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An Assessment of Burbot Life History in Minnesota with a Focus on Movement Dynamics and Spawning Vulnerability

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STATEMENT BY THE AUTHOR

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Chapter 1: Seasonal variations in home-range size concerning the spawning vulnerability of Burbot

Abstract.- Burbot have a circumpolar range spanning from rivers of Alaska to lentic systems in Minnesota. Although Burbot population dynamics have been studied, their movement dynamics have been rarely investigated. Our objectives were to assess seasonal home range changes of Burbot in a closed-lentic system and quantify the scale of spawning aggregations. Sixty-six Burbot were implanted with acoustic transmitters in Bad Medicine Lake, Minnesota, with 32 surviving the length of the study period between 10 April 2019 to 11 June 2020. The peak spawning date for Burbot in Bad Medicine Lake was estimated to be mid-March, when home range estimates were two times larger than at any other point in the study. Female estimated home range size was significantly larger than males across the study. Fish movement was synchronized with ice formation in December and continued through March when they explored new areas. Home range estimates were smallest in mid-April, likely due to post-spawn behaviors. Spawning locations were estimated using the ArcGIS Optimized Hot Spot Analysis tool. Results show there are multiple locations in Bad Medicine Lake that Burbot used during the spawn. However, Burbot heavily used the eastern shore, which includes steep, rocky drop-offs compared to the west side. Our results provide evidence to suggest Burbot do cluster during spawning, potentially increasing their vulnerability to anglers. High exploitation rates are likely to occur in situations where spawning Burbot, which are actively feeding, are met by intense angling pressure. Our results will assist fisheries managers in determining appropriate measures to protect the fish during a potential vulnerable stage. Results highlight how movement patterns differ in the species throughout its circumpolar distribution. Future research should continuously monitor Burbot populations and assess how populations can be affected by changes in their environment, specifically climate change.

Introduction

Burbot *Lota lota* is the only freshwater species of the Gadidae family and one of two fish species with a circumpolar distribution in the northern hemisphere (McPhail and Lindsey 1970). Found in rivers and lakes, Burbot habitat preferences vary by life stage. Throughout their life, Burbot inhabit waters ranging from the pelagic zone as larvae (Ghan and Sprules 1993; Wang and Appenzeller 1998; Fischer 1999) to the littoral zone as juveniles (Scott and Crossman 1973; Ryder and Pesendorfer 1992; Hofmann and Fischer 2001), and the profundal zone as adults (Lawler 1963; Scott and Crossman 1973). In lakes, larval Burbot are typically pelagic (Hofmann and Fischer 2001), and juvenile Burbot occupy the same substrates as riverine Burbot, including rocky shorelines (Fischer and Eckmann 1997; Fischer 1999). Adult Burbot in lakes typically inhabit depths below the thermocline (Carl 1995). In unique cases, Burbot were found as deep as 300 m in Lake Superior (Boyer et al. 1989), where researchers found them burrowing into the soft substrate. However, these depths contain temperatures below Burbot reported optimum of 15 to 18 ˚C (Scott and Crossman 1973). In rivers, adult Burbot inhabit main channels and enter backwater tributaries during the fall, preparing to spawn (Chen 1969; Stein et al. 1973). Fisher (2000) found juvenile Burbot occupying depths greater than 1.5 m with some flow, temperatures below 20 ˚C, and neighboring vegetation. Larval Burbot seek refuge in weed beds, under rocks, and near cut-banks (Hanson and Qadri 1980).

Burbot circumpolar distribution reaches as far north as the Northwest Territories (Cott et al. 2015) to as far south as Kansas in the Missouri River drainage (Harlan et al. 1987). Knowledge of Burbot abundance in their southern range is limited, and population sizes appear low. Harlan et al. (1987) classified Burbot as a species of little consequence because of their uncommon status throughout Iowa and Kansas due to upper water temperature limits. A similar population status exists in southern Wisconsin, where Burbot are rarely found in standard surveys. This trend is shared through the rest of the northern United States. However, Burbot are invasive in some southern reservoirs, becoming abundant enough to be a problem (Brauer et al. 2019). Biologists in Minnesota have raised concerns that decreases in Burbot abundance in Lake Mille Lacs might stem from increases in warmer water temperatures beginning in the 1980s (Stapanian et al. 2010), raising additional concerns about how climate change may affect the overall population dynamics of the species.

As adults, Burbot typically spawn from January to March in water temperatures ranging between 0 to 4 ˚C (Becker 1983). However, Burbot spawned as late as May when water temperatures reached 5.6 ˚C in Lake Constance, Germany (Fischer 1999). In lentic systems, reproduction typically occurs under the ice (Scott and Crossman 1973), in shallow depths ranging between 1.5 to 10 m (Clemens 1951; McCrimmon 1959; Becker 1983; Boag 1989). Known spawning substrate consists of sand, gravel, or cobble (McCrimmon and Devitt 1954; Chen 1969; Sorokin 1971; Boag 1989). In riverine systems, Burbot travel long distances upwards of 100 to 200 km to spawn (Breeser et al. 1988; Evenson 1993). However, there is minimal knowledge of spawning locations for lentic Burbot populations, except in Idaho and Wyoming reservoirs, where Burbot spawn in tributaries (Evans et al. 2019).

Burbot movement has been studied using various sampling techniques throughout their latitudinal and longitudinal range. Using combinations of hydroacoustic surveys (Vehanen et al. 1998; Probst 2008), radio telemetry (Evenson 1993; Arndt and Baxter 2006; Mouton et al. 2012), and acoustic telemetry (Breeser et al. 1988; Paragamian and Wakkinen 2008; Harrison et al. 2015, 2016). Movement research has often focused on migration patterns in riverine and reservoir systems, with few studies conducted on lakes (Cott et al. 2015). Studies documented timing, periodicity, and spatial movement from feeding to spawning and overwintering areas. However, no known studies have characterized Burbot's home-range size and seasonal movement patterns of lentic populations with no inlet or outlet. Likewise, few studies have investigated male and female Burbot movement patterns, with no known studies quantifying differences in home-range size. Home-range differences between male and female fish have been investigated in other species, including the close relative, the Atlantic Cod *Gadus morhua*. Dean et al. (2014) investigated spawning migrations and habitat selection of Atlantic Cod using fine-scale telemetry. Male cod were found to have more extensive home ranges than females during the spawning period. While both male and female home ranges increased at night compared to daytime, the size of male cod's home ranges was 50% larger than females.

Acoustic telemetry is a widespread practice for assessing animals movement patterns, migration habits, and general use of an area. In fishes, acoustic telemetry helps assess passage, survival, habitat use, home range size, and potential changes due to human influences or climate change (Donaldson et al. 2014). Advances in technology have allowed researchers to discover daily and seasonal patterns in fish movement (Donaldson et al. 2014). Additionally, with continued and repetitive monitoring of a species using temperature sensing tags, researchers may notice small-scale shifts in temperature use that could help quantify the effects of climate change. Understanding fish home range can result in important management implications for biologists and fisheries researchers. Knowledge of species movements associated with their habitat may reveal environmental requirements. Subsequently, these requirements may influence the success of fish populations. For example, information on home range patterns helps fisheries managers indicate the best times and places to sample, resulting in the data used to estimate the population dynamics of that species. Because generous harvest quotas can deplete small, localized populations, home range data can help managers establish seasons and harvest quotas.

This project studies the movement and habitat use of Burbot over 16 months, using acoustic telemetry, and evaluates the spawning habits of Burbot in a closed lentic system. Results can help fisheries managers understand the vulnerability of Burbot and implement management strategies to protect the species from elevated angling exploitation. Previous knowledge indicates Burbot spawn in clusters of a few to numerous fish. However, no understanding of spawning location preferences exists or if a lake population spawns at one or many sites. We hypothesized that (1) the home range size of Burbot increases during the winter months to coincide directly with their spawning season; (2) spawning occurs in few centralized locations of the lake, increasing Burbot's vulnerability to anglers; and (3) males and females will have different home-range sizes across seasons.

Methods

Study Site. – The study occurred at Bad Medicine Lake, located approximately 35 km northwest of Park Rapids, Minnesota, United States (Figure 1.1). Bad Medicine Lake is a 325 ha, spring-fed mesotrophic lake that undergoes thermal stratification during the summer months (MPCA 2020). Approximately 6 km long and 700 m at its widest, Bad Medicine Lake reaches a maximum depth of approximately 25 m. Historical water quality data show a mean ice-free Secchi disk reading of 7.79 m since 2015 (MPCA 2020). The fish community consists primarily of Burbot, Rainbow Trout *Oncorhynchus mykiss,* and Smallmouth Bass *Micropterus dolomieu*. Northern Pike *Esox Lucius*, Walleye *Sander vitreus*, Yellow Perch *Perca flavescens*, Black Crappie *Pomoxis nigromaculatus*, and

Bluegill *Lepomis macrochirus* are also present. Bad Medicine Lake is stocked annually in spring and fall with, on average, 16,000 yearling Rainbow Trout (MNDNR 2019). Historically plentiful in the lake, Walleye are stocked on even years with a total of 5,000 – 17,000 fingerlings per year (MNDNR 2019).

Study Animals. – Burbot (*n* = 66; mean ± SD = 484.0 ± 78.3 mm TL) were implanted with V9TP-2L transmitters (Innovasea, Vemco Ltd; Halifax, Canada) during the 2019 spawning season. Burbot were caught by anglers through the ice using standard ice fishing equipment. Fish were immediately transferred to an aerated trough, where they were deemed healthy or not healthy enough to undergo surgery. Fish that exhibited normal buoyancy and swim patterns were considered good candidates for implantation. In contrast, fish that showed signs of barotrauma or angling effects were considered unsuitable for surgical implantation of an acoustic transmitter. Sixty of the transmitters broadcasted unique coded acoustic signals at random intervals between 880 and 1,080 seconds, with six transmitters having delays of 300 to 420 seconds. Transmitters had an expected lifespan of 24 months. All transmitters contained a pressure sensor that reported swimming depth (± 0.5 m) at transmission and a temperature sensor that reported internal body temperature. Sensors would alternate the type of transmission that the receivers could detect. Transmitters were divided among males (*n* = 23), females (*n* = 22), and fish of undetermined sex (*n* = 21). Transmitters were dispersed across the system to limit tag collision. Fish were targeted between depths of 3 to 10 m to avoid potential effects of barotrauma, and fishing occurred each night at a new location.

Surgical Procedure. – Surgical procedures followed those outlined by (Wagner et al. 2011). Tagging started on 18 March and concluded on 2 May 2019. Fish were measured for total length (mm), weight (g), and sex (male, female, unknown). Fish deemed unfit for surgery were immediately released after measurements were taken. Fish saved for surgery were placed in a holding tray while immobilized with ventral side up using Smith-Root's Fish Handling Gloves (Smith-Root, Inc., Vancouver, Washington). Gills were continuously irrigated during the surgical process. Before each surgery, surgical equipment was disinfected with Nolvasan S (0.78% dilution in water). An incision of 1 to 2 cm was made 5 cm posterior to the pelvic fin and approximately 2 cm lateral to the midline. The incision was closed with absorbable sutures. Fish were additionally tagged with a coded T-bar anchor tag on the left side directly below the dorsal fin for anglers identification. Immediately after surgery, fish were placed in an aerated trough. Fish were released if they exhibited standard swimming patterns and buoyancy. Locations and times of both capture and release were taken.

Fine-scale acoustic telemetry. – An acoustic array consisting of 38 VEMCO acoustic receivers was placed throughout Bad Medicine Lake with Innovasea staff assistance that determined the equipments optimal locations (Figure 1.1). Receivers were placed approximately 350 m apart to utilize the Vemco Positioning System (VPS). The VPS receiver array was deployed on 6 April 2019 and left in the system until 28 September 2020. VPS uses simultaneous detections of a single acoustic transmission with a minimum of three and a maximum of six acoustic receivers with synchronized clocks (maximum set by the manufacturer) to determine fish locations (e.g., < 10 m precision) at the time of transmission (Smith 2013). If more than six receivers detected the same transmission, the first six receivers were used. The positions were estimated using the principle of time difference of arrival, in a process referred to as hyperbolic positioning (Smith 2013). Positions were weight-averaged for each set of three hydrophones of the six used, and a relative error of sensitivity was supplied for each calculated position (horizontal position error; “HPE”) (Smith 2013). More details on HPE and VPS can be found in Smith (2013).

Data Analysis

Data processing and statistical analyses were performed in *R* statistical computing package (hereafter “*R*”; R Core Team, 2020). Before analysis, telemetry data were filtered for quality assurance. First, depth detection plots were used to filter fish that appeared to have shed their tag (same depth reading for long durations) or died immediately following surgery (no change in depth ten days post-surgery). Next, depth data deeper than the known depth of Bad Medicine (25 m) were removed. Data that had timestamps less than the minimum ping rate for each fish were removed. Using Meckley et al. (2014) methods, twice the distance root mean square (2DRMS) was calculated for each sync tags position measured easting and northing error within each one-unit interval bin of the HPE.

Data from sync tags were analyzed to determine the relationship of HPE to measured error (HPEm). Sync tag 2DRMS was calculated for each of the four tags in Bad Medicine Lake. Although sync tag detection percentage varied across the four tags, the HPE to HPEm relationship remained similar. Results show that our array had good coverage during the study, with lower detection rates during the summer, which results in high positioning error. Linear regression analysis was run for the one-unit HPE interval bins and their equivalent 2DRMS of measured error using all sync tag positions throughout the study period. An HPE value of 17 was accepted as an appropriate level for filtering fish detections (Figure 1.2). This value filtered out data with a meter error greater than eight meters while retaining 84% of all location data from the 32 fish that survived the study period. Having a small error estimate while retaining a large bulk of data helps classify habitat types preferred by fish Meckley et al. (2014), in our case, spawning locations.

Home Range Analyses. – Home-range analysis can be conducted using multiple techniques, most commonly through minimum convex polygons (MCP) and kernel utilization distributions (KUD). Minimum convex polygons are used to measure the full extent of animal home range over time, while KUDs supply information about the use of space within the field (March et al. 2010). For this study, home range analysis was performed in *R* through the package adehabitatHR (Calenge 2006). Kernel utilization distributions were used to quantify the home-range size of Burbot using 50%, 90%, and 95% contours (Plotz et al. 2016). The bandwidth (smoothing parameter; h) can affect the kernel's size and shape (Pillans et al. 2014). Choice of bandwidth varies among study goals and sample size (Worton 1989). For this study, bandwidth was computed using the ad hoc method (href) within the kernelUD function of adehabitatHR. The home range was compared using 90% KUD estimates, while the core range was compared using 50% KUD estimates. Home and core ranges were estimated individually for each of the 32 fish that survived the length of the study. Fish locations were grouped in 25-day spans, ranging 12 days before and after both dates of the 13th and 25th of each month. Any fish that contained fewer than 30 locations per period was removed from analyses.

Generalized linear mixed effect models (GLMM) were used to determine if there was significant difference in home and core range size of Burbot between; (1) season (ice-on and open water), (2) sex (male, female, unknown) or (3) basin the fish was tagged in (north, middle, south). The unique fish identification code was used as the random effect. GLMMs were conducted using *R* and the ‘lme4’ package (Bates et al. 2015) with a gamma (log link) error form to account for non-normal positive skewed data. Akaike’s Information Criterion (*AICc*) was used to determine the best-supported model given small sample sizes (Hurvich and Tsai 1989). All model combinations were examined using a visual assessment of residual plots (Zuur et al. 2009). Post-hoc analysis was performed using the *emmeans* package in *R* (Lenth 2021).

Spawning Aggregations. – Field analysis of spawning shows that Burbot cluster in large groups and broadcast their spawn throughout the water column (Cahn 1936; Fabricius 1954). To understand the scale of spawning aggregations of Burbot in Bad Medicine Lake, we needed to measure the clusters of fish locations across time. To do so, we incorporated ESRI’s Optimized Hot Spot Analysis tool, hereafter OHSA, tool (ESRI ArcGIS Pro 2.8 2021) to evaluate spatial patterns in Burbot areas of use. This tool has had minimal use across ecology; however, Nordstrom et al. (2020) used OHSA to assess jellyfish distributions and their associations with Leatherback Sea turtles *Dermochelys coriacea*. Additionally, Balazik et al. (2020) used acoustic telemetry detections from Atlantic Sturgeon *Acipenser oxyrinchus*, paired with the OHSA tool to monitor spawning migrations while active dredging was performed in the James River, Virginia. OHSA uses the data, in our case fish detections, to automatically obtain settings that generate the best possible hot spot results, commonly known as a Getis-Ord Gi* statistic (Ord and Getis 1995). The output from the tool adjusts for both multiple testing and spatial dependence using the false discovery rate correction method outlined in Benjamini and Hochberg (1995).

The Getis-Ord Gi* statistic measures the intensity of clusters of high or low values in a space-time bin concerning its neighboring bins. The sum of a bin and its neighbors is then compared to the sum of all bins. If the sum of one bin is different from anticipated and the difference is significant, then it cannot result from random chance; in fact, it is statistically significant, resulting in a large Z score. This Getis-Ord Gi* statistics generates the *Z* score (standard deviations) and *p*-values (statistical probabilities) for each bin across the study area, indicating that Burbot locations in that bin are statistically clustered compared to neighboring bin location clusters. The larger the Z score in a bin, the more significant the clustering of values, in other words, a hot spot.

