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Application of a population status model on several recreational lake trout (*Salvelinus namaycush*) fisheries in Manitoba, Canada

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Abstract Current data on lake trout (*Salvelinus namaycush*) populations in Manitoba are limited but essential for guiding effective management decisions. To address this gap, academics and provincial fisheries biologists collaborated to conduct standardized netting surveys across seven lake trout fisheries in Manitoba during 2021 and 2022. Life history characteristics were quantified and compared, with length-at-age back-calculated from individual lake trout, and growth assessed using von Bertalanffy growth functions. Significant differences in growth parameters (L_∞, K, t_0, and ω) were observed across lakes. A sustainable exploitation model applied to the data revealed most lake trout fisheries are healthy. However, some underlying concerns exist that could jeopardize the future sustainability of a few of the fisheries. Findings highlight the need for ongoing population monitoring to support management objectives. We propose several actionable strategies for lake trout conservation in Manitoba, including incorporating citizen science and collaborating with Indigenous communities for co-production of knowledge.

Keywords Von Bertalanffy · Growth curves · Freshwater fisheries · Trophy fish · Mortality

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Introduction

In the early 2000s, Post et al. (2002) introduced the concept of the "invisible collapse" of Canada's recreational fisheries. Due to the vast number of lakes across the Canadian landscape, the collapse of an individual fishery would primarily affect local communities and go largely unnoticed on a broader scale (Post et al. 2002). Additionally, fisheries management has been hindered by limited resources, making it difficult to obtain accurate assessments of specific fisheries (Post et al. 2002). A recent follow-up study in Alberta (2000–2018) supported Post et al.'s claims, demonstrating that inland fisheries are highly susceptible to overexploitation, with angling regulations playing a crucial role in their protection (Cahill et al. 2022).

Recreational fishing can have significant impacts on fish populations, including loss of genetic diversity (Guinand et al. 2003), changes in size structure (Radomski 2003), evolutionary shifts (Magnan et al. 2005), and declines in population size and recruitment (Lewin et al. 2006). Numerous studies have also highlighted key knowledge gaps regarding life-history traits (e.g., growth, size at maturity, and mortality) essential for guiding best management practices (e.g., Cooke and Cowx 2006). Filling these knowledge gaps with data from a variety of species and populations is especially crucial in the context of intensifying pressures on aquatic ecosystems, driven not only by recreational fishing but also by climate change, habitat loss, and other anthropogenic stressors.

A key recreational species in Canada are the lake trout (*Salvelinus namaycush*), a cold-water salmonid that is commonly caught and harvested by anglers (Brownscombe et al. 2014). Lake trout thrive in deep, well-oxygenated oligotrophic lakes (Scott and Crossman 1973) and exhibit high phenotypic and morphological diversity (Chavarie et al. 2021), leading to a wide range of life histories (McDermid et al. 2010). During summer stratification, lake trout are typically restricted to waters below the thermocline, except for occasional vertical migrations for feeding (Dolson et al. 2009; Guzzo et al. 2017). Consequently, their distribution within lakes is largely governed by thermal preferences that minimize metabolic costs (Guzzo et al. 2017). Notably, lake trout mature late, grow slowly, and can attain lengths exceeding 1 m (Campana et al. 2008; Gallagher et al. 2021), making them particularly vulnerable to anthropogenic stressors such as recreational fishing (Campana et al. 2020).

Manitoba ranks fourth in resident angling license sales (~12% of the national total), indicating a strong participation in recreational fishing activities (Statistics Canada 2015; DFO 2019). Despite this, Manitoba Department of Natural Resources and Indigenous Futures (MDNRIF) lacks contemporary data on the status of its lake trout fisheries (Kroeker, personal communication 2021). This knowledge gap is concerning given the importance of lake trout fisheries to rural economies through tourism and angling-related revenue. Furthermore, the stocking of lake trout throughout the twenty-first century (MBGOV 2023a) has seemingly increased fishing pressure (Kroeker, personal communication). Social media also may be facilitating the rapid dissemination of information about potential recreational fishing "hotspots", which may be exacerbating the strain on recreational lake trout fisheries (Kroeker, personal communication 2021). This is especially the case for fisheries that hold "Manitoba Master Angler"-sized trophy lake trout ≥ 89 cm. The lack of contemporary data on key life-history traits (e.g., growth, maturity, age) puts Manitoba's lake trout fisheries at risk of an "invisible collapse". This risk is particularly acute for southern lake trout populations, which are more accessible to major urban centres and subject to higher recreational fishing pressure.

Acquiring up-to-date information on lake trout populations is essential for effective fisheries management, the development of sustainable harvest practices, and a better understanding of lake trout fishery ecology. Furthermore, this study would better improve our understanding of lake trout population dynamics across different sized lakes through the examination of life history characteristics. Based on provincial needs, our study addresses this gap by assessing the current status of several lake trout fisheries in Manitoba, quantifying and comparing life-history characteristics. We also applied our data to a recently developed sustainability model to evaluate the status of these fisheries and their underlying population dynamics (Lester et al. 2021) and provide support for actionable recommendations for future research and management initiatives.

Methods

Study area

In collaboration with provincial fisheries biologists, seven stratified lakes were chosen to be sampled because they offered possible contrasting situations with varying degrees of recreational fishing quality in Manitoba (Fig. 1). In southeastern Manitoba, the sampled lakes included Davidson Lake (DL), George Lake (GL), High Lake (HL), Mantario Lake (ML), and West Hawk Lake (WHL). In northwest Manitoba, the lakes sampled were Clearwater Lake (CW) and Second Cranberry Lake (SCL). Several of these lakes are easily accessible by road, including CW, DL, SCL, and WHL. In contrast, GL, HL, and ML require either hiking and portaging or access via float plane. All southern lakes

