Ministry of Natural Resources and Forestry

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CLIMATE CHANGE RESEARCH REPORT

Responding to Climate Change Through Partnership

Projected changes in lake trout habitat in Quetico Provincial Park and the Atikokan area with climate change





Ministry of Natural Resources and Forestry

Ontario

Projected changes in lake trout habitat in Quetico Provincial Park and the Atikokan area with climate change

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Lake trout from small unnamed lake in Quetico Provincial Park (Photo credit: Jill Legault)

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Summary

For most Ontario lake trout populations, the magnitude of habitat loss due to climate change remains unknown. Here we document results of our examination of the historical, current, and future habitat suitability of lakes in Quetico Provincial Park (QPP) and the Atikokan (ATK) area of northern Ontario, Canada, for lake trout. We applied a new model to estimate a habitat suitability index (HSI) value for 280 QPP and ATK lakes using mean annual air temperature, lake surface area, and mean and maximum lake depth. Results indicated that 80% of the lakes reported to contain lake trout had HSI values >0.9, whereas <20% of the lakes with lake trout had HSI values <0.4. Lake trout lakes in QPP had higher HSI values than those in ATK. Between the historical (1971–2000) and current (2000–2019) periods, on average, HSI values decreased by 2.4% in QPP and by 4.4% in ATK. By 2070–2100, under the representative concentration pathway (RCP) 2.6, 4.5, and 8.5 emissions scenarios, habitat suitability was projected to decline by 6.6–18.5% for lake trout lakes in QPP and by 12.1–31.6% for those in ATK. Based on their suitability in 2070–2100 under RCP 8.5 and the presence of introduced fishes or aquatic invasive species, each lake was assigned a climate change conservation ranking. Fifty-four per cent of lake trout lakes in QPP and ATK had conservation rankings of *high* or *very high* indicating that these lakes may be strongholds for lake trout population persistence. The higher HSI values in QPP relative to ATK lake trout lakes and the benefits provided by protected areas, such as reduced access and angling pressure, suggest that QPP may be an important future refuge for lake trout. However, of the lake trout lakes in QPP, data to estimate habitat suitability is lacking for 55%, highlighting the need for additional data collection to confirm these findings. These results may inform aquatic planning, conservation, and management activities in northwestern Ontario.

Résumé

Changements prévus de l’habitat du touladi dans le parc provincial Quetico et la région d’Atikokan en raison des changements climatiques

Pour la plupart des populations de touladi de l’Ontario, l’importance de la perte d’habitat liée aux changements climatiques est inconnue. Nous avons examiné si les lacs du parc provincial Quetico (PPQ) et de la région d’Atikokan (ATK), dans le nord-est de l’Ontario, au Canada, étaient historiquement adéquats comme habitats pour le touladi, s’ils l’étaient actuellement et s’ils allaient l’être pendant les années à venir. Nous documentons ici les résultats de cet examen. Nous avons mis en application un nouveau modèle afin d’estimer l’indice de qualité de l’habitat (IQH) de 280 lacs du PPQ et d’ATK, lequel repose sur la température de l’air moyenne annuelle, la superficie du lac, sa profondeur moyenne et sa profondeur maximale. Les résultats ont indiqué que

80 % des lacs censés renfermer des touladis avaient une valeur d'IQH > 0,9, tandis que < 20 % des lacs à touladis avaient une valeur d'IQH < 0,4. Les lacs à touladis du PPQ avaient des IQH supérieurs à ceux d'ATK. Quand on compare les périodes historique (1971–2000) et actuelle (2000–2019), en moyenne, les valeurs d'IQH ont diminué de 2,4 % dans le PPQ et de 4,4 % à ATK. D'ici 2070–2100, si l'on suit les scénarios d'évolution des concentrations de gaz à effet de serre (*representative concentration pathway*, RCP) de 2,6, 4,5 et 8,5, la qualité de l'habitat devrait baisser de 6,6 à 18,5 % dans les lacs à touladis du PPQ et de 12,1 à 31,6 % pour ceux d'ATK. D'après leur qualité en 2070–2100 dans le cadre du scénario RCP de 8,5 et avec la présence de poissons introduits ou d'espèces aquatiques envahissantes, chaque lac a ainsi reçu une cote de conservation à la lumière des changements climatiques. Cinquante-cinq pour cent des lacs à touladis du PPQ et d'ATK ont obtenu une cote de conservation *élevée* ou *très élevée*, ce qui indique que ces lacs pourraient être de véritables bastions de persistance pour la population de touladi. Les IQH plus élevés des lacs à touladis du PPQ par rapport à ceux d'ATK, de même que les avantages dont jouissent les zones protégées (p. ex., réduction de l'accès et de la pression exercée par la pêche), laissent entendre que le PPQ pourrait devenir un important refuge pour le touladi. Cela dit, il manque des données pour bien estimer la qualité des habitats de 55 % des lacs à touladis du PPQ, ce qui souligne qu'il faudrait mener une collecte de données supplémentaire en vue de confirmer ces résultats. Ces résultats pourront servir à éclairer les activités de planification, de conservation et de gestion des milieux aquatiques dans le nord-ouest de l'Ontario.

Acknowledgements

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Contents

Summary iii
Résumé iii
Acknowledgements iv
1.0 Introduction 1
2.0 Study area 2
3.0 Methods 2
4.0 Results 5
4.1 Habitat suitability index values for lakes with and without lake trout 5
4.2 Habitat suitability and projected climate change effects on lake trout lakes 6
4.3 Conservation rankings for lake trout lakes 8
5.0 Discussion 9
6.0 Conclusions 11
7.0 Literature cited 12
Appendix 1. Lake trout habitat suitability model explained 14
Appendix 2. Habitat suitability, introduced species, and conservation ranking for 125 lake trout lakes in Quetico Provincial Park and the Atikokan area 15
Appendix 3. Lake trout lakes in Quetico Provincial Park missing depth data 19
Appendix 4. Estimating mean lake depth and habitat suitability from maximum depth 22

1.0 Introduction

In Ontario, the lake trout (*Salvelinus namaycush*), or Namaygoos in Anishinaabemowin, is one of the most important coldwater species for both commercial and recreational fishing activities across inland lakes and the Laurentian Great Lakes. They are top predators and the status of their populations are indicators of lake ecosystem health. However, lake trout and other important coldwater fish species are increasingly at risk from climate change (Williams et al. 2015). Guzzo and Blanchfield (2017) have already observed declines in lake trout habitat in small boreal shield lakes of northwestern Ontario. Sharma et al. (2009) projected that smallmouth bass (*Micropterus dolomieu*) will expand into new habitats with climate warming, and this expansion will put lake trout populations at risk, particularly in smaller lakes (<100 ha). Despite this evidence, the magnitude of habitat loss due to climate change remains unknown for most, if not all, Ontario lake trout populations.

Jackson (2007), examined the potential effects of climate change on lake trout and attempted to identify high risk lakes in the Atikokan (ATK) area. He evaluated risk based on (1) the loss of hypolimnetic habitat needed for lake trout survival and (2) changes in fish community structure resulting from the introduction of littoral zone predators, particularly in lakes without deep-water prey such as cisco (*Coregonus artedi*). Hypolimnetic habitat loss was based on the principle that shallow lakes were more at risk of warming than deeper lakes. While generally true, this approach was overly simplistic and did not identify a threshold at which habitat loss resulted in lake trout loss, nor did it provide a way to assess how this threshold might change as the climate warms. Data collected since 2007 supports that the associated community structure analysis may have been overly simplistic as it did not factor in how, for example, lake size and shape may moderate the negative effects of introduced littoral predators (see Jackson 2017, 2018).

Lester et al. (2021) developed a habitat suitability index (HSI) model for lake trout in lakes (Appendix 1). This model improves on the depth approach used by Jackson (2007) because it estimates hypolimnetic volume as a function of lake area and maximum and mean depth (lake shape). It also explicitly incorporates mean annual air temperature to estimate thermocline depths (and hypolimnetic volume), an inclusion that allows estimation of the effect of climate warming under different emissions scenarios on habitat suitability.

The objectives of this study were to apply the model developed by Lester et al. (2021) to (1) estimate HSI values for Quetico Provincial Park (QPP) and ATK lakes; (2) compare those values in lakes with and without lake trout to determine how HSI predictions align with observed lake trout occurrences; (3) forecast changes in lake trout habitat under historical, current, and future climate conditions; and 4) assign conservation rankings to each lake trout lake based on projected changes in habitat and the presence of

deleterious introduced species. With air temperatures in this area of the province warming faster than those in the south, a better understanding of the potential effects of climate change on lake trout habitat suitability in QPP and ATK is needed. The overall goal is to provide information that can be used to inform lake trout conservation and management in northwestern Ontario.

2.0 Study area

Quetico Provincial Park and ATK are in the Ministry of Natural Resources and Forestry's Fort Frances District in northwestern Ontario (Figure 1). Both areas are in the Pigeon River and Lake Wabigoon ecoregions in the Ontario Shield Ecozone. These ecoregions are characterized by mixed forests, shallow soils over bedrock, and abundant deep clear lakes.