Burbot in Bad Medicine Lake are predicted to spawn from mid-February to the first week of April. The OHSA was used to assess three 14-day periods between 24 December 2019 to 28 April 2020. This date range encompassed all data during the pre-spawn period ranging to the tail end of the post-spawning window. The pre-spawn period covered the dates from 24 December 2019 to 6 January 2020; the period classified as spawning ranged from 6 March to 19 March 2020, and the post-spawn period ran between 15 April to 28 April 2020. An additional period of summer, 15 August to 28 August 2019, was used as a basis for habitat selection during the non-peak movement stage of Burbot. Due to prior knowledge of Burbot spawning during mid-winter under ice and at night (Cahn 1936, Scott and Crossman 1973, McPhail and Paragamian 2000), only data between sunset and sunrise were used. Although total detections and range of detections varied across spawning seasons, OHSA parameters were consistent.

Points were aggregated in hexagonal cells with a size of 15 meters. This measure was most suitable for a visual representation and statistically valuable as this value was three times the amount of the average nearest neighbor in each study period. Any smaller cell size resulted in many sporadic hot spots, which were just as easy to visualize by looking at the raw data points. A larger cell size appeared to overestimate the hot spots resulting in hexagonal cells that were relatively far from any location value compared to the scale of the lake. A distance band of 56 meters was used throughout the analysis. This distance was the average nighttime horizontal movement rate of Burbot in Alexie Lake (Cott et al. 2015). Spawning aggregations were then determined by looking at hot spots found during the spawning period (6 March to 19 March 2020). Using a combination of the cells classified as significant hot spots (GI_BIN score ≥ 2 = 95% confidence), cells with average depths less than 10 meters, and cells that contain or neighbor multiple unique fish, we estimated the scale of spawning in Bad Medicine Lake.

Results

Acoustic tagged Burbot length did not vary between sex (X^2 = 4.68, df = 2, p = 0.096). Males had the largest median length of 505 mm (n = 23), followed by females (median = 492, n = 22) and finally, unknown sexed fish (median = 450, n = 21). Of the 66 fish tagged in 2019, one was caught and kept by an angler on 28 February 2020; three died following surgery, and 13 fish appear to have shed their tag or died from natural mortality. Another 14 seemed to disappear from the array, but the fish appeared to be swimming regularly before. The following scenarios are possible because there are no inlets or outlets on Bad Medicine Lake; the fish was removed via anglers, or the tag became faulty. Three fish had tags that failed, resulting in irregular positions, temperature, or depths transmissions, and were removed from the analysis. The remaining 31 Burbot survived the length of the study period, which spanned from 10 April 2019 to 12 June 2020, and were used for home range analysis (Table A.1.1). Also included in analyses is one Burbot that was implanted with an acoustic transmitter on 2 May 2019.

Over six million detections were recorded from the remaining 32 fish used in the data analysis. However, many detections were duplicates due to simultaneous detections across multiple receivers in the array. VPS processing supplied us with 812,979 individual locations. After filtering data by the protocols above, 32 fish (ten males, twelve females, and ten unknown) had adequate positions for estimating home range (489,459 individual locations). Calculated location totals for each fish ranged between 3,450 to 41,970. Fish tagged with the short delay transmitter (n = 3) averaged 37,187 locations, while fish tagged with the long delay transmitter (n = 29) averaged 13,079 during the study period (Table A.1.1). On average, 1,144 Burbot locations were estimated per day (range = 230 – 2030).

Home Range Analysis. – The home range of Burbot was best depicted by the model consisting of terms for season and sex and their interaction (Table 1.1). Home ranges for each season were significantly different for both males and fish of unknown sex ($p < 0.001$; Figure 1.3); however, female Burbot home range was not statistically significant among seasons ($p = 0.531$). The average home range was largest in Burbot of unknown sex, followed by females and males (Table 1.2). Average home range size by fish sex peaked on the 25 days ranging around 13 March 2020 (Table 1.3). In contrast, the smallest average home range by date fell on 13 April, both in 2019 and 2020 for males and females. Unknown sexed fish had their smallest home range estimate on 13 August 2019 (Figure 1.3). Males accounted for 15 of 20 of the smallest averaged estimated home ranges across all dates.

Core Range Analysis. – Patterns in core range size estimates followed similar patterns as the home range estimates, resulting in the best-supported model including an interactive effect of season and sex (Table 1.1). Fish with large home range estimates also had large core range estimates. Core ranges (Figure 1.4) of females were not significantly different among seasons ($p > 0.39$), while core ranges of males and unknown sex fish were statistically significant among seasons ($p < 0.01$; Table 1.2). Fish of unknown sex had the largest average core range during the period of ice on (0.185 km^2), followed by females (0.150 km^2) and finally males (0.137 km^2). The same pattern was found during the open water period, with unknown fish having an average core range of (0.160 km^2), followed by females (0.152 km^2) and finally males (0.071 km^2). The peak average core range by date fell on the same 25-day date range as the peak average home range of Burbot (Table 1.3). In comparison, the smallest average core range by date fell on 13 April, both in 2019 and 2020 for males and females. Fish of unknown sex had their lowest average home range fall on 25 January 2020 (Table 1.3).

Optimized Hot Spot Analysis. – The OHSA identified statistically significant hot spots for Burbot use in each study period. Due to the nature of this research, we focused on the quantity of significant hot spots (GI_BIN score ≥ 2 = 95% confidence) by season and a specific focus on hot spots during the spawning time with a high number of individual fish that occupied them. Locations of hot spots varied across periods (Figure 1.5). Hot spot cells were quantified for average depth within the cell using a rasterized map of the lake contours. Only 32 cells out of 16,101 were deemed hot spots in each period. These locations were found in the north basin with depths between 5.88 and 6.56 meters and the middle basin with depths between 11.80 and 12.35 meters. A Kruskal-Wallis rank-sum test indicated a significant difference in depth of hot spot cells among periods ($X^2 = 2{,}792$, df $= 3$, $p < 0.001$). In addition, a pairwise Wilcoxon rank-sum test was performed to assess the difference in average depth of significant hot spot cells between each period. All periods were statistically significantly different from one another (Figure 1.6). The average depth of hot spot cells ranged between 7.97 meters during the pre-spawn to 16.33 meters during the summer. Additionally, we compared the average depth of Burbot by period using a Wilcoxon rank-sum test that resulted in each period being statistically significant among one another ($p < 0.001$) besides the periods of post-spawn and summer ($p = 0.052$) (Figure 1.6). The average depth of Burbot by period ranged between 6.764 meters in pre-spawn to 9.051 meters during the post-spawn.

A total of 1,201 unique cells were found and used to determine spawning aggregations. Incorporating our knowledge of the lake bottom, we established that spawning is spread across the system (Figure 1.7). Spawning clusters were located more on the east than the west shore (Figure 1.8). Spawning was also focused near shore, with few clusters occurring offshore. Burbot appear to congregate in Bad Medicine Lake's north area and the steep shoreline of the eastern shore in the central basin for spawning (Figure 1.8).

Discussion

In Bad Medicine Lake, Burbot exhibit changes in location use depending on the season. The range of movement is directly associated with the time of the year. The home range size of Burbot has previously been described in lake systems; however, research is minimal and focuses on summer, open-water periods (Guzzo et al. 2016). Burbot in Bad Medicine Lake were shown to increase their home range size during ice-on periods, with the most extensive home range estimate being found around the spawning period. The mean estimated home range size of Burbot in Bad Medicine Lake was 0.511 km^2 during the ice period, while the open water period resulted in a mean home range estimate of 0.392 km^2.

The estimated home range of Burbot in Bad Medicine Lake during the summer was smaller than the estimated home range size found by Guzzo et al. (2016). Researchers found Burbot to have a home range size of 1.08 km^2 during the summer. Additionally, our results suggest Burbot, with large home range estimates in the winter, also had large home range estimates in the summer, falling in line with findings from Harrison et al. (2015). Harrison et al. (2015) classified Burbot into two groups, one being “resident” fish with small home range and high site fidelity, or “mobile” fish with large home range and continuous location shifts. Our fish could also be classified into these two groups. Of the 32 fish, 16 were considered residents, while the remaining 16 were considered mobile. However, of the 16 fish classified as mobile, four had average home range estimates larger in the ice-off period than the ice-on period. We found that fish with large home and core range estimates were the same fish with the most variation in lake area used between seasons. These Burbot occupied distinct regions of the lake (north, middle, or south) during the ice-off period; however, the same fish used new areas of those lake regions during the year and did not select for one specific area. Most tagged Burbot used the entire lake during the peak spawning. Burbot traveled from south to north or north to south during early March, choosing to explore the system. Some Burbot showed an affinity to their core region in the lake, but that same fish could be found on the opposite side of the system a week later, potentially looking for a mate. In contrast, our few resident fish would live in one region of the lake in both the summer and winter, with few migrations to new areas of the lake. The few migrations they made were during early and mid-March, which was associated with the spawn.

The sex of fish was also an essential parameter for explaining variation in home range size across seasons. Although most studies, including our data, indicate that Burbot length was not significantly different between sex (Chen 1969, Kjellman 2003, Cott et al. 2013). Paragamian and Wakkinen (2008) evaluated Burbot habitat preferences and movement rates with known sex. They reported that home range did not vary between sex, a contradiction to our findings. Our results indicated that female Burbot had double the estimated home range size compared to males during the open-water period. However, the home range size was only 15% larger during the ice-on period. We hypothesized that this difference in home range size is associated with the females need to consume more food due to their larger weight and greater energy needs for reproduction (Ashton et al. 2019). Most studies that have predicted home range size or migration distance of Burbot occurred in reservoirs and lotic systems of western United States to Canada and Alaska (Evenson 1993, Paragamian and Wakkinen 2008, Stephenson et al. 2013, Harrison et al. 2015). To our knowledge, this study is the largest of its kind in terms of the number of known sexed fish and the use of fine-scale home range estimation across a period of more than a year.

Our model indicated significant importance in the interactive effect of sex and season. Although females did not significantly differ in home range size between seasons, unlike males and fish of unknown sex, there is unmistakable evidence that Burbot home range size increases during the spawning period. Past research shows that Burbot in riverine systems migrate to the mouths of rivers leading up to the spawn (Stephenson et al. 2013). However, this behavior does not apply to Bad Medicine Lake as it is a closed system with no inlet or outlet. Our data suggest that movement increases from December to February, peaking in mid-March and dropping in April. This pattern suggests that activity levels from December to February are pre-spawn movements. The home range size peak in March is the spawning migration.

Furthermore, the post-spawn stage was in April, where we estimated the average home range size of all fish to only be 0.191 km^2 on 13 April 2020, the smallest home range estimate for all dates. In the present study, Burbot had a home range estimate more than six times larger on 13 March 2020 than Burbot had one month later, on 13 April 2020, 1.301 and 0.191 km^2, respectively. Spawning of Burbot in similar systems to Bad Medicine Lake occurs under the ice in late January to early February (McCrimmon 1959 and Cott et al. 2013). Our assumption of spawning occurring in March follows the patterns found in Burbot populations from Alberta fisheries of Lac Ste. Anne and Cold Lake (Boag 1989). During the first two weeks of March, Boag (1989) observed and caught ripe Burbot through the ice in less than two meters of water in the early morning hours, with catch rates deteriorating in the afternoon. Our estimated spawning date of March 16th falls later than what was found by Muth and Smith (1974) for Burbot in Lake of the Woods. Researchers predicted that Lake of the Woods Burbot populations spawned during the last two weeks of February, as most females collected after the first week of March were spent.

The overarching goal of this study was to assess Burbot movements and quantify home range size concerning their peak spawning period. Using our acoustic telemetry results, we quantified the scope of Burbot migration during mid-March, which we have evidence to suggest is the peak spawning time for Burbot in Bad Medicine Lake. From November to January, leading up to the expected spawn, Burbot began to expand from their summer and fall areas and explore other lake regions. Fish that occupied southern areas of the lake started to swim towards the north side of the system or the opposite direction of movement for fish that lived in the north basin. We categorized this movement as a pre-spawn exploration search for food or mates leading towards the spawn. As winter progressed, the 25-day span around 13 March 2020, had the most peak home range estimates (n = 10), followed by 25 March 2020 (n = 7), and finally 25 February 2020 (n = 3). The average home range size saw a 190% increase from February to March, where the size then decreased by 85% from March to April. These results validate our claim that Burbot prefer to spawn around the second and third weeks in March. Our VPS location results showed a significant increase in travel from all tagged Burbot during these dates. Burbot would go from residing in their core range to traversing the whole lake in some instances. For example, fish 161, a 522 mm female tagged in the south basin, resided primarily in the south basin. This fish was detected near the far south bay on 13 March 2020, where it then was detected 24 hours later and 3.63 km north. By 11:00 am on 16 March 2020, this fish was then another 1.63 km north in the north basin and returned to the south basin by 11:00 am on 17 March 2020, migrating more than 5 km. This fish was one of the most extreme movement cases; however, all fish exhibited some form of migration to a new lake area from their normal core range. These findings are the first of their kind in highlighting Burbot spawning migrations in a closed lentic system.

Our study is the first to utilize the OHSA tool in ArcGIS Pro to assess potential spawning locations in freshwater fishes. Using our assumptions related to the timing of the spawning period in Bad Medicine Lake, we were able to quantify and pinpoint the desired spawning locations and assess the scale of fish aggregations at these sites. Although few studies have indicated the Burbot will spawn in deep water habitats (Clemens 1951), most studies suggest a preference for shallow humps (McCrimmon 1959) or along the rocky shoreline (Boag 1989). Using this knowledge, we determined Burbot used the steep eastern shores of Bad Medicine Lake. These locations saw increases in fish use during the second and third weeks of March. Although we only tracked movements of 32 Burbot in Bad Medicine Lake, the prior knowledge of Burbot reproducing in large balls (Cahn 1936) allows us to infer that there is the potential for large quantities of fish to use these locations.

We found statistically significant differences in Burbot hot spot cell depth between periods. The pre-spawn period had a mean depth of 7.97 m, the spawning period was 8.31 m, the post-spawn period was 9.31 m, and summertime was 16.33 m. Although there was statistical significance between periods, we believe a 1.34 m difference in average hot spot cell depth during all spawning periods is not biologically significant in determining Burbot movement patterns. The average water temperature ranged from 2.82 to 4.31˚C during the spawning periods. Żarski et al. (2010) investigated optimal thermal levels for Burbot reproductive success. Their results showed an elevated level of larval survival when spawning occurred around 2˚C and a 99% mortality rate in embryos when water temperatures spiked to 5˚C. Comparing the average water temperature at average hot spot cell depth, we can infer that Burbot in Bad Medicine Lake spawned when the water temperature was around 3˚C. At those locations, the average dissolved oxygen ranged between 8.85 to 10.2 mg/L, well above the lethal limit for cold water species. The average depth of hot spot cells during spawning time did fall in the known average spawning depth for Burbot, but it is on the deeper end of the range.

The average vertical depth of Burbot at location was calculated during each period. During the spawning period, the average depth of Burbot was similar to the average hot spot cell depth at 8.264 and 8.312 meters, respectively. These results indicate an affinity for following the lake bottom, a known trait in Burbot movement (Cott et al. 2015). In contrast, in the summer, Burbot appear to suspend over deep water as the average depth of Burbot was 8.9 m compared to 16.3 m for the average depth of hot spot cells. These findings have not been discussed in literature focused on Burbot movement or habitat use and open a pathway for future research. The possibility of Burbot suspending has not been documented in other systems (Cott et al. 2015) but could be explained by determining the oxy-thermal niche of the species. Additionally, due to the number of stocked trout in the system, Burbot may be actively targeting the species.

Burbot range and distribution across the world highlights their habitat plasticity, from large lakes such as Lake Superior (Boyer et al. 1989) to the Missouri River (Fisher 2000), as far north as Alaska (Breeser et al. 1988), and even adapting to the brackish waters of the Baltic Sea (Rohtla et al. 2014). Burbot also will alter their activity levels and habitat preferences with changes in light (Cott et al. 2013), food availability (Muth 1973), and reproductive needs (Schram 1983). This study provides new and improved knowledge of the movement dynamics of Burbot in lentic systems. Quantifying the space use, distribution, and fine-scale movement of Burbot across 16 months has never been discussed, and results show how mobile the species is, specifically during the winter. Our estimates of home range size differences for known sexed Burbot between ice-on and ice-off periods are essential in broadening the knowledge base relative to Burbot movement dynamics and habitat use. The locations determined to be potential spawning locations were also highly used by recreational anglers during the ice fishing season. As there currently is no season or bag limit for Burbot in Minnesota, this might raise concerns for fisheries managers.

