Supplementary Material

Spawning behaviour of lake whitefish in Lake Huron revealed by fine-scale acoustic telemetry and Indigenous ecological knowledge

Camilla M. Ryther[1,2]*, Ryan Lauzon[3], Mary-Claire Buell[4], Ruth Duncan[4], Breanna Redford[3],

and Erin S. Dunlop[1,2]

[1]Environmental and Life Science Graduate Program, Trent University, 1600 W Bank Drive, Peterborough, ON K9L 0G2, Canada
[2] Aquatic Research and Monitoring Section, Ontario Ministry of Natural Resources and Forestry, Trent University, DNA Bldg., 2140 East Bank Drive, Peterborough, ON K9L 1Z8, Canada
[3]Chippewas of Nawash Unceded First Nation Fisheries Assessment Program, 50 Farm Road, Neyaashiinigmiing, ON, N0H 2T0, Canada
[4]Collective Environmental Inc., 251 Prince Street, Peterborough, ON K9J 2A6, Canada
*Corresponding author: camilla.ryther@ontario.ca

Table of Contents

Appendix S1 Lake whitefish tagging and total positions summary

Table S1. Details for individual lake whitefish fish (n = 50) tagged at the Little Port Elgin shoal, Lake Huron. Table includes the number of positions calculated by the VEMCO Positioning System pre- and post- horizontal positional error (HPE) filtering. Bolded values indicate fish that remained in the system post-HPE filtering.

Transmitter ID	Sex	Fork length (mm)	Weight (g)	Number of positions calculated by VPS	Number of positions post-HPE filtering
4278	Female	608	-	-	-
4279	Male	611	-	-	-
4280	Male	612	3500	-	-
4281	Male	679	3800	-	-
4282	Female	548	2400	24	-
4283	**Female**	**605**	**3000**	**2119**	**1883**
4284	Female	635	4200	-	-
4285	Male	583	2850	-	-
4286	**Female**	**634**	**4050**	**2815**	**2137**
4287	**Male**	**655**	**3600**	**1193**	**751**
64588	Female	628	-	-	-
64589	Female	626	-	-	-
64590	**Male**	**671**	**-**	**1896**	**1602**
64591	Male	637	3200	-	-
64592	**Male**	**560**	**2400**	**3300**	**2843**
64593	**Male**	**574**	**2500**	**4958**	**4114**
64594	Male	590	3200	-	-
64595	**Male**	**602**	**3050**	**5852**	**4065**
64596	**Male**	**668**	**3600**	**6345**	**5482**
64597	Female	611	3300	-	-
64598	Female	570	3000	-	-
64599	**Male**	**581**	**2550**	**7160**	**5763**
64600	**Female**	**583**	**2850**	**234**	**121**
64601	**Female**	**601**	**3700**	**25762**	**19647**
64602	Male	540	1850	-	-
64603	**Male**	**570**	**2750**	**5089**	**4283**
64604	**Female**	**615**	**4300**	**1794**	**1505**
64605	**Female**	**675**	**5350**	**27727**	**23802**
64606	Female	608	3950	-	-
64607	**Female**	**667**	**4000**	**2008**	**1663**
64608	Male	650	3450	-	-
64609	Female	580	2350	-	-
64610	**Male**	**605**	**2900**	**3517**	**2383**
64611	Male	552	2550	-	-
64612	Female	581	3450	-	-
64613	Male	571	2800	-	-
64614	Male	609	3550	-	-
64615	Female	576	2850	-	-
64616	**Male**	**615**	**3200**	**2742**	**1351**
64617	**Male**	**596**	**3000**	**6869**	**5147**
64618	Male	593	2950	-	-
64619	Female	587	3100	1	-
64620	Female	590	3600	-	-
64621	**Female**	**598**	**3300**	**9165**	**6861**
64622	Female	616	3950	1	-
64623	**Male**	**665**	**4300**	**9651**	**7702**
64624	Male	692	4650	-	-
64625	**Male**	**576**	**2500**	**4830**	**4107**
64626	**Male**	**608**	**2900**	**4935**	**4230**
64627	**Male**	**671**	**4100**	**3331**	**2419**

Appendix S2 Range testing

Methods

 Range testing was conducted at the study site on 25-26 August 2021. Four range tests were completed where tags were placed at roughly 100 m increments (100 m up to 600 m then 200 m increments up to 1 km if space allowed) from a receiver that was slightly east of the main shoal (Fig. S1). This receiver was one of two sentinel receivers placed in the LPE shoal to detect fish year-round. Each test ran a different direction from the receiver (N, E, SW, W), as we tried to cover as much of the area as possible of the proposed array location (Fig. S1). Transmitters were moored by rope and anchored by a small 5 lb weight, where the tag was attached roughly 1 m off bottom and connected to a flotation flag for visual identification. Each range test lasted 2 hours and tags were programmed to randomly transmit every 60 – 180 s (nominal 120 s). Range test results were plotted using the 'Range Test' software from Innovasea Ltd. (Bedford, Nova Scotia).

