweed water bodies[a]		103.9	112.8	96.3	85.3	96	5.8	7	13	
Indian lake	28	97.3	103.9	89.4	70.9	89	4.8	10	25	16
Kawartha lakes	21	104.9	130.3	85.1	85.6	86	4.4	6	12[d]	18
Niagara river[b]	3	104.9	130.3	85.1	85.6	86	4.4	6	12[d]	11
Nogies Creek	23	82.3	89.4	75.2	72.6	75	2.7	6	12	13
Maskinonge lake	14	70.6	77.2	66.3	63.0	66	1.9	6	15	14
Mean ± 95% CI		104.4 ± 7.6	116.0 ± 9.2	94.8 ± 7.5	80.6 ± 5.1	95	6.1 ± 1.3	8.1 ± 1.0	20.1 ± 2.5	16.4 ± 4.1

[a] Male data were not available for these water bodies, so male growth was estimated from regressions of the relationship between female and male growth (Casselman et al. 1999)

[b] Data were calculated from concordance sum of square comparisons (Casselman et al. 1999)

[c] Values were adjusted to an equal confidence interval because original values were unrealistically large

[d] Age at which the slowest-growing muskellunge reached the ultimate size, which was less than the minimum size limit because the minimum reproductive size limit was greater and was used rather than the minimum ultimate size limit

females was 115.0 ± 10.3 cm, compared with 94.8 ± 7.5 cm for males, 17.6% smaller. Female growth was much more variable than male growth.

Estimates of weight came from a length-weight relationship and are probably more variable than length but are provided for descriptive and comparative purposes and were not used for setting size limits that were based entirely on length. Estimates of mean ultimate weight were 11.1 ± 2.6 kg for females compared with 6.1 ± 1.3 kg for males, 44.6% smaller.

The predicted youngest and oldest mean ages at which individuals would reach minimum ultimate length ranged from 12 to 23 years for females, a difference of 11 (Table 3), and from 8 to 20 years for males, a difference of 12 (Table 4). Age of the oldest observed females in the samples ranged from 10 to 30 years (mean 19.4) and for males, 11 to 25 years (mean 16.4).

Setting minimum ultimate size limits

MUSL is set in relation to reproductive and growth potential. Fig. 1 illustrates these two important length-limit benchmarks for (A) relatively slow-growing fish that would reach a large ultimate length and (B) initially fast-growing fish that would reach a smaller ultimate length. MUS in slow-growing fish would invariably exceed length at maturity and minimum reproductive size by a considerable amount, whereas young, very fast-growing fish that result in a lower ultimate size might result in a minimum reproductive size that could exceed the MUS (Fig. 1B). For males from the Kawarthas and the Niagara River, this reproductive size exceeded the MUSL, so reproductive size became the recommended minimum upper size limit (Table 4).

MUSL, which is the lower 99% CL but rounded down to the nearest centimetre or inch, is used to ensure that fewer large fish are excluded. Average MUSL for females for these Ontario populations was 115 cm (Table 3) and for males, 95 cm (Table 4). These values vary substantially across water bodies, ranging from 75 to 135 cm for females and from 66 to 110 cm for males.

Trophy standards and comparable indices of relative size and status

MUS can be used to more precisely define a trophy muskellunge based on minimum standards for comparing within and among populations (Fig. 2), providing a more consistent definition of a trophy. This minimum, or trophy, standard varied considerably across water bodies and was strongly influenced by sex of the fish. Average length of a trophy female for 14 Ontario populations was 114.8 cm, with mean and maximum ultimate lengths 7% and 17% higher, respectively

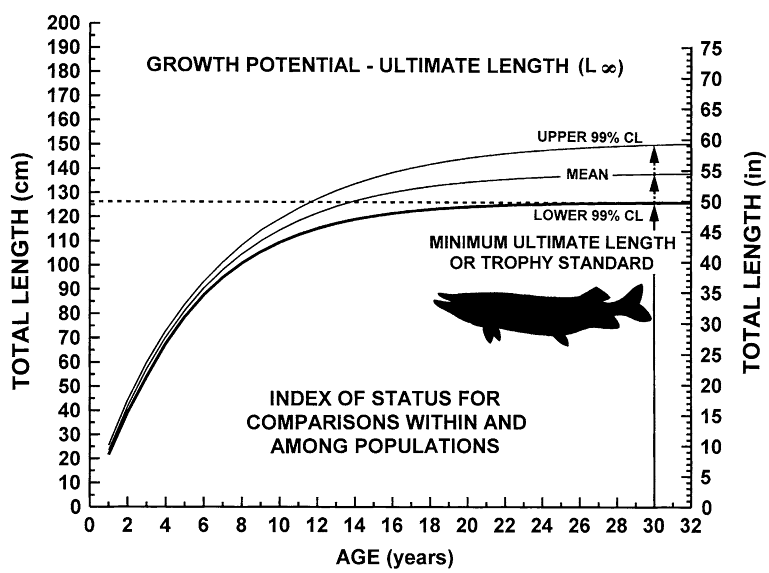

Fig. 2 Illustration of size-at-age growth trajectories for determining growth potential using minimum ultimate length (lower 99% confidence limits, dark curve) for developing trophy standards and indices for comparing relative size or growth status of individuals within and among populations