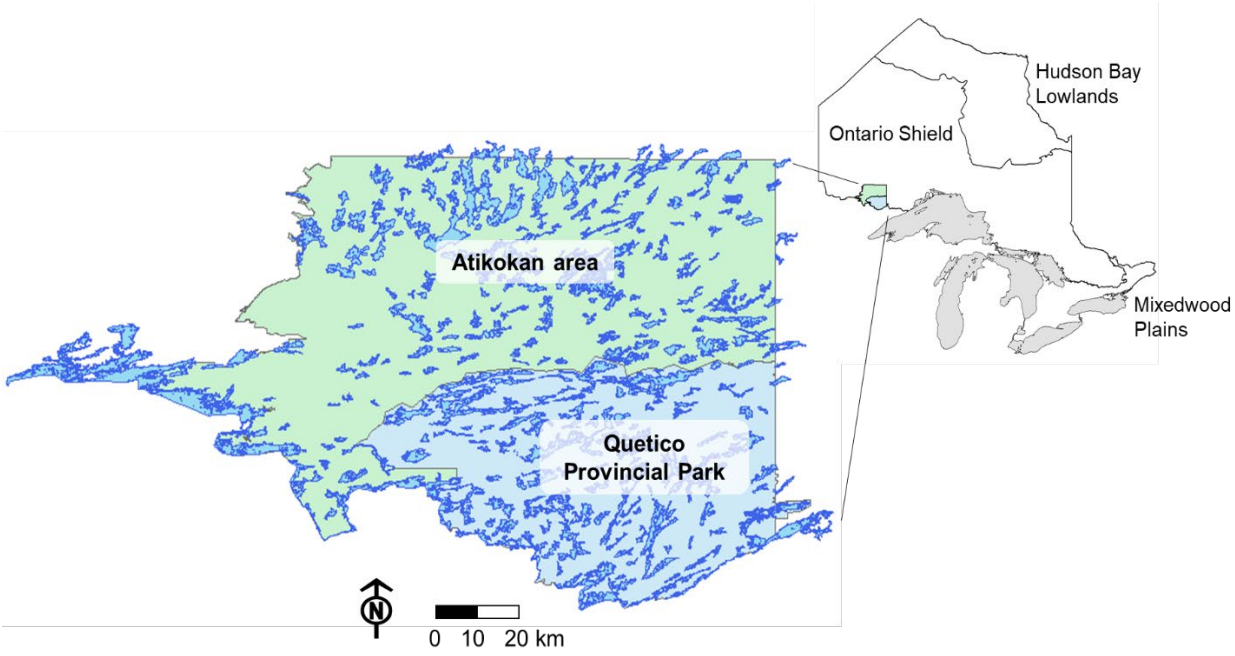


Figure 1. Map showing lakes ≥10 ha in Quetico Provincial Park and the Atikokan area in northwestern Ontario. Inset map shows study area location in the Ontario Shield Ecozone.

3.0 Methods

To meet the objectives of this study, lake trout distribution, lake characteristic, and climate data were compiled. More than 650 lakes ≥10 ha occur in QPP and ATK. Lake surveys conducted between 1970 and 1990 were used to determine whether lake trout were present and provided the bathymetric information needed to estimate mean and maximum lake depths. Of the more than 650 lakes, 280 had lake trout presence/

absence, surface area, and maximum and mean depth data. Of those 280 lakes, lake trout occurred in 39 lakes in QPP and 86 in ATK. Lake trout lakes ranged from 18 to 8,249 ha, with maximum depths of 8 to 115 m and mean depths of 2 to 37 m. Non-lake trout lakes ranged from 4 to 5,474 ha, with maximum depths of 1.5 to 67 m and mean depths of 0.5 to 19 m. Although the surveys provided information for more than 25% of the lakes in QPP and ATK, some of the lake trout occurrences have not been verified in about 40 years.

The historical (1971–2000) and current (2000–2019) observed mean annual air temperatures used in our analyses were measured at Atikokan, Ontario (Environment and Climate Change Canada 2020). The historical temperature was 1.6 °C and the current temperature is 2.7 °C. This difference represents an increase of more than 1 °C and is consistent with climate change projections for the period 2011–2040 (McDermid et al. 2015, Jackson 2016). We assessed climate change effects on lake trout habitat using three representative concentration pathway (RCP) emissions scenarios (McDermid et al. 2015): RCP 2.6, 4.5, and 8.5.

The first scenario, RCP 2.6, assumes emissions peak early and then fall due to active removal of atmospheric carbon dioxide because all the main greenhouse gas emitters and developing countries participate in early climate change mitigation. Under this scenario, the mean annual air temperature for the study area is predicted to rise to 4.7 °C for the period 2070–2100. For RCP 4.5, climate change drivers stabilize by 2100 and the mean annual air temperature for the study area is predicted to rise to 6.6 °C during 2070–2100. Lastly, for RCP 8.5, emissions are not curtailed and greenhouse gas emissions are as much as seven times higher than pre-industrial levels (McDermid et al. 2015). The mean annual air temperature is predicted to rise to 10.1 °C by 2070–2100.

A lake trout habitat suitability model (Lester et al. 2021) was used to estimate HSI values for each of the 280 lakes for each time period. The HSI values range from 0 (no suitable habitat) to 1 (good habitat suitability) based on lake shape and mean annual air temperature (Appendix 1). The values were summarized in four ways. First, the historical (when the lakes were sampled between 1970–1990) HSI values of all 280 lakes were binned into 10 classes (0–<0.1, 0.1–<0.2, 0.2–<0.3, etc.) and the number of lakes with and without lake trout were compared to determine the agreement between high suitability values and observed lake trout presence. Second, the mean and standard deviation of the HSI values were calculated for the QPP and ATK lakes with and without lake trout and for each time period. Third, the per cent change in HSI values were calculated for each lake trout lake (n=125) for the current and future periods relative to the historical period, as follows:

$$Per\ cent\ change = 1 - \left(\frac{current\ or\ future\ habitat\ suitability}{historical\ period\ habitat\ suitability}\right) \times 100$$

Finally, lake trout are sensitive not only to climate change but also to the presence of introduced fish species and aquatic invasive species (AIS) that affect lake ecosystems in different ways. Fish species such as smallmouth bass and walleye (*Sander vitreus*) can directly compete with lake trout for resources and may prey on lake trout or lake trout eggs (Vander Zanden and Rasmussen 1999). In contrast, AIS such as *Bythotrephes* and *Dreissenid* mussels can disrupt food webs and affect water quality and clarity (Ricciardi 2001). Historical records and recent information (e.g., from MNRF's inland lakes broad-scale monitoring) were used to identify lakes with introduced fishes or AIS.

Conservation rankings were assigned to each lake trout lake in QPP and ATK (n=125) based on projected changes in habitat suitability and the presence of deleterious species. Lakes that retained high suitability in 2070–2100 under RCP 8.5 and had no deleterious species were assigned the highest conservation ranking for two reasons (Table 1). First, lake trout populations in lakes with the best habitat are likely to be strongholds for the species and will be more resilient to multiple stressors than lakes with marginal habitat. Second, although all lakes are managed, identifying those resilient to climate change will focus management attention on their preservation, e.g., as potential sanctuaries or through more stringent harvest regulations.

Table 1. Conservation rankings for lake trout lakes in Quetico Provincial Park and the Atikokan area in northwestern Ontario. RCP=representative concentration pathway; AIS=aquatic invasive species

Habitat suitability 2070–2100 under RCP 8.5	Presence (Y)/absence (N)		Conservation ranking
	Deleterious species	AIS	
≥0.9	N	N	Very high
≥0.9	Y	N	High
≥0.9	N	Y	High
≥0.9	Y	Y	High
<0.9–≥0.7	N	N	Very high
<0.9–≥0.7	Y	N	High
<0.9–≥0.7	N	Y	High
<0.9–≥0.7	Y	Y	Moderate
<0.7–≥0.4	N	N	Moderate
<0.7–≥0.4	Y	N	Moderate
<0.7–≥0.4	N	Y	Moderate

Habitat suitability 2070–2100 under RCP 8.5	Presence (Y)/absence (N)		Conservation ranking
	Deleterious species	AIS	
<0.7–≥0.4	Y	Y	Low
<0.4	N	N	Low
<0.4	Y	N	Low
<0.4	N	Y	Low
<0.4	Y	Y	Low

4.0 Results

4.1 Habitat suitability index values for lakes with and without lake trout

Habitat suitability index values for the 280 lakes in QPP and the ATK area during the historical period ranged from 0.04 to 1, with a mean (± standard deviation) of 0.29 ± 0.38. Most lakes with lake trout (n=125) had HSI values ≥0.9. Eight per cent of lake trout lakes had HSI values <0.4. (Figure 2). Conversely, 68% of lakes without lake trout had HSI values <0.4.