Results

 In general, there was ~60% detection probability around 400-600 m, depending on the test location. However, after consultation with GLATOS experts, it was revealed that our range testing was compromised due to the testing design and collision rates. According to Binder et al. (2016), eight tags pinging at once with a nominal delay of 120 seconds is estimated to have a ~45% collision rate. The low detection probabilities were likely driven by collisions, which includes the flat curves observed in Figures S2-3. Effectively, the number of tag collisions leads to counterintuitive results because the maximum detection probability at a given distance decreases when range increases. Based on consultation with GLATOS, it was established that tag range was likely >1 km (T. Binder, C. Vandergoot, and C. Holbrook, personal communication).

Based on this and consultation with SON harvesters, receivers within the VPS array were placed no more than 750 m apart.
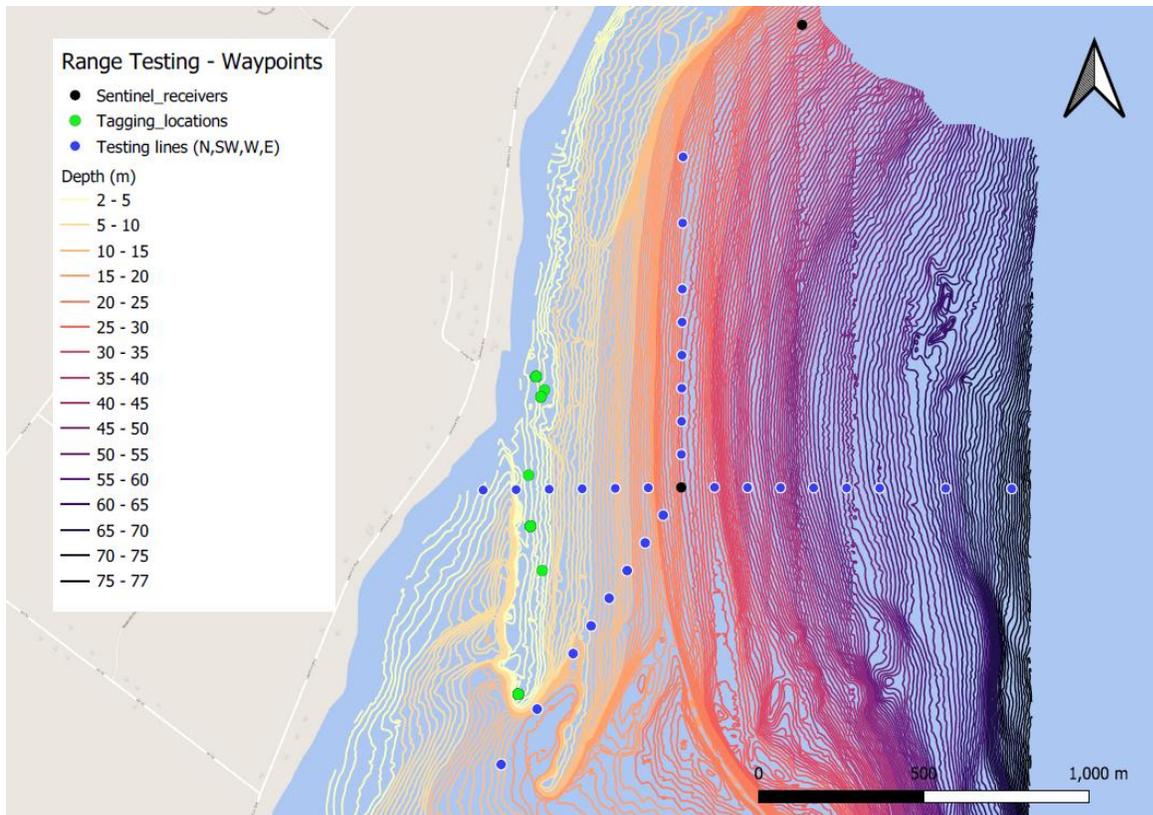
Figure S1. Range tests (N, SW, W, E) that occurred at Port Elgin Bay on 25 - 26 August 2021. Each line represents a separate range test. Green circles are depicting lake whitefish capture locations in November 2020.
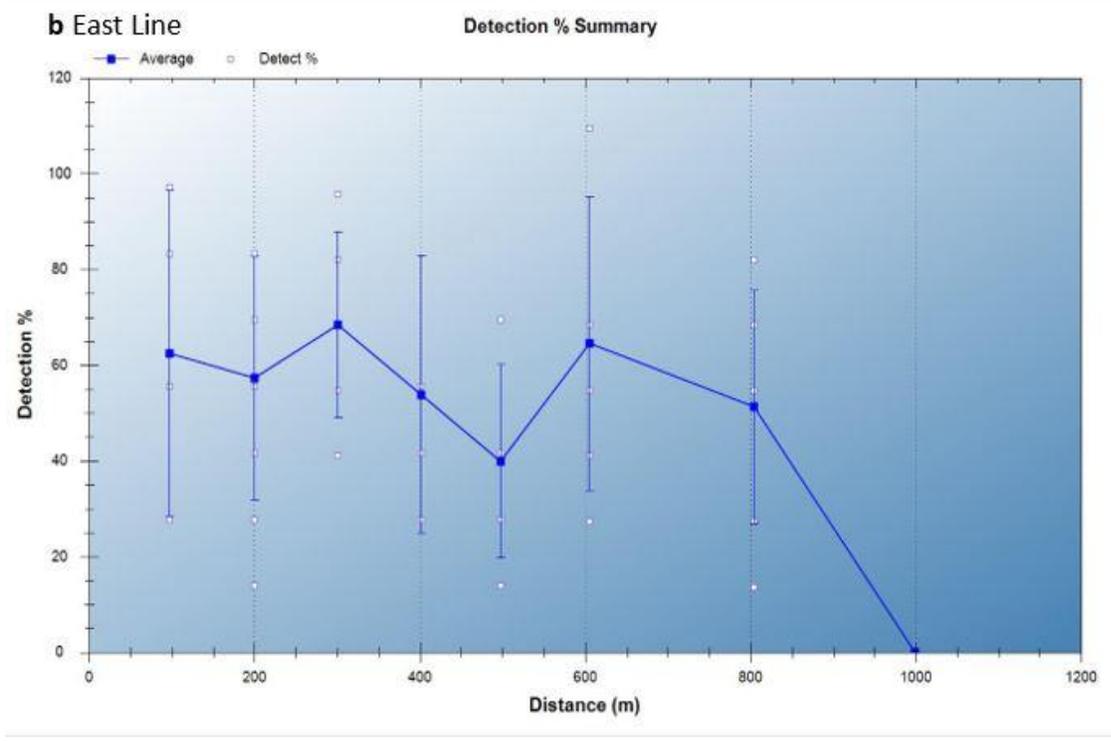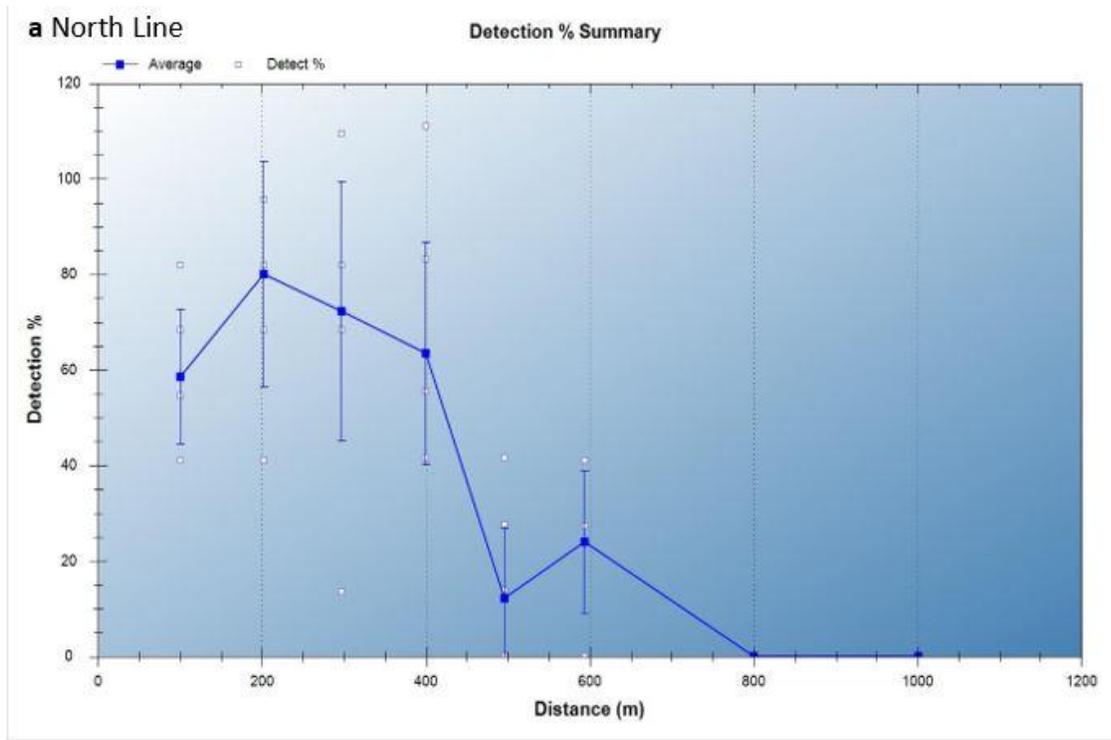
a North Line

b East Line

Figure S2. Range testing results from the North (a) and East (b) lines of ranges tests that were completed in the study area (see Figure S1 for reference on what the tests looked like). Plots were created using the Innovasea Ltd. VEMCO Range Test software.

Figure S3. Range testing results from the West (a) and Southwest (b) lines of ranges tests that were completed in the study area (see Figure S1 for reference on what the tests looked like). Plots were created using the Innovasea Ltd. VEMCO Range Test software.