Table 5 Minimum ultimate length and estimated weight of female and male muskellunge, which provide a minimum ultimate, or trophy, standard for muskellunge from 14 sources in Ontario. Mean ultimate and maximum ultimate length (cm) and corresponding weights (kg) as a proportion of the minimum ultimate or trophy standard are provided. Overall means, as well as 95% and 99% confidence limits (CL), are also provided. Provides a basis for comparing size relative to growth potential and a trophy standard within and between muskellunge populations and individuals

Source	Females						Males					
	Length			Weight			Length			Weight		
	Minimum or trophy standard (cm)	Proportion of minimum		Minimum or trophy standard (kg)	Proportion of minimum		Minimum or trophy standard (cm)	Proportion of minimum		Minimum or trophy standard (kg)	Proportion of minimum	
		mean	maximum		mean	maximum		mean	maximum		mean	maximum
Lac Seul	135.6	1.03	1.10	18.0	1.10	1.33	104.4	1.10	1.21	7.9	1.37	1.82
Lake of the woods	130.3	1.05	1.14	15.9	1.15	1.51	110.0	1.04	1.12	9.3	1.14	1.43
Ottawa river	128.7	1.06	1.11	14.6	1.18	1.38	101.6	1.05	1.10	7.3	1.17	1.36
Eagle-Wabigoon lakes	128.0	1.04	1.10	15.1	1.13	1.36	104.4	1.10	1.21	7.9	1.37	1.82
St. Lawrence river	126.7	1.10	1.24	14.6	1.34	1.93	106.2	1.08	1.18	8.0	1.27	1.71
Georgian bay	126.0	1.07	1.19	14.3	1.22	1.69	100.6	1.10	1.23	6.8	1.35	1.93
Lake St. Clair	119.1	1.04	1.10	12.1	1.14	1.34	96.8	1.11	1.23	6.2	1.39	1.92
Kawartha lakes	116.6	1.11	1.23	11.3	1.39	1.88	85.1	1.23	1.53	4.1	1.95	3.91
French river	115.8	1.15	1.29	11.1	1.52	2.19	106.2	1.08	1.18	8.0	1.27	1.71
Niagara river	114.3	1.02	1.14	10.6	1.06	1.51	85.1	1.23	1.53	4.1	1.95	3.91
Tweed water bodies	111.3	1.10	1.21	9.8	1.33	1.81	96.3	1.08	1.17	6.1	1.27	1.66
Indian lake	98.0	1.19	1.38	6.6	1.71	2.69	89.4	1.09	1.16	4.8	1.31	1.62
Nogies Creek[a]	83.6	0.98	0.98	4.0	0.93	0.93	75.2	1.10	1.19	2.8	1.33	1.74
Maskinonge lake	75.7	1.07	1.16	3.0	1.26	1.62	66.3	1.07	1.17	1.9	1.22	1.61
Mean	114.8	1.07	1.17	11.5	1.25	1.66	94.7	1.10	1.23	6.1	1.38	2.01
95% CL—lower	104.6	1.04	1.11	8.9	1.13	1.40	87.1	1.07	1.15	4.8	1.24	1.54
95% CL–upper	125.0	1.10	1.23	14.1	1.36	1.91	102.6	1.14	1.31	7.4	1.53	2.48
99% CL—lower	100.6	1.03	1.09	7.9	1.09	1.31	84.3	1.06	1.12	4.5	1.18	1.35
99% CL–upper	129.0	1.12	1.25	15.1	1.41	2.00	105.2	1.15	1.34	7.9	1.59	2.67

[a] Because of the age and size of the samples, $L\infty$ for the von Bertalanffy growth relationships for the mean and maximum of females were less than the minimum

Table 6 Minimum ultimate length and estimated weight of muskellunge (sexes combined equally), which provide a minimum ultimate, or trophy, standard for muskellunge from 14 sources in Ontario. Mean ultimate and maximum ultimate length (cm) and corresponding weights (kg) as a proportion of the minimum ultimate or trophy standard are provided. Overall means and 95% and 99% confidence limits (CL) are also given