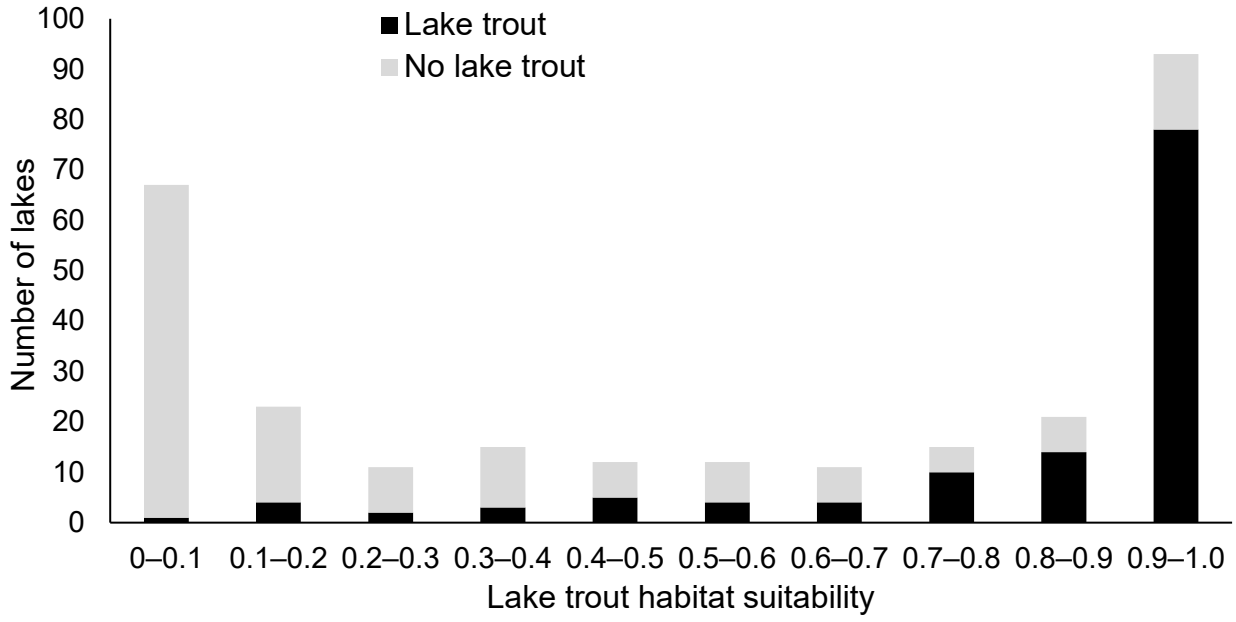


Figure 2. Number of lake trout (black) and non-lake trout (grey) lakes (n=280) in Quetico Provincial Park and the Atikokan area in northwestern Ontario in each estimated habitat suitability index class during the historical (1971–2000) period.

4.2 Habitat suitability and projected climate change effects on lake trout lakes

For all time periods, lake trout lakes in QPP had higher average HSI values than those in ATK (Table 2). Habitat suitability of lake trout lakes was projected to decline more in ATK than in QPP (Table 2; Figure 3). For the 39 lake trout lakes in QPP, HSI values were predicted to decline by, on average, 6.6%, 10.5%, and 18.5% under RCP scenarios 2.6, 4.5 and 8.5, respectively. For the 86 lake trout lakes in ATK, HSI values were predicted to decline by 12.1%, 19.1%, and 31.6% under RCP scenarios 2.6, 4.5, and 8.5, respectively (Figure 3).

Table 2. The number of lakes in Quetico Provincial Park (QPP) and the Atikokan (ATK) area, northwestern Ontario, with and without lake trout and mean (± standard deviation) habitat suitability values for the historical (1971–2000), current (2000–2019), and future (2070–2100; based on representative concentration pathway (RCP) scenarios) periods (n=280).

Area	Lake trout presence	Lake count	Historical	Current	RCP 2.6	RCP 4.5	RCP 8.5
QPP	Yes	39	0.89 ± 0.22	0.88 ± 0.23	0.86 ± 0.25	0.84 ± 0.26	0.77 ± 0.27
	No	33	0.37 ± 0.36	0.34 ± 0.36	0.3 ± 0.35	0.27 ± 0.34	0.21 ± 0.30
ATK	Yes	86	0.81 ± 0.24	0.79 ± 0.25	0.75 ± 0.28	0.70 ± 0.30	0.61 ± 0.32
	No	122	0.30 ± 0.31	0.27 ± 0.31	0.23 ± 0.29	0.20 ± 0.28	0.15 ± 0.25

Habitat suitability indices for lake trout lakes in both QPP and ATK (n=125) were binned into four categories (≥0.9, <0.9 and ≥0.7, <0.7 and ≥0.4, and <0.4) based on the distribution of suitability observed for lakes with and without lake trout (Figure 2). The number of lakes in each of these bins were counted for each time period. For the historical period, 62.4% of lake trout lakes had HSI values ≥0.9, 19.2% were <0.9 and ≥0.7, 10.4% were between <0.7 and ≥0.4, and 8% were <0.4 (Figure 4). Under all three future scenarios, the number of lakes with HSI values ≥0.9 declined the most. These declines ranged from 35% to 54% for RCP 2.6 and RCP 8.5, respectively. Under the RCP 8.5 scenario, the number of lakes with HSI values <0.4 increased from 8% to 26% (Figure 4).

The distribution of HSI values was heavily skewed to the right; with higher median HSI values for lake trout lakes in QPP than in ATK (Figure 5). These distributions shifted to the left (less suitable) under the 2070–2100 RCP 2.6, 4.5, and 8.5 scenarios with larger decreases in ATK than in QPP lakes.

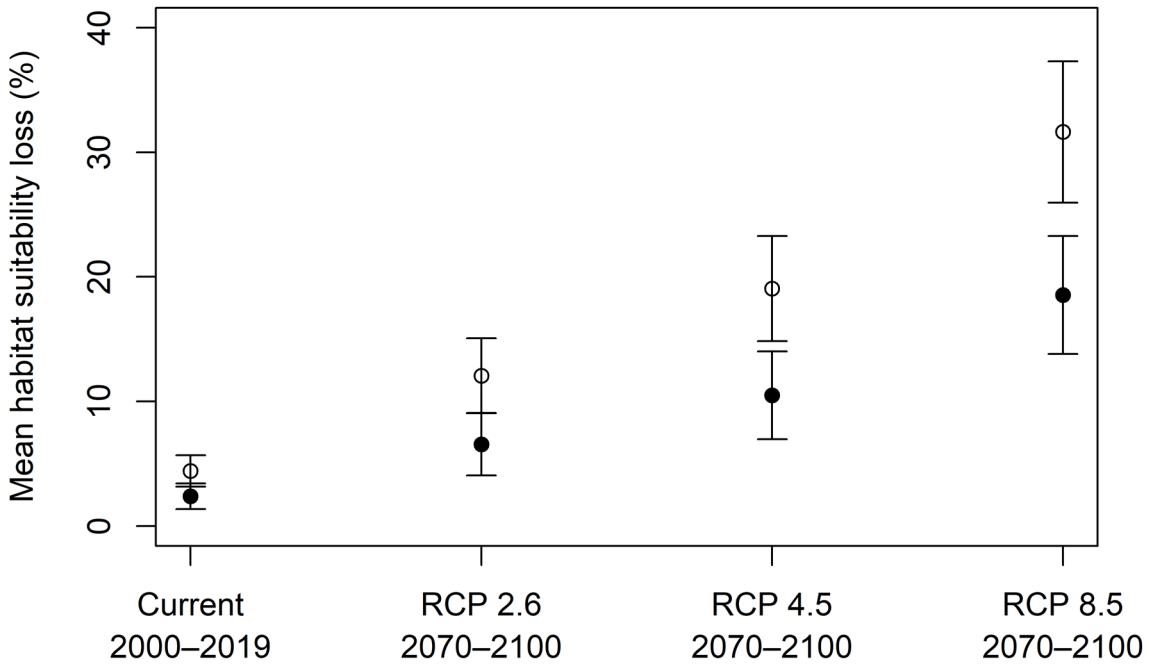


Figure 3. Habitat suitability loss (%) relative to the 1971–2000 (historical) period for Quetico Provincial Park (QPP) and Atikokan area (ATK) lake trout lakes (n=125) in northwestern Ontario for current and future (by representative concentration pathway (RCP) scenario) periods. Closed circles represent QPP lake trout lakes, open circles represent ATK lake trout lakes; circles are means and error bars represent 95% confidence limits.

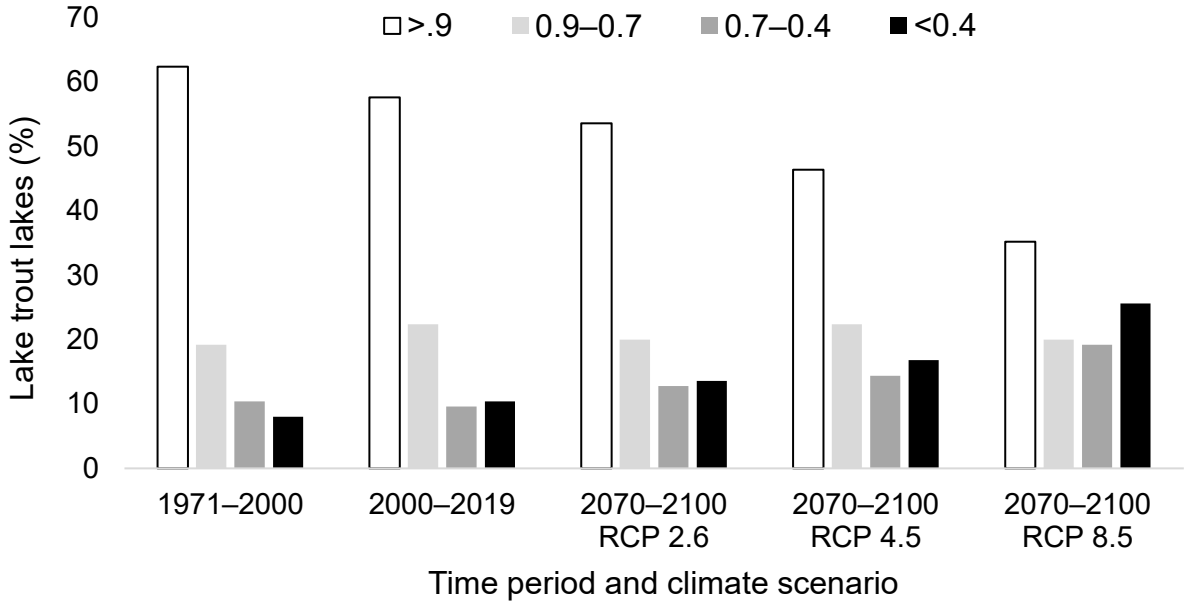


Figure 4. Lake trout lakes (%) in each habitat suitability category in Quetico Provincial Park and the Atikokan area in northwestern Ontario for the historical (1971–2000), current (2000–2019), and future (2070–2100; based on representative concentration pathway (RCP) scenarios 2.6, 4.5, and 8.5) periods (n=125).