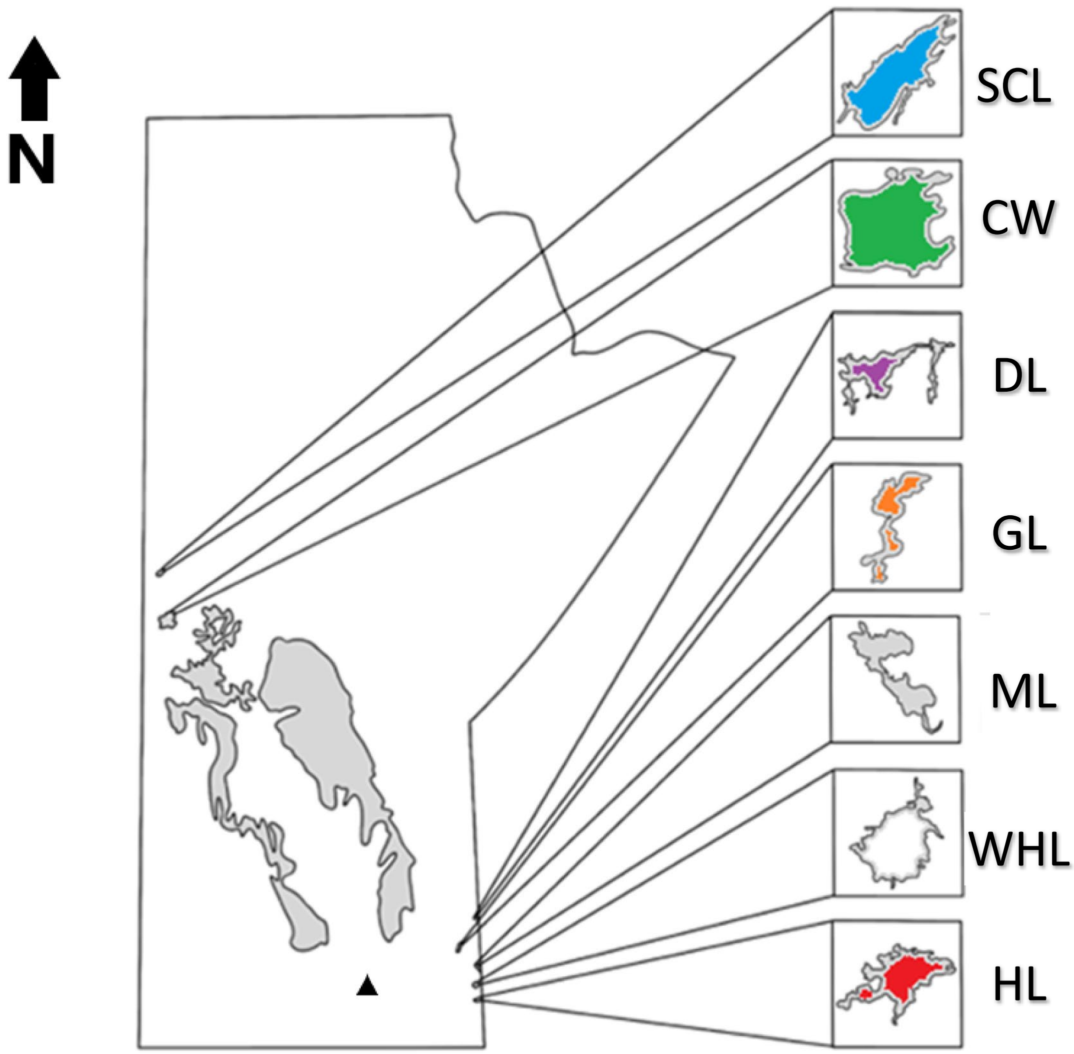

Fig. 1 Map of lakes sampled in Manitoba. Black triangle = Winnipeg. Blue = Second Cranberry Lake (54°38′N 101°11′W), green = Clearwater Lake (54°03′N 101°03′W), purple = Davidson Lake (50°27′N 95°09′W), orange = George Lake (50°13′N 95°29′W), grey = Mantario Lake (49°59′N 95°09′W), white = West Hawk Lake (49°45′N 95°11′W), and red = High lake (49°42′N 95°08′W)

(DL, GL, HL, and ML) have been stocked using CW individuals.

The lakes differ in geological composition. Second Cranberry Lake contains a mix of granite and other Pre-Cambrian formations in its northern half, with Paleozoic substrates, such as limestone, dominating the southern region (Butler 1950). George Lake, DL, HL and ML also contain mainly granite-based Canadian Shield (Butler 1950). Clearwater Lake, situated in the Palaeozoic region, also has a dolomite and limestone-based substrate (Butler 1950). Uniquely, WHL is a meteor-crater lake on the Canadian Shield, with a primarily clay-based substrate (Teller et al. 2008).

Gillnetting protocol

The sampling in our study was based on the Summer Profundal Index Netting (SPIN) protocol (Sandstrom and Lester 2009), a method designed for rapid assessments of lake trout population integrity with minimal mortality. This protocol is applicable across a range of lake sizes and is implemented during summer stratification once surface waters reach 18 ˚C (Sandstrom and Lester 2009). To determine surface temperatures and hypolimnion depth, we used a temperature and dissolved oxygen probe (Pro20, YSI Inc.©, Yellow Springs, OH, USA) to record the temperature and dissolved oxygen profile for the first 30 m of each lake, which guided the depths at which the nets were set.

The gillnets used were 64 m long, standard monofilament multi-mesh nets, consisting of eight randomly ordered panels (8 m long by 1.8 m high) with mesh sizes ranging from 57 to 127 mm (Sandstrom and Lester 2009). The nets were set on the bottom of the lake, targeting lake trout that were ≥ 300 mm fork length, a size commonly caught by anglers (Sandstrom and Lester 2009). The suggested number of nets was based on the following equation:

$$N_s = 0.0184a + 24$$

whereby N_s was the number of defined sets, and a was the surface area (hectares) that covers different lake depths > 10 m. Lake area with depths > 10 m were roughly estimated using old bathymetric maps provided by the province biologists. The defined number of nets were deployed randomly at various depths depending on available lake strata (i.e., 0–10 m, 10–20 m) and the observed thermocline (Sandstrom and Lester 2009). The majority of net sets were set at depth strata around the hypolimnion depth of each lake. Although the SPIN protocol typically requires nets to be soaked for 2 h, high non-target mortality of lake whitefish (*Coregonus clupeaformis)* in preliminary sets of both northern lakes (SCL and CW) led us to adjust net soak times to 30 min for the remainder of the surveys, following the advice of provincial fisheries biologists. High non-target mortality of lake whitefish also occurred in HL, which led us to abstain from setting the remainder of our net sets (7), again following the advice of provincial fisheries biologists.

For each captured lake trout, we recorded total length (mm), and weight (g). We targeted up to 10 lake trout individuals from every 50 mm size class encountered for lethal sampling (starting from 300 mm with no maximum length threshold); however, some size classes had greater representation due to gillnet-induced mortality. Fish designated for lethal sampling were further assessed for diet, sex, and maturity. Weight measurements of some released individuals were not reliably recorded due to field conditions affecting our digital scale (Berkley Digital Fish Scale–22.7 kg Pure Fishing Inc., Columbia, SC, USA). Sagittal otoliths were collected from sacrificed lake trout for aging purposes.

To supplement the SPIN sampling, we also used angling in certain southeastern lakes (HL, ML, and WHL) due to low catch rates using the SPIN program. However, fish caught using angling methods were not included in the CPUE estimations nor the population status model. Rather, angled fish were only included in the age and growth analyses described below. Fishing lures selected for angling were between 7 and 14 g to target fish within the range that SPIN targets. All animal handling and collections were approved by the University of Winnipeg Animal Ethics Committee, in accordance with the Canadian Council on Animal Care (Protocol #AE 10491). A Provincial Scientific Collection (General) Permit (#22,758,865) was also granted by the province for our research.

Otoliths thin-sectioning and aging

We followed previously described procedures to thin-section sagittal otoliths (MFFP 2017; see Supplementary materials). Briefly, otolith cores were marked with a fine permanent marker and embedded into a 4:1 mixture of epoxy and hardener ratio (Buehler EpoxiCure™, Lake Bluff, Illinois). Two 1 mm sections were cut through the core of each otolith using a low-speed saw (Buhler Iso-met) with a single diamond wafering blade (M412L, MetLab, Niagara Falls, New York; MFFP, 2017). Otolith sections were then lightly polished using polishing paper (3 M™ Wet-or-Dry™ 2000 µm), followed by 5 µm and 1 µm micro-lapping aluminum-oxide film (3 M™, Saint Paul, MN; Morissette et al. 2018). Digital images of the prepared otolith sections were captured between × 20 and × 100 magnification using both reflected and transmitted light.

Two observers aged all otolith images. The primary observer (observer 1) had some prior experience with lake trout aging, while the second observer (observer 2) had no prior experience. Both were provided with an aging primer outlining the typical annuli growth patterns of lake trout otoliths, common aging errors, and techniques for identifying and avoiding false annuli (Osborne et al. 2022). Each otolith was aged three times by both observers, with a minimum one-week interval between successive age estimations of the same otolith to prevent familiarity with specific samples (Gallagher et al. 2021).

Final ages for each observer were determined by majority rule (e.g., if an observer recorded ages of 5, 6, and 5, the final age would be 5). In cases where all three readings differed, the median value was selected as the final age for that observer. To determine the overall final age of each lake trout, the final ages from both observers were compared. When discrepancies occurred, the observers discussed and compared the otolith images, each with marked annuli, to reach a consensus (Burnham-Curtis and Bronte 1996). Replicability and observer bias were assessed before determining the final consensus ages using the "Fisheries Stock Analysis" package in R (Ogle et al. 2023; Supplementary Table S1–S3).

Growth, maturity and survival estimates

We reconstructed lake trout growth by back-calculating length-at-age for individual fish using a macro written for ImageJ version 1.53 (provided by Dr. Timothy Spier, Murray State University). This method involves measuring the distance between successive annuli on the otolith (Supplementary Fig. S4). The length-at-age increment was calculated using the biological intercept model (Campana 1990):

$$L_a = L_c + (O_a - O_c)(L_c - L_o)(O_c - O_o)^{-1}$$

whereby L_a= length at age increment a, L_c= length at capture, O_a= otolith radius length at age increment a, O_c=otolith radius length at capture, L_o= fish length at hatching, and O_o= otolith size at hatching. We applied biological intercept values for lake trout as estimated by Hansen et al. (2012), where L_0=*21.7* mm, and O_o=0.137 mm.