Source	Length			Weight		
	Minimum or trophy standard (cm)	Proportion of minimum		Minimum or trophy standard (kg)	Proportion of minimum	
		Mean	Maximum		Mean	Maximum
Lac Seul	120.1	1.06	1.14	13.0	1.18	1.48
Lake of the woods	120.1	1.04	1.13	12.7	1.15	1.48
St. Lawrence river	116.6	1.09	1.21	11.3	1.31	1.85
Eagle-Wabigoon lakes	116.3	1.07	1.15	11.5	1.21	1.52
Ottawa river	114.3	1.05	1.11	10.9	1.18	1.37
Georgian bay	113.3	1.08	1.20	10.6	1.26	1.77
French river	111.0	1.11	1.24	9.8	1.41	1.99
Lake St. Clair	108.0	1.07	1.16	9.2	1.22	1.53
Tweed water bodies	103.9	1.09	1.19	7.9	1.31	1.75
Kawartha lakes	100.8	1.16	1.36	7.7	1.54	2.42
Niagara river	99.8	1.11	1.31	7.4	1.31	2.18
Indian lake	93.7	1.14	1.28	5.7	1.54	2.24
Nogies creek	79.5	1.03	1.08	3.4	1.09	1.26
Maskinonge lake	71.1	1.07	1.17	2.4	1.25	1.61
Mean	104.9	1.08	1.20	8.4	1.28	1.75
95% CL–lower	96.3	1.06	1.15	6.9	1.20	1.54
95% CL–upper	113.5	1.10	1.24	10.7	1.36	1.95
99% CL–lower	93.0	1.05	1.13	6.2	1.17	1.46
99% CL–upper	106.8	1.11	1.26	11.4	1.39	2.03

(Table 5). In the case of males, mean minimum trophy standard for these populations was 94.7 cm, with mean and maximum ultimate lengths 10% and 23% higher, respectively (Table 5). It is possible to define a trophy standard in terms of either length or weight. However, weight can be quite variable and is probably less reliable than length. Sexual dimorphism in growth emphasized the importance of developing sex-specific trophy standards. But if sex is unknown or unidentified, an overall sex-independent trophy standard was developed that used equally weighted male and female data (Table 6). Appendix C presents these trophy standards for female and male muskellunge and sexes combined in inches and pounds.

Discussion

Growth potential, and particularly MUS or lower 99% CL, is an important benchmark not only for setting minimum size limits (MUSL) based on length but also for defining and evaluating size of trophy muskellunge. By refining growth analysis and developing the MUS, it is now possible to use a mathematically defined lower estimate of growth potential to develop trophy standards that specifically define trophy muskellunge and set sex-specific size limits. These can be used to evaluate and manage muskellunge populations and sport fisheries much more appropriately. Determining growth potential makes it possible to set size length limits that continue to use fish resources without unknowingly excluding large segments of the population.

Increasing length limits to MUS would reduce harvest mortality and protect fish to an older age. In Ontario populations, for females this would be at least from 8 to 16 years of age (mean 12). This would protect individuals for many more spawning seasons than would a reproductive size limit, hence reproductive capacity and natural recruitment of the population would be greatly enhanced. Although harvest would be reduced with this increased size limit, disproportionately more females than males would be harvested because of growth differential and ultimate size. Indeed, few if any males would be harvested at these higher length limits. This differential harvest would be eliminated only by applying sex-specific length regulations, which could be calculated or are now available (e.g., Tables 3, 4; Appendices A, B), and employing external sexing techniques. I believe that some day, length-limit regulations will be more precise and even sex-specific.

The lower 99% CL provides an MUS that most individuals with a reasonable life expectancy can reach. Calculations using 90%, 95%, and 99% CL at age indicated that L_∞ of the 99% limits produced length limits almost twice as broad as the 90% and 95% (Casselman unpublished data). This confirmed that the extreme limit produced the lowest value for minimum ultimate length. MUS provided by the 99% CL is broad, with the lower including a higher proportion of large fish than would any other confidence limit.