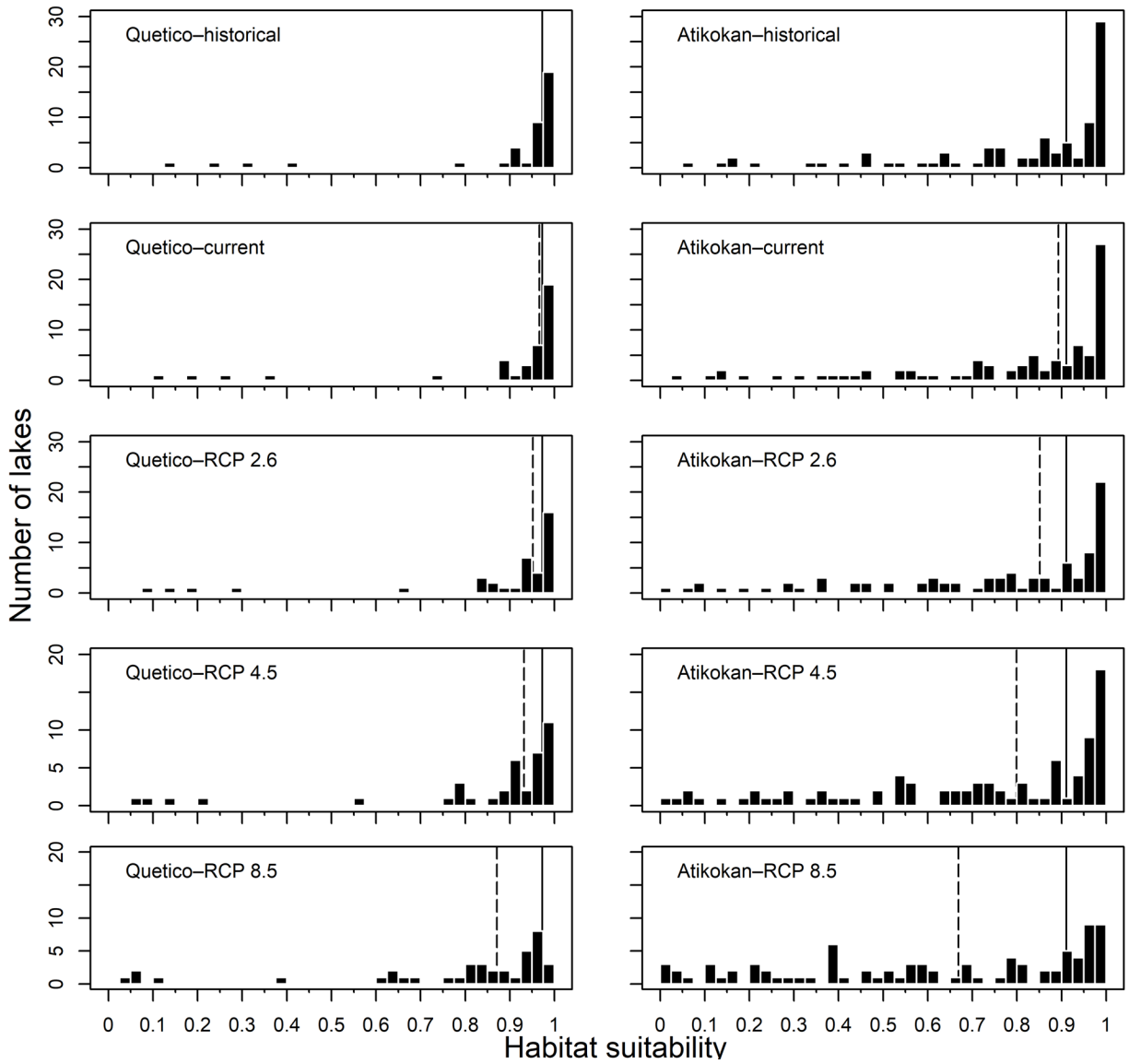


Figure 5. Histograms of habitat suitability (HSI) values for Quetico Provincial Park and Atikokan lake trout lakes in northwestern Ontario for the historical (1971–2000), current (2000–2019), and future (2070–2100; based on representative concentration pathway (RCP) scenarios) periods (n=125). Solid vertical lines represent the median HSI for the historical period and dashed vertical lines represent the median HSI for each respective period and RCP scenario.

4.3 Conservation rankings for lake trout lakes

Eighty-eight of the 125 lake trout lakes had an introduced or invasive species. In 51 lakes, smallmouth bass were the only introduced species, six lakes only had introduced walleye, and five lakes were invaded by several fish species and spiny water flea (*Bythotrephes longimanus*). The remaining lakes were invaded by some combination of

smallmouth bass, walleye, rainbow smelt (*Osmerus mordax*), or black crappie (*Pomoxis nigromaculatus*) (Appendix 2).

Based on the future suitability of lakes for lake trout and the presence of introduced fishes or AIS, of the 125 lakes examined in this study, 19 or 15% had *very high* conservation rankings. Rankings for 39% of lakes were *high*, 21% were *moderate*, and 25% were *low* (Table 3; Appendix 2). Fifty-four per cent of lake trout lakes in QPP and ATK had conservation rankings of *high* or *very high*.

Table 3. Conservation ranking for lake trout lakes in Quetico Provincial Park and the Atikokan area in northwestern Ontario (rankings defined in Table 1).

Ranking	Quetico Provincial Park (n=39)	Atikokan (n=86)
Very high	1	18
High	27	22
Moderate	5	21
Low	6	25

5.0 Discussion

Lake trout presence was positively related to estimated habitat suitability with most lake trout lakes having indices higher than 0.7. This finding lends credence to the habitat suitability model and suggests that it can be used to effectively distinguish between lakes that likely support lake trout populations vs. those that do not. The findings also suggest that the model, which was developed using North American data (Lester et al. 2021), can be applied in the QPP and ATK area.

On average, QPP lakes were found to have higher HSI values than ATK lakes. This result suggests that QPP lakes have more high-quality habitat than those in the ATK area, which may be attributable to the larger hypolimnetic volumes in QPP lakes. However, the number of QPP and ATK lakes included in the analyses were limited by data availability. Additional lake survey data (see Appendix 3 for list) are needed to better understand the risk of climate change in QPP and ATK and assess changes through time.

While it is straightforward to estimate lake area and mean annual air temperature for remote lakes using readily available spatial and climate data, measurements of maximum and mean lake depth involve considerably more cost and effort. Measuring bathymetry necessitates deploying field crews or acquiring remote sensing data (for clear lakes). In QPP, because most lakes can be reached only by float plane or canoe and paddle bathymetric mapping can be time consuming and too costly to be feasible. Alternatively, models can be used to estimate maximum lake depth using topographic features (e.g., Hollister et al. 2011), but available models were calibrated using lakes

from areas where the landscape is more uniform than that of the Canadian Shield, on which our study area lies. On the shield, many lakes are characterized by erratic slopes and depths so a model that works for one lake or region may not be transferable to others. In northwestern Ontario, maximum depth is available for more lakes than is mean depth, and the former is also easier to measure. Therefore, the possibility of estimating mean depth from maximum depth for QPP and ATK lakes was assessed along with how HSI values differ based on observed versus estimated mean depths (Appendix 4).

Comparisons of lake suitability for lake trout during the historical and current periods indicated that suitability has already declined. Not surprisingly, decreases were highest for RCP 8.5 and lowest for RCP 2.6, which were associated with temperature increases of 10.1°C and 4.7°C, respectively. These findings are consistent with those of other studies examining the effects of climate change on lake trout habitat. Guzzo and Blanchfield (2017) found that optimal lake trout habitat availability has decreased from 1970–2013 in the Experimental Lakes Area of northwestern Ontario. Mackenzie-Grieve and Post (2006) projected that lake trout thermal habitat volume in southern Yukon lakes could decrease by 40% before 2100.