We used back-calculated length-at-age data from captured and sacrificed lake trout to generate von Bertalanffy growth functions (VBGFs) to estimate the growth characteristics of each sampled fishery (Ogle 2016; Ogle et al. 2023). Specifically, we applied the Beverton and Holt (1957) VBGF model:

$$L = f\left(T, L_\infty, K, t_0\right) = L_\infty(1 - e^{-K\left(t - t_0\right)})$$

whereby L is length, t is age, L_∞ is the asymptotic mean length of the population, t_0 represents the theoretical age when mean length is zero, and K describes the curvature of the VBGF (i.e., rate of approach to L_∞). The early growth rate ω was calculated using the Gallucci and Quinn (1979) equation:

$$\omega = KL_\infty$$

where ω represents the theoretical growth rate at mean length at time zero. We used a hierarchical model to generate growth functions for each population., with all VBGF parameters modelled as random factors using the *nlme* function in the "nlme" package in R (Pinheiro et al. 2024). This allowed each individual lake trout to have its own set of growth estimates for a given lake (Ogle 2016). We then created mean growth functions for each lake based on individual replicates.

To model maturity schedules, we used maturity-at-age and length data, where sufficient data was available, and pooled sexes, given the absence of sexual size dimorphism in lake trout (McDermid et al. 2010). Maturity at age and length curves were calculated using logistic regressions and maturity using the equation:

$$p_{x1} = \frac{e^{\left(b_0 + b_1 * x_1\right)}}{1 + e^{\left(b_0 + b_1 * x_1\right)}}$$

whereby, p_{x1} is the probability that a lake trout is mature at a given age or length (x_1), b_0 is the intercept and b_1 is the slope of the curve (Hannah et al. 2009). From these curves, we estimated age at 50% maturity (A_{50}) and length at 50% maturity (L_{50}), using parametric bootstrapping ($n = 1000$) to generate confidence intervals for each variable associated the maturity curves (Ogle 2016).

For populations with sufficient data (CW, GL, HL, ML, SCL, WHL), we estimated the instantaneous mortality (Z) using the Chapman-Robson method based on our cross-sectional age-frequency data (Chapman and Robson 1960). This method analyzes the descending slope of the catch curve after the age class with the highest catch in the sample (indicating full recruitment to the sampling gear applied) and is more robust than weighted regression methods (Smith et al. 2012). The Chapman-Robson estimate for instantaneous mortality is:

$$Z = -\log\left(\hat{S}\right) - \frac{(n-1)(n-2)}{n(A+1)(n+A-1)}$$

whereby Z is the estimate for instantaneous mortality, whereby $\hat{S}$ is the annual survival rate, n is the total number of individuals observed along the descending slope of the catch curve, and A is the total recoded age of individuals along the descending slope of the catch curve. We then generated 95% confidence intervals for each population using the *confint* function in the "stats" package in R (R Core Team 2024). The *confint* function uses a bootstrap resampling method to generate confidence intervals (R Core Team 2024). We deemed Z to be significantly different from each other if confidence intervals did not overlap.

Sustainable exploitation analyses

Lester et al. (2021) developed a general life-history based sustainability model for lake trout across a climatic gradient based on 749 Canadian lakes. The model was developed by pooling environmental and habitat data with estimates of lake trout biomass (Lester et al. 2021). This model can be applied to several maximum sustainable yield reference points including angling effort, biomass density, and total mortality rate (Lester et al. 2021). There are four unique status levels estimated by the model: stage 1 (healthy), characterized by low recreational fishing mortality and high biomass; stage 2 (overfishing early), characterized by high recreational fishing mortality and high biomass; stage 3 (overfishing, late), which has high recreational fishing mortality and low biomass; and, stage 4 (overfished, recovering), showing low recreational fishing mortality and low biomass (Lester et al. 2021). For the purposes of our study, we used the biomass density and total mortality rate reference points to evaluate the status of lake trout populations (CW, GL, HL, ML, SCL, WHL). Only gillnet-captured fish were included in our analysis.

To determine whether a population was overfished, an exploitation ratio (E) was used:

$$E = Z/M$$

whereby Z is the instantaneous mortality rate of a population, which is the sum of the natural and recreational fishing mortality rates and M is the natural mortality rate of a population. If $E > 2$, then the population has high recreational fishing mortality (Lester et al. 2021). The natural mortality rate of a population can be estimated by using metabolic approach that incorporates life-history characteristics of a population as derived by Lester et al. (2021):

$$M = \frac{91.8e^{0.021*T+0.0004*T^2}}{L_\infty^{0.96}}$$

whereby T is mean annual air temperature and L_∞ is the mean asymptotic length of a population. Mean annual air temperature values were procured from the CMIP6 (CanDCS-U6) climate model dataset (Cannon et al. 2015; Climatedata.ca 2023).

To assess biomass levels in a population, a biomass ratio (B_x) was calculated:

$$B_x = B/B_{\mathrm{MSY}}$$

whereby B is the estimated biomass density of a population and B_{MSY} is the estimated biomass density when a population is exploited at maximum sustainable yield. If $B_x > 1$, then the population is deemed to have a high biomass (Lester et al. 2021). To calculate B_{MSY} (biomass per unit hectare), the following equation derived by Lester et al. (2021) was used:

$$B_{\mathrm{MSY}} = 8.47 * D_{mn} * pV_{eb} * S * W_\infty^{-1.33}$$

whereby D_{mn} is the mean depth of a lake, pV_{be} is the proportion of the lake volume in the epibenthic zone,

S is the habitat suitability index for lake trout, and W_∞ is the mean asymptotic weight of the population. To estimate B, density was first calculated. To calculate density, the selectivity adjusted catch-per-unit-effort (CPUE) is required. Sandstrom and Lester (2009) developed a selectivity relationship to account for the varying vulnerabilities that different size classes have towards the SPIN gillnets. Therefore, CPUE was calculated as follows:where V is the selectivity score, and n is the number two-hour sets, or 120 min soak time. The CPUE values were standardized to 2-h soak times to account for the different soak times across lakes and allow for direct comparison). Because we did not have accurate bathymetric maps, we were unable to weight CPUE by depth strata to estimate adjusted CPUE, therefore, we used a lake wide CPUE. Sandstrom and Lester (2009) created a relationship between density and the CPUE of lake trout captured in SPIN nets in a given lake that hold large-bodied lake trout (defined in the SPIN manual as lake trout that are > 450 mm in total length and where ciscoes are present),

$$D = \text{CPUE} * 4.86$$

where D is the number of lake trout per hectare (density). Biomass density was calculated as follows:

$$B = x^{-}{}_{w} * D$$

whereby $\bar{x}_w$ is the mean weight of a lake trout population (biomass per unit hectare). All other equations required to solve all of the aforementioned variables used to calculate B_{MSY} can be found within the supplementary materials.

Statistical analyses

For lake comparisons of individual fish observations (total length, weight, age) we used non-parametric tests. Total length, weight, age, and VBGF parameters were compared across populations by using a Kruskal–Wallis test. We also used Dunn's tests to identify specific pairwise differences across populations. Statistical significance was tested at $\alpha = 0.05$.

Results

A total of 468 lake trout were caught across all seven lakes in Manitoba, of which 297 were sacrificed for aging (Table 1). Clearwater Lake had the highest CPUE of 6.49 lake trout/2 h net set, while DL, HL, ML, and WHL all had CPUE values below 1 lake trout/2 h (Table 1). Furthermore, less than 30 lake trout were caught at DL, HL, ML, and WHL (Table 1). Because we only caught a single lake trout in DL, we omitted this population from subsequent analyses.