It is unfortunate that accurate age and growth determination of muskellunge requires killing the fish to obtain the cleithrum. Indeed, fewer muskellunge are killed now than ever before (Casselman et al. 1996). Luckily, relatively young muskellunge (age 8–10 ± 2 years) are old enough to provide a good approximation of ultimate size. However, more confidence could be placed in the results if older individuals were used. The fish used to calculate ultimate size should be as old as possible, since early growth can be variable and may change with age. It is especially fortunate that as few as 12 ± 4 fish are required to provide valid von Bertalanffy growth trajectories and ultimate length. Although for the present analysis, there were only enough samples in The Cleithrum Project to examine 14 Ontario populations, some examples exist for other water bodies, and it would be quite easy to acquire the few samples that would be needed to construct the growth analysis provided here. If an archive such as The Cleithrum Project is maintained, samples can be added and accumulated as they become available to acquire enough fish to describe a particular water body. Since size limits are currently set to protect faster-growing, reproductively important females, initially it would be most important to acquire samples from females. Indeed, if for some reason sex of an individual is unknown or undetermined, it is possible to identify sex by analyzing the growth trajectory, using von Bertalanffy growth parameters (Casselman et al. 1999). This, however, assumes that females are faster-growing and reach a larger ultimate size than males. Fortunately, sexually dimorphic growth is quite extreme in muskellunge (Casselman and Crossman 1986; Casselman et al. 1999).

Estimates of extreme ultimate size are useful indices not only for setting size limits on a biological basis but also for determining just how large a muskellunge might grow. For those interested in maximum size and growth potential of a population or water body, ultimate size associated with means and upper 99% CL provides mathematical estimates of potential capability. Even though these exceptional fish are rarely seen, these theoretical maximum estimates provide interesting insights.

In setting size limits, reproductive potential as well as growth potential should be taken into consideration (Fig. 1). Reproductive potential protects reproductive capacity of populations, whereas if size limits are increased to MUS, then this upper limit will greatly improve the quality of muskellunge populations and fisheries and decrease angling mortality through reduced harvest. However, it permits harvest of large individuals and sets a level low enough to allow eventual exploitation of virtually all females. Most importantly, this increase in upper size limit ensures increased reproductive capacity and many more years of egg production and spawning before harvest occurs. For the 14 Ontario populations, the predicted mean age when females reach this size was, for the youngest, 12 years; for the oldest, 23 years (Table 3); and for males, 8–20 years (Table 4).

Methods for calculating MUS, MUSL, and trophy standards developed here (Figs. 1, 2) could also be applied to other species. However, this growth analysis requires accurate age assessment and adequate samples. Age at first maturity and spawning experience would also need to be taken into consideration. Using a similar approach but for a slightly different purpose, these two benchmark size length limits were used to reduce harvest of large northern pike in the northeastern region of Ontario. As an alternative to a protected-size slot limit, daily harvest was reduced to two over the reproductive limit, one of which could be over MUS. Again, this used specific growth biology of the species to set length limits quite precisely, eliminating ambiguity and debate.

Increasing size limits has specific and well-proven advantages. In Largon Lake, Wisconsin, an increase from no length limit to a 32–inch minimum length limit resulted in a high-quality northern pike fishery (Benike 2004). Nordwall et al. (2000) used comparative modelling to examine size-limit strategies for exploited brook trout, *Salvelinus fontinalis* populations. They reviewed the effects of various types of size limits and confirmed the advantages of setting the largest sizes of fish in the population as a minimum size that can be legally retained. However, they were not specific as to how to set the limits and at what level. These observations reinforce the advantage of using MUS as one possible method for setting larger size limits. They documented, as expected, that with increased minimum size limits and harvest of progressively larger fish, there was a positive shift in size structure, with an increased proportion of larger fish in the population and, as had been demonstrated by Quinn et al. (1994), an increase in population size reduced exploitation.

In contrast, Power and Power (1996) suggested that protected slot limits were superior to minimum size limit in terms of population size, yield, and structure for brook trout. However, Nordwall et al. (2000) felt that the difference they found in their own study was due to lower density-dependent mortality, longer life spans, and larger size at first maturity, features considered to be associated with a "slower life history." These features are more typical of muskellunge populations.

Wright (1992), in a review of brook trout size limits, emphasized that minimum length limits should be set at a level that allows a full age class of females to spawn at least once to ensure maintenance of the population's reproductive potential but that this limit needed to be set at the upper end of the length-frequency distribution for the age at which the majority of the females were mature. It is encouraging that independently I have come to the same conclusions and recommendations for muskellunge.

Dunning et al. (1982) studied minimum size limits and their effects on northern pike, using a simulation modelling approach. Contrary to the expectation that increased size limits would increase yield of larger fish by reducing harvest of younger fish and increasing recruitment, the increased size limit actually decreased yield of older fish. In this case, intense fishing pressure shifted to older fish, reducing their relative abundance. Heavy selective exploitation of the vulnerable size group explained this result. This would probably not be a problem if size limits were set appropriately high, as is recommended with the minimum ultimate length limits proposed here for muskellunge.

I must emphasize that if minimum size limits are to be effective, hooking and handling mortality must be held at a very low level. Unfortunately, it is unknown just how low this level needs to be, nor it is measured in any quantifiable way for muskellunge populations. Furthermore, handling methods would be extremely variable among anglers and fish, making it difficult to generalize concerning catch-and-release mortality.