Future research should address Burbot movement and spatial use across multiple years to quantify the potential for Burbot returning to the exact spawning location. Additionally, home range analysis should be assessed in the future to compare the space use of Burbot in Bad Medicine Lake and how their patterns of use might vary due to changes from climate change. Knowing how climate change may alter movement dynamics in fish can help managers better protect the species and specifically the most vulnerable bodies of water. Results for the OHSA showed a mixture of areas used by Burbot. Burbot occupied areas that were used to tag fish in 2019, and results showed movement into regions that were never used in 2019 for tagging, indicating that spawning occurs throughout the system. Our results opened the door for fisheries managers to appropriately regulate and protect the species. Furthermore, we improved the knowledge of an ecologically important fish by setting a solid baseline for future research that will help us gain a clearer understanding of the space use and selectivity of Burbot.

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Tables

Table 1.1. Top five candidate Generalized Linear Mixed Effect models and the null model for assessing estimated home range size of acoustic tagged Burbot from Bad Medicine Lake between 10 April 2019 and 11 June 2020. Model components include sex; female, male, unknown, season; ice on, open water, tagged basin; north, middle, south. The lowest ΔAIC_C indicates the best-supported model.

Model	**df**	**AIC_C**	**ΔAIC_C**	**Weight**
Home Range				
(Sex * Season) + (1| Fish)	8	135.62	0.00	0.7066
(Sex * Season) + Basin + (1| Fish)	9	137.39	1.77	0.2909
Season + (1| Fish)	4	147.75	12.13	0.0016
Sex + Season + (1| Fish)	6	150.79	15.18	0.0004
Sex + (Season * Basin) + (1| Fish)	8	151.98	16.36	0.0002
(1| Fish)	3	184.67	49.05	1.57^{-11}
Core Range				
(Sex * Season) + (1| Fish)	8	-1928.79	0.00	0.7180
(Sex * Season) + Basin + (1| Fish)	9	-1926.92	1.88	0.2810
Sex + (Season * Basin) + (1| Fish)	8	-1914.69	14.11	0.0006
(Season * Basin) + (1| Fish)	6	-1912.56	16.23	0.0002
Sex + Season + (1| Fish)	6	-1910.31	18.48	6.96^{-5}
(1| Fish)	3	-1894.73	34.06	2.89^{-8}

Table 1.2. Mean (SD) estimates of home range size (90% KUD) and core range size (50% KUD) of Burbot in Bad Medicine Lake from 2019 to 2020 among females, males, and unknown sex, and by season in km^2. The *p*-values represent the pairwise comparison of home range estimates by sex between seasons.

Sex	**Season**	**HR90 (SD)**	**CR50 (SD)**	***p* - value**
Female	Ice on	0.511 (0.644)	0.150 (0.212)	0.53
	Open Water	0.460 (0.458)	0.152 (0.169)	
Male	Ice on	0.441 (0.573)	0.137 (0.230)	< 0.01
	Open Water	0.231 (0.261)	0.071 (0.098)	
Unknown	Ice on	0.582 (0.640)	0.185 (0.185)	< 0.01
	Open Water	0.475 (0.457)	0.160 (0.181)	

Table 1.3. The largest and smallest average home (HR90) and core (CR50) range estimates of acoustic tagged Burbot from Bad Medicine Lake by 25-day date range and sex, with standard deviations (SD). Letters of F, M, and U represent females, males, and unknown sex fish. Home and core range was estimated using kernel utilization distributions and are shown in km^2. Maximum represents the date where home and core range estimates peaked, while minimum data represents the date where home and core range estimates were smallest.

			Maximum			**Minimum**	
Sex	**Season**	**Date**	**HR90 (SD)**	**CR50 (SD)**	**Date**	**HR90 (SD)**	**CR50 (SD)**
M	Ice	Mar 13, 2020	1.328(0.728)	0.401(0.266)	Apr 13, 2019	0.107(0.084)	0.028(0.029)
	Open	Sep 25, 2020	0.371(0.373)	0.132(0.170)	Jun 25, 2019	0.115(0.057)	0.033(0.022)
F	Ice	Mar 25, 2020	1.185(0.814)	0.345(0.278)	Apr 13, 2019	0.114(0.109)	0.029(0.029)
	Open	Oct 13, 2020	0.681(0.531)	0.234(0.231)	Jul 25, 2019	0.261(0.330)	0.084(0.119)
U	Ice	Mar 13, 2020	1.478(0.738)	0.565(0.535)	Jan 25, 2020	0.233(0.146)	0.050(0.027)
	Open	May 13, 2020	0.721(0.646)	0.254(0.196)*	Aug 13, 2019	0.184(0.234)	0.066(0.095)

*Maximum core range for unknown sex fish during the open water period fell on the date of 25 September 2019.

Figures

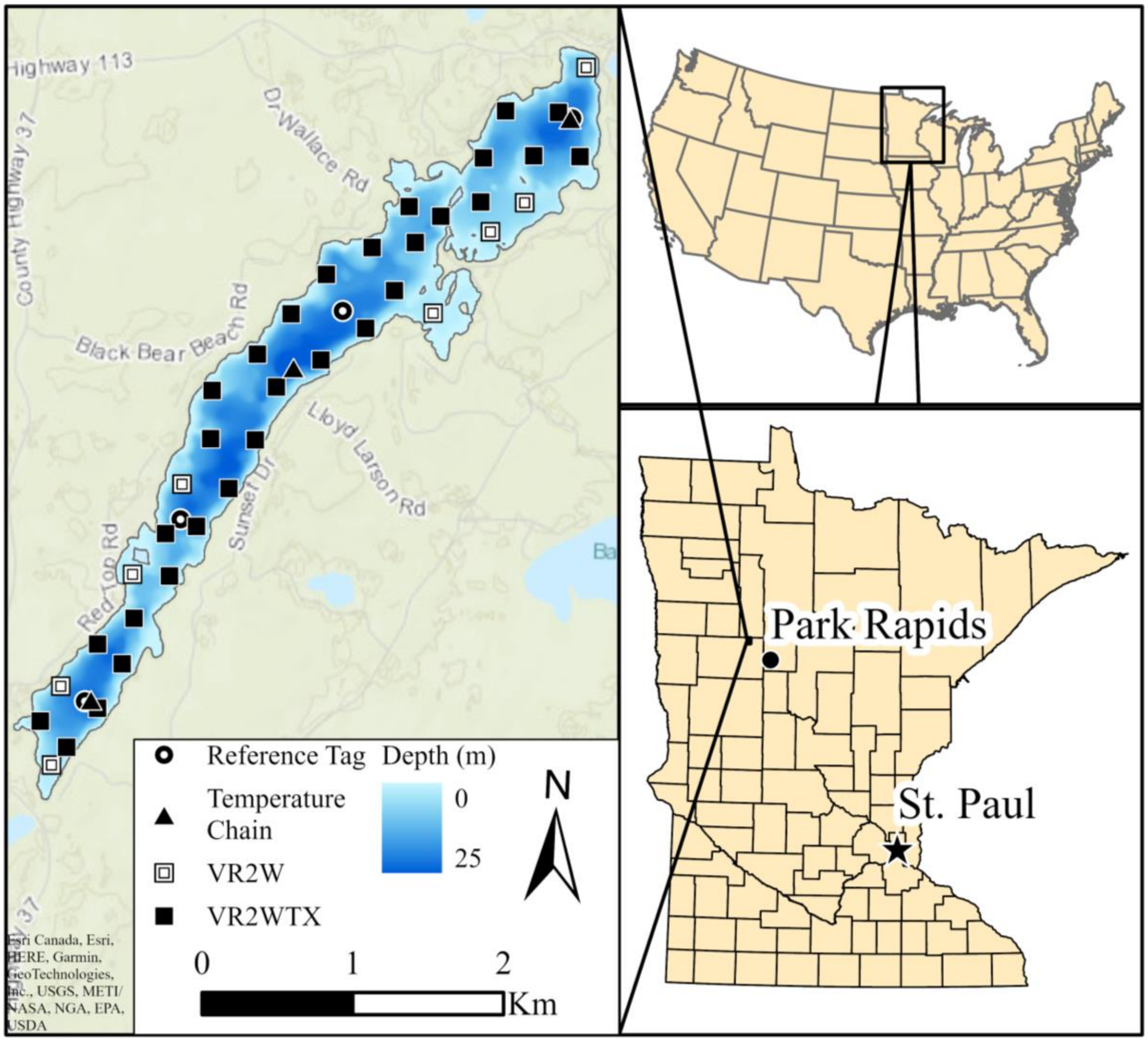

Figure 1.1. Location of Bad Medicine Lake (47°07’36.7” N, 95°24’02.0 “W) and its position in Minnesota, United States. The map of Bad Medicine Lake contains the locations of 38 Vemco Positioning System receivers, the four reference tags, and the three temperature chains. The middle-temperature chain (triangle symbol) is where the dissolved oxygen loggers were located.

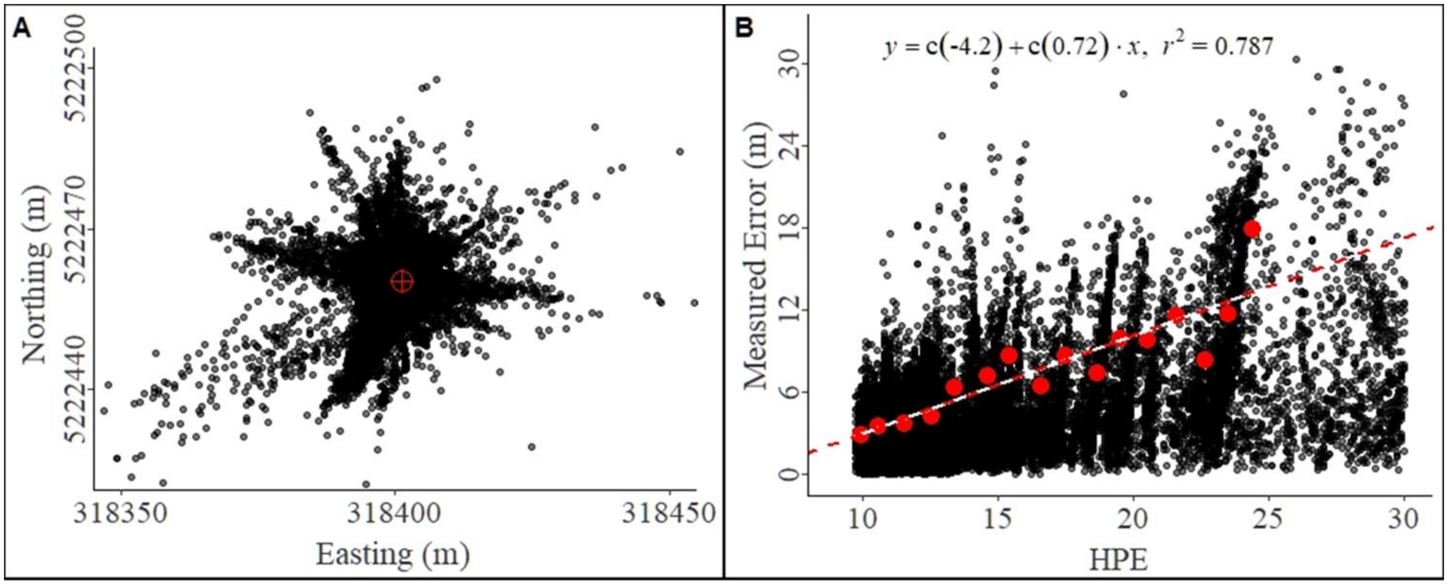

Figure 1.2. Represents all Vemco Positioning System (VPS) location estimates of reference tag 2 in the Bad Medicine acoustic array (A) and (B) the associated relationship between Horizontal Position Error and Horizontal Positioning Error in meters (HPEm). The red circle with an x in the center represents the known location for reference tag 2 (A). The red circles represent twice the distance root mean square error (2DRMS) of x and y components within an HPE bin (B). The line through these points represents the 2DRMS relationship. The equation and fit are shown in the upper left corner.

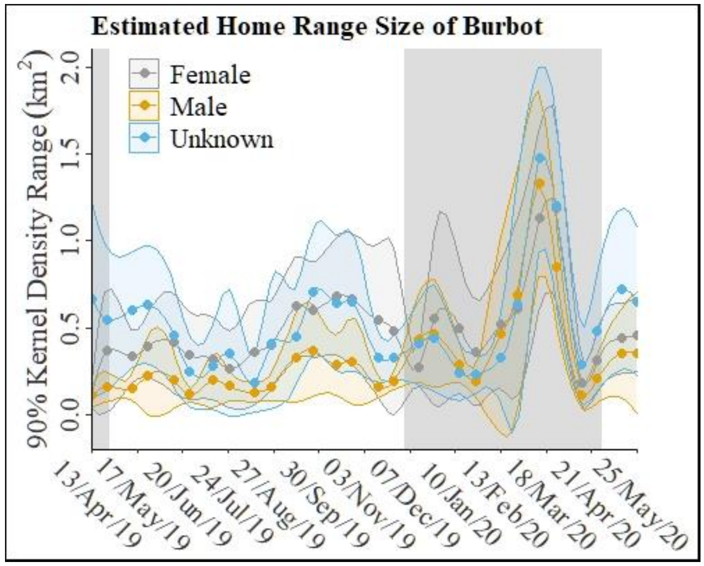

Figure 1.3. Average home range estimate (km^2) by sex of Burbot using 25-day periods. Gray dots are females, orange dots are males, and blue dots are unknown sex. Lines and color-coded shading of 95% confidence intervals were spline interpolated between data points by date. Gray rectangles are time frames when Bad Medicine Lake was ice-covered.

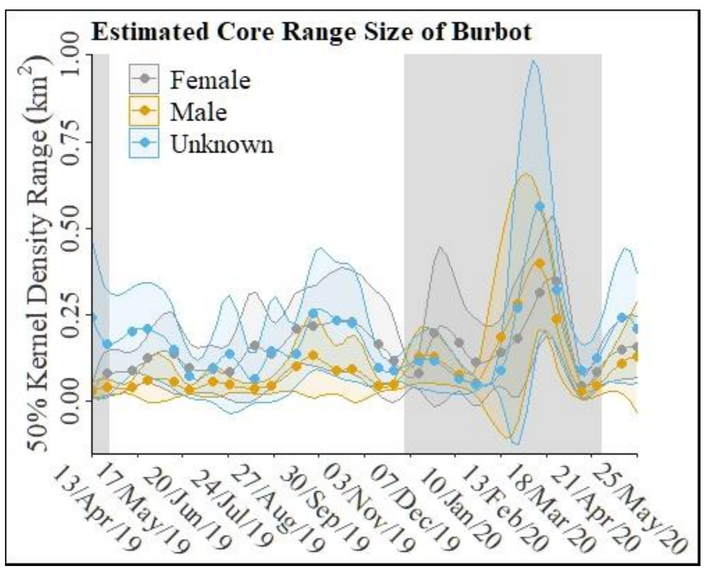

Figure 1.4. Average core range estimate (km^2) by sex of Burbot using 25-day periods. Gray dots are females, orange dots are males, and blue dots are unknown sex. Lines and color-coded shading of 95% confidence intervals were spline interpolated between data points by dates. Gray rectangles are time frames when Bad Medicine Lake was ice-covered.

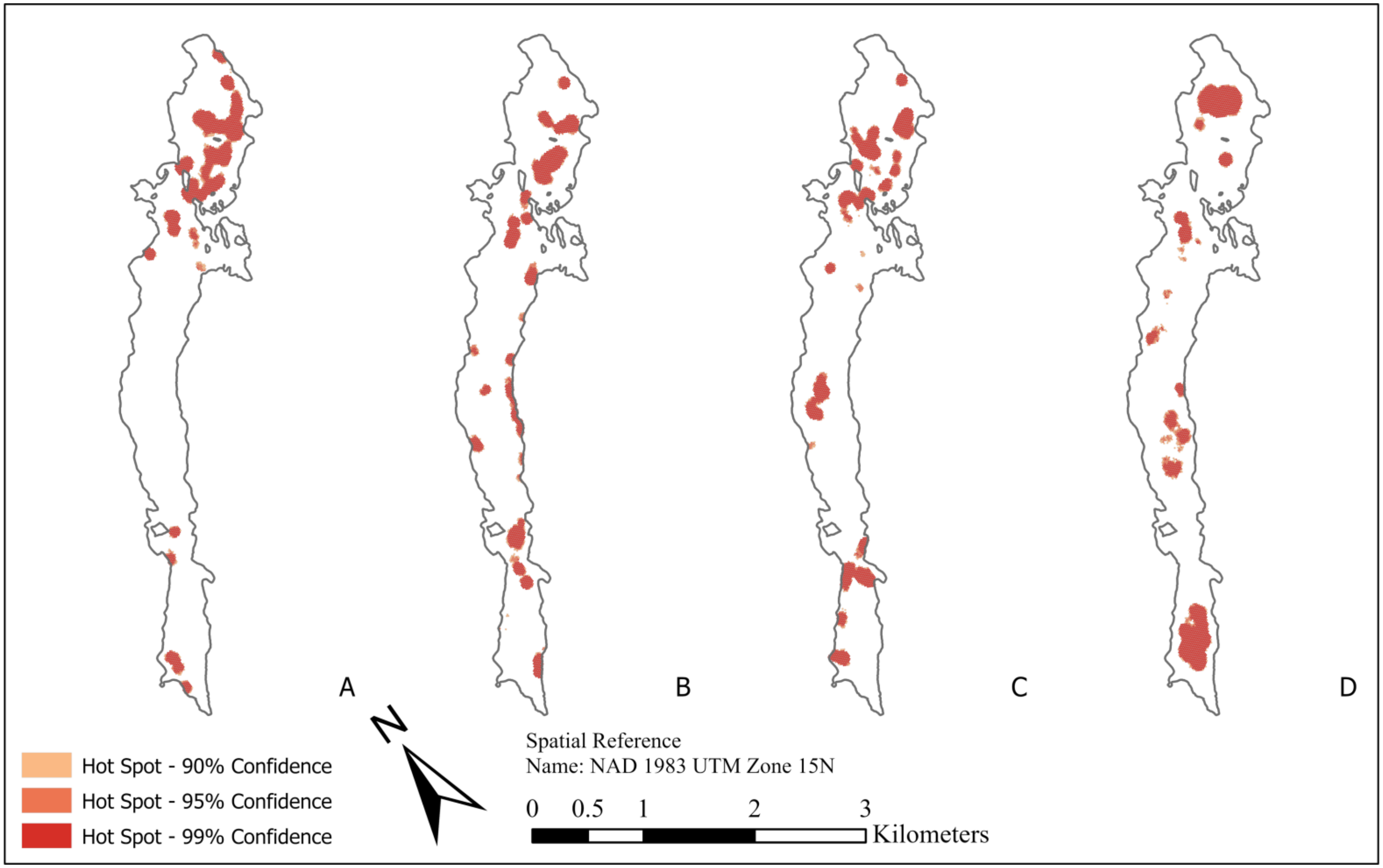

Figure 1.5. Optimized Hot Spot Analysis of the Burbot locations during four seasonal periods (pre-spawn, A; spawn, B; post-spawn, C; and summer, D) in Bad Medicine Lake, Minnesota. The locations are aggregated by 15-meter hexagonal cells with a distance band of 56 meters. Regions in shades of red are considered a hot spot with at least 90% confidence.