Fish size

The total length of lake trout varied significantly across populations ($X^2{}_{5,\ 442} = 58.0$, $P < 0.001$), whereby SCL lake trout were significantly longer than those from CW, GL, HL, ML, and WHL (Fig. 2a; Table S4). The highest mean total length was observed in SCL (670 mm, SD = 125.89), while GL had the lowest mean total length (508 mm, SD = 81.78) among sampled populations

Table 1 Lake trout (*Salvelinus namaycush*) caught (SPIN/angling) in Manitoba. Bolded lakes indicate that 30-min net sets were used

Lake	Surface area (km^2)	Average depth (m)	Number of nets Set	Total hours soaked	Lake trout caught	Lake trout sacrificed	CPUE (fish per 2 h)
Clearwater (CW)	285.07	13.10	150	92.80	254/0	120/0	6.49
Second Cranberry (SCL)	23.83	19.81	58	32.46	47/0	47/0	4.71
Davidson (DL)	2.25	9.11	26	54.70	1/0	1/0	0.04
George (GL)	21.5	12	30	60.36	88/12	65/0	3.81
High (HL)	8.04	12	21	43.40	12/10	11/10	0.98
Mantario (ML)	4.12	15	30	60.95	22/7	22/7	0.81
West Hawk (WHL)	14.6	33.13	48	97	12/1	12/1	0.33
Total	–	–	363	–	436/30	278/18	–

(Fig. 2a). Both CW and SCL had individuals exceeding the "trophy-size" threshold of 890 mm total length. In CW, four trophy-sized lake trout were recorded (909 mm, 944 mm [two fish], and 955 mm; Fig. 3a), while three trophy-sized lake trout were caught in SCL (897 mm, 905 mm, and 925 mm); Fig. 3b). In contrast, the total length distributions in GL, ML, and WHL were skewed toward smaller sizes for (Fig. 3c, d, f). Using 50 mm size bins, CW had the greatest representation of length classes (12), followed by HL (11; Fig. 3e). The mean weight of lake trout also varied significantly across populations ($X^2_{5,\ 312}=48.5$, $P<0.001$; Fig. 2b). As with total length, lake trout from SCL were the heaviest (mean weight = 2797 g, SD = 1571.12), significantly heavier than those from all other examined populations (Table S5). In contrast, lake trout from ML were the lightest (mean weight = 1143 g, SD = 493.48).

Age and growth

Lake trout ages, estimated from otoliths collected across six populations, ranged from 4 to 45 years (Fig. 4c). Clearwater Lake had the youngest mean age at 9 years (SD = 5.904; Fig. 4a), with 52.5% of fish belonging to the 4–6 years age-classes (Fig. 4a). In contrast, SCL contained the oldest individuals, including a 45-year-old lake trout, and had the highest mean age of 18 years (SD = 9.148). Only 21% of the lake trout in SCL were younger than 10 years old (Fig. 4b). Among the southeastern populations, GL had the oldest mean age at 13 years (SD = 7.139), with the 12 years age-class being the most prominent (16%; Fig. 4c). Lake trout populations in HL, ML, and WHL appeared to be age-impoverished, with fewer age-classes represented and lower overall abundance (Fig. 4d, e, f). The final consensus estimated ages differed significantly across populations ($X^2_{5,\ 289}=65.7$, $P<0.0001$). Lake trout from SCL were significantly older than those from CW, HL and WHL (Table S6). Additionally, the mean age of fish in CW was significantly younger than those in GL and ML (Table S6).

The von Bertalanffy growth curves for lake trout populations differed significantly across lakes in several parameters (Table 2; Fig. 5). The asymptotic length parameter (L_∞) varied significantly across populations ($X^2_{5,\ 289}=78.813$, $P<0.0001$; Table 2), with SCL lake trout achieving a significantly longer L_∞ compared to several southeastern populations, including GL, ML, and the other northern population CW (Table S7). Among all populations, GL had the lowest L_∞ value. The early growth rate (ω) also differed significantly ($X^2_{5,\ 289}=140.764$, $P<0.0001$; Table 2), with CW exhibiting a significantly higher ω than all other lakes (Supplementary Table S8).

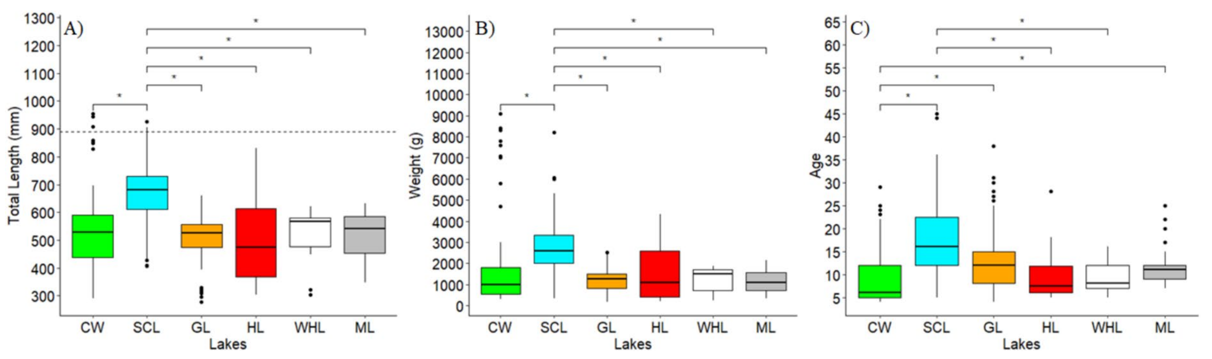

Fig. 2 **A** Boxplot representing total length distribution for six Manitoban lake trout (*Salvelinus namaycush*) populations (Clearwater Lake = CW [n = 248], Second Cranberry Lake = SCL [n = 47], George Lake = GL [n = 86], High Lake = HL [n = 20], West Hawk Lake = WHL [n = 13], and Mantario Lake = ML [n = 29]). The dashed line represents the 89 cm threshold for trophy-sized lake trout in Manitoba. **B** Boxplot representing weight distribution for six Manitoban lake trout populations (CW [n = 117], SCL [n = 47], GL [n = 85], HL [n = 21], WHL [n = 13], and ML [n = 29]). Using a Kruskal–Wallis test and a subsequent Dunn test, * indicate significant differences across populations at a threshold of $\alpha < 0.05$. **C** Boxplot representing the estimated age distributions for six Manitoban lake trout populations (CW [n = 118], SCL [n = 47], GL [n = 64], HL [n = 18], WHL [n = 13], and ML [n = 29]

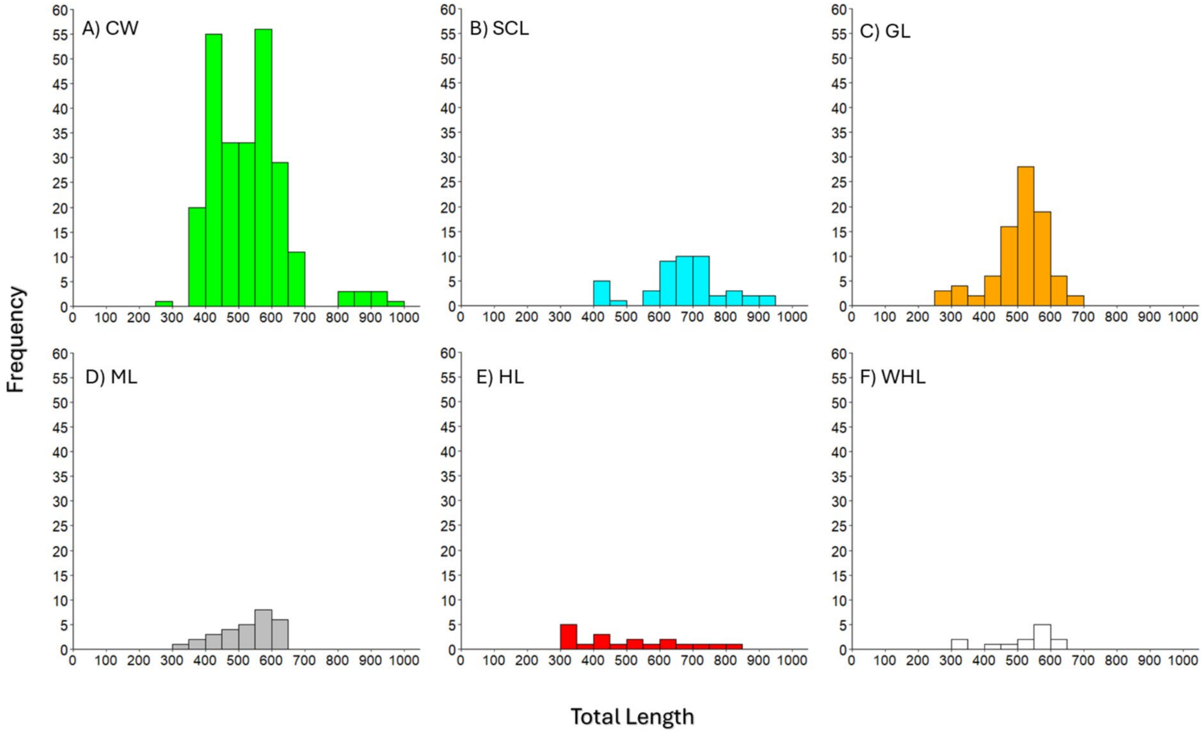

Fig. 3 Total length frequency histograms separated by 50 mm bin sizes for six Manitoban lake trout (*Salvelinus namaycush*) populations (Clearwater Lake = CW [n = 248], Second Cranberry Lake = SCL [n = 47], George Lake = GL [n = 86], High Lake = HL [n = 20], West Hawk Lake = WHL [n = 13], and Mantario Lake = ML [n = 29])