Using the growth analysis presented here, it is now possible to quite specifically define size of trophy muskellunge based on growth potential. If MUS is used as a trophy standard (Fig. 2), it is possible to determine the smallest, slowest-growing trophy-sized fish for each population. This trophy can be defined by either length or weight and can produce a standard that makes all fish comparable. It not only quantifies growth potential of a particular water body but allows individuals to be compared consistently across water bodies. It even makes males and females comparable in terms of ultimate, or trophy, size. The real advantage is that growth potential standardizes the definition, making it possible to evaluate different water bodies and body sizes relative to a universal trophy standard. This means that fish from small- and medium-bodied populations from water bodies with a lower growth potential can be related in a quantitative and comparable way to larger individuals from large-bodied populations. The advantage of this process is that growth data come directly from the population and growth potential is an empirical description of the fish and its water body.

Trophy standard provides a water-body-specific size description that quantitatively defines one trophy muskellunge unit. It can be evaluated on either length or weight by or independent of sex, and all fish can be compared to these units on a proportional and relative basis (e.g., males and females, Table 5, and sex unknown or not determined, Table 6; Appendix C). This trophy standard unit provides a specific quantitative value to assess catch that would be universally comparable among fish and water bodies. Most importantly, the standard makes it possible for anglers to evaluate catch on a relative basis, independent of absolute size.

Since anglers almost exclusively evaluate catch based on absolute size, it would be a progressive approach if muskellunge anglers accepted that smaller muskellunge from a population with a lower growth potential might also be defined as trophies. Indeed, muskellunge anglers are well informed and very much appreciate the limits of the resource they enjoy. As in the implementation of voluntary catch-and-release, they would probably be the first to realize that to restrict their impressions of success based on absolute size would greatly limit their appreciation of all muskellunge resources. With the inevitable increase in fishing pressure and the natural limits on fish resources, it is hoped that muskellunge anglers will maximize their use and enjoyment of all muskellunge populations by starting to compare and relate angling success based on the science and concepts of ultimate size and comparable trophy units.

It might be said that water-body-specific size limits would create significant enforcement problems. However, the experience in Ontario in recent decades, when several categories of size limits based on the MUS concept were applied across the province, indicates that almost without exception, anglers respect the intent, seeing the purpose when the science is adequately explained and transferred. In the case of Ontario, enforcement was far less a concern than had been anticipated. I believe that the rare problems, if they did exist, were probably well worth the benefits. If there is a need to emphasize compliance, violations can be easily tested and regulations enforced with genetic analyses to provide precedent-setting cases.

It is quite apparent from the number of mathematical estimates that were required to complete the comparison reported here for Ontario (e.g., use of concordance sum of squares and regression estimates by sex) that more samples are required, particularly for larger, older males from some water bodies. So biological data and cleithra should be obtained from every harvested muskellunge, not only to strengthen datasets but to monitor and, if necessary, check and from time to time re-evaluate trophy standards and minimum upper size limit regulations. Additional samples make it possible to evaluate whether growth is changing and limits need to be updated. It is important to monitor population status after implementing size-limit changes to make sure that with increased population size, density-dependent growth changes do not occur, a condition that is rarely seen in muskellunge populations unless fish are extremely abundant. Similarly, trophy size and status might change over time. There is strong evidence that with increasing water temperatures, muskellunge are now growing at a faster rate and reaching a larger size (Robinson 2005). Muskellunge populations should also be monitored for changes in maximum age and mortality rate because these provide important measures of population status (Casselman et al. 1996) and fish quality. Hence, every opportunity should be taken to collect biological data, length, weight, sex, and cleithra from each muskellunge that is harvested or found dead, regardless of origin (stocked or wild).

For example, a significant die-off of very large, mature muskellunge occurred in the upper St. Lawrence River, beginning in the fall of 2004, throughout 2005, and into the spring of 2006. Anglers, park wardens, biologists, and researchers worked together to collect carcasses, data, and cleithra from 61 muskellunge from Canadian waters (Casselman unpublished data) killed by an epizootic caused by viral hemorrhagic septicemia. This die-off also emphasizes an important concern that when muskellunge populations are being managed to produce disproportionately large numbers of large, old fish (present minimum size limit for the St. Lawrence River—122 cm, 48 in), they may be particularly vulnerable to stressors, disease, and catastrophic die-offs and quite ephemeral.

Samples used in this study were, for the most part, provided by muskellunge anglers in a cooperative and mutually beneficial project. Anglers provided cleithra and data from harvested, mounted fish, detailed growth data were extracted, and more appropriate size limits were developed that are being used to manage for quality muskellunge populations and fisheries, particularly in Ontario (Ontario Ministry of Natural Resources 1999). In addition, a new method that defines trophy muskellunge and indexes individuals in relation to trophy status has been detailed here for males and females (Table 5) and less precisely for fish of unknown sex (Table 6).