Appendix S3 HPE filtering

　　All analyses were conducted in R 3.6.3 (R Core Team 2022; https://www.r-project.org/).
Along with calculating synctag and animal positions, Innovasea provides error estimates
calculated from algorithms used when calculating positions (Smith, 2013). These error estimates
are associated with each position, known as horizontal positioning error (HPE). HPE is provided
for both sync and animal tags where it is a relative, unitless estimate of error sensitivity (Smith,
2013). Additionally, a measured error estimate (HPE_m) is provided for sync tag positions only, as
we know the actual position of where the sync tags are (ie. the location of where the receiver is).
HPE_m is the horizontal distance between a calculated sync tag position and the known location of
the sync tag (Smith, 2013). To filter positions using HPE, we followed methods from Coates *et
al*., (2013) and a GLATOS expert to bin HPE values (bin width = 1 up to 200) and calculate the
90th and 95th percentiles of HPE_m. Following discussions of project goals and future uses of the
data (Meckley *et al*., 2014), we decided that having most of our errors be at or less than 10 m for
fish positions would be sufficient. To preserve as much data as possible and filter out positions
with higher error scatter, we chose to use the 90th percentile of HPE_m as the cut-off. We
determined if there was a relationship between HPE and HPE_m, a typical step when deciding to
filter using HPE, using a linear model (Meckley *et al*., 2014). We found there was a significant
relationship between HPE and HPE_m (n = 98,613, p<0.0001). For synctag positions, a 90th
percentile of HPE_m at 10 m corresponded to HPE 14. When filtered by HPE 14, synctag
positions were left with a mean ± SE HPEm of 3.29 m ± 0.01 m, indicating that, generally, our
filtering methods adhered to our project goals. Filtering by HPE 14 left us with a 79.4% retention
of fish positions (113,861). Filtering by HPE 14 resulted in a loss of three fish in the VPS dataset

(64622 female, number of positions = 1; 64619 female, number of positions = 1; 4282 female, number of positions = 24).

Appendix S4 Full and alternative model tables

Table S2. Linear mixed model results for predicting variation in vertical movement (n = 12,688). Sex (male or female) and diel period (night or day) were included as explanatory variables. ΔAIC is the difference between the model with the lowest AIC (the top-ranked model; i.e. ΔAIC = 0) and each subsequent alternative model. Hourly mean vertical movement is measured in meters per hour.

Linear mixed models: Main and (random effects)	AIC	ΔAIC	Independent variables	Estimate (Direction of effect)	Std. Error	F-value	P-value
Vertical movement ~ Diel + (Hour)	59105.19	0	Intercept	-0.130 (-)	0.274	-	-
			Diel	0.314 (+)	0.110	8.197	0.004
Vertical movement ~ Sex + Diel + (1|Hour)	59110.33	5.14	Intercept	-0.060 (-)	0.281	-	-
			Sex	-0.050 (-)	0.046	1.199	0.274
			Diel	0.312 (+)	0.110	8.053	0.005
Vertical movement ~ Sex + (Hour)	59113.8	8.61	Intercept	0.135 (+)	0.272	-	-
			Sex	-0.053 (-)	0.046	1.342	0.247
Vertical movement ~ Sex + Diel + Sex:Diel + (Hour)	59114.08	8.89	Intercept	-0.145 (-)	0.292	-	-
			Sex	0.018 (+)	0.073	0.679	0.410
			Diel	0.452 (+)	0.170	7.035	0.008
			Sex:Diel	-0.101 (-)	0.093	1.158	0.282

Table S3. Linear mixed model results for predicting variation in the horizontal movement (n = 13,106). Sex (male or female), diel period (night or day), and the number of raw values were included as explanatory variables. Hour (hour of the day), Day (each day of the study period), and Individual fish (unique IDs of the fish) were included as random variables with Hour nested within Day. ΔAIC is the difference between the model with the lowest AIC (the top-ranked model; ΔAIC = 0) and each subsequent alternative model. Horizontal movement is measured in meters per second.