The conservation rankings can be used to inform monitoring, planning, and management activities in northwestern Ontario. For example, a subset of lakes ranked *very high* and *high* can be selected for long-term water temperature and fish community monitoring. These data could then be used to track whether predicted declines in habitat suitability and lake trout populations occur. Fisheries management plans can include actions such as public awareness campaigns to reduce the introduction of non-native fish and AIS. Harvest regulations can be used to control or reduce introduced fish species abundance.

Our results indicated that many lake trout lakes in the study area already have introduced smallmouth bass and walleye, which are known to negatively affect lake trout. Studies have shown that smallmouth bass can shift lake trout diets from littoral to predominantly pelagic prey sources (Vander Zanden and Rasmussen 1999; Jackson 2017, 2018). In lakes with introduced smallmouth bass and without pelagic prey fishes, body sizes of lake trout are reduced because they are forced to feed primarily on lower energy zooplankton during periods of thermal stratification (Pazzia et al. 2002). In lakes with walleye, stocked fingerling lake trout are particularly vulnerable to predation, especially in spring during stocking and post-spawning when walleye are actively feeding (McMahon and Bennett 1996). In southeastern Ontario, lake trout populations in many small lakes are believed to have been extirpated due to widespread walleye introductions (Evans et al. 1991, Kerr and Grant 2000). The recommendation is to monitor invaded lakes to evaluate and track the status of lake trout.

A threat to lake trout posed by climate change that was not examined in this study is the effect of warmer fall temperatures on lake trout spawning. While evidence exists that lake trout reach their spawning peak on shoals when the water temperature has cooled

to 12 °C (Redick 1967), warmer temperatures could delay the onset of spawning and reduce egg survival and recruitment (Casselman 2002). This additional threat associated with warming will further affect population persistence regardless of a lake's habitat suitability. Therefore, further research is needed to understand the effects of warming on spawning phenology and success.

Our results indicate that many lakes in QPP and ATK currently offer good quality habitat for lake trout, but climate change may put some of these populations at risk. The conservation rankings assigned here are an effective approach to inform conservation and management decisions in the area. Continued research and monitoring are needed to (1) estimate HSI values for other lakes in the study area; (2) assess if predicted decreases in HSI values are occurring; and (3) determine how observed changes in HSI values are affecting lake trout growth, demographics, phenology, and persistence.

6.0 Conclusions

Based on the results of our study, we conclude that:

- Most lake trout lakes in the study area currently have good quality habitat for this species. Lakes in QPP have higher suitability, on average, than those in ATK. Combined with the benefits provided by protected areas (e.g., reduced access and angling pressure), QPP may be an important refuge from climate change for lake trout.
- On average, between the 1971–2000 and 2000–2019 periods, HSI in lake trout lakes has declined by 2.4% in QPP and 4.4% in ATK.
- Reduced HSI values are predicted by 2070–2100, with an average decrease of 18.5% in QPP and 31.6% in ATK lake trout lakes projected for the RCP 8.5 scenario. Introductions of fish and invasive invertebrate species since the early 1970s has further elevated the vulnerability of the lakes.
- Fifty-four per cent of lake trout lakes in QPP and ATK had conservation rankings of *high* or *very high* and these lakes may be important for future lake trout population persistence.
- For at least 59 (55%) of lake trout lakes in QPP and 21 (20%) in ATK, the basic data necessary to estimate HSI values and assess changes in habitat suitability over time are missing. Understanding of the potential effects of climate change on these lakes and fish populations would be improved with more focused monitoring and bathymetric mapping of these lakes.

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Appendix 1. Lake trout habitat suitability model explained

The lake trout habitat suitability model of Lester et al. (2021) estimates suitability using the following understandings and equations:

- Differences in lake trout habitat suitability are due partly to variation in the cross-sectional shape of the lake and is estimated by the depth ratio:

$$Depth\ ratio = Max\ depth / Mean\ depth$$

- Thermocline depth can be estimated from lake area (ha), mean depth (m), and air temperature (˚C). Increases in mean annual air temperature result in a shallower thermocline (i.e., in hotter temperatures, lakes warm faster, which results in shallower thermoclines compared to cooler conditions):

$$Thermocline\ depth = 3.26 \times Area^{0.109} \times\ Mean\ depth^{0.213} \times\ e^{-0.0263 \times Mean\ ann\ temp}$$

- The proportion of the lake volume below the thermocline describes the potential habitat available to lake trout during the summer when habitat space is most limiting. It is estimated from thermocline depth (m), maximum depth, (m) and the depth ratio:

$$Relative\ volume\ of\ hypolimnion = (1 - Thermocline\ depth / Max\ depth)^{Depth\ ratio}$$

Habitat suitability is predicted to be highest in very deep lakes where hypolimnetic volume is large and epibenthic volume (i.e., volume of lake shallower than where the thermocline touches bottom) is small, but this relationship is affected by temperature. Increasing temperature tends to increase the productivity (or rate of biomass turnover) in shallower areas of the lake. In addition, higher temperatures increase the length of time the lake remains stratified, which isolates the hypolimnion from oxygen input for a longer period. Overall, increased biomass turnover results in higher oxygen demand in the hypolimnion as organisms die and decompose, for increasing periods of time, which reduces the amount of hypolimnetic oxygen available for use by lake trout. Lake trout habitat suitability is estimated to increase with relative hypolimnion volume and decrease with mean annual air temperature by the following relationship:

$$Habitat\ suitability = 1/(1\ +\ e^{2.47 + 0.386 \times Mean\ ann\ temp - 16.8 \times Relative\ volume\ of\ hypolimnion})$$

Appendix 2. Habitat suitability, introduced species, and conservation ranking for 125 lake trout lakes in Quetico Provincial Park and the Atikokan area

Table A2.1. List of 125 lake trout lakes in Quetico Provincial Park (QPP) and the Atikokan area (ATK) in northwestern Ontario and the habitat suitability index values (HSI) for the historical (1971–2000), current (2000–2019), and future (2070–2100; based on representative concentration pathway (RCP) 2.6, 4.5, and 8.5 scenarios) periods. Introduced fish species were smallmouth bass (SMB), largemouth bass (LMB), black crappie (BC), walleye (W), rainbow smelt (RS), the aquatic invasive invertebrate was spiny waterflea (SWF), and UKN = unknown.

Lake name	Study area	Introduced species	HSI - 1971–2000	HSI - 2000–2019	HSI - RCP 2.6	HSI RCP 4.5	HSI RCP 8.5	Conservation ranking
Agnes	QPP	SMB	0.99	0.99	0.98	0.97	0.94	High
Argo	QPP	SMB	0.99	0.99	0.99	0.98	0.97	High
Bart	QPP	SMB	0.23	0.19	0.14	0.1	0.05	Low
Batchewanung	QPP	SMB, RS	0.99	0.99	0.98	0.98	0.95	High
Beaverhouse	QPP	SMB	0.99	0.99	0.99	0.98	0.97	High
Blackstone	QPP	SMB	0.91	0.89	0.85	0.8	0.66	Moderate
Burke	QPP	SMB	0.99	0.99	0.99	0.98	0.96	High
Burntside	QPP	SMB	0.78	0.74	0.65	0.56	0.38	Low
Burt	QPP	SMB	1	1	1	0.99	0.98	High
Cirrus	QPP	SMB, BC	1	0.99	0.99	0.99	0.97	High
Darkwater	QPP	SMB, BC	0.99	0.99	0.98	0.97	0.94	High
French	QPP	SMB, RS, SWF	0.96	0.95	0.93	0.9	0.82	Moderate
Jean	QPP	SMB	0.99	0.99	0.98	0.97	0.93	High
Kahshahpiwi	QPP	SMB	1	0.99	0.99	0.99	0.97	High
Kasakokwog	QPP	SMB	1	1	0.99	0.99	0.98	High
Louisa	QPP	UKN	1	1	0.99	0.99	0.98	Very high
Mcalpine	QPP	SMB	0.99	0.99	0.98	0.98	0.95	High
Mcaree	QPP	SMB, BC	0.94	0.93	0.9	0.86	0.75	High
Mcewen	QPP	SMB	0.95	0.94	0.92	0.88	0.79	High
No Man	QPP	SMB	0.14	0.12	0.08	0.06	0.03	Low
Olifaunt	QPP	SMB, RS	0.96	0.95	0.93	0.91	0.83	High
Oriana	QPP	SMB	0.91	0.89	0.84	0.79	0.65	Moderate
Other Man	QPP	SMB	0.96	0.95	0.93	0.9	0.82	High
Pickerel	QPP	SMB, RS, SWF	0.97	0.96	0.95	0.92	0.85	Moderate
Pond	QPP	SMB, W	0.97	0.97	0.95	0.93	0.87	High
Poohbah	QPP	SMB, LMB, SWF	0.98	0.98	0.97	0.95	0.9	High
Quetico	QPP	SMB	0.9	0.88	0.83	0.76	0.61	Moderate
Rawn	QPP	SMB, RS, SWF	0.91	0.89	0.84	0.79	0.65	Low
Robinson	QPP	SMB	0.96	0.96	0.94	0.91	0.83	High
Roland	QPP	SMB	0.97	0.96	0.94	0.92	0.85	High