By working together, we have acquired detailed information, making it possible to set increased size limits. Quite importantly, minimum size and trophy standards give anglers the ability to appreciate each fish they have caught in relation to growth potential of the water body and a new trophy standard that involves either length or weight, as well as the ability to calculate an index to assess the status of individual fish in relation to lake-specific or any other trophy standard. Also, fish can be compared within and among populations, and sexes and comparable trophy units can even be accumulated. The real advantage of these new indices, however, is that they emphasize the quality of each fish and provide a relative way to evaluate and appreciate every fish for what it represents in relation to its specific population and origin, independent of its absolute size. All this has been done to provide a biological basis to better appreciate, evaluate, and maintain quality muskellunge populations and sports fisheries.

Dedication and acknowledgements The paper is dedicated to the late Dr. E.J. Crossman, a colleague and friend of all those interested in muskellunge. We worked jointly on The Cleithrum Project with enthusiasm to make sure that all possible information was collected when fish were harvested. Ed was particularly concerned that the science to manage ‘‘his fish’’ was appropriately assembled, conserved, and used to maintain and improve the quality of muskellunge populations and sport fisheries. It is obvious that in the province of Ontario over the past three decades, muskellunge populations have improved and fish have gotten bigger and more abundant, a turn of events that particularly pleased Ed.Thanks to the many anglers, guides, taxidermists, and members of organized muskellunge fishing groups, Muskies, Inc. and Muskies Canada, who assisted Ed and me in assembling this archive of samples and data. Chris Robinson assisted with some of the data analysis, and Jim Diana and Terry Margenau provided helpful reviews of the manuscript. Muskies, Inc. and Muskies Canada helped fund the initial extraction of data presented by Casselman et al. (1999), and these have been used to expand our understanding of muskellunge populations throughout Ontario by providing and using more precise data on growth potential and ultimate size.

Appendices

The three appendices that follow present, in inches and pounds, the ultimate length and growth data for setting length limits and trophy standards for female and male muskellunge from 14 Ontario populations. These correspond to the metric tables in text (Tables 3 and 4, as well as Tables 5 and 6 combined).

Appendix A Presentation of data in Table 3 in inches and pounds. Growth and age data important for setting length limits (in) based on reproductive size and growth potential for female muskellunge from 14 Ontario sources. Ultimate length (in) provides a measure of growth potential, whereas reproductive potential is indicated by the upper 99% confidence limits (CL) at age seven (2 years after first maturity, age 5). Minimum ultimate size limits with estimates of weight (lb) are provided. Overall means and 95% confidence intervals (CI) are provided

Females		Ultimate length (in)			Upper 99% CL at age seven (in)	Minimum ultimate size limit	
		Mean	99% CL			Length (in)	Estimated weight (lb)
Source	*N*		Upper	Lower			
Lac Seul	11	55.1	58.5	53.4	35.0	53	38.5
Lake of the woods	27	53.7	58.6	51.3	38.4	51	34.7
Eagle-Wabigoon lakes	46	52.4	55.6	50.4	36.7	50	32.6
St. Lawrence river	15	54.8	61.7	49.9	39.9	49	30.6
Ottawa river[a]	4	52.7	55.4	49.9	37.9	49	30.6
Georgian bay	30	52.8	58.5	49.6	37.7	49	30.6
Lake St. Clair	31	48.9	51.5	46.9	38.3	46	25.1
Kawartha lakes	74	51.1	56.3[b]	45.9	35.4	45	23.5
French river	17	52.2	58.8[b]	45.6	39.9	45	23.5
Niagara river[a]	6	45.9	51.4	45.0	42.6	45	23.5
Tweed water bodies	20	48.0	53.0	43.8	39.5	43	20.4
Indian lake	38	45.9	53.2[b]	38.6	31.6	38	13.8
Nogies creek	21	32.2	32.2	32.9	29.1	32[c]	8.1
Maskinonge lake	39	32.0	34.7	29.8	26.8	29	5.6
Mean ± 95% CI		48.4 ± 4.3	52.8 ± 5.1	45.2 ± 4.1	36.3 ± 2.6	45	24.4 ± 5.6

[a] Data were calculated from concordance sum of square comparisons (Casselman et al. 1999)

[b] Values were adjusted to an equal confidence interval because original values were unrealistically large

[c] Minimum length limit was suspect because mean ultimate length was less than the lower 99% CL