Similarly, the growth coefficient (K) varied significantly across populations ($X^2_{5,\ 289} = 122.970$, $P < 0.0001$; Table 2), and CW lake trout had a significantly higher K than all other lakes (Table S9). In addition, SCL had a significantly lower mean K compared to HL, and ML. The age at length 0 mm, t_0, significantly differed across populations ($X^2_{5,\ 289} = 80.673$, $P < 0.0001$; Table 2). CW reached a significantly higher t_0 than GL, HL, ML, and SCL (Table S10). Furthermore, SCL had a significantly lower mean t_0 value than, GL, ML, and (Table S10).

Age and length-at-maturity

Age-at-maturity (A_{50}) curves and values showed significant variation among lake trout populations, as indicated by the non-overlapping 95% confidence intervals (Table 3; Fig. 6a). Based on bootstrapped mean A_{50} values, CW lake trout reached 50% maturity at the youngest age (5 years), which was significantly younger than both GL A_{50} (6 years) and SCL (9.6 years). Similarly, the length-at-maturity (L_{50}) logistic regressions differed significantly across populations, with clear distinctions in L_{50} values (Fig. 6b). Bootstrapped mean L_{50} values suggest that lake trout from GL reached 50% maturity at the shortest length (386 mm), which was significantly different from CW and SCL (Table 3). The two northern lakes, CW and SCL, also showed significant differences in mean L_{50} values, with CW trout reaching maturity at a smaller size than those from SCL.

Instantaneous mortality

Instantaneous mortality rates differed across GL-SCL, ML-SCL, ML-SCL, and SCL-WHL pairs (0.109–0.212; Table 4). Mantario Lake had the highest instantaneous mortality rate, while SCL had the lowest observable instantaneous mortality rate (Table 4).

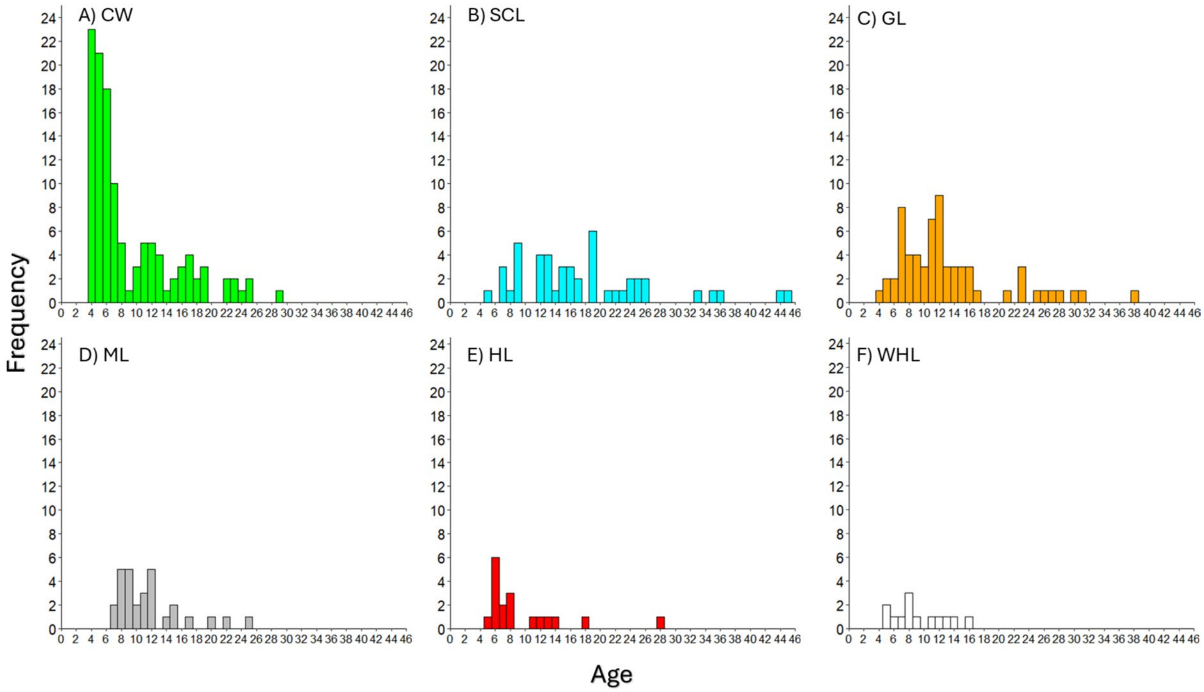

Fig. 4 Estimated age frequency histograms separated by 1 year bin sizes for six Manitoban lake trout (*Salvelinus namaycush*) populations (Clearwater Lake = CW [n = 117], Second Cranberry Lake = SCL [n = 47], George Lake = GL [n = 64], High Lake = HL [n = 18], West Hawk Lake = WHL [n = 13], and Mantario Lake = ML [n = 29])

Sustainability reference points

Clearwater Lake, GL, HL, ML, and SCL are deemed "healthy" under the framework adopted here (stage 1; Lester et al. 2021; Fig. 7). All populations were found to have low fishing mortality rates (Fig. 7). West Hawk Lake lies below to the $B/B_{MSY} > 1.0$ threshold, which indicates that it is overfished and recovering from low biomass levels (stage 4; Lester et al. 2021; Fig. 7).

Discussion

Life-history characteristics of six Manitoban lake trout populations were quantified and applied to a fisheries sustainability model to assess their current status. However, it should be noted that due to the lack of data in DL, HL, ML, and WHL, maturity schedule analyses could not be conducted due to the risk of low accuracy. According to the model, five fisheries (CW, HL, GL, ML, and SCL) were classified as "stage 1—healthy", indicating low recreational fishing mortality and high biomass levels (Lester et al. 2021). In contrast, the WHL fishery was categorized as "stage 4—overfished and recovering", characterized by low recreational fishing mortality and biomass (Lester et al. 2021). These findings offer positive insights for management, suggesting that the majority of these lake trout fisheries are in a healthy state. Given that these fisheries were selected for their differing levels of recreational fishing quality according to provincial biologists, the results are encouraging for sustainable fisheries management in the province.