Linear mixed models: Main and (random effects)	AIC	ΔAIC	Variables / Parameters	Estimate (Direction of effect)	Std. Error	F-value	P-value
Horizontal movement ~ Sex + Diel + Sex:Diel + Number of raw values + (Day/Hour) + (Individual fish)	-25037.29	0	Intercept	0.216 (+)	0.008	-	-
			Sex	0.006(+)	0.008	12.203	0.002
			Diel	-0.028 (-)	0.003	503.803	<0.0001
			Sex:Diel	-0.063 (-)	0.003	359.310	<0.0001
			Number of Positions	-0.001 (-)	0.0002	20.942	<0.0001
Horizontal movement ~ Sex + Diel + Sex:Diel + (Day/Hour) + (Individual fish)	-25034.37	35.13	Intercept	0.205 (+)	0.007	-	-
			Sex	0.006 (+)	0.008	12.642	0.002
			Diel	-0.028 (-)	0.003	501.512	<0.0001
			Sex:Diel	-0.063 (-)	0.003	371.447	<0.0001
Horizontal movement ~ Sex + Diel + Number of raw values + (Day/Hour) + (Individual fish)	-24694.43	375.07	Intercept	0.233 (+)	0.008	-	-
			Sex	-0.032 (-)	0.007	18.169	0.0004
			Diel	-0.053 (-)	0.003	396.454	<0.0001
			Number of Positions	-0.001 (-)	0.0002	33.354	<0.0001
Horizontal movement ~ Diel + Number of raw values + (Day/Hour) + (Individual fish)	-24691.33	378.17	Intercept	0.223 (+)	0.008	-	-
			Diel	-0.053 (-)	0.003	397.595	<0.0001
			Number of Positions	-0.001 (-)	0.0002	33.661	<0.0001
Horizontal movement ~ Sex + Diel + (Day/Hour) + (Individual fish)	-24679.78	389.72	Intercept	0.221 (+)	0.007	-	-
			Sex	-0.033 (-)	0.007	18.944	0.0003
			Diel	-0.053 (-)	0.003	392.097	<0.0001
Horizontal movement ~ Diel + (Day/Hour) + (Individual fish)	-24676.39	393.11	Intercept	0.210 (+)	0.008	-	-
			Light	-0.053 (-)	0.003	393.24	<0.0001
Horizontal movement ~ Sex + Number of raw values + (Day/Hour) + (Individual fish)	-24356.24	713.26	Intercept	0. 200 (+)	0.008	-	-
			Sex	-0.033 (-)	0.007	20.061	0.0002
			Number of Positions	-0.001 (-)	0.0002	27.134	<0.0001
Horizontal movement ~ Sex + (Day/Hour) + (Individual fish)	-24347.59	721.91	Intercept	0.188 (+)	0.007	-	-
			Sex	-0.033 (-)	0.007	20.812	0.0002

Appendix S5 Yearly detections and patterns on a sentinel receiver
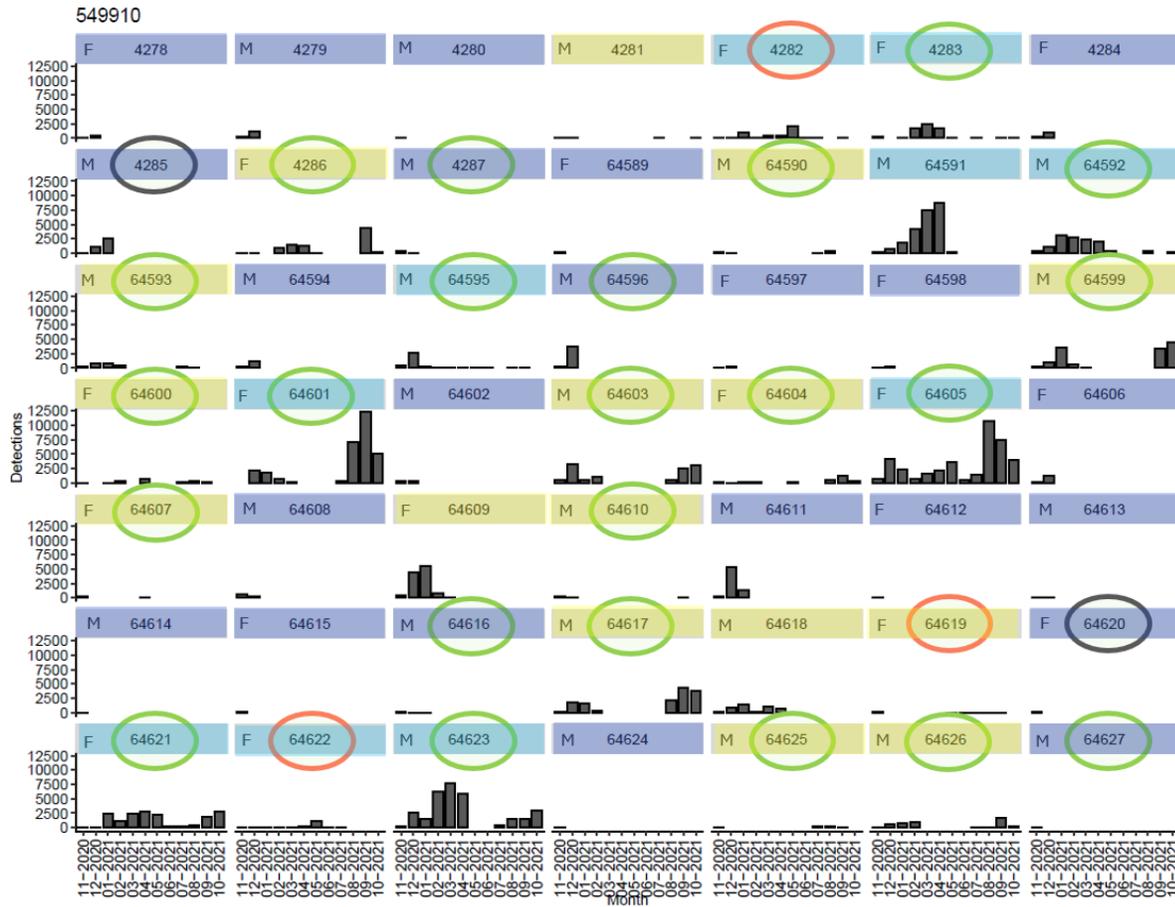