Lake name	Study area	Introduced species	HSI - 1971–2000	HSI - 2000–2019	HSI - RCP 2.6	HSI RCP 4.5	HSI RCP 8.5	Conservation ranking
Saganagons	QPP	SMB, RS, SWF	0.32	0.27	0.19	0.13	0.07	Low
Sarah	QPP	SMB	0.99	0.98	0.98	0.96	0.93	High
Sheridan	QPP	SMB	0.98	0.98	0.97	0.96	0.92	High
Silence	QPP	SMB	0.41	0.36	0.28	0.21	0.12	Low
Soho	QPP	SMB	1	0.99	0.99	0.99	0.97	High
Sunday	QPP	SMB, BC	0.99	0.99	0.98	0.97	0.94	High
That Man	QPP	SMB, BC	0.98	0.98	0.97	0.95	0.9	High
This Man	QPP	SMB, BC	0.96	0.95	0.93	0.9	0.82	High
Wolseley	QPP	SMB, BC	0.92	0.91	0.87	0.82	0.7	High
Abbess	ATK	SMB	0.99	0.98	0.98	0.97	0.93	High
Adele	ATK	UKN	0.9	0.88	0.83	0.77	0.62	Moderate
Below Bow (S.E. Basin)	ATK	SMB, W	0.16	0.13	0.08	0.06	0.03	Low
Bethune	ATK	W	0.45	0.39	0.29	0.22	0.12	Low
Bow (Lower Bow)	ATK	SMB, W	0.73	0.69	0.59	0.5	0.33	Low
Bow (Upper Bow)	ATK	SMB, W	0.22	0.18	0.13	0.09	0.04	Low
Campus	ATK	SMB	0.65	0.61	0.51	0.43	0.28	Low
Clearwater West	ATK	SMB	1	1	0.99	0.99	0.98	High
Cole	ATK	SMB	0.91	0.89	0.85	0.8	0.68	Moderate
Como	ATK	SMB, W	0.77	0.73	0.65	0.56	0.4	Moderate
Crook	ATK	UKN	0.71	0.67	0.58	0.48	0.32	Low
Crowrock	ATK	SMB, W	0.53	0.47	0.36	0.27	0.15	Low
Crystal	ATK	SMB, W, RS	0.99	0.98	0.97	0.96	0.92	High
Dashwa	ATK	SMB, W	0.96	0.95	0.92	0.89	0.8	High
Doan	ATK	SMB	0.63	0.57	0.47	0.38	0.23	Low
Dovetail	ATK	SMB, W	0.06	0.04	0.02	0.01	0	Low
Dragon	ATK	UKN	0.85	0.82	0.77	0.7	0.56	Moderate
East Hardtack	ATK	W	0.52	0.47	0.37	0.29	0.17	Low
Elbow	ATK	SMB	1	1	1	0.99	0.98	High
Elsie	ATK	SMB	0.98	0.98	0.97	0.95	0.9	High
Emery	ATK	UKN	1	1	1	1	0.99	Very high
Eva	ATK	SMB, RS	0.95	0.94	0.91	0.87	0.77	High
Eye	ATK	SMB, W	0.13	0.1	0.07	0.04	0.02	Low
Factor	ATK	SMB	0.95	0.94	0.92	0.88	0.78	High
Finlayson	ATK	SMB	0.98	0.97	0.96	0.95	0.89	High
Fish (E. Campus)	ATK	SMB	0.93	0.92	0.88	0.84	0.72	High
Flora	ATK	UKN	0.99	0.99	0.99	0.98	0.96	Very high
Forsberg	ATK	W	0.92	0.9	0.86	0.81	0.68	Moderate
Gamble	ATK	SMB	0.89	0.86	0.8	0.74	0.58	Moderate
Gargoyle	ATK	UKN	0.17	0.13	0.08	0.05	0.02	Low
Grey Trout	ATK	W	0.98	0.98	0.97	0.96	0.91	High
Gulliver	ATK	UKN	0.84	0.8	0.73	0.65	0.47	Moderate
Hardtack	ATK	W	0.96	0.95	0.92	0.89	0.79	High
Herb	ATK	UKN	0.98	0.97	0.96	0.94	0.89	Very high

Lake name	Study area	Introduced species	HSI - 1971–2000	HSI - 2000–2019	HSI - RCP 2.6	HSI RCP 4.5	HSI RCP 8.5	Conservation ranking
Heuston	ATK	UKN	1	0.99	0.99	0.99	0.97	Very high
Holmes	ATK	UKN	0.99	0.99	0.99	0.98	0.96	Very high
Irene	ATK	W, SMB	1	1	1	0.99	0.98	High
Jim	ATK	SMB	0.77	0.73	0.65	0.57	0.41	Moderate
Kingfish	ATK	SMB	0.87	0.84	0.78	0.71	0.55	Moderate
Lake 20	ATK	UKN	0.98	0.98	0.97	0.95	0.91	Very high
Lake 26	ATK	UKN	0.99	0.99	0.99	0.98	0.96	Very high
Lake 39	ATK	UKN	0.95	0.94	0.92	0.89	0.8	High
Lake 42	ATK	UKN	0.81	0.78	0.71	0.63	0.47	Moderate
Little Bow	ATK	SMB, W	0.47	0.41	0.32	0.24	0.14	Low
Little Greytrout	ATK	UKN	0.91	0.89	0.85	0.8	0.66	Moderate
Little Gull	ATK	SMB, W	0.95	0.94	0.92	0.88	0.78	High
Little Irene	ATK	UKN	0.99	0.99	0.98	0.98	0.95	Very high
Little Sanford	ATK	UKN	0.97	0.97	0.95	0.93	0.87	Very high
Mabel	ATK	SMB	0.87	0.84	0.79	0.73	0.58	Moderate
Marion	ATK	SMB	0.59	0.53	0.43	0.34	0.2	Low
Mccaulay	ATK	UKN	1	1	0.99	0.99	0.98	Very high
Miller (Wolf)	ATK	W	0.75	0.71	0.63	0.54	0.38	Low
Monte	ATK	UKN	0.97	0.96	0.95	0.93	0.86	Very high
Mount	ATK	SMB	0.92	0.9	0.87	0.82	0.69	Moderate
Narrow	ATK	SMB	0.82	0.79	0.73	0.67	0.52	Moderate
Nevison	ATK	UKN	0.74	0.7	0.62	0.54	0.38	Low
Niobe	ATK	SMB	0.42	0.37	0.28	0.21	0.12	Low
Niven	ATK	UKN	0.86	0.83	0.76	0.69	0.52	Moderate
Norway	ATK	UKN	1	1	1	0.99	0.98	Very high
Nydia	ATK	SMB	0.9	0.88	0.83	0.77	0.62	Moderate
Nym	ATK	SMB, W	0.63	0.57	0.47	0.37	0.23	Low
Owl	ATK	SMB	0.47	0.43	0.36	0.3	0.2	Low
Pekagoning	ATK	SMB	0.84	0.81	0.74	0.66	0.5	Moderate
Peterson	ATK	UKN	0.99	0.99	0.98	0.97	0.94	Very high
Pettit	ATK	SMB	0.74	0.7	0.62	0.54	0.39	Low
Redpaint	ATK	UKN	0.96	0.95	0.93	0.9	0.82	High
Riverview	ATK	UKN	1	1	0.99	0.99	0.98	Very high
Roughstone	ATK	UKN	0.87	0.85	0.79	0.73	0.58	Moderate
Rutter	ATK	UKN	0.33	0.27	0.2	0.14	0.07	Low
Sandbeach	ATK	SMB	1	1	0.99	0.99	0.97	High
Sandford	ATK	SMB	1	1	1	1	0.99	High
Scotch	ATK	UKN	0.65	0.6	0.5	0.41	0.27	Low
Secret	ATK	UKN	0.99	0.98	0.98	0.97	0.93	Very high
Sedgwick	ATK	UKN	1	1	1	0.99	0.98	Very high
Serpent	ATK	UKN	0.88	0.85	0.79	0.72	0.56	Moderate
Silvertip	ATK	SMB	0.99	0.99	0.98	0.97	0.94	High
Sparkle	ATK	UKN	0.75	0.71	0.62	0.54	0.38	Low
Star	ATK	UKN	0.99	0.99	0.98	0.98	0.95	Very high

Lake name	Study area	Introduced species	HSI - 1971–2000	HSI - 2000–2019	HSI - RCP 2.6	HSI RCP 4.5	HSI RCP 8.5	Conservation ranking
Thompson	ATK	SMB	0.86	0.83	0.77	0.69	0.53	Moderate
Turtle	ATK	SMB, W	0.37	0.32	0.24	0.18	0.1	Low
UNNAMED (north Of Finlayson)	ATK	UKN	1	0.99	0.99	0.99	0.97	Very high
Van Nostrand	ATK	UKN	0.77	0.73	0.65	0.56	0.4	Moderate
Walt	ATK	UKN	0.96	0.95	0.93	0.9	0.81	High
Wasp	ATK	SMB, W	0.6	0.55	0.45	0.36	0.22	Low
White Otter	ATK	SMB	0.98	0.98	0.97	0.95	0.91	High
Windigoostigwan	ATK	SMB	0.99	0.99	0.99	0.98	0.97	High

Appendix 3. Lake trout lakes in Quetico Provincial Park missing depth data

Table A3.1. List of lake trout lakes in Quetico Provincial Park, northwestern Ontario, lacking depth information as of March 2020. NA=not available