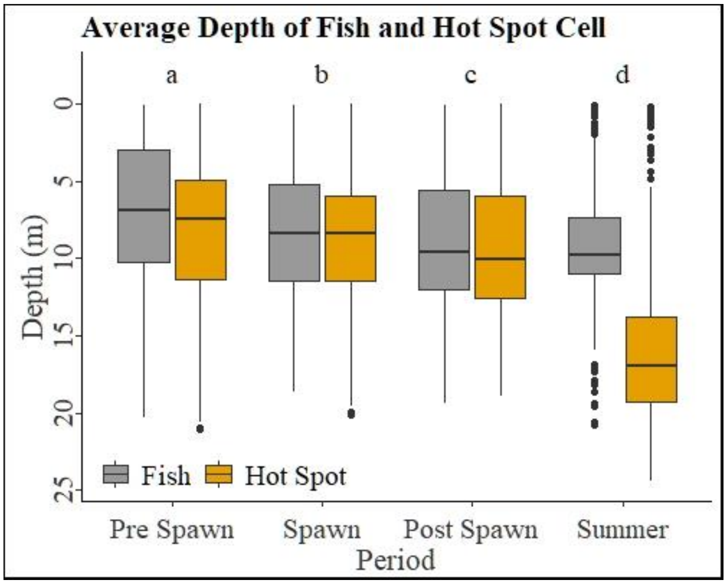

Figure 1.6. Comparison of the average depth (m) of Burbot by period (gray data) and the average depth of each statistically significant hot spot cell from the Optimized Hot Spot Analysis (orange data; pre-spawn, spawn, post-spawn, and summer) using acoustic tagged Burbot in Bad Medicine Lake. Letters indicate periods that are significantly different from each other.

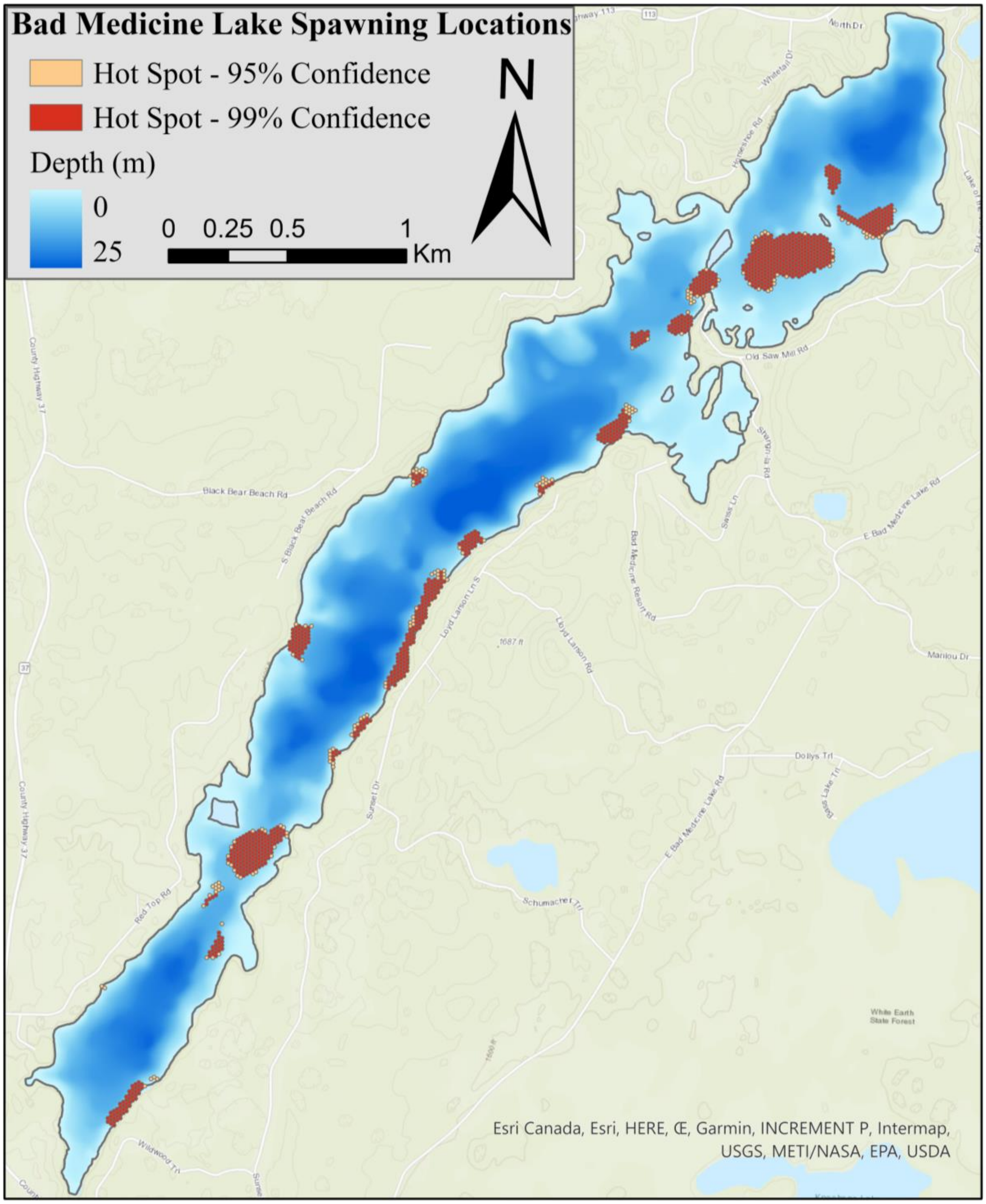

Figure 1.7. Optimized Hot Spot Analysis results from acoustic tagged Burbot location data received during predicted peak spawning time in Bad Medicine Lake. Data are filtered by cells with greater than 95% confidence in a hot spot and by depth contours of less than 10 meters, with only hot spots containing or neighboring fish locations.

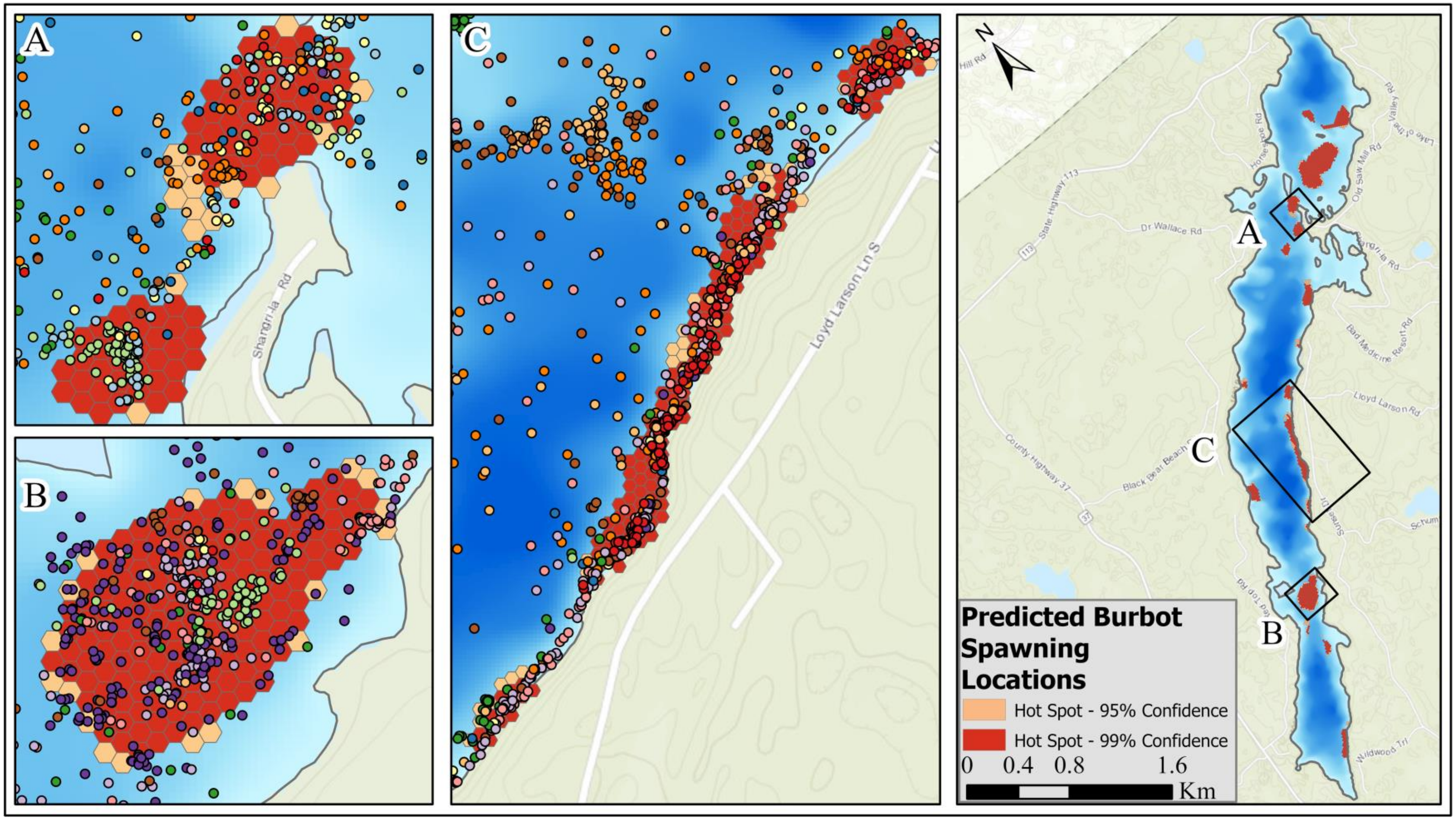

Figure 1.8. Predicted spawning locations for Burbot in the northern (A), middle (B), and southern (C) basins of Bad Medicine Lake. Each colored dot represents a unique acoustic tagged Burbot. Data represents only locations and significant hot spots during the spawning period from 6 March to 19 March 2019.

APPENDIX A

Table A.1.1 Summary of acoustic tagged Burbot from Bad Medicine Lake in 2019. Females, males, and fish of unknown sex are identified by F, M, and U, respectively. VPS represents the total number of calculated Vemco Positioning System locations used in home range analysis. Columns with labels HR and CR represent the respective home and core range estimate for each fish during the ice-on and open water periods. Fish without VPS or home range values were not used in data analysis.

Fish ID	Length	Weight	Sex	Basin	Date Tagged	VPS	Ice HR	Ice CR	Open HR	Open CR
B172	382	603	F	2	Mar 30, 2019	X	X	X	X	X
B135	410	710	F	1	Mar 27, 2019	16,223	1.154	0.446	0.770	0.269
B107	434	805	F	3	Mar 23, 2019	X	X	X	X	X
B47	445	1198	F	2	Mar 19, 2019	X	X	X	X	X
B9	469	920	F	1	Mar 18, 2019	X	X	X	X	X
B164	476	1184	F	3	Mar 29, 2019	13,157	0.439	0.121	0.581	0.177
B116	476	1049	F	1	Mar 23, 2019	X	X	X	X	X
B7	480	1046	F	1	Mar 18, 2019	12,430	0.125	0.031	0.199	0.058
B8	480	892	F	1	Mar 18, 2019	X	X	X	X	X
B141	492	872	F	2	Mar 28, 2019	3,450	0.520	0.163	0.393	0.119
B106	492	1116	F	3	Mar 23, 2019	X	X	X	X	X
B51	502	1485	F	2	Mar 19, 2019	12,519	0.149	0.034	0.238	0.070
B124	504	1399	F	2	Mar 26, 2019	14,971	0.807	0.215	0.622	0.192
B14	512	1164	F	1	Mar 18, 2019	X	X	X	X	X

Table A.1.1 Continued

Fish ID	**Length**	**Weight**	**Sex**	**Basin**	**Date Tagged**	**VPS**	**Ice HR**	**Ice CR**	**Open HR**	**Open CR**
B160	515	1153	F	3	Mar 29, 2019	41,970	0.295	0.076	0.229	0.063
B161	522	1194	F	3	Mar 29, 2019	17,992	0.678	0.127	0.255	0.100
B2	543	1564	F	1	Mar 18, 2019	13,597	0.318	0.073	0.220	0.062
B112	543	1422	F	3	Mar 23, 2019	14,844	0.289	0.085	0.396	0.162
B143	556	1548	F	2	Mar 28, 2019	12,032	0.443	0.153	0.662	0.212
B159	584	1754	F	3	Mar 29, 2019	16,792	0.942	0.282	0.929	0.323
B131	845	5062	F	1	Mar 27, 2019	X	X	X	X	X
B73	366	556	M	1	Mar 13, 2019	15,111	0.210	0.041	0.226	0.062
B127	380	456	M	2	Mar 26, 2019	X	X	X	X	X
B117	385	455	M	3	Mar 23, 2019	X	X	X	X	X
B50	392	595	M	2	Mar 19, 2019	9,936	0.176	0.044	0.076	0.020
B92	406	555	M	3	Mar 22, 2019	14,658	0.454	0.113	0.679	0.216
B12	407	776	M	1	Mar 19, 2019	11,950	0.259	0.068	0.165	0.049
B108	443	840	M	3	Mar 23, 2019	18,299	0.444	0.127	0323	0.123
B129	467	870	M	2	Mar 26, 2019	X	X	X	X	X
B35	471	980	M	2	Mar 19, 2019	13,646	0.544	0.155	0.244	0.068
B138	475	1006	M	1	Mar 27, 2019	6,213	0.679	0.248	0.159	0.042
B1	477	926	M	1	Mar 18, 2019	X	X	X	X	X

Table A.1.1 Continued

Fish ID	Length	Weight	Sex	Basin	Date Tagged	VPS	Ice HR	Ice CR	Open HR	Open CR
B33	505	1114	M	2	Mar 19, 2019	X	X	X	X	X
B83	510	1191	M	3	Mar 22, 2019	X	X	X	X	X
B136	514	1243	M	1	Mar 27, 2019	X	X	X	X	X
B165	516	1146	M	3	Mar 29, 2019	37,326	0.495	0.137	0.173	0.057
B175	523	1323	M	2	Mar 31, 2019	X	X	X	X	X
B34	527	1175	M	2	Mar 19, 2019	13,329	0.180	0.048	0.057	0.015
B31	534	1281	M	2	Mar 19, 2019	X	X	X	X	X
B121	552	1188	M	2	Mar 26, 2019	X	X	X	X	X
B153	561	949	M	3	Mar 29, 2019	X	X	X	X	X
B137	570	1350	M	1	Mar 27, 2019	23,347	0.973	0.386	0.197	0.055
B86	601	1643	M	3	Mar 22, 2019	X	X	X	X	X
B27	609	1619	M	2	Mar 19, 2019	X	X	X	X	X
B20	367	510	U	1	Mar 18, 2019	5,269	0.521	0.149	0.219	0.056
B10	375	499	U	1	Mar 18, 2019	X	X	X	X	X
B152	388	590	U	2	Mar 28, 2019	X	X	X	X	X
B44	396	581	U	2	Mar 19, 2019	X	X	X	X	X
B163	396	740	U	3	Mar 29, 2019	X	X	X	X	X
B36	404	715	U	2	Mar 19, 2019	17,174	0.379	0.109	0.251	0.091

Table A.1.1 Continued

Fish ID	**Length**	**Weight**	**Sex**	**Basin**	**Date Tagged**	**VPS**	**Ice HR**	**Ice CR**	**Open HR**	**Open CR**
B61	414	603	U	1	Mar 20, 2019	X	X	X	X	X
B182	418	631	U	2	Apr 3, 2019	X	X	X	X	X
B23	423	777	U	1	Mar 18, 2019	X	X	X	X	X
B30	440	840	U	2	Mar 19, 2019	16,715	0.479	0.128	0.642	0.198
B6	450	912	U	1	Mar 18, 2019	X	X	X	X	X
B89	450	1057	U	3	Mar 22, 2019	16,170	0.450	0.136	0.207	0.061
B91	461	865	U	3	Mar 22, 2019	X	X	X	X	X
B4	468	975	U	1	Mar 18, 2019	X	X	X	X	X
B88	474	626	U	3	Mar 22, 2019	8,419	0.647	0.184	0.470	0.141
B54	489	1150	U	2	Mar 19, 2019	11,620	0.299	0.068	0.868	0.336
B184	524	1191	U	2	Apr 8, 2019	8,613	1.088	0.384	1.034	0.373
B3	526	1439	U	1	Mar 18, 2019	10,596	0.964	0.420	0.336	0.107
B37	545	1237	U	2	Mar 19, 2019	X	X	X	X	X
B99	566	1647	U	3	Mar 22, 2019	9,036	0.494	0.153	0.082	0.023
B185	625	2920	U	2	May 2, 2019	32,055	0.639	0.172	0.549	0.152

Chapter 2: Life History and Population Dynamics of Burbot in Minnesota Waters

Introduction

Once historically abundant in Lake of the Woods (Muth 1973), Burbot populations declined severely during the same period Burbot declined out west (Stapanian et al. 2010). The primary source of this decline seemed centralized around the commercial fishing industry. Previously classified as a rough fish, the species became a target during low catch rates of Walleye during the winter. Researchers and industrial businesses found uses for rough fish species. Specifically, Burbot fat oils were used as supplements, and their meat was used for processed foods (Bell 1985). Although the species appeared abundant to anglers, it prompted new research conducted in the 1970s to 1980s. That research indicated that Burbot stocks declined in Lake of the Woods due to increased pressure from commercial harvest. The studies conducted by Muth (1973) and Carlender (1944) were the most in-depth study of the species across Minnesota. However, the status of the fish in the 2000s has been investigated briefly across the state, with few studies only looking at small parts of their population dynamics in a system.