However, certain issues, such as age and length class asymmetries and low sample sizes, may indicate underlying concerns that warrant closer monitoring by fisheries managers (Kritzer et al. 2001). These discrepancies could potentially impact the future status of some fisheries, and it is crucial that management efforts continue to focus on these aspects to ensure long-term sustainability (Kritzer et al. 2001). Fisheries managers can use the findings presented here to inform management strategies and guide future initiatives. Below, several recommendations are presented

Table 2 Asymptotic length (L_∞), early growth rate (ω), growth coefficient (K), and age at length 0 mm (t_0) parameter values for lake trout (*Salvelinus namaycush*) from six Manitoban populations. N represents the number of individuals for the estimation of the mean parameter values presented. Letters denote groupwise differences based on an α

Lake	Metric	N	Mean	Upper confidence interval (95%)	Lower confidence interval (95%)
Clearwater (CW)	L_∞ (mm)	118	655.065[a]	678.676	631.454
George (GL)	L_∞ (mm)	64	640.604[ac]	668.276	612.932
High (HL)	L_∞ (mm)	18	751.712[abc]	857.674	645.751
Mantario (ML)	L_∞ (mm)	29	645.987[ac]	682.720	609.254
Second Cranberry (SCL)	L_∞ (mm)	47	835.258[b]	870.075	800.442
West Hawk (WHL)	L_∞ (mm)	13	727.139[bc]	742.167	712.111
Clearwater (CW)	K	118	0.239[a]	0.254	0.225
George (GL)	K	64	0.136[bc]	0.150	0.123
High (HL)	K	18	0.155[b]	0.191	0.119
Mantario (ML)	K	29	0.154[b]	0.170	0.138
Second Cranberry (SCL)	K	47	0.099[bc]	0.109	0.091
West Hawk (WHL)	K	13	0.141[bc]	0.163	0.119
Clearwater (CW)	w (mm/year)	118	149.485[a]	156.516	142.454
George (GL)	w (mm/year)	64	82.492[b]	87.662	77.323
High (HL)	w (mm/year)	18	102.231[b]	116.641	87.820
Mantario (ML)	w (mm/year)	29	96.725[b]	104.297	89.152
Second Cranberry (SCL)	w (mm/year)	47	81.370[b]	88.001	74.738
West Hawk (WHL)	w (mm/year)	13	102.086[b]	117.103	87.069
Clearwater (CW)	t_0	118	0.130[a]	0.202	0.0580
George (GL)	t_0	64	−0.268[b]	−0.111	−0.424
High (HL)	t_0	18	−0.174[bc]	−0.174	−0.174
Mantario (ML)	t_0	29	−0.265[b]	−0.0951	−0.435
Second Cranberry (SCL)	t_0	47	−0.885[c]	−0.648	−1.121
West Hawk (WHL)	t_0	13	−0.121[abc]	0.114	−0.355

to help improve data collection, address potential concerns, and foster stronger relationships with stakeholders in order to maintain or enhance the sustainability status of these lake trout fisheries.

Five lakes (CW, GL, HL, ML, and SCL) were classified as "healthy" fisheries. Among these, CW exhibits a size distribution heavily skewed toward younger fish around 400 mm, but it also produces trophy-sized lake trout (> 890 mm), as several were captured during the study. Clearwater Lake's high 75th percentile values for ω and K, combined with a low A_{50}, indicate that this is a relatively fast-growing, early-maturing population with respect to the geographic average (Hansen et al. 2021). The high ω and K values fall in line with a previous CW lake trout study conducted roughly 40 years ago (Leroux 1983). Furthermore, mean age has decreased since the last lake trout assessment in 1981 from 12.6 years (Leroux 1983) to 9 years. This shift could be driven by an abundance of young lake trout in our study relative to the 1981 assessment and/or due to max size harvest limit of 65 cm that was introduced in late 1980s, thus allowing more unhindered recruitment. This shift in mean age is likely due to the use of 55 mm mesh size for SPIN compared to the 1981 study which used 77 mm as the smallest mesh size (Leroux 1983). Based on the calculated growth parameters and mortality rates, CW's lake trout population does not face immediate concerns regarding age or length distributions. Second Cranberry Lake ranks as the healthiest lake in the model due to its high biomass, driven by its top 75th percentile total length and above-average asymptotic L_∞ compared to other lake trout populations across their native range (Hansen et al. 2021). However, SCL's above average A_{50} and L_{50} values, coupled with a below average ω, indicate it is a slow-growing, late-maturing population relative to the norm (Hansen et al. 2021). Despite these traits, only six fish caught

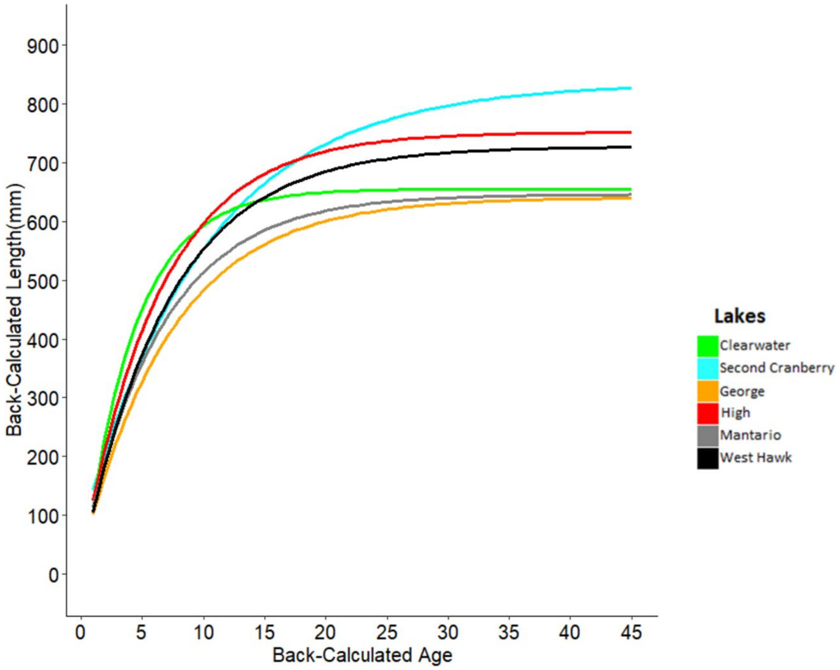

Fig. 5 von Bertalanffy growth functions of the six Manitoban lake trout (Salvelinus namaycush) populations based on mean parameter values. (Clearwater Lake = green [n = 118], Second Cranberry Lake = turquoise [n = 47], George Lake = orange [n = 64], High Lake = red [n = 18], West Hawk Lake = black [n = 13], and Mantario Lake = grey [n = 29])

Table 3 Age at which 50% probability individuals are mature (A50) and 50% maturity threshold, for three lake trout (Salvelinus namaycush) populations. Parametric bootstrapping was procedure was conducted to recreate an artificial dataset of 1000 replicates. Letters denote groupwise differences based on an $\alpha < 0.05$

Lake	Variable	*N*	Mean	Upper confidence interval (95%)	Lower confidence interval (95%)
Clearwater (CW)	A_{50}	1000	5.405 years[a]	5.422	5.387
George (GL)	A_{50}	1000	6.696 years[b]	6.733	6.659
Second Cranberry (SCL)	A_{50}	1000	9.599 years[c]	9.677	9.523
Clearwater (CW)	L_{50}	1000	449.583 mm[a]	468.882	430.591
George (GL)	L_{50}	1000	385.695 mm[b]	420.776	348.450
Second Cranberry (SCL)	L_{50}	1000	553.689 mm[c]	500.498	598.720

were under 500 mm in total length and few fish were aged less than 6 years. This does raise possible concerns about the recruitment success of this fishery. This could suggest that the lake has reached its carrying capacity (Hillborn and Walters 1992). Monitoring recruitment rates and focusing on smaller size classes, potentially outside the scope of the current SPIN method, could provide valuable insights into the long-term sustainability of this fishery. Another limitation of our methodology was the implementation of 30-min net sets in CW and SCL. Although we have adjusted the CPUE values to allow for comparison, there is an underlying assumption that lake trout will interact with the net at the same rate over the 30 min compared to the 2-h net sets, which likely means we underestimated CPUE due to the possibility that 30 min was not long enough to reduce the disturbance caused by setting the net and the potential that lake trout avoided the area. Moreover, Further validation of our protocol is needed if SPIN can be used in this fashion to sample lake trout fisheries, where bycatch limits exist.