Name (English)	Name (Anishinaabemowin)	Easting	Northing	Area (ha)	Mean depth (m)	Maximum depth (m)
Anchor Lake	NA	61533	615550	88	NA	NA
Antoine	NA	60537	609069	336	NA	NA
Art Lake	NA	62538	626250	100	NA	NA
Basswood	Baasiminaani Zaaga'igan	60532	606947	4840	NA	NA
Bell	NA	63534	639292	62	NA	NA
Birch	NA	61532	618906	174	NA	NA
Bock	NA	63533	635000	57	NA	NA
Brent	Gaa'aabaji gamaag	59535	593829	945	NA	NA
Buckingham	NA	62537	628312	300	NA	NA
Cache	NA	64537	643916	521	NA	NA
Carp	NA	62532	627652	466	NA	NA
Cone	NA	59534	593723	68	NA	NA
Cullen	NA	64535	647196	177	NA	NA
Dack	NA	62534	626845	193	NA	NA
Deer	NA	60534	603150	90	NA	NA
Delahey	NA	60535	608130	251	NA	NA
Dore	NA	61538	614771	296	NA	NA
Draper	NA	60537	602582	180	NA	NA
Elk	NA	59534	593070	155	NA	NA
Emerald	NA	63533	630699	250	NA	NA
Ferguson	NA	63537	635701	483	NA	NA
Fran	NA	64534	641911	40	NA	NA
Glacier	NA	63534	631631	115	NA	NA
Goodier	NA	61533	618457	58	NA	NA
Hamburg*	Gaazhiibaa'aandagaawi Zaaga'igan	60538	602208	172	NA	NA
Hoare*	NA	60536	606556	79	NA	NA
Hurlburt	NA	61535	618452	136	NA	NA
Hurn	NA	59534	595029	111	NA	NA
Jeff	NA	61533	617775	119	NA	NA
Josey (Lake 8 Block 5 - east of Darkwater)	NA	59534	591000	45	9.2	NA
Joyce	NA	60534	610779	433	NA	NA
Kawnipi	Gaawawegamaag or Gaa'aniib minaanikaag	62536	627000	4488	NA	NA
Keefer	NA	61535	615055	230	NA	NA
Keewatin	NA	62535	624697	64	NA	NA

Name (English)	Name (Anishinaabemowin)	Easting	Northing	Area (ha)	Mean depth (m)	Maximum depth (m)
Kett	NA	60533	601650	146	NA	NA
Lake between Argo and Cone	NA	59534	591500	21	NA	NA
Lake Between Sarah and Kahshahpiwi	NA	60534	608000	99	NA	NA
Lemay	NA	62536	629587	172	NA	NA
Little Jean	NA	59537	597820	124	NA	NA
Little Lousia Lake (NW of Louisa)	NA	62533	623500	38	NA	NA
Little Poohbah (unnamed lake just west of Poohbah)	NA	59535	594450	130	NA	NA
Littlerock	NA	63533	633736	22	NA	NA
Lonely	NA	60537	603932	386	NA	NA
Magie	NA	62533	625332	35	NA	NA
Marj	NA	60534	607388	231	NA	NA
McDougall	NA	61536	614959	372	NA	NA
McIntyre	NA	60534	602763	553	NA	NA
McKenzie	NA	64537	644666	1957	NA	NA
McNaught *	NA	60533	605322	54	NA	NA
McNiece	NA	61534	614295	58	NA	NA
Milt	NA	58534	596600	67	NA	NA
Murdoch *	NA	62535	627885	275	NA	NA
Nest	NA	60533	608241	75	NA	NA
Paulene	NA	60534	604123	72	NA	NA
Plough	NA	63533	634631	52	NA	NA
Poacher	NA	61532	618929	123	NA	NA
Ram	Baanaabe Zaaga'igan	60537	609632	80	NA	NA
Russell	NA	61537	612563	1092	NA	NA
Sark	NA	61535	616414	283	NA	NA
Shade	NA	61533	615209	213	NA	NA
Side	NA	60533	608900	27	NA	NA
Summer	NA	61534	617516	53	NA	NA
Suzanette	NA	60535	603009	281	NA	NA
Ted	NA	59534	597677	110	NA	NA
Tuck	NA	60533	601697	287	NA	NA
Walter	NA	60537	605057	305	NA	NA
Williams	NA	62535	621928	180	NA	NA
Yum Yum	NA	61534	613397	85	NA	NA
Saganaga	NA	65534	650500	857	NA	85

Name (English)	Name (Anishinaabemowin)	Easting	Northing	Area (ha)	Mean depth (m)	Maximum depth (m)
Little Knife	NA	63533	637660	118	NA	56
Knife	NA	63532	632992	608	NA	55
Ottertrack	Nigig Gaabimikawed	64533	642870	325	NA	35

* Suspected lake trout lake

Appendix 4. Estimating mean lake depth and habitat suitability from maximum depth

While maximum lake depth is relatively easy to collect, mean depth estimates require some level of bathymetric mapping to obtain lake volume estimates, which involves increased time and cost. As such, we explored the possibility of estimating mean depth from maximum depth for lakes in QPP and ATK. If successful, this approach would allow lake trout HSI to be estimated for remote lakes using only maximum depth data.

Currently, maximum depth estimates are available for 348 lakes in QPP and ATK but mean depth is available for only 287 of those lakes (82%). For several lakes, some of which are known or suspected to have lake trout, depth data is not available. Missing data is even more of an issue in QPP, which has 105 known lake trout lakes, of which both mean and maximum depth values are available for only 39, with estimates of maximum depth available for another 4, leaving over half the lakes without the data needed to assess lake trout HSI (see Appendix 3 for list of lakes without data). For many of these lakes obtaining an estimate of maximum depth is feasible, but getting bathymetry data is more difficult, especially from the remote ones. In these cases, the option to estimate mean depth accurately enough to use the lake trout habitat suitability model would be valuable in these cases.

In the past, mean depth estimates were made using a rule of “1/3 maximum depth” or slope of 0.33 (Richard Ryder, MNRF scientist, unpublished data). We compared lakes from QPP and ATK with measured maximum depth and mean depths to determine the accuracy of this rule and found that a power regression fit the data (r^2 = 0.85) better than the “rule of 1/3 maximum depth” (Figure A4.1). Habitat suitability indices were calculated for all QPP and ATK lakes using the observed mean depths and estimated mean depths derived using the power equation $Dmean=0.5959 \times Dmax^{0.8134}$ for the historical period (Figure A4.2) and RCP 8.5 2070–2100 (Figure A4.3).

Habitat suitability indices derived from observed and estimated mean depths were similar (Figure A4.2-4.3). However, differences between the estimates increased as HSI decreased and as temperatures increased with future predictions (Table A4.1). These results suggest that the maximum depth and mean depth relationship derived here could provide temporary HSI estimates, particularly for lakes with a high HSI. Lakes with HSI values <0.9 should be prioritized for bathymetric mapping to increase the precision of HSI estimates.

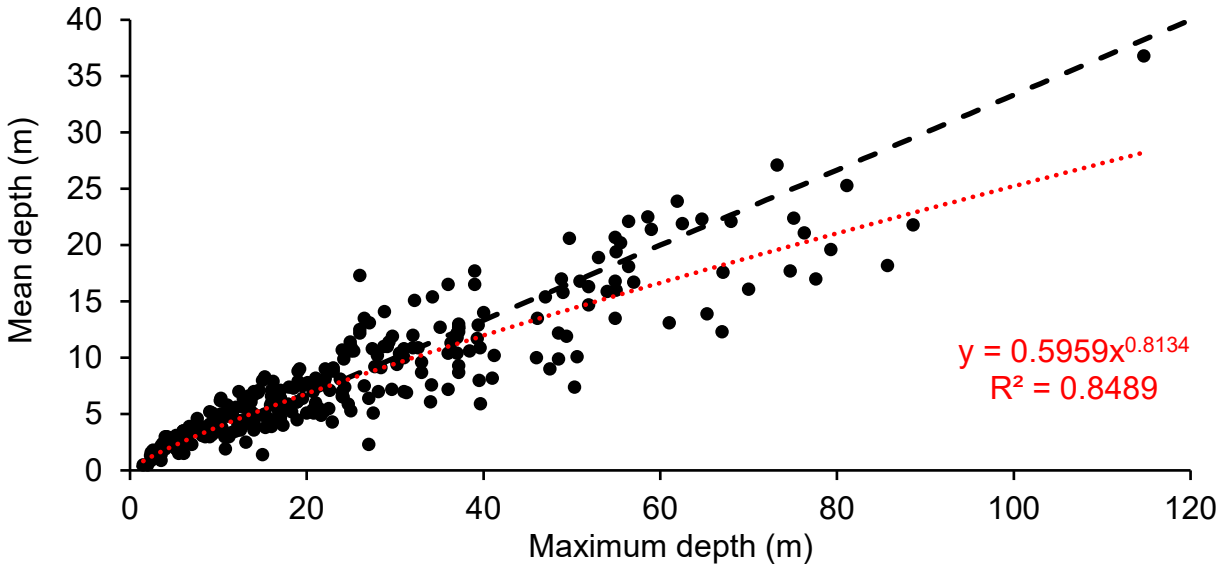


Figure A4.1. Mean depth vs. maximum depth for all lakes with observed mean and maximum depth data in Quetico Provincial Park and Atikokan area in northwestern Ontario (n=287). Black dashed line is the 1/3 rule to estimate mean depth from maximum depth and orange dotted line is the power fit.