Appendix B Presentation of data in Table 4 in inches and pounds. Growth and age data important for setting length limits (in) on a biological basis, considering reproductive size and growth potential for male muskellunge from 14 Ontario sources. Ultimate length (in) provides a measure of growth potential, whereas reproductive potential is indicated by the upper 99% confidence limits (CL) at age six (2 years after first maturity, age four). Minimum ultimate size limits with estimates of weight (lb) are provided. Overall means and 95% confidence intervals (CI) are provided

Males		Ultimate length (in)			Upper 99% CL at age six (in)	Minimum ultimate size limit	
		Mean	99% CL			Length (in)	Estimated weight (lb)
Source	*N*		Upper	Lower			
Lake of the woods[a]		45.0	48.4	43.3	32.5	43	20.3
St. Lawrence river[b]	6	45.0	49.4	41.8	33.3	41	17.6
French river[b]	5	45.0	49.4	41.8	33.3	41	17.6
Lac Seul[b]	5	45.3	49.6	41.1	31.1	41	17.6
Eagle-Wabigoon lakes	17	45.3	49.6	41.1	31.1	41	17.6
Ottawa river[b]	3	42.0	44.0[c]	40.0	33.7	40	16.3
Georgian bay[b]	6	43.5	48.6	39.6	34.1	39	15.1
Lake St. Clair	25	42.2	46.7	38.1	32.6	38	13.9
Tweed water bodies[a]		40.9	44.4	37.9	33.6	37	12.7

Appendix B continued

Males		Ultimate length (in)			Upper 99% CL at age six (in)	Minimum ultimate size limit	
		Mean	99% CL			Length (in)	Estimated weight (lb)
Source	*N*		Upper	Lower			
Indian lake	28	38.3	40.9	35.2	27.9	35	10.6
Kawartha lakes	21	41.3	51.3	33.5	33.7	34	9.7
Niagara river[b]	3	41.3	51.3	33.5	33.7	34	9.7
Nogies creek	23	32.4	35.2	29.6	28.6	29	5.9
Maskinonge lake	14	27.8	30.4	26.1	24.8	26	4.2
Mean ± 95% CI		41.1 ± 3.0	45.7 ± 3.6	37.1 ± 2.9	31.7 ± 1.6	37	13.5 ± 2.8

[a] Male data were not available for these water bodies, so male growth was estimated from the regressions of the relationship between female and male growth (Casselman et al. 1999)

[b] Data were calculated from concordance sum of square comparisons (Casselman et al. 1999)

[c] Values were adjusted to an equal confidence interval because original values were unrealistically large

Appendix C Presentation of data in Tables 5 and 6 in inches and pounds. Minimum ultimate length (in) and estimated weight (lb) of female and male muskellunge, separately and combined, which provide a trophy standard, or minimum ultimate size, for muskellunge from 14 sources in Ontario. Overall means, as well as 95% and 99% confidence limits (CL), are also provided. Provides a basis for comparing size relative to growth potential and a trophy standard within and between muskellunge populations and individuals

Source	Females		Males		Sexes combined	
	Length (in)	Weight (lb)	Length (in)	Weight (lb)	Length (in)	Weight (lb)
Lac Seul	53.4	39.7	41.1	17.5	47.3	28.6
Lake of the woods	51.3	35.1	43.3	20.6	47.3	27.9
Eagle-Wabigoon lakes	50.4	33.2	41.1	17.5	45.9	25.0
St. Lawrence river	49.9	32.2	41.8	17.7	45.8	25.4
Ottawa river	49.9	32.2	40.0	16.0	45.0	24.1
Georgian bay	49.6	31.6	39.6	14.9	44.6	23.3
Lake St. Clair	46.9	26.6	38.1	13.7	43.7	21.1
Kawartha lakes	45.9	24.9	33.5	9.1	42.5	20.2
French river	45.6	24.4	41.8	17.7	40.9	17.5
Niagara river	45.0	23.4	33.5	9.1	39.7	17.0
Tweed water bodies	43.8	21.5	37.9	13.5	39.3	16.3
Indian lake	38.6	14.6	35.2	10.6	36.9	12.6
Nogies creek	32.9	8.9	29.6	6.1	31.3	7.5
Maskinonge lake	29.8	6.5	26.1	4.1	28.0	5.3
Mean	45.2	25.3	37.3	13.4	41.3	19.4
95% CL–lower	41.2	19.7	34.3	10.6	37.9	15.3
95% CL–upper	49.2	31.0	40.3	16.3	44.7	23.6
99% CL–lower	39.6	17.4	33.2	9.4	36.6	13.6
99% CL–upper	50.8	33.3	41.4	17.4	46.0	25.2