In Minnesota, the popularity of targeting Burbot, *Lota lota*, has increased over the last two decades for anglers (Dokken 2012). With increased concern that enhanced angling pressure would damage Burbot stock throughout Minnesota, the Minnesota Department of Natural Resources (MNDNR) sought to change the status of the fish from under-utilized or “rough fish” to a game fish in the fall of 2019 (Minn Stat. § 97A.015). However, this regulation classification change did not include new limits or seasons on the fish, and anglers can target the species all year long while possessing as many Burbot as they want. However, the current knowledge of the population status of Burbot in Minnesota is limited to a few studies as well as incidental catches during MNDNR sampling. This lack of understanding prompted the MNDNR to begin a new study focused on learning movement patterns of Burbot in a Northern Minnesota lake, processing Burbot life history data, and a literature review of Burbot life history information applicable to Minnesota’s lakes, rivers, and connecting bodies of water.

Methods

Reference material was primarily accessed through well-known search engines, including, but not limited to, Google Scholar, ResearchGate, as well as other search engines provided through school and state access. Keywords searched contained; Burbot or *Lota lota*, movement, population dynamics, reproduction, acoustic telemetry, survival, management, Minnesota, life history, behavior, diet, habitat. The material used focused on published theses, manuscripts, articles from scientific magazines, state and federal agency surveys, and other peer-reviewed literature, with the occasional use of non-scientific magazines or newspaper outlets.

Keywords were assigned according to each piece of literature its focus:

Age and Growth – Data includes age, length, and weight

Behavior – Presents patterns of life-stage habits and interactions between species

Distribution – Geographic locations past and present

Feeding – Diet items and food gathering methods

Harvest – Commercial, recreational, and incidental catches

Management – Describes population assessment and harvest recommendations

Morphology – Physical parameters of the body

Mortality – Contains data on natural and fishing mortality in all life stages

Movement – Contains migrations, movement patterns, as well as spatial and temporal locations from sampling, tracking, and visual captures

Population Dynamics – Data consisting of dynamic population rates, abundance estimates, presence in a system

Reproduction – Presents knowledge of spawning locations, preferences, age at maturity, fecundity, and early life history

Sampling – Describes sampling procedures for specifically targeting Burbot or gear used for incidental catches

Species Description – General species knowledge

Utilization – Describes overall use of harvested Burbot

Thirty documents were found and summarized, including peer-reviewed literature published in scientific journals, doctoral dissertations, masters' theses, and magazine and newspaper articles.

Documents

1. Anderson, E. D., and L. L. Smith. 1971. A synoptic study of food habits of 30 fish species from Western Lake Superior. University of Minnesota, Technical Bulletin 279, Agricultural Experiment Station.

    This papers' objective was to fill a void in diet data of multiple species that inhabit the western shores of Lake Superior. Their study areas included the Apostle Island of Wisconsin and the Duluth/Superior area. Sampling spanned from the fall of 1965 through 1968 using bottom and midwater trawls, larval nets, and gill nets. In addition, 78 Burbot stomachs were sampled, 30 from the Duluth area and 48 from the Apostle Islands. Top diet items included crustaceans and fish, insects, fish eggs, and mollusks. Fish (Smelt) were the primary diet item in all but April, where *Mysis* and amphipods were important.

KEYWORDS: Distribution, Feeding, Sampling

2. Appelget, J. G. 1949. Preliminary report on abundance and life history of the Burbot (*Lota lota maculosa*) in Bass Lake (14-29) and Moose Lake (14-600), Itasca County. Pages 1–6. Division of Game and Fish, Section of Research and Planning, Investigational 88, Minnesota Department of Conservation.

    The Bureau of Fisheries Research sampled Burbot in Moose and Bass lakes during the winter of 1948-49. 216 Burbot in Moose Lake and 237 fish in Bass Lake were sampled. Abundance in both lakes was tough to calculate as catch ratios varied across summer and winter; results showed that in Moose Lake, personnel sampled 0.036 pounds per set. Test sampling in the winter of 1946 resulted in 4.14 pounds per set. Sampling was conducted from February 17 to March 7 to determine the spawning period for Burbot in those lakes. Burbot numbers peaked in Moose Lake on February 23 and Bass Lake on February 28. The diet patterns of Burbot consisted primarily of crayfish, yellow perch, and insects.

KEYWORDS: Age and Growth, Feeding, Population Dynamics, Reproduction, Sampling

3. Bailey, M. M. 1972. Age, growth, reproduction, and food of the Burbot, *Lota lota* (*Linnaeus*), in Southwestern Lake Superior. Transactions of the American Fisheries Society 101(4):667–674.

This study sampled 1,285 Burbot in Western Lake Superior, with 19 coming from Duluth's shores, while the others came from the Apostle Island region and Keweenaw Bay of Michigan. There were no differences in length and weight of Burbot by region of capture; data from all kept fish were pooled together. Males were found at a 59% maturity rate in their second year of life, whereas females were only 7%. All fish at age five and older were mature. The length and weight of Burbot appear to be larger than other fish from around the great lakes. Spawning occurred near Bayfield in late February and was completed by March 11. In early March, a small number of fish sampled in the Apostle Island region were not spent. Like other studies, the primary food source was fish and crustaceans.

KEYWORDS: Age and Growth, Feeding, Reproduction, Sampling

4. Bell, H. 1985. There's more to eelpout than meets the eye. UMD Statesman 22:11. Duluth, Minnesota.

   H. Bell wrote this news article to highlight the many benefits found in Burbot. He discusses the monetary benefits of the Eelpout Festival, and the human benefits of consuming their meat, given the high vitamin content of the liver. Also discussed are the fundamental life history knowledge of spawning locations and feeding habits from firsthand witnesses.

KEYWORDS: Harvest, Utilization

5. Bonde, T., and J. E. Maloney. 1960. Food habits of Burbot. Transactions of the American Fisheries Society 89(4):374–376.

   Bonde and Maloney assessed Burbot diets from Mille Lacs Lake in 1949 and 1958-59. In 1949, 56 fish were sampled, all containing fish, while in 1958-59, 89.1% of the stomachs with diets had fish 53.6% of the fish were determined to be perch. This report also highlighted a few anomalies where they found one stomach that contained small Burbot, 30 perch, and one shiner, while another included 40 perch, an unidentified fish, and one shiner. Although these quantities were not typical during that timeframe, biologists raised a slight concern as Burbot and Walleye live and compete for similar resources.

KEYWORDS: Feeding, Harvest, Utilization

6. Boyer, L. F., R. A. Cooper, D. T. Long, and T. M. Askew. 1989. Burbot (*Lota lota*) biogenic sedimentary structures in Lake Superior. Journal of Great Lakes Research 15(1):174–185.

This journal article shares the unique discovery of biogenic structures and excavating behaviors of Burbot in Lake Superior. Burbot were found in water depths ranging from 140 to 366 meters, and found burrowed into sediments or inhabiting natural cavities. The authors formed two hypotheses for this behavior. Burbot seek refuge from predators, or they suggest it enhances feeding efficiency. This research showed a considerable gap in knowledge of Burbot behavior in deepwater systems and showed how much Burbot are still connected to their saltwater relatives.

KEYWORDS: Behavior, Distribution

7. Boyer, L. F., P. L. McCall, F. M. Soster, and R. B. Whitlatch. 1990. Deep sediment mixing by Burbot (*Lota lota*), Caribou Island Basin, Lake Superior, USA. Ichnos 1(2):91–95.

This research hypothesized that Burbot made trenches found by Boyer et al. (1989) instead of other invertebrates due to the excavation depth of the trench. Researchers resurveyed areas from previously sampled areas in 1985, where core samples and photos were taken to assess the quantity of Burbot-made trenches. Although, the authors suggest future research needs to be conducted to evaluate the frequency of trenches and the distribution across substrates.

KEYWORDS: Behavior, Distribution

8. Burrows, C. R. 1951. Status of the Lake of the Woods Fisheries, 1938 through 1949, with special reference to the Walleye. Pages 1 – 5. Division of Game and Fish, Section of Research and Planning, Investigational 106, Minnesota Department of Conservation.

Lake of the Woods was the focus of this investigational report by the State of Minnesota. This report focused on the state of the commercial “walleyed-pike” fishery but briefly discussed Burbot as bycatch by commercial fishermen. Dependent on gear, Burbot ranged from 5 to 37% of the catch, most coming from trap nets between the years 1945 to 1949.

KEYWORDS: Harvest, Sampling

9. Cahn, A. R. 1936. Observations on the breeding of the lawyer, Lota maculosa. Copeia 1936:163–165.

   This observational document summarizes spawning Burbot in Burntside Lake, Ely, Minnesota. The author shares that they witnessed increased Burbot activity at night, with males beginning to show up in shallow water and one lake outlet. Following a few days behind were females. Burbot were observed in a short stretch of open water only during the night. However, nightly observations under the full moon were witnessed during a shorter period, indicating a high sensitivity to light. Finally, on February 12, 1936, during one year of the observations, Burbot were seen to form a spawning ball containing multiple males and females. This document was one of the most detailed observational write-ups of Burbot spawning to date; however, the reasons why it occurred when it did are lacking.

KEYWORDS: Behavior, Feeding, Movement, Reproduction

10. Carlender, K. 1944a. Notes on the minor species of fish taken in the commercial fisheries at Lake of the Woods, 1939 to 1943. Pages 12–13, 25–27. Division of Game and Fish, Section of Research and Planning, Investigational 42, Minnesota Department of Conservation.

    This report highlights all non-target or bycatch species caught in the commercial fisheries study of Lake of the Woods. Briefly highlighted are the few Burbot that were captured and analyzed. The sex ratio between 1939 and 1943 was 39 males to 13 females. Additionally, they caught a 711 mm fish with 903,060 eggs in its body in December 1941. Diets of 11 Burbot consisted of crayfish, minnow species, and perch.

KEYWORDS: Age and Growth, Feeding, Harvest, Reproduction, Sampling

11. Carlender, K. 1944b. The commercial fisheries of Lake of the Woods. Page 57. Division of Game and Fish, Section of Research and Planning, Investigational 42, Minnesota Department of Conservation.

    This document is another supplementary document discussing the fishery of Lake of the Woods. They talk about the increase in catch rates of rough fish from 1942 to 1943 due to higher market prices. Fyke and pound nets were most successful in catching Burbot. The pound of catch for Burbot peaked in 1936 at 178,649 total pounds.

KEYWORDS: Harvest, Sampling, Utilization

12. Dokken, B. 2012. Eelpout, the "ish of fish," in apparent decline. St. Paul Pioneer Press.

This news article discusses the popularity of Burbot due to recent catches of state record Burbot in Minnesota's Lake of the Woods. Additionally, this article talks about the decline in the number caught, specifically at Eelpout Festival on Leech Lake. Biologists point to warming water temperatures and the lack of cold areas for Burbot to hide during the summer.

KEYWORDS: Harvest, Management, Mortality, Reproduction

13. Fisher, S. J., D. W. Willis, and K. L. Pope. 1996. An assessment of Burbot (*Lota lota*) weight–length data from North American popuplations. Canadian Journal of Zoology 74(3):570–575.

Researchers assessed 79 Burbot populations across Canada and the United States and analyzed their length-weight relationship. Of the 79 populations sampled, four of them came from Minnesota waters of Lake Superior, Leech Lake, Lake Mille Lacs, and Rainy Lake. Populations of Burbot were classified by a large or small lake, reservoir, and river, and relative weights were compared between environments. Results showed that Burbot from rivers and reservoirs had a lower relative weight than lake dwelling Burbot. The authors hypothesized that their results might validate that two different phenotypes exist. Therefore, more research should be conducted to determine appropriate ranges for relative weight values between Burbot in lakes versus rivers.

KEYWORDS: Age and Growth, Distribution, Morphology, Population Dynamics

14. Gorman, O. T., and S. P. Sitar. 2013. Ups and downs of Burbot and their predator Lake Trout in Lake Superior, 1953–2011. Transactions of the American Fisheries Society 142(6):1757–1772.

This article summarizes the relationship between Burbot and Lake Trout throughout Lake Superior. Researchers assessed trends in catch records from gillnets and bottom trawls between 1953 and 2011. Catch per unit effort of Burbot in gillnet surveys decreased as Lake Trout catch increased. Researchers also determined that mean density in bottom trawl catches of all sizes of Burbot decreased between 1978 to 2011; specifically, juvenile Burbot decreased rapidly starting in 1980 with the recovery of Lake Trout. These results suggest that Lake Trout kept Burbot populations in check at young ages; however, due to Burbot populations being spread across near and offshore areas, populations should maintain a healthy level if Lake Trout populations stay stable.

KEYWORDS: Age and Growth, Behavior, Mortality, Population Dynamics, Sampling

15. Gorman, O. T., D. L. Yule, and J. D. Stockwell. 2012a. Habitat use by fishes of Lake Superior. I. Diel patterns of habitat use in nearshore and offshore waters of the Apostle Islands region. Aquatic Ecosystem Health & Management 15(3):333–354.

This research paper discusses diel migrations patterns of fish species from Lake Superior near the Apostle Islands. Personnel used bottom trawls to catch fish across four depth ranges between 15 and 120 m. Although Burbot were not sampled in large numbers in proportion to other species, diel patterns still were found between varying size classes of Burbot. In addition, the research showed increases in catches during the night with larger Burbot densities at night in shallower depths. However, no determination of diel migration strategy was coined.

KEYWORDS: Distribution, Movement

16. Gorman, O. T., D. L. Yule, and J. D. Stockwell. 2012b. Habitat use by fishes of Lake Superior. II. Consequences of diel habitat use for habitat linkages and habitat coupling in nearshore and offshore waters. Aquatic Ecosystem Health & Management 15(3):355–368.

This research dove further in-depth into analyzing the diel migration patterns of fish populations in the Apostle Islands concerning the magnitude of diel migrations associated with biomass of species at depth zones. Results showed that Burbot exhibited circular migrations from benthic to benthopelagic zones but not attributed to diel vertical or bank migrating. Therefore, researchers summarized that Burbot diel migrations should be investigated to a more significant extent to validate if a pattern of bank or vertical diel migration exists or if a circular way of diel migration still exists.

KEYWORDS: Distribution, Movement

17. Heyerdahl, E. G., and L. L. Smith. 1972. Fishery resources for Lake of the Woods, Minnesota. University of Minnesota, Technical Bulletin 288, Agricultural Experiment Station.

    This document examines the historical commercial fishery use of Lake of the Woods, Minnesota. The commercial fishery of Lake of the Woods went through shifts during the mid-1900s, as trawling was introduced, and fishing improved for Tullibee and Burbot and decreased for Walleye. The total catch of Burbot peaked at 880,000 pounds in 1961, with steady decreases following. The authors also discussed the sampling gear used and which was more effective at catching Burbot. Results show Pound and Fyke nets were overwhelming the most successful sampling gear for targeting Burbot. Additionally, the authors discuss the implications of commercial fish management and the modifications that could have been made to increase desired species. This topic of discussion was one of the first of its kind concerning Burbot abundance and harvest. The research presented here helps understand the importance of Burbot across Minnesota and is beneficial with today's rising popularity in Burbot.