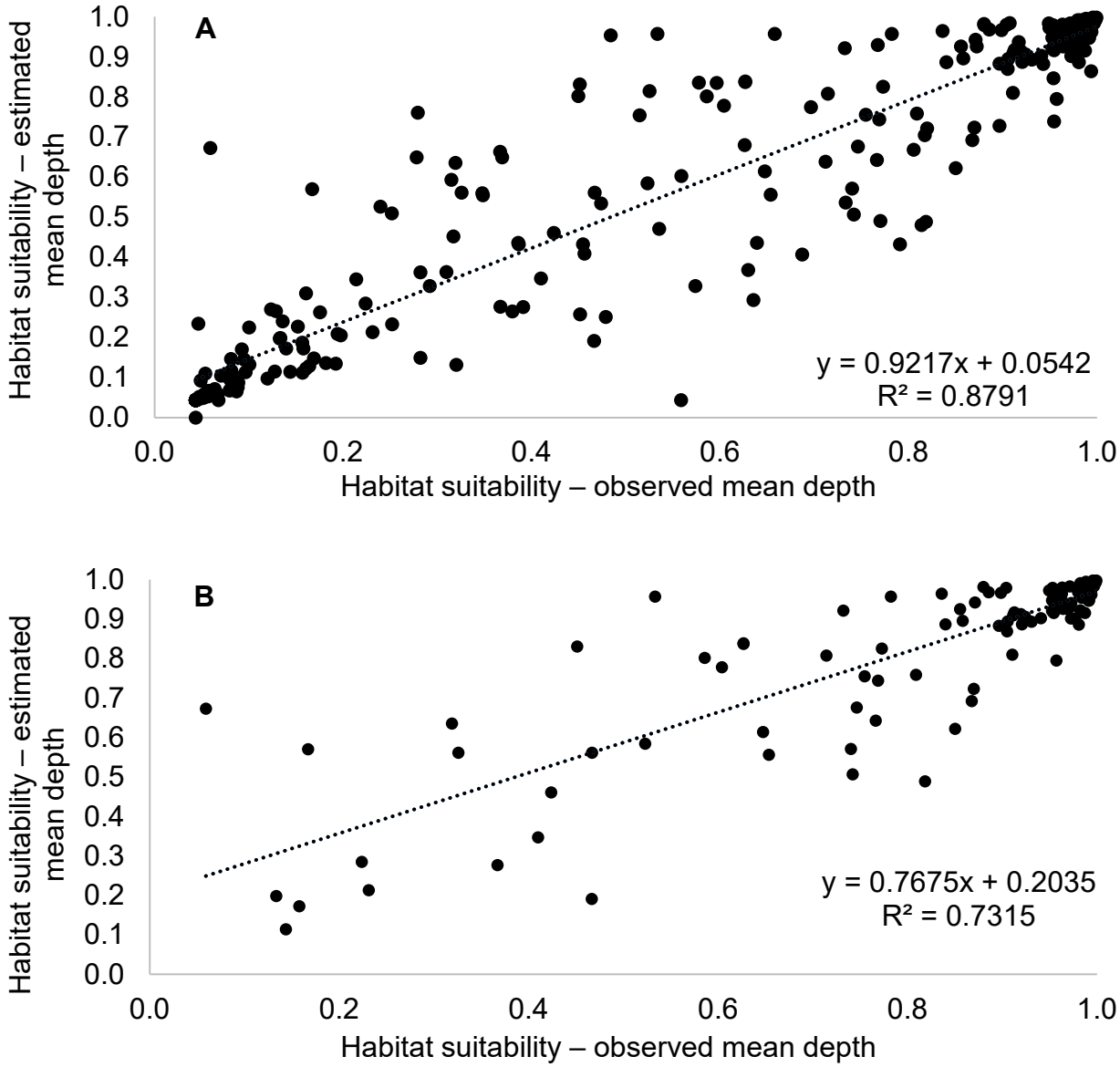


Figure A4.2. Comparison of lake trout habitat suitability for the historical (1971–2000) period calculated using estimated vs. observed mean depth. Panel A shows all lakes in Quetico Provincial Park (QPP) and Atikokan (ATK) area (n=280) in northwestern Ontario; panel B shows only lake trout lakes in QPP and ATK (n=125).

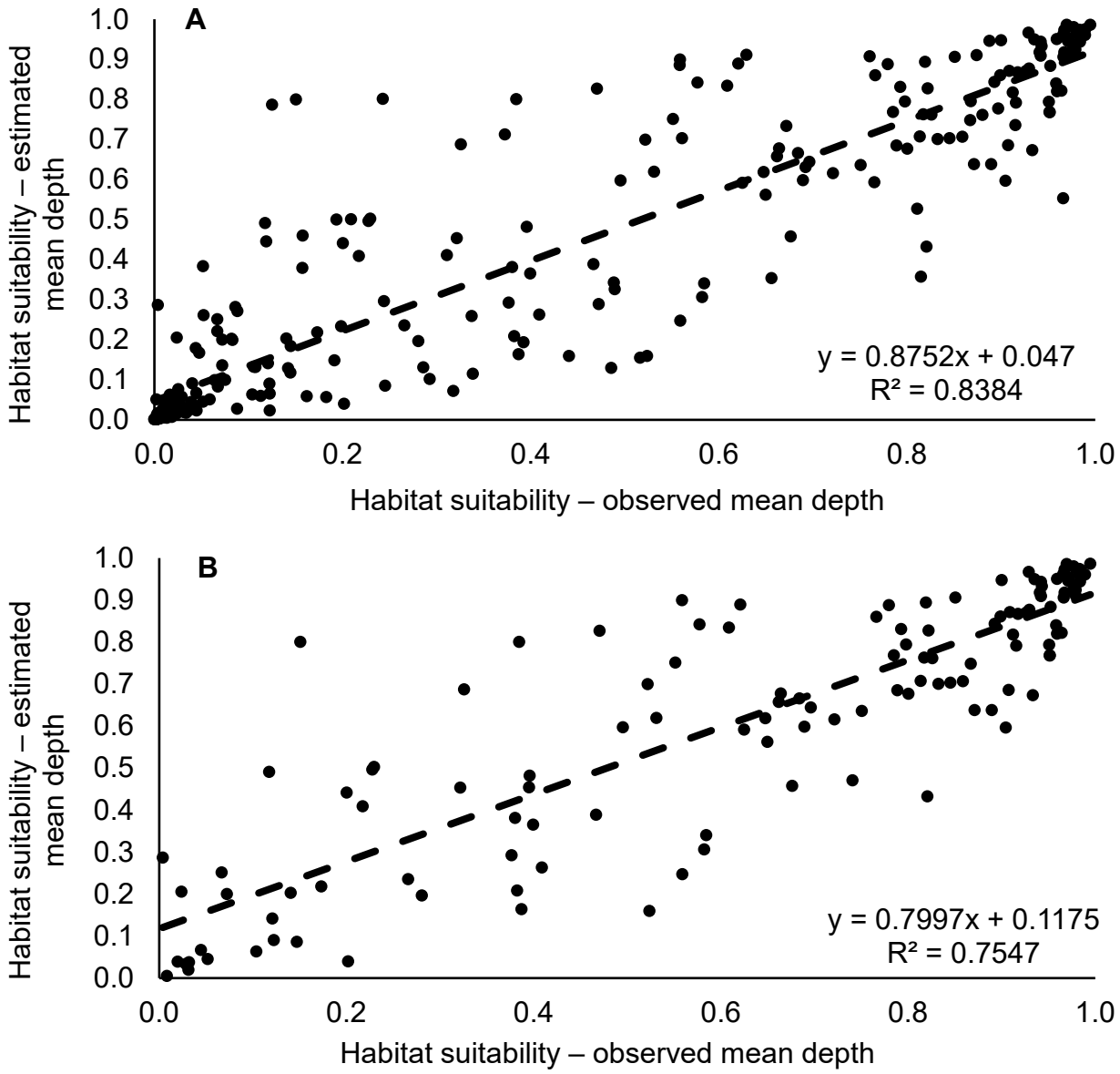


Figure A4.3. Comparison of lake trout habitat suitability for the future (RCP 8.5 2070–2100) period calculated using estimated vs. bathymetric mean depth. Panel A shows all lakes for Quetico Provincial Park (QPP) and Atikokan (ATK) area (n=280) in northwestern Ontario; panel B shows all lake trout lakes for the QPP and ATK area (n=125).

Table A4.1. Percent differences between habitat suitability index values calculated from estimated versus observed mean depth for lakes in Quetico Provincial Park (QPP) and Atikokan (ATK) area in northwestern Ontario. Data are shown for all lake trout lakes (n=125) for the historical (1971–2000) and future (RCP 8.5 2070–2100) periods and for QPP only lake trout lakes (n=39).

	QPP and ATK lakes		**QPP lakes**	
Difference category	Historical	RCP 8.5	Historical	RCP 8.5
Moderate overestimate (>0.1)	11	18	5	8
Small overestimate (0 to 0.1)	24	18	23	21
Small underestimate (0 to -0.1)	58	40	69	49
Moderate underestimate (<-1)	7	25	3	23

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