References

Benike HM (2004) Evaluation of a 32 inch minimum length limit for northern pike Largon Lake, Polk County, WI, MWBIC Code (2668100)

Casselman JM (1974) External sex determination of northern pike, *Esox lucius* Linnaeus. Trans Am Fish Soc 103:343–347

Casselman JM (1996) Age, growth and environmental requirements of pike, *Esox lucius*. In: Craig J (ed) Pike: biology and exploitation. Chapman and Hall, London, pp 69–101

Casselman JM (2002) Effects of temperature, global extremes, and climate change on year-class production of warmwater, coolwater, and coldwater fishes in the Great Lakes Basin, pp 39–59. In: McGinn NA (ed) Proceedings of American Fisheries Society Symposium 32, Fisheries in a changing climate. 295p

Casselman JM, Crossman EJ (1986) Size, age and growth of trophy muskellunge and muskellunge-northern pike hybrids—The Cleithrum Project, 1979–1983, pp 93–110. In: Hall GE (ed) Managing muskies—a treatise on the biology and propagation of muskellunge in North America. American Fisheries Society Special Publication 15

Casselman JM, Crossman EJ, Robinson CJ (1996) Assessing sustainability of trophy muskellunge fisheries, pp 29–39. In: Kerr SJ, Olver CH (eds) Managing muskies in the '90s. Proceedings Southern Region Science and Technoloty Transfer Unit Workshop, WP-007, Ontario Ministry of Natural Resources, Toronto, 169p

Casselman JM, Robinson CJ, Crossman EJ (1999) Growth and ultimate length of muskellunge from Ontario water bodies. North Am J Fish Manage 19:271–290

Casselman JM, Scott KA (2000) A general procedures manual for CSAGES—calcified structure age-growth data extraction software (Version 5.2). Spec. Publ. Glenora Fisheries Station, Aquatic Ecosystems Science Section, OMNR, Picton, Ont., 90p

Crossman EJ, Casselman JM (1996) The cleithrum project: an update to 1995. In: Kerr SJ, Olver CH (eds) Managing muskies in the '90s. Proc. South. Reg. Sci. Tech. Transfer Unit Workshop, WP-007, Ontario Ministry of Natural Resources, Toronto, pp 147–151

Dunning DJ, Ross Q, Gladden J (1982) Evaluation of minimum size limits for St. Lawrence river northern pike. North Am J Fish manage 2:171–175

Hunt RL (1970) A compendium of research on angling regulations for brook trout conducted at Lawrence Creek, Wisconsin. Wisconsin Department of Natural Resources, Research Report 54, Madison

Koppleman JB, Philipp DP (1986) Genetic application in muskellunge management. A Fish Soc Special Publ 15:111–121

Lebeau B, Pageau G (1989) Comparative urogenital morphology and external sex determination in muskellunge, *Esox masquinongy* Mitchill. Canadian J Zoo 67:1053–1060

Margenau TL, Hanson DA (1996) Survival and growth of stocked muskellunge: effects of genetics and environmental factors. Wisconsin Department of Natural Resources Research Report 172, May 1996

Nordwall F, Lundberg P, Eriksson T (2000) Comparing size-limit strategies for exploitation of a self-thinned stream fish population. Fish Manage Ecol 2000(7):413–424

Ontario Ministry of Natural Resources (1983) The identification of overexploitation. Report of SPOF working group No. 15. Strategic Planning for Ontario Fisheries Policy Development, Toronto, pp 84

Ontario Ministry of Natural Resources (1986) Report of the committee to review provincial muskellunge angling regulations. Ontario Ministry of Natural Resources Fisheries Policy Committee, Toronto

Ontario Ministry of Natural Resources (1999) Size limit regulations for Ontario muskellunge: a new approach. Ontario Ministry of Natural Resources Fisheries Policy Committee, Toronto

Power M, Power G (1996) Comparing minimum-size and slot limits for brook trout management. North Am J Fish Manage 16:49–62

Quinn NWS, Korver RM, Hicks FJ, Monroe BP, Hawkins RR (1994) An empirical model of lentic brook trout. North Am J Fish Manage 14:692–709

Robinson CJ (2005) Factors affecting estimates of year-class strength and growth of muskellunge (*Esox masquinongy*): a long-lived, low-density, trophy fish. Watershed Ecosystems Graduate Program, Trent University, Peterborough, pp 222

Wright S (1992) Guidelines for selecting regulations to manage open-access fisheries for natural populations of anadromous and resident trout in stream habitats. North Am J Fish Manage 12:517–527

Younk JR, Strand RF (1992) Performance evaluation of four muskellunge *Esox masquinongy* strains in two Minnesota lakes. Minnesota Department of Natural Resources Investigational Report 418