Figure S4. Total detections from the sentinel receiver ID 549910, located closest to the main Little Port Elgin shoal that was present during and post-tagging in the study area between 26 November 2020 – 15 October 2021. Dark blue labels represent fish that were present in the area 1-3 months post-tagging and then left (n = 23). Yellow labels represent fish that returned at various times throughout 2021 (n = 16). Light blue labels represent fish that could be classified as more resident in nature (n = 10). All circles represent fish detected during the VEMCO Positioning System (VPS) deployment (n = 28). Green circles indicate fish that were kept in the VPS analysis (n = 23). Grey circles indicate fish that the VPS was not able to calculate positions for (n = 2). Orange circles indicate fish that were removed post-HPE filtering. M denotes males and F denotes females. Fish 64588 was not detected at all and therefore does not appear in the figure.

Appendix S6 Mean daily temperature over time

Figure S5. Mean daily temperature (°C) measured at 11 receivers in Port Elgin Bay, Lake Huron.

Values were recorded on receivers once per hour.

Appendix S7 Abacus plot individual fish positions over time

Figure S6. Abacus plot displaying the presence of individual lake whitefish as detected on the VEMCO Positioning System over the study period (15 October 2021 – 18 January 2022). ID is the unique identifier for each fish. Each open circle represents one position. Red represents females and black represents males. Note: Fish ID 64592 was harvested in early December 2021.

Appendix S8 Pre-activity and Post-activity heatmaps

Figure S7. Heatmap displaying the percentage of male and female lake whitefish during the day (n = 12, 7) and night (n = 12, 6), respectively, present in each grid cell (10 m x 10 m) in the study area during the pre-activity stage (15 October - 1 November 2021). The number of positions for each sex for the day and night were 1340 and 2639 for males and 4122 and 6738 for females, respectively.

Figure S8. Heatmap displaying the percentage of male and female lake whitefish during the day (n = 1, 3) and night (n = 1, 3), respectively, present in each grid cell (10 m x 10 m) in the study area during the post-activity stage between 20 December 2021 – 18 January 2022. The number of positions for each sex for the day and night were 78 and 20 for males and 3728 and 13,322 for females, respectively.