Lake trout populations in the southeastern fisheries show diverse growth patterns and potential

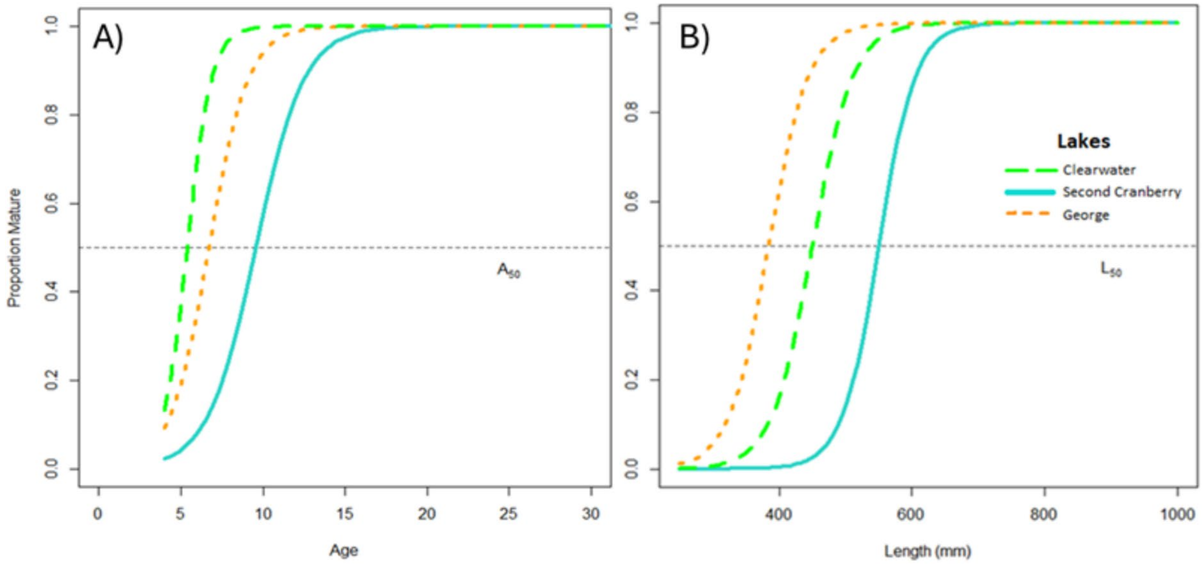

Fig. 6 **A** Age at maturity curves for Clearwater Lake, George Lake, and Second Cranberry Lake lake trout (*Salvelinus namaycush*) populations. Maturity curves are based on bootstrapped values ($n = 1000$ per population). **B** Length-at-maturity curves for Clearwater Lake, George Lake, and Second Cranberry Lake lake trout populations. The dashed grey line represents the estimated age where 50% of individuals in the population will be mature (A_{50} and L_{50}). Clearwater Lake = green dashed line, George Lake = orange small dashed line, and Second Cranberry Lake = turquoise solid line

recruitment concerns that require targeted management. The GL fishery stands out as the only southeastern lake with an abundance of lake trout, which is consistent with its classification as "healthy" in the sustainability model. However, the GL population exhibited below-average values for both growth rate (ω) and asymptotic length (L_∞), indicating that it is a long-lived, slow-growing population (Hansen et al. 2021). Similar to other lakes, GL faces a recruitment concern, with a notable gap in small fish; few fish smaller than 450 mm aged less than 7 years were recorded. This imbalance, with many middle-aged and middle-sized lake trout, could lead to potential issues with recruitment or survival of younger fish (Mills et al. 2002). The HL fishery was also identified as "healthy", though the population sample size was small, with only 22 lake trout caught. This low number is considered small based on SPIN standards (Sandstrom and Lester 2009). Furthermore, not all the allotted SPIN nets were deployed on HL due to high lake whitefish bycatch, thus contributing to the lake trout sample size issue. The low sample size makes it difficult to extrapolate findings from HL and may be biased and not precise (Kritzer et al. 2001); however, the lack of fish is a result in itself. Based on the biomass and recreational fishing mortality results, HL appears to be a small population with low recreational fishing pressure, and therefore can persist due to low recreational fishing mortality rates. Lastly, of the southeastern lakes, ML lies closest to the threshold between "healthy" (stage 1) and "recovering" (stage 4). This situation bears resemblance to HL, as ML experiences low recreational fishing pressure and has low biomass. Once again due to a low sample size, VBGF parameter and mortality estimates may not be accurate. However, a comparison of a stock assessment by Robert (1994) to recent data indicates a decline in mean body mass, from 1636 g in 1993 to 1143 g in 2022. The historical assessment also highlighted concerns such as a lack of young lake trout (<8 years), *Triaenophorus* infection, and reduced reproductive success. Robert (1994) further suggested that lakes in eastern Manitoba may not be well-suited to support lake trout populations, with even minimal recreational fishing pressure potentially impacting the populations. Given our observed reduction in mean body mass and low sample size (29 individuals), we concur with Robert's (1994) assessment.

Most concerning are the WHL and DL lake trout populations. West Hawk Lake was the only lake

Table 4 Chapman-Robson estimated instantaneous mortality rates (*Z*) from six Manitoban lake trout (*Salvelinus namaycush*) populations. Letters denote groupwise differences based on an α

Lake	*N*	Instantaneous mortality rate (Z)	Upper confidence interval (95%)	Lower confidence interval (95%)
Clearwater (CW)	117	0.169[ab]	0.201	0.136
George (GL)	64	0.124[a]	0.159	0.087
High (HL)	18	0.161[a]	0.231	0.092
Mantario (ML)	29	0.212[a]	0.265	0.159
Second Cranberry (SCL)	47	0.109[b]	0.140	0.078
West Hawk (WHL)	13	0.208[a]	0.271	0.144

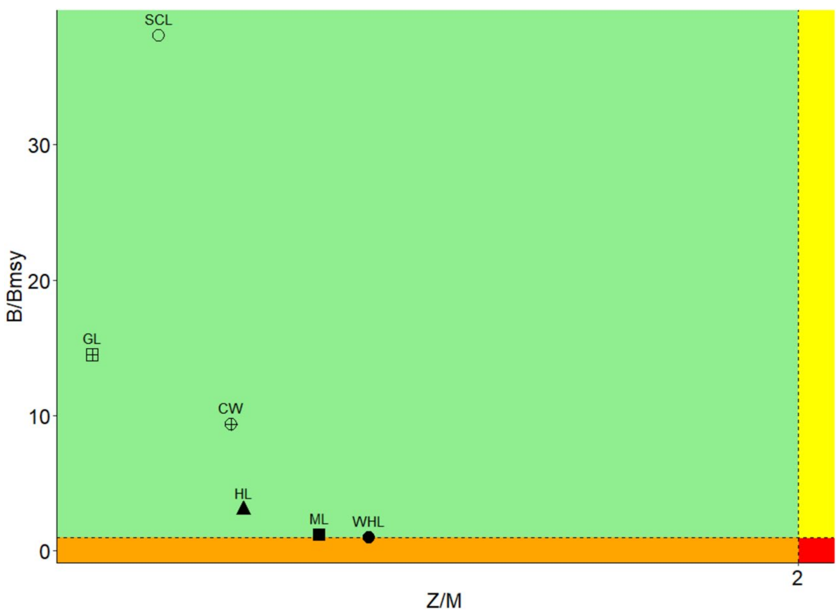

Fig. 7 Implementation of mortality and biomass reference points for lake trout (*Salvelinus namaycush*) populations designed by Lester et al. (2021). Stage 1 (top left, green) = healthy, stage 2 (top right, yellow) = overfishing-early, stage 3 (bottom right, red) = overfishing-late, and stage 4 (bottom left, orange) = overfished-late. Clearwater Lake (CW), George Lake (GL), High Lake (HL), Mantario Lake (ML), and Second Cranberry Lake (SCL) are considered stage 1 (healthy). West Hawk Lake (WHL) is considered stage 4 (overfished, and recovering)

classified as "overfished and recovering" (stage 4). There are a variety of possibilities for why this southeastern lake trout fishery has not fared well. Firstly, historically high recreational fishing pressure likely negatively impacted the lake trout population. According to Butler (1950), WHL was a great destination for lake trout anglers, therefore it is in reason to believe that WHL was once a productive lake trout fishery. Despite this and an extensive stocking history (MBGOV 2023a), we only caught 13 lake trout after our SPIN survey and supplemental angling. Secondly, low recruitment may be an issue. The most common size class found in WHL is 550–599 mm and the age-classes are skewed toward older fish. The pattern of few small and young fish and many older larger fish may indicate recruitment issues. The low sample size may also bias the instantaneous mortality rates, which were used in the sustainability model. This may have affected WHL's classification as a stage 4 lake. It is also unclear if lake trout are native to WHL. If lake trout are not native to WHL, particularly if it is because lake characteristics are not favorable for them, then their recruitment success and population size may have been dependent on the routine stocking that has occurred in the lake. This pattern may also hold true for DL. Davidson Lake was the only fishery where we only caught one lake trout. As a result, no meaningful analyses could be done. This population appears to be depauperate despite recent stocking events (MBGOV 2023a), which may indicate stocking programs have not been effective for this fishery due to unsuitable habitat.