KEYWORDS: Age and Growth, Behavior, Harvest, Management, Population Dynamics, Sampling, Utilization

18. Isaac, E. J. 2010. An evaluation of the importance of *Mysis relicta* to the Lake Superior fish community. Master's Thesis, University of Minnesota - Duluth, Duluth, Minnesota.

    This thesis discussed the feed habits of multiple Lake Superior fish. Burbot were found to select for *Mysis* and deepwater sculpin throughout the year and Rainbow Smelt in the spring, and *Diporeia* in the summer. Larger fish preferred smelt while smaller Burbot preferred *Mysis*. However, only 37 Burbot were found with diets during the study. Additionally, this document quantified other population dynamics, including age, growth rates, consumption, and bioenergetics from sampled Burbot near the Apostle Islands.

KEYWORDS: Age and Growth, Behavior, Distribution, Feeding, Population Dynamics

19. Michels, N. O., T. R. Hrabik, and A. F. Mensinger. 2021. Comparison of multipiscivore foraging success on native and invasive prey fish under variable light intensities. Transactions of the American Fisheries Society 150(3):361–374.

    Michels et al. focused their research on the foraging success of Smallmouth Bass and Burbot on sculpins and goby while manipulating light intensities. Results showed Burbot had a 5% success rate in the retention of the prey species. Additionally, they suggested that their results show Burbot rely on visual keys to feed than previously thought, as they had a higher success rate at twilight hours than during the night.

KEYWORDS: Behavior, Feeding, Morphology, Movement, Species Description

20. Minn Stat. § 97A.015 2019.

    This statute, made to the law in 2019, reclassified Burbot from under-utilized or rough fish up to the game fish label. Although this did not bring regulations, this statute allows the opportunity to bring about regulations or seasons in the future.

KEYWORDS: Management

21. Muth, K. M. 1973. Population dynamics and life history of Burbot, *Lota lota* (*Linnaeus*), in Lake of the Woods, Minnesota. Doctoral Dissertation, University of Minnesota, Minneapolis, Minnesota.

    This dissertation is the most comprehensive summary of Burbot's life history in the state of Minnesota. The author, Kenneth Muth, covered all topics from length and weight to utilization. He concluded that rough fish catches averaged 60% of the commercial catch, resulting in an average of $50,000, with Burbot comprising $30,000. A total of 2617 Burbot were processed for detailed analysis, while an additional 2912 fish were used for just length-frequency analysis and 469 young-of-the-year fish. Burbot appeared to grow quickly, with five-year-old fish reaching lengths upwards of 575 mm, reaching sexual maturity at age 3. In addition, Muth found that Burbot activity levels could be inferred using catch rates in different sampling gear and their relationship with water temperature. Over the summer months of July and August, fish were caught in high quantities using trawls when temperatures were high. Gear that relies on fish movement, gill, and pound nets, were used exclusively in spring, and fall, with fyke nets finding their primary use over the winter when fish mobile and clustered to spawn. This document opened the discussion for regulations on commercial fishermen of Lake of the Woods.

KEYWORDS: Age and Growth, Behavior, Distribution, Feeding, Harvest, Management, Movement, Population Dynamics, Reproduction, Sampling, Utilization

22. Muth, K., and L. L. Smith. 1974. The Burbot fishery in Lake of the Woods. Pages 1–68. University of Minnesota, Technical Bulletin 296, Agricultural Experiment Station.

    Muth and Smith were the leaders in Burbot research in Minnesota during the late 1900s. This document is one of their most expansive write-ups of all Burbot data knowledge from Lake of the Woods. Highlighted here are data revolving around the commercial fishery of Burbot that was overexploited across the 1900s. They focused this document on understanding data on age, growth, mortality, and reproductive success of the fishery. They sampled Burbot across a year. Most fish came during the summer, and another large quantity came during the February period, associated with the spawning period. Length studies tallied nearly 6,000 fish, while roughly 2,000 fish were used to calculate a length-to-weight relationship. Additionally, research on the diets of Burbot were assessed through all months of the year besides April, one of the first diet studies of its kind to eliminate the bias in short-term diet studies. They used their data to recommend a safe harvest level for Burbot by year if commercial fishing for them continued.

KEYWORDS: Age and Growth, Harvest, Management, Mortality, Population Dynamics Reproduction, Utilization

23. Reinan, J. 2020, January 2. You better not pout: Minnesota's International Eelpout Festival canceled. Minneapolis Star Tribune.

    The Minnesota Star Tribune has covered multiple articles about Burbot across the years. This one is most important as they highlight the increased popularity of Walker, Minnesota's International Eelpout Festival, which was canceled in 2020.

This festival started in 1979 and continued through 2019, attracting more and more participants each year. Labeled as "catfish-like critters," Burbot were the focus of multiple games; some more focused on the fish while some focused more on adult activities. The article cites that increased regulations and increased costs are the sources of the permanent cancellation of the festival. The article also references the status change from rough fish to game fish.

KEYWORDS: Harvest, Management

24. Schram, S. T. 1983. Seasonal movement and mortality estimates of Burbot in Wisconsin waters of western Lake Superior. Pages 90–95 in V. L. Paragamian and D. W. Willis, editors. Burbot biology, ecology, and management. American Fisheries Society, Spokane, Washington.

Burbot were sampled from 1979 to 1982 using trap and fyke nets in the western shores of Lake Superior, resulting in 1,466 fish, with 354 fish used for age determination. The age of Burbot ranged from 3 to 14, with 24% of the sample falling at seven years old. Fish in that section of Lake Superior appear to grow smaller than other populations around the great lakes found in other studies. Summer distribution was unknown; however, it was suspected that Burbot remained near their spawning locations of the Nemadji and Amnicon rivers, moving eastward until June. They then began their migration back west to the river mouths by November. Total mortality was estimated to be 43%, similar to Great Lakes studies.

KEYWORDS: Age and Growth, Distribution, Mortality, Movement

25. Schram, S. T., T. B. Johnson, and M. J. Seider. 2006. Burbot consumption and relative abundance in the Apostle Islands region of Lake Superior. Journal of Great Lakes Research 32(4):798.

This study discusses 30 years of sampling data from the Apostle Islands region of Wisconsin. Burbot were found to have decreased in abundance by a significant margin from 1978 to 1998. Additionally, Burbot, less than 400 mm in total length, primarily consumed smaller prey items such as bugs, fish eggs, and sculpins. In comparison, larger Burbot focused on fish such as rainbow smelt. They hypothesized that Burbot populations decreased due to increased lean and siscowet lake trout abundances.

KEYWORDS: Age and Growth, Distribution, Feeding, Mortality

26. Stapanian, M. A., C. P. Madenjian, C. R. Bronte, M. P. Ebener, B. F. Lantry, and J. D. Stockwell. 2008. Status of Burbot populations in the Laurentian Great Lakes. Pages 111–130 in V. L. Paragamian and D. Bennett, editors. Burbot: Ecology, Management, and Culture. American Fisheries Society, Bethesda, Maryland.

This document summarizes Burbot population trends and how they were influenced by other species such as Sea Lamprey, Alewife, and Lake Trout during a 20-to-30-year span from 1978 to 2004. The goal was to learn about food web dynamics in regions and the Great Lakes. Results show Burbot abundance remained constant but low (0.35 fish/ha) before 1995, where it began to drop to record lows (0.02 fish/ha) in 2003. Predation from siscowet Lake Trout is believed to keep the Burbot population lower in Lake Superior.

KEYWORDS: Distribution, Population Dynamics, Sampling

27. Stapanian, M. A., V. L. Paragamian, C. P. Madenjian, J. R. Jackson, J. Lappalainen, M. J. Evenson, and M. D. Neufeld. 2010. Worldwide status of Burbot and conservation measures. Fish and Fisheries 11(1):34–56.

This report summarizes the status and conservation of Burbot across the world. Researchers deemed the quality of Burbot stock from Minnesota secure, with localized populations seeing decreased abundance during the late 1900s.

KEYWORDS: Distribution, Management, Population Dynamics, Sampling

28. University of Minnesota Agricultural Extension Service. 1975. Fish Fillets. University of Minnesota Agricultural Extension Service. Consumer Radio Briefs.

The document highlights a brief radio discussion that shares that a University of Minnesota scientist thinks Burbot could be utilized as meat for fish sticks or cakes with new advances in equipment.

KEYWORDS: Utilization

29. University of Minnesota Agricultural Extension Service. 1979. Rough Fish. University of Minnesota Agricultural Extension Service. Consumer Radio Briefs.

Another brief radio discussion that UMN researchers estimate is that 17 million pounds of rough fish, including Burbot, could be harvested annually. In addition, they would serve a purpose as a source of revenue for rural Minnesota for consumer products.

KEYWORDS: Utilization

30. Wagner, G. 1908. Notes on the fish fauna of Lake Pepin. Pages 23–37. Transactions of the Wisconsin Academy of Sciences Arts and Letters, 1st edition.

This observational report summarizes the species of fish found in Lake Pepin, an expanded area of the Mississippi River in Wisconsin and Minnesota. The author spent multiple years using seines to collect fish species he believed inhabited the river. Forty-four species occupy Lake Pepin, including Burbot. He claims residents believe the eelpout is a stage of the eel. They only captured one specimen but noted that the fish used to be familiar and caught on set lines to be sold at fish markets.

KEYWORDS: Harvest, Utilization

Summary

Burbot are understudied throughout their range and specifically with data associated with populations across Minnesota. The most comprehensive and in-depth studies are from the Lake of the Woods fishery. Burbot populations in Lake of the Woods succumbed to commercial anglers as people found new uses for the fish, specifically the liver oils that were a good source of vitamin A. Researchers at the University of Minnesota conducted a comprehensive life history study on all aspects of the population, ranging from a diet analysis to population estimates and beyond. Results show that Burbot populations experienced a sharp decline following the peak harvest of the species in 1961, prompting more research to assess the overall population status of the fish. Researchers from the University of Minnesota and the Minnesota Division of Fish and Game focused many years on understanding the population and the changes the fish experienced from commercial harvest. However, they did not put restrictions on the fish following their efforts but instead urged commercial harvesters to manage how many fish were removed from areas. At the time, commercial gear was able to access waters sport fishermen were unable to, which they assumed that the overall population was relatively stable.

Following the Lake of the Woods research, a reasonably large gap in the literature for Burbot studies in Minnesota occurred. Researchers began to focus their efforts on fish populations in Lake Superior from the 1980s to present. They focused their efforts on the distribution of the fish throughout the Great Lakes. Burbot were found to inhabit deeper water than previously thought. Research also found that Burbot might be one of the top predators in aquatic systems, which progressed claims that their populations should be kept in check to maintain healthy game fish population levels. Gorman et al. (2012) assessed Burbot migration patterns from 2004 to 2008. They were one of the first to monitor the diel movement of the fish in association with other predators and prey in the waters of Western Lake Superior. Researchers classified their movements as neither diel vertical nor horizontal but instead indicated an affinity for increased activity at night. This claim would be challenged by researchers in Canada in the mid-2010s.

In the 2000s, Stapanian et al. (2010) classified Burbot as endangered western United States rivers and reservoirs species. They synthesized documentation in the "Worldwide status of Burbot and conservation measures," which summarized Burbot stock worldwide. Briefly mentioned in the document were the Burbot populations of Minnesota; they motioned that the population was secure. However, the authors addressed how populations in Mille Lacs and Lake of the Woods decreased during the warming period of the 1980s. In hindsight, this "apparently secure" classification should have been addressed further, and reclassification should have occurred.

During the 2000s, Burbot had not been studied outside of Lake Superior until 2020, when a University of Minnesota – Duluth study assessed the foraging success of Burbot from a lake near Ely, Minnesota (Michels et al. 2021). Researchers concluded that Burbot, known as an ambush predator, on average, did not attack prey that was more than a body length away from the fish and even shorter of a distance during the dark. However, during the periods of light, Burbot were more successful at prey detection than during dark periods. Additionally, researchers found that most Burbot reactions to prey occurred anterior to the head. These results indicate that Burbot are more of a visual feeder than previously thought.

Overall, this annotated bibliography highlights the lack of information on a newly classified game fish in the state of Minnesota. As their popularity has increased each year, it might be time for regulations to protect a fish that historically shows declines in population size with a large harvest of the species. However, more research needs to be done on populations that inhabit the interior water bodies of Minnesota, as these populations are severely lacking data. Research should focus again on diet analysis, relating to how invasive species such as zebra mussels and rusty crayfish have changed the food web dynamics. Additionally, researchers should get a baseline population assessment of Burbot as they might be a key indicator species for climate change. Although challenging, sampling the populations using standard gear is an option, but a more plausible use would be to use recreational anglers. For example, managers could conduct creel surveys and use camera traps on some of the more well-known Burbot fisheries across the state to better understand how much pressure the species experiences and assess how many fish anglers encounter on a typical night. Not only would it provide area staff with a change of pace from their typical winter day in the office, but it also helps them understand the status of the population throughout the state. Finally, receiving an estimate of how large Burbot populations are across multiple systems in Minnesota will help managers successfully maintain the status and level of fish. The more known about the population, the more anglers will protect and respect the fish.

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APPENDIX B

During the study period ranging from 2019 to 2021, 306 Burbot were caught via angling. Bemidji State University researchers sampled 274 fish across three years, while local anglers willing to assist in the study provided 32 fish. In 2019, 190 Burbot were angled from Bad Medicine Lake. In 2020, only 45 Burbot were sampled. The COVID-19 pandemic forced travel restrictions and hindered efforts to sample the population in 2020, and a local guide provided twenty-six fish in February of 2020. These fish were filleted in the field and could not be used for weight metrics, and in 2021, 71 Burbot were sampled.

Length. – Burbot length differed significantly by sex ($X^2 = 40.87$, df = 2, $p < 0.001$; Figure B.1.1). Females were largest with a median length of 499.5 mm (n = 88), males were second with a median length of 483 mm (n = 117), and fish of unknown sex had a median length of 444 mm (n = 101). Unknown sexed fish resulted from fish being too small to expel milt or eggs, or the fish was long enough but were not ripe enough to determine the sex. Acoustically tagged fish (n = 66) had a similar length distribution. Due to the bodyweight to tag weight ratio, the smallest taggable fish was 350 mm. No significant difference was found in the length of tagged Burbot by sex ($X^2 = 4.68$, df = 2, $p = 0.096$; Figure B.1.2). Males had the largest median length of 505 mm (n = 23), followed by females (median = 492, n = 22) and finally, unknown sexed fish (median = 450, n = 21).

Weight. – A total of 280 fish were used to calculate weight metrics. Burbot weight had a large range during the study period due to the status of a fish being in either pre-spawn, spawn, or post-spawn stage. Burbot in pre-spawn compared to post-spawn had noticeable physical differences in girth. Prior knowledge of Burbot reproduction indicates that Burbot can expel one to two million eggs depending on their body size (Clark et al. 1991, McPhail 2007). A similar relationship to length was found while comparing Burbot weight by sex. The weight of fish was significantly different among the three sex groups ($X^2 = 49.82$, df = 2, $p < 0.001$; Figure B.1.3). Females were larger than both males and fish of unknown sex (median: Female = 1158.5 g, Male = 958.0 g, Unknown = 770.0 g). The weight comparison by sex of tagged fish was identical to all fish, with females being the largest, followed by males and finally fish of unknown sex (Figure B.1.4).

Weight – Length Relationship. – Burbot followed a consistent weight–length relationship across years. We computed the log measurements for length and weight to account for variability among data. We assessed the relationship between weight and length across all fish using linear regression. Regression analysis resulted in statistical significance in the relationship between length and weight ($R^2 = 0.9$, $F_{(1,2506)} = 2506$, $p < 0.001$). For graphical purposes, the raw values of weight to length were plotted for all 280 Burbot used in the analysis (Figure B.1.5).

Condition. – Relative weight (W_r) of Burbot was assessed following Fisher et al. (1996). Researchers used 10,293 samples of Burbot across 79 North American populations. We classified our fish into the same standard-length categories of stock, quality, preferred, memorable, and trophy as Fisher et al. (1996) (Table B.1.1). Fisher (1996) found the mean estimates of W_r for small lakes (< 19,000 km^2) to be less than 100 across all standard-length groups. Burbot from Bad Medicine Lake resulted in W_r for all groups larger than 115 (Figure B.1.6). The condition of Burbot in Bad Medicine Lake appear healthy. Bad Medicine Lake has a known high abundance of crayfish, and a high quantity of rainbow trout stocked yearly, a high-quality food source if caught. Pope and Willis (1996) suggested that fish should be sampled in a standardized process across systems due to fluctuations in the condition by season. However, we could not follow this rule, as fish were only sampled during their spawning window. This period is when Burbot are the heaviest due to the extra weight of eggs or sperm. Therefore, our results should only be compared in moderation, and future studies should attempt to catch Burbot at other times of the year.

Burbot W_r was assessed by Julian day across the three years. Average W_r began to decrease on March 30th (Figure B.1.7). The relative weight of Burbot ranged between 115 and 135 during the middle of March, while after 30 March 2020, W_r dropped to lower than 115. Although data is scarce, understanding when the condition of Burbot begins to decrease can be used as an indication of the fish population reaching the post-spawn stage. Our data suggest that most Burbot are in the post-spawn stage following 30 March 2020.

Age and Growth. – Burbot age was estimated using whole, cracked, and sectioned sagittal otoliths. A total of 56 Burbot were used for aging fish from Bad Medicine Lake. Fish were sacrificed when they could not swim down the hole because of barotrauma or angling stress. Growth rates were assessed using a von Bertalanffy growth function (Figure 2.8). Burbot appear to grow rapidly in their first three years of life, reaching nearly 450 mm. Otoliths were challenging to age as fish got older. Growth rings crowded the anterior margin of the otolith (Figure B.1.9). Muth and Smith (1974) assessed the ages of over 5,000 Burbot across multiple years. Their results showed that age five Burbot, the most frequent age in their study, had a length range between 551 to 575 mm. Whereas, Burbot in Bad Medicine Lake grew slower as the average length of an age five Burbot was 506 mm. Additionally, our oldest estimated fish was aged 15 years old and 692 mm. Muth estimated their oldest fish to be 13 years old and averaged 745.6 mm long, indicating Burbot from Lake of the Woods experienced faster growth than Bad Medicine Lake Burbot. However, the sample size in the present study was modest, at only 56 fish. Future research should assess the age and growth in a large quantity of fish to better assess the growth patterns of the present Burbot populations.

Length at Maturity. – Length at maturity was unable to be determined due to the lack of small fish caught during sampling. Only five fish below 350 mm were observed during the study, one of which was kept and brought back to the lab for analysis. This fish was classified as an immature female. However, due to mechanical issues, the age of that fish was unable to be determined. The other four fish were returned to the lake immediately following capture.

Diet. – The diets of Burbot have been studied across their range (Bonde and Maloney 1960, Bailey 1972, Muth 1973). Studies have indicated an affinity for fish to be a frequent food source of the species, indicating the possibility of Burbot being a top predator in systems. However, few studies have addressed the diets of other predator species simultaneously, and a lack of diet analyses across multiple periods.

The diets of 56 fish caught from 2019 to 2021 were analyzed. Study results suggest Burbot regularly consume crayfish, with 32 of the 44 stomachs containing crayfish (Figure B.1.10). Fish were the second most dominant item in the diets, with Yellow Perch being the top consumed fish (Figure B.1.11). Invertebrates, including annelids, were also found in diets at low rates, a unique item observed was rocks or substrate. Ten of the 44 stomachs containing contents had varying quantities of rocks and bottom substrate, likely indicating that Burbot targeted crayfish. Their aggressive nature causes them to inhale more than just the crayfish. Our results only capture a short window of feeding habits that may show bias towards a specific food source that might be readily available. However, these results might not indicate a preference for a food source but may indicate the most accessible food available to Burbot. Future research should assess diets across a yearly period to monitor changes and preferences in the consumption of Burbot.

Abundance. – Burbot encountered during the 2019 tagging season were additionally tagged with T-bar anchor tags, hereafter FLOY, for a potential population estimate. A total of 164 fish were released back into Bad Medicine Lake in 2019. Throughout the sample period of 2019, all angled fish were inspected for a FLOY tag. If a caught Burbot did not have a FLOY tag, the fish was then implanted with one and released. On 27 March 2019, one FLOY tagged Burbot was recaptured. This fish was the only one recaptured by researchers during the 2019 season. Using the Schnabel method for quantifying population size, given multiple sampling and tagging events, we estimated the population size of Burbot from Bad Medicine Lake to be 6,122 fish, with 95% confidence intervals of 1,863 to 11,941 individuals (Figure B.1.12). Given the low number of recaptured fish, the population in Bad Medicine Lake appears stable. However, we suggest that more sampling be conducted to better understand the actual population size of the Burbot in Bad Medicine Lake.

Mortality. – Survival was estimated using Kaplan-Meier staggered entry design (Pollock et al. 1989). We estimated Burbot survival using acoustic telemetry detections between 4 April 2019 to 18 August 2020. The most conservative, least conservative, and most realistic survival estimates were calculated. In the most conservative model, fish that had locations that did not move immediately following surgery were classified as a surgery death. If a fish was caught and reported by an angler who kept it, it was classified as dead. All other fish disappearances from the array of fish that did not change their location for an extended period were censored. In the least conservative model, all fish that left the array and fish that did not move from a location for an extended period were classified as dead. For the most reliable model, fish were classified as dead when they exhibited normal movement but disappeared from the array during peak ice fishing season, indicating angler mortality. Additionally, fish were also classified as dead if they showed regular activity for multiple months and then stopped moving but were continued to be detected in the array. All other fish that disappeared from the array or any fish that exhibited uncharacteristic movement patterns were classified as censored.

Burbot survival during the study period varied across estimation methods (Figure 2.13). The least conservative model estimated survival at 51.6%, the most conservative model estimated survival at 77.5%, and the most realistic model estimated survival at 63.8% (Table B.1.2). Using the most realistic survival model, we estimated Burbot annual survival at 62.5%. This estimate includes the removal of the ten censored fish and the three fish that died immediately following surgery. Four-tagged Burbot appeared to die immediately following surgery. June through September seem to be the most stressful months for Burbot as we predicted 11 of the tagged fish died during this period. Three fish were estimated to have been killed by anglers in February and March, with one of those fish being reported by anglers.

APPENDIX B References

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Tables

Table B.1.1. Summary table of condition measurements for Burbot sampled between 2019 and 2021 in Bad Medicine Lake. Length groups were categorized and relative weight (*Wr*) following the methods of Fisher (1996).

	Quality	**Preferred**	**Memorable**	**Trophy**
N	16	206	55	3
Mean *Wr*	125.51	124.40	115.44	153.90
SD	17.02	17.03	18.35	45.16

Table B.1.2. Summary of Kaplan-Meier survival estimate of acoustic tagged Burbot in Bad Medicine Lake using a most conservative, most realistic, and least conservative approach. Survival estimates are calculated with 95% confidence intervals (CI).

Survival											
			Most Conservative			Least Conservative			Most Reliable		
Date	At Risk	Added	Deaths	Censored	% Survival (± CI)	Deaths	Censored	% Survival (± CI)	Deaths	Censored	% Survival (± CI)
Mar 19, 2019	0	26	0	0	100 (0)	0	0	100 (0)	0	0	100 (0)
Mar 23, 2019	26	16	0	0	100 (0)	0	0	100 (0)	0	0	100 (0)
Mar 27, 2019	42	9	0	0	100 (0)	0	0	100 (0)	0	0	100 (0)
Mar 31, 2019	51	12	0	0	100 (0)	0	0	100 (0)	0	0	100 (0)
Apr 4, 2019	63	1	3	0	95.24 (5.13)	3	0	95.24 (5.13)	3	0	95.24 (5.13)
Apr 8, 2019	61	1	0	0	95.24 (5.22)	0	0	95.24 (5.22)	0	0	95.24 (5.22)
Apr 23, 2019	62	0	2	0	92.17 (6.43)	2	0	92.17 (6.43)	2	0	92.17 (6.43)
May 8, 2019	60	1	0	0	92.17 (6.53)	0	0	92.17 (6.53)	0	0	92.17 (6.53)
May 23, 2019	61	0	0	1	92.17 (6.48)	0	1	92.17 (6.48)	0	1	92.17 (6.48)
Jun 7, 2019	60	0	2	1	89.09 (7.44)	3	0	87.56 (7.82)	3	0	87.56 (7.82)
Jun 22, 2019	57	0	1	2	87.53 (8.02)	3	0	82.95 (8.89)	2	1	84.49 (8.64)
Jul 7, 2019	54	0	1	0	85.91 (8.60)	1	0	81.41 (9.36)	1	0	82.92 (9.14)
Jul 22, 2019	53	0	0	0	85.91 (8.68)	0	0	81.41 (9.45)	0	0	82.92 (9.23)
Aug 6, 2019	53	0	1	1	84.29 (9.00)	2	0	78.34 (9.81)	2	0	79.79 (9.66)
Aug 21, 2019	51	0	0	3	84.29 (9.17)	3	0	73.73 (10.37)	1	2	78.23 (10.02)
Sep 5, 2019	48	0	0	0	84.29 (9.45)	0	0	73.73 (10.69)	0	0	78.23 (10.33)
Sep 20, 2019	48	0	0	4	84.29 (9.45)	4	0	67.59 (10.89)	2	2	74.97 (10.61)
Oct 5, 2019	44	0	0	1	84.29 (8.87)	1	0	66.05 (11.37)	0	1	74.97 (11.09)
Oct 20, 2019	43	0	0	2	84.29 (9.99)	1	1	64.52 (11.49)	1	1	73.22 (11.32)
Nov 4, 2019	41	0	0	1	84.29 (10.23)	0	1	64.52 (11.77)	0	1	73.22 (11.59)

Table B.1.2. Continued

Survival

Date	At Risk	Added	Most Conservative		% Survival (± CI)	Least Conservative		% Survival (± CI)	Most Reliable		% Survival (± CI)
			Deaths	Censored		Deaths	Censored		Deaths	Censored	
Nov 19, 2019	40	0	0	1	84.29 (10.36)	1	0	62.90 (11.87)	0	1	73.22 (11.74)
Dec 4, 2019	39	0	0	1	84.29 (10.49)	1	0	61.29 (11.97)	1	0	71.35 (11.99)
Dec 19, 2019	38	0	0	0	84.29 (10.62)	0	0	61.29 (12.12)	0	0	71.35 (12.15)
Jan 3, 2020	38	0	0	1	84.29 (10.62)	1	0	59.68 (12.05)	1	0	69.47 (12.21)
Jan 18, 2020	37	0	0	0	84.29 (10.77)	0	0	59.68 (12.21)	0	0	69.47 (12.37)
Feb 2, 2020	37	0	0	0	84.29 (11.21)	0	0	59.68 (12.21)	0	0	69.47 (12.37)
Feb 17, 2020	37	0	1	0	82.01 (11.72)	1	0	58.06 (12.11)	1	0	67.59 (12.40)
Mar 3, 2020	36	0	1	0	79.73 (12.18)	1	0	56.45 (12.17)	1	0	65.71 (12.57)
Mar 18, 2020	35	0	1	0	77.45 (12.36)	1	0	54.84 (12.39)	1	0	63.84 (12.72)
Apr 2, 2020	34	0	0	0	77.45 (12.36)	0	0	54.84 (12.39)	0	0	63.84 (12.91)
Apr 17, 2020	34	0	0	0	77.45 (12.36)	0	0	54.84 (12.39)	0	0	63.84 (12.91)
May 2, 2020	34	0	0	0	77.45 (12.36)	0	0	54.84 (12.39)	0	0	63.84 (12.91)
May 17, 2020	34	0	0	0	77.45 (12.36)	0	0	54.84 (12.39)	0	0	63.84 (12.91)
Jun 1, 2020	34	0	0	0	77.45 (12.36)	0	0	54.84 (12.39)	0	0	63.84 (12.91)
Jun 16, 2020	34	0	0	2	77.45 (12.36)	2	0	51.61 (12.07)	0	2	63.84 (12.91)
Jul 1, 2020	32	0	0	0	77.45 (12.74)	0	0	51.61 (12.44)	0	0	63.84 (13.30)
Jul 16, 2020	32	0	0	0	77.45 (12.74)	0	0	51.61 (12.44)	0	0	63.84 (13.30)
Jul 31, 2020	32	0	0	0	77.45 (12.74)	0	0	51.61 (12.44)	0	0	63.84 (13.30)
Aug 15, 2020	32	0	0	0	77.45 (12.74)	0	0	51.61 (12.44)	0	0	63.84 (13.30)

Figures

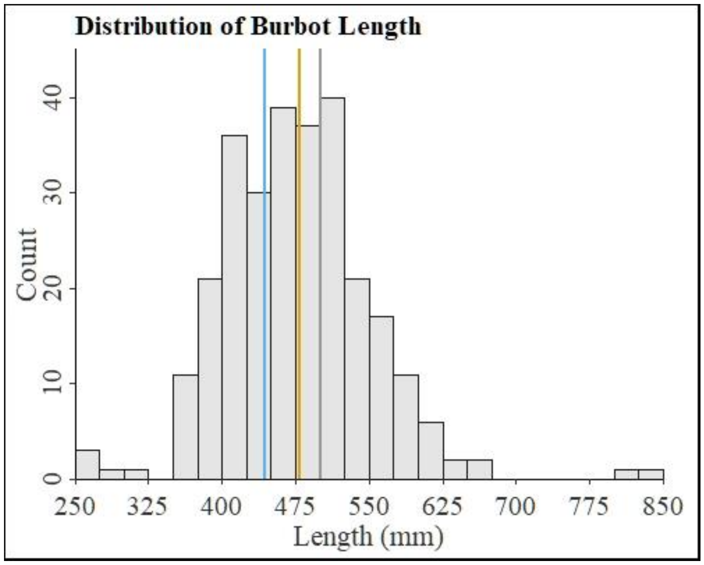

Figure B.1.1 Distribution of length for all sampled Burbot from 2019 to 2021 from Bad Medicine Lake. The gray vertical line represents the median length for females, the orange vertical line represents males' median length, and the blue vertical line represents the median length for fish of unknown sex.

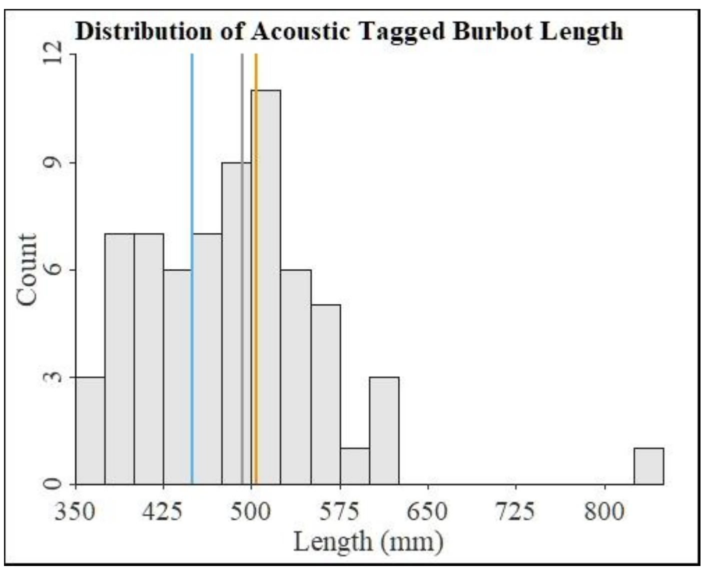

Figure B.1.2. Distribution of length for all Burbot implanted with acoustic transmitters (n = 66) in 2019 from Bad Medicine Lake. The gray vertical line represents the median length for females, the orange vertical line represents males' median length, and the blue vertical line represents the median length for fish of unknown sex.

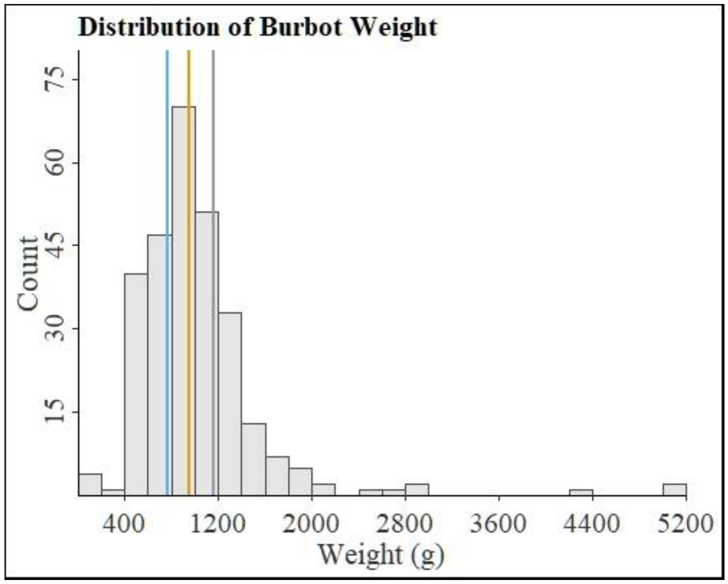

Figure B.1.3. Distribution of weight for all sampled Burbot from 2019 to 2021 from Bad Medicine Lake. The gray vertical line represents the median weight of females, the orange vertical line represents the median weight of males, and the blue vertical line represents the median weight of unknown sexed fish.

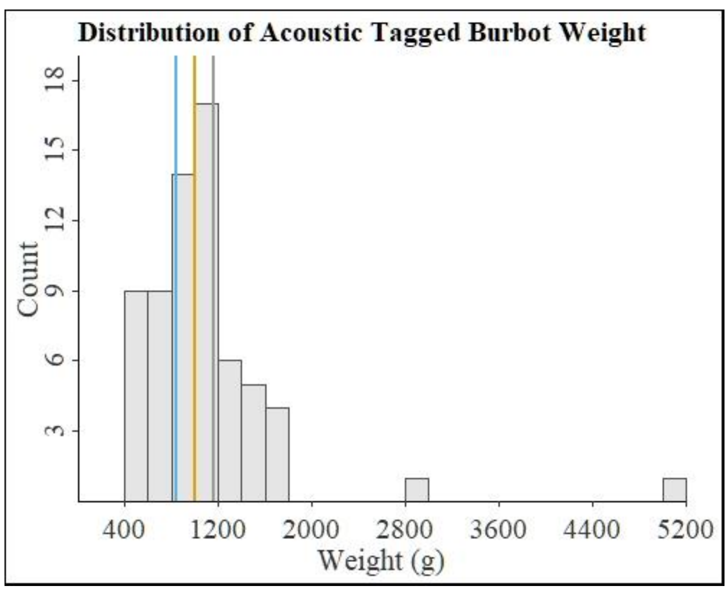

Figure B.1.4. Distribution of length for all Burbot implanted with acoustic transmitters (n = 66) in 2019 from Bad Medicine Lake. The gray vertical line represents the median weight of females, the orange vertical line represents the median weight of males, and the blue vertical line represents the median weight of unknown sexed fish.

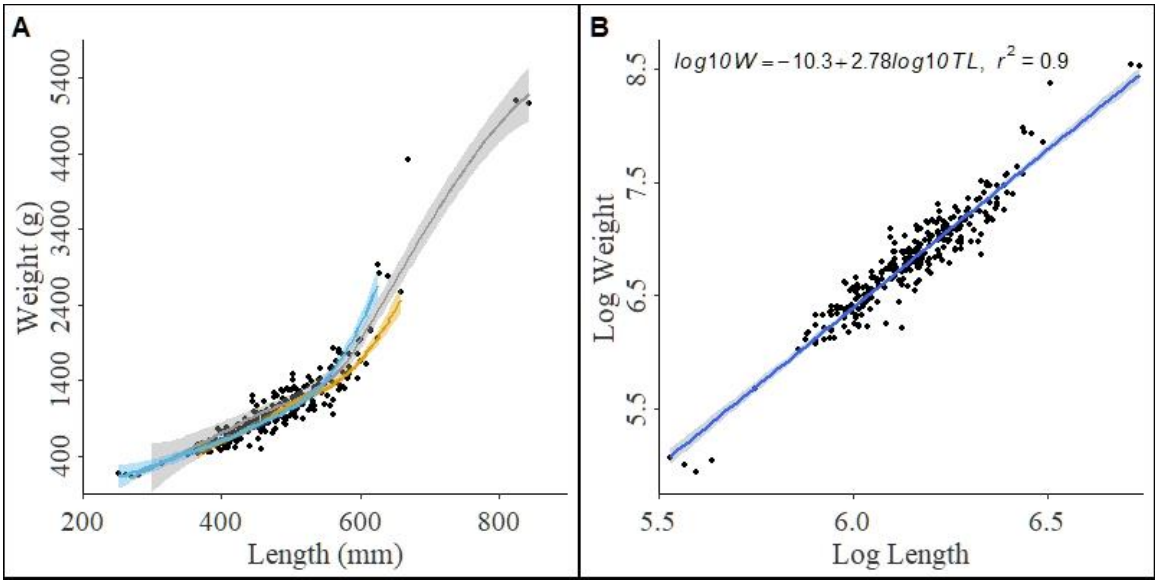

Figure B.1.5. Total length (mm) to weight (g) relationship of Burbot from Bad Medicine Lake from 2019 to 2021. Lines in plot (A) represent the line of best fit by sex; females are gray, males are orange, and unknown sexed fish are blue. Plot (B) is the log transformation of length and weight; the equation given is the line of best fit using linear regression.

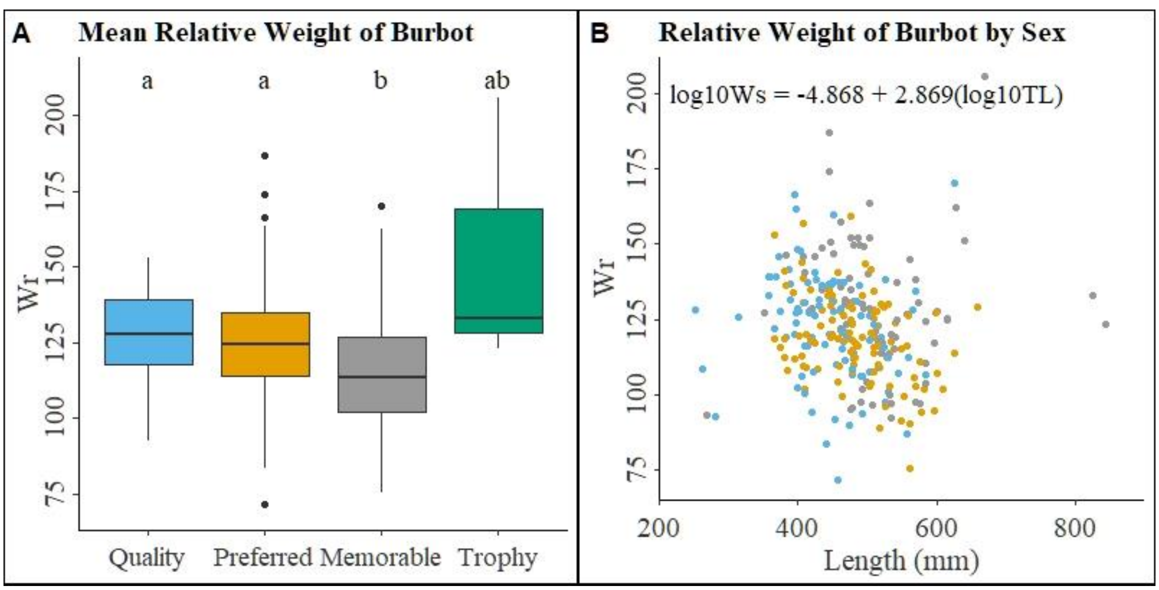

Figure B.1.6. Boxplot of the calculated relative weight (*Wr*) of Burbot from Bad Medicine Lake (A) using the equation shown in (B). Fish were categorized following measures used by Fisher (1996). Groups in figure (A) with the same letter were not significantly different from each other. Figure (B) is the distribution of calculated *Wr* of Burbot by sex. The gray dots represent females, the orange dots are males, and the blue is unknown sexed fish.

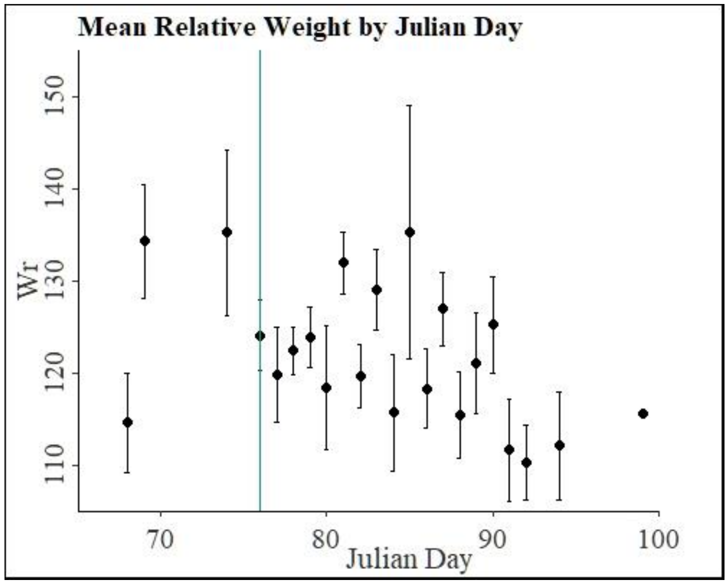

Figure B.1.7. Average relative weight (*Wr*) of sampled Burbot from Bad Medicine Lake from 2019 to 2021. Each point represents the average calculated *Wr* by Julian day. Error bars represent one standard error above and below the mean. The green line represents the predicted peak spawning date (16 March 2020) from the home range analysis.

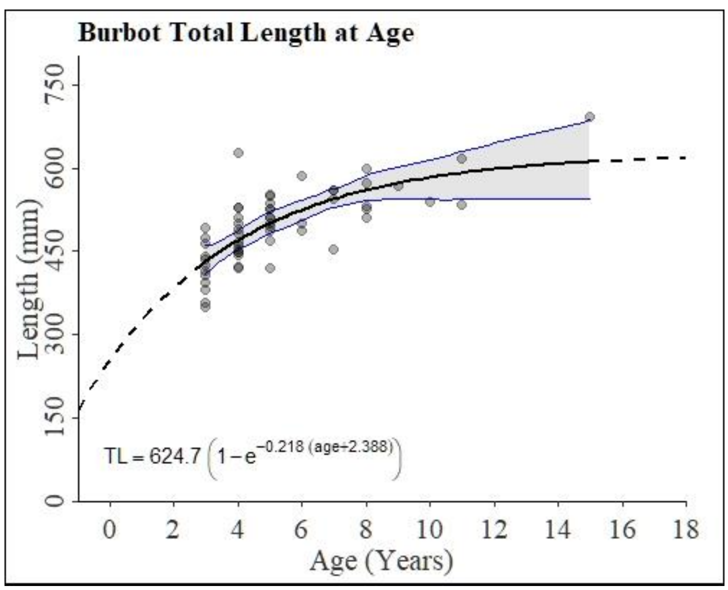

Figure B.1.8. The von Bertalanffy growth curve of Burbot with observed total length at age estimated from otoliths. The solid black line is the predicted mean length for observed ages, while the dashed line is the predicted length at age for estimates outside our observed ages. The gray polygons represent 95% confidence intervals.

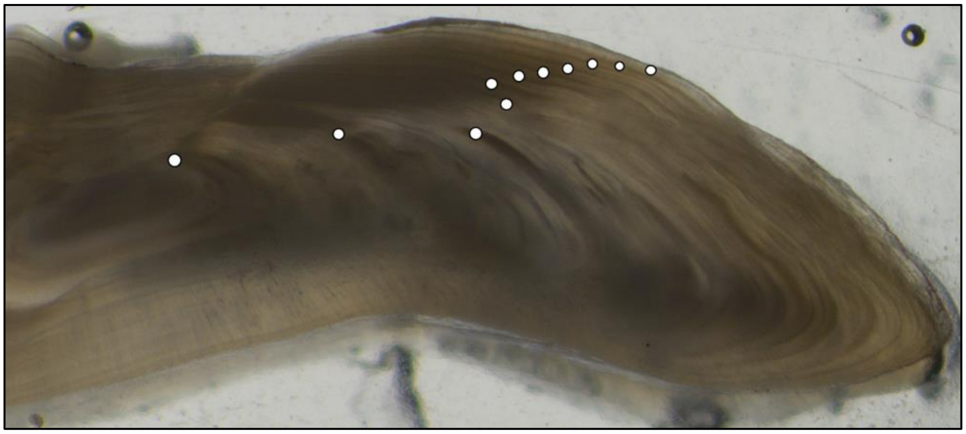

Figure B.1.9. Sectioned sagitta otolith from an 11-year-old 534 mm female Burbot caught from Bad Medicine Lake on February 26, 2020. White circles indicate annuli.

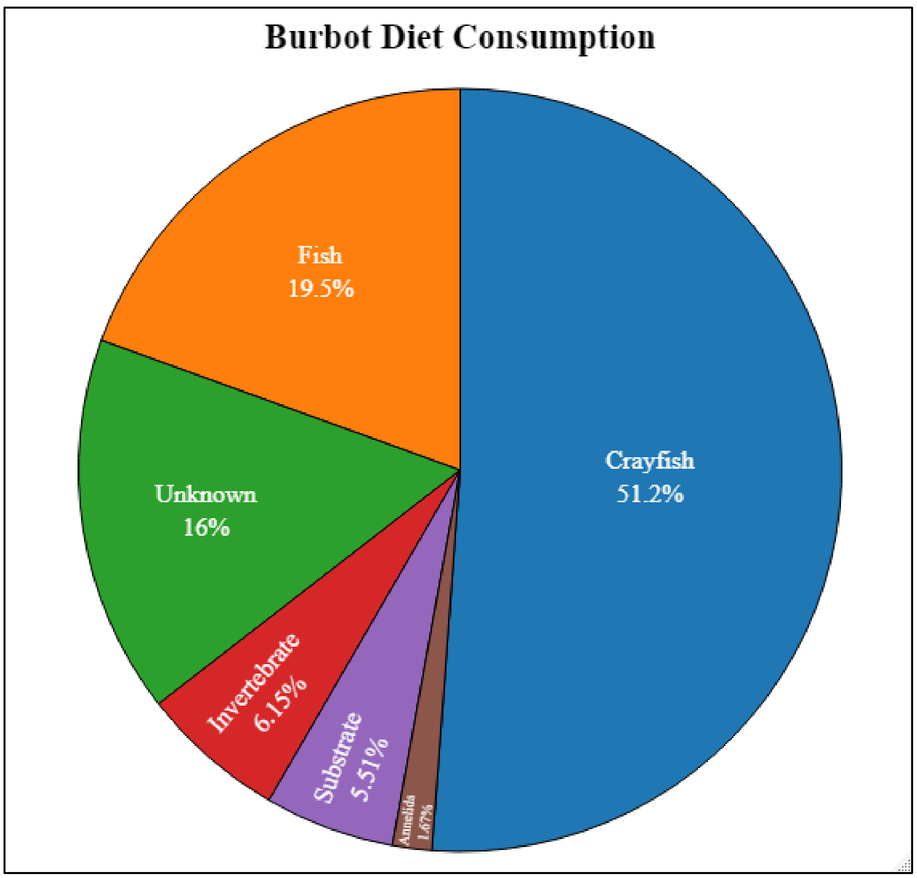

Figure B.1.10. Pie chart representing the total percentage of diet items consumed by weight from 56 sampled Burbot in Bad Medicine Lake from 2019 to 2021.

Figure B.1.11. Examples of diet contents of sampled Burbot. Explanation of diets moving clockwise starting in the upper left corner; crayfish, Yellow Perch, invertebrate assumed to be juvenile crayfish, and finally unidentified material, likely fish bones, and crayfish.

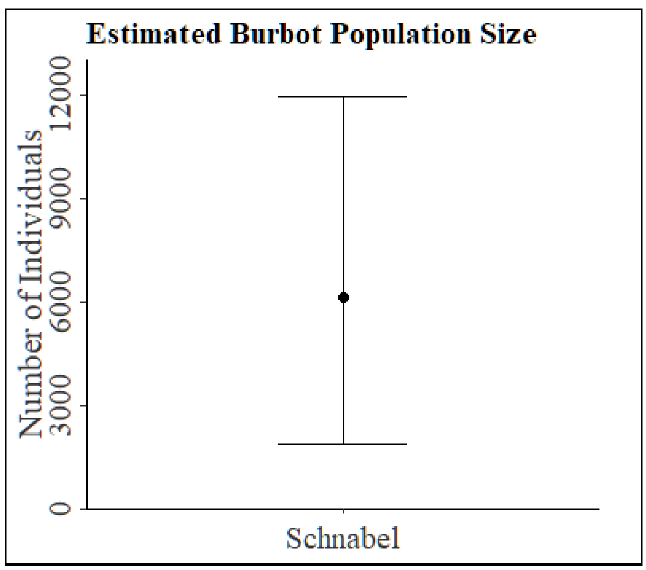

Figure B.1.12. The estimated population size of Burbot in Bad Medicine Lake using the Schnabel method for multiple sampling and tagging events using 2019 sampling data. The estimated population size of Burbot is predicted to be 6,122 individuals. Error bars represent estimated 95% confidence intervals.

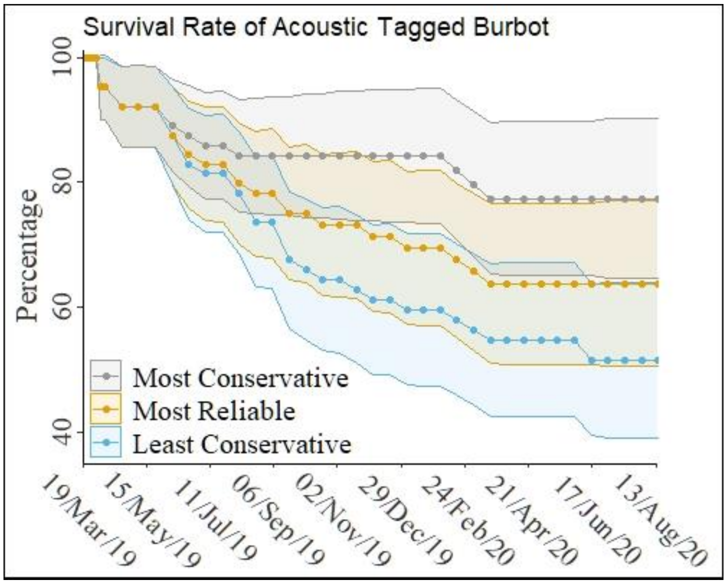

Figure B.1.13. Estimated survival rates of acoustic tagged Burbot in Bad Medicine Lake using the Kaplan-Meier staggered entry method. The gray data represents the most conservative estimate, the orange data represents the most reliable scenario, and the blue data is the least conservative survival estimate. Shaded areas represent 95% confidence intervals.