Appendix S9 Weekly heatmaps

Fig. S9 Heatmaps depicting the number of individual male and female lake whitefish present in each grid cell (10 m x 10 m) during the day (n = 8, 5) and night (n = 7, 5), respectively, from 15 – 21 October 2021. Total number of positions during the day and night for males was 503 and 1421 and for females was 1421 and 2487, respectively.
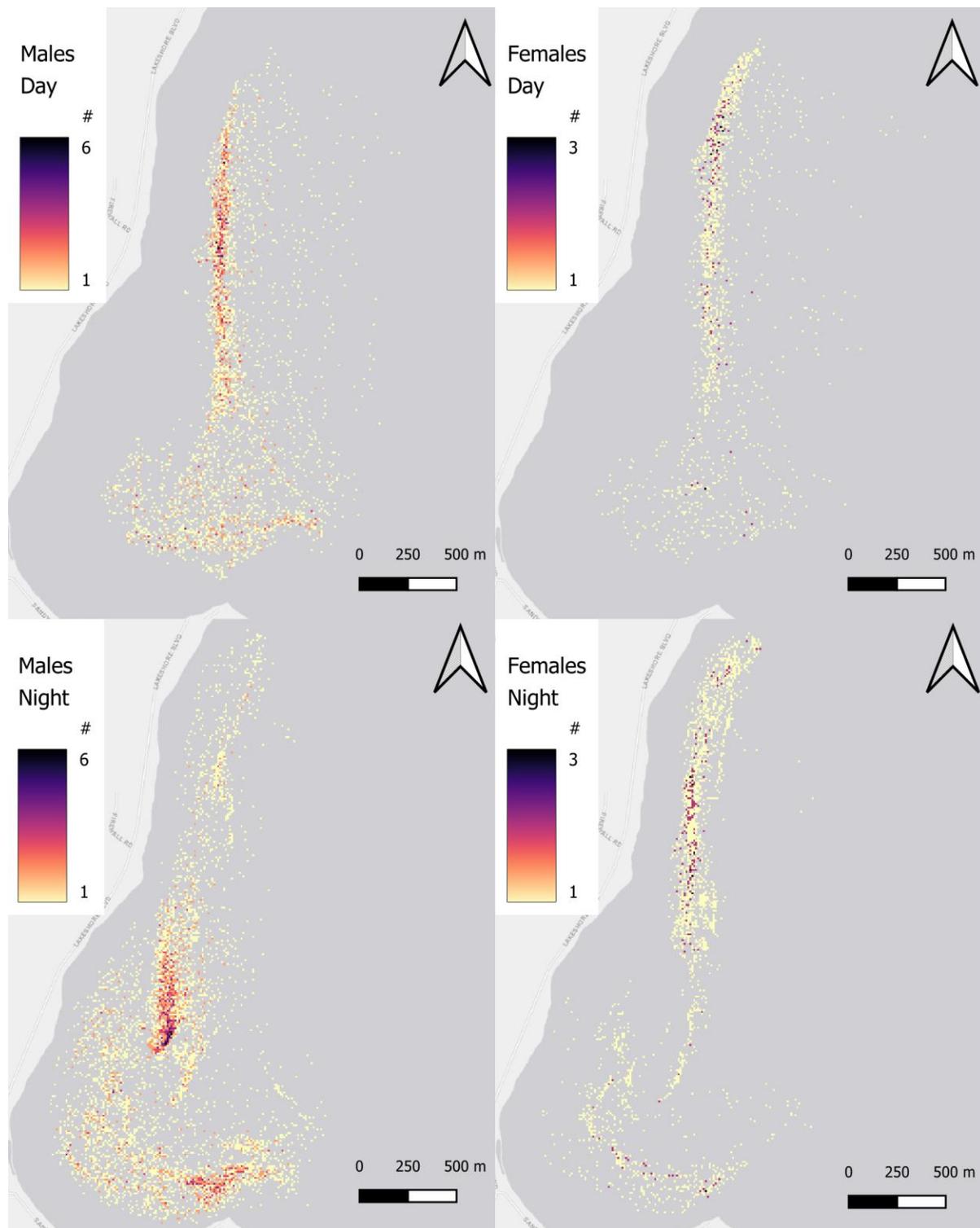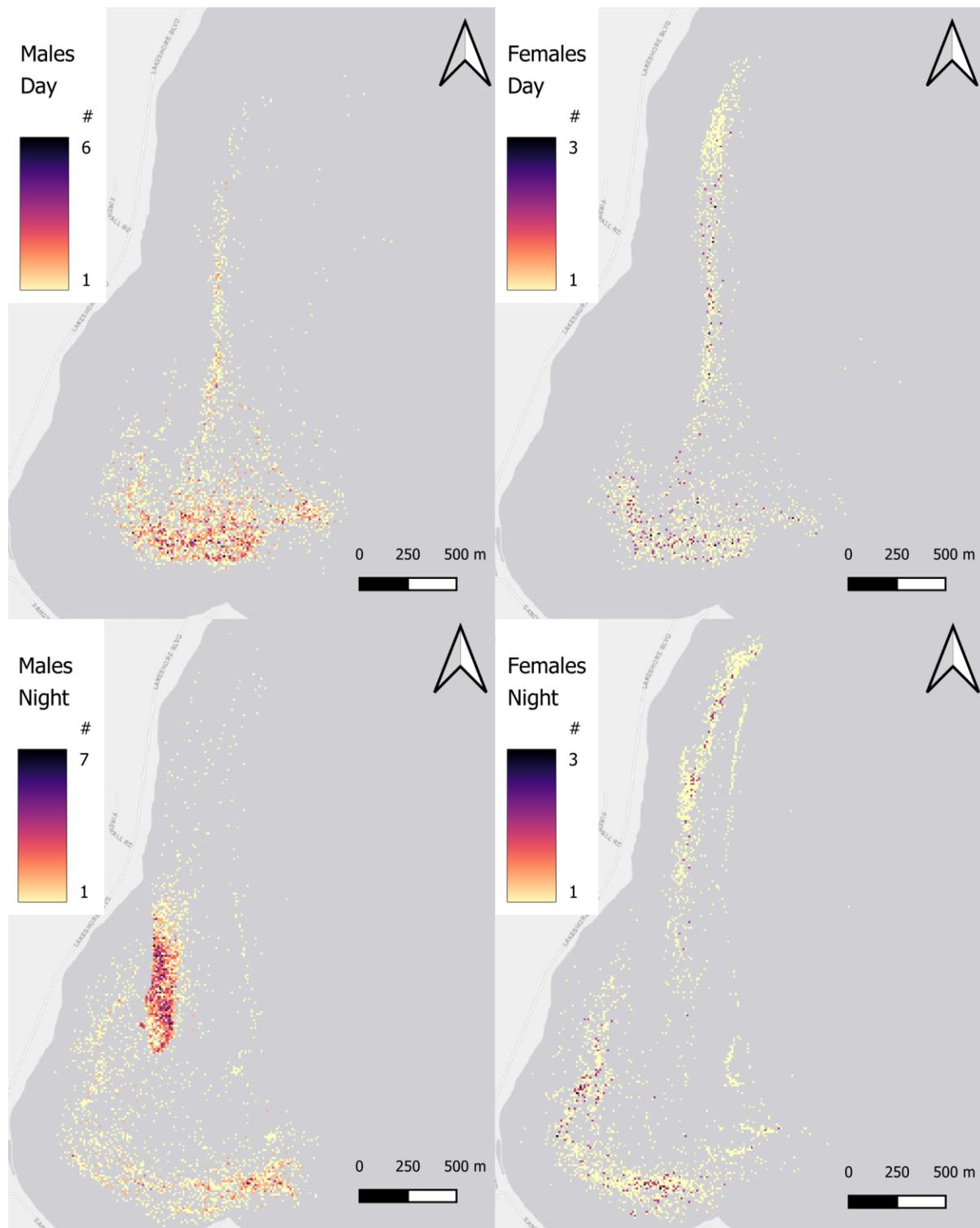
Fig. S10 Heatmaps depicting the number of individual male and female lake whitefish during the day (n = 5, 5) and night (n =5, 4), respectively, from 22 – 28 October 2021. Total number of positions during the day and night for males was 626 and 1198 and for females was 1440 and 2304, respectively.

Fig. S11 Heatmaps depicting the number of individual male and female lake whitefish present in each grid cell (10 m x 10 m) during the day (n = 7, 3) and night (n = 7, 4), respectively, from 29 October – 04 November 2021. Total number of positions during the day and night for males was 763 and 2093 and for females was 2006 and 3542, respectively.

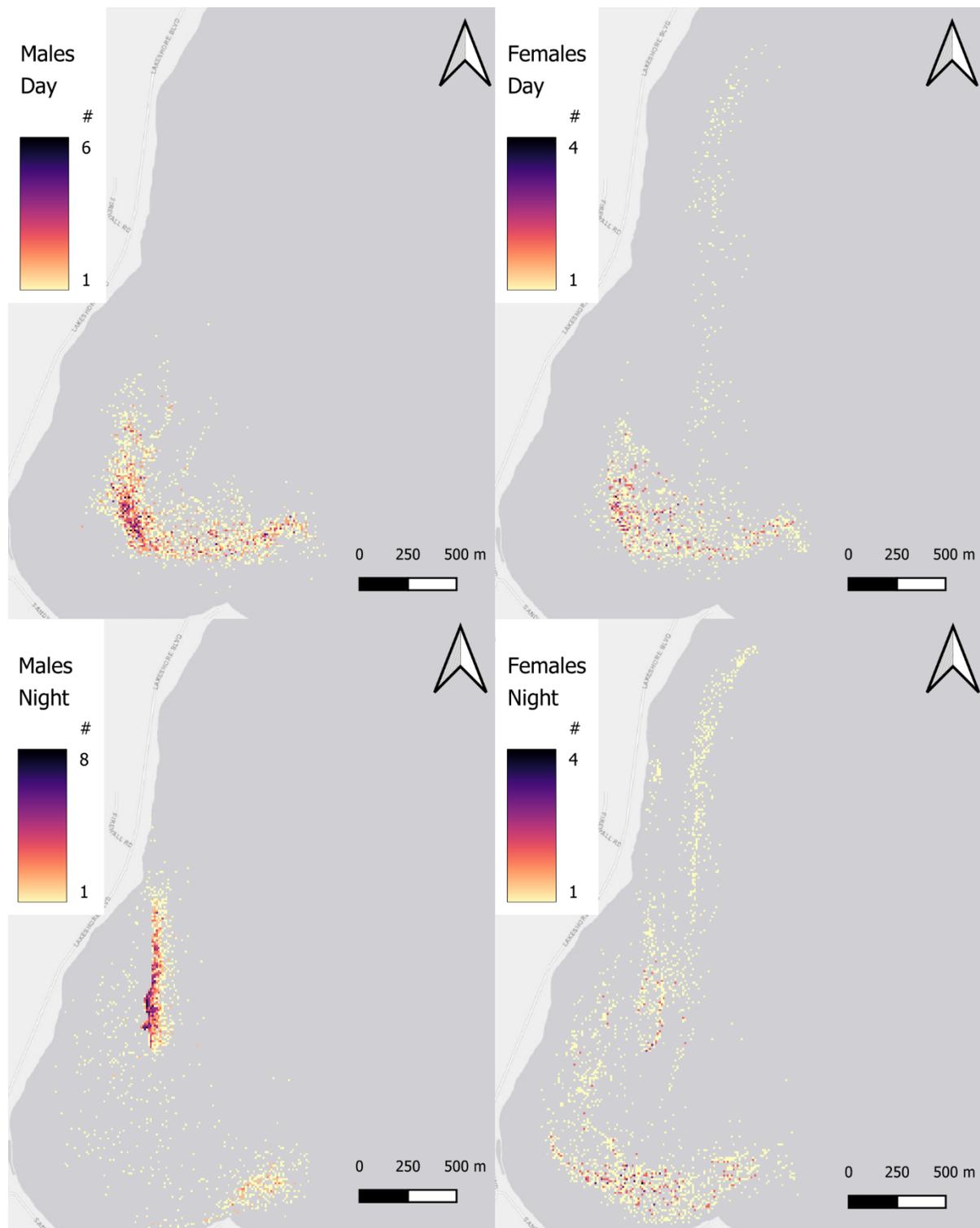Fig. S12 Heatmaps depicting the number of individual male and female lake whitefish during the day (n = 9, 3) and night (n = 9, 3), respectively, from 05 – 11 November 2021. Total number of positions during the day and night for males was 1852 and 5502 and for females was 1776 and 4060, respectively.