Implications for fisheries management

The sustainability model used in our study provides managers the ability to estimate realistic expectations of potential harvest (B_{MSY}) across a climactic gradient, thus allowing managers to use the model in any environment (Lester et al. 2021). To achieve the stage 1 classification for a given fishery, the goal of managers is to increase the biomass of a fishery while reducing the total mortality rate. One way to reduce the natural mortality rate is to increase L_∞ and/or W_∞ of a population due to its inverse relationship (Lester et al. 2021). In Manitoba, anglers are only allowed to keep a single lake trout and it must be < 65 cm (MBGOV 2023b). One possible management strategy is to introduce narrow harvest slot limits to restrict harvest to a certain range of lengths, typically smaller and more abundant age classes, to protect older and larger fish that are important to the recruitment success of a fishery (Gwinn et al. 2015). Narrow harvest slot limits have been shown to produce better trophy fish catches (Gwinn et al. 2015), which can lead to increased biomass levels by way of increased mean weight and sheer number of individuals, lower recreational fishing mortality rates and higher L_∞ and W_∞ of a fishery. This can be achieved by simply incorporating L_{50} values as a guide for the minimum size threshold and using the already existing 65 cm upper threshold. Provincial managers may choose to make the harvest slot limit narrower by increasing the minimum harvest size threshold to account for maturation variability, while also decreasing the maximum size limit. This is designed to balance fish conservation and angling opportunities (Power and Power 1996). However, in practice, anglers tend to be less compliant with slot limits due to the added complexity, thus reducing their efficacy (Caroffino 2013). Managers need to weigh the levels of angler discontentment and potential of non-compliance to new regulations and the conservation goals of a given lake trout stock. Lakes such as WHL, which are characterized by low lake trout abundance and deemed to be overfished (Lester et al. 2021) will require additional management strategies. Imposing strict catch-and-release regulations might be a viable option to protect these fragile populations. However, fisheries managers should exercise caution when attempting a strict catch-and-release strategy because anglers almost exclusively target lake trout at increased depths in the summer, and there is evidence to suggest that post-release mortality in lake trout is the highest in summer months (DePasquale et al. 2023; Howell et al. 2024).

One strength of the MDNRIF has been their willingness to support research initiatives (e.g., Howell et al. 2023, 2024; DePasquale et al. 2023). Therefore, it is reasonable to expect that such collaborations between government and academics will continue. Based on our results and the limitations of SPIN, it would be worth considering gillnet surveys that target smaller size classes than SPIN (< 300 mm). The aforementioned lack of small fish in several lakes, especially in the healthy lakes (GL and SCL), is a concern that potentially jeopardizes the future sustainability of these fisheries. Conducting gillnet surveys on smaller size classes would enable researchers and managers to determine whether any underlying issues regarding recruitment success and mortality of young lake trout exist.

Another promising research avenue for data collection is the integration of citizen science into lake trout management strategies. Social media platforms such as *YouTube* and *Travel Manitoba*'s "Master Angler" website enable anglers to find lakes that offer prime opportunities for trophy-sized lake trout. This increased visibility can lead to heightened angler effort on specific lakes. The "Master Angler" program exemplifies citizen science by allowing anglers to submit photos of trophy fish, along with details such as the date, location, and total length of their catches, in exchange for prizes (Travel Manitoba 2024). This initiative has resulted in a publicly accessible record book that directs future angler efforts toward lakes highlighted by their peers. For fisheries managers, this social media activity provides a valuable means to track trends, identify key fisheries, and proactively monitor these popular locations to better assess their health. This is a more modern method of data acquisition that is low cost compared to traditional creel surveys (Vølstad et al. 2006; Venturelli et al. 2017), and should act as a supplement to more traditional surveys in states and provinces that do not have a "Master Angler" program. At a minimum, this technique allows managers to acquire timely data on popular lakes. For example, the majority of Master Angler lake trout catch totals indicate CW is the most fishery that routinely provides anglers with trophy-sized fish. Thus, based on these findings, CW lake trout monitoring programs should continue to ensure the fishery's sustainability. Provinces and states that do not have a citizen science rewards program would likely benefit from the increased data generated by this system.

While not incorporated into our study, academics and government biologists should strive to include Indigenous as part of any fisheries management program/project. Our study could have benefitted from the inclusion of Indigenous knowledge holders by promoting active engagement and consultation in the study. This would have likely improved our knowledge of lake trout fisheries we studied through a historical and contemporary lens. Furthermore, building a genuine relationship between academia and Indigenous communities can benefit both parties in understanding each other and become allies to future endeavours. Involvement should extend beyond merely assimilating Indigenous knowledge into existing management practices; both knowledge systems are unique and can benefit from being used in conjunction with each other (Reid et al. 2021). This approach involves co-producing objectives and questions, independently applying both knowledge systems to examine the same problem, and collaboratively generating insights and decisions (Reid et al. 2021). A notable example of collaboration is the ongoing relationship between the Cree Nation of Mistissini and scientists working to conserve fisheries in Mistassini Lake (see Bowles et al. 2020; Fraser et al. 2006, 2013; Marin et al. 2017). Collaborative fieldwork, involving community members fishing guides in the collection of biometric data (such as length, weight, fin clips, otoliths, and sex), has built trust between parties and demonstrated the benefits of scientific research (Fraser et al. 2006). Such targeted data collection would have improved the models presented in our study, allowing for more tailored management recommendations. Successful collaborations do exist in Manitoba for lake sturgeon (*Acipenser fulvescens*) in the form of Sturgeon Management Boards (MEDITNR 2024). These boards provide Indigenous communities opportunities to participate in sharing their knowledge and actively participate in conservation initiatives (MEDITNR 2024). These collaborative efforts have the potential to successfully blend western science and Indigenous knowledge, ultimately advancing the shared goal of fisheries conservation while ensuring that the data collected is actionable for fisheries managers.

Conclusion

Manitoba's recreational lake trout fisheries possess unique characteristics that require tailored management strategies. Most fisheries assessed in our study appear to be in good health, which is encouraging for unsampled lake trout populations across the province (Lester et al. 2021). However, concerns about recruitment, particularly in the southeastern lakes, underscore the need for targeted gillnet surveys focused on younger age classes to proactively address potential challenges. Regular monitoring and adaptive management strategies will be essential for sustaining these fisheries. Additionally, incorporating citizen science and Indigenous knowledge offers valuable opportunities to address data gaps and enhance lake trout conservation efforts. By taking these steps, we can ensure the long-term health and resilience of Manitoba's lake trout populations.

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Author contribution The study was designed by G.N., B.E.H., E.J.M., and C.T.H.; methodology: G.N., E.J.M., C.T.H., M.D.R., and O.M.; data acquisition: G.N., B.E.H., E.J.M., and A.W.R.M; data analysis: G.N.; funding: G.N. and C.T.H.; draft writing: G.N.; draft review and editing: B.E.H., E.J.M., A.W.R.M, C.T.H., M.D.R., and O.M.; supervision: C.T.H. All authors read and approved the final manuscript.

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Data availability Data associated with the manuscript is available upon reasonable request.

Declarations

Ethics approval The research (Protocol #AE 10491) conducted upon the Lake Trout populations and individuals was approved by the University of Winnipeg Animal Ethics Committee, in accordance with the Canadian Council on Animal Care. A Provincial Scientific Collection (General) Permit (#22758865) was also granted by the province to collect the biological data.

Conflict of interest Dr. Olivier Morissette acts as an Advisory Editor on the Editorial Board of Environmental Biology of Fishes but was not involved in the peer review process of this article and had no access to information regarding its peer review. All other authors declare that they have no conflicts of interest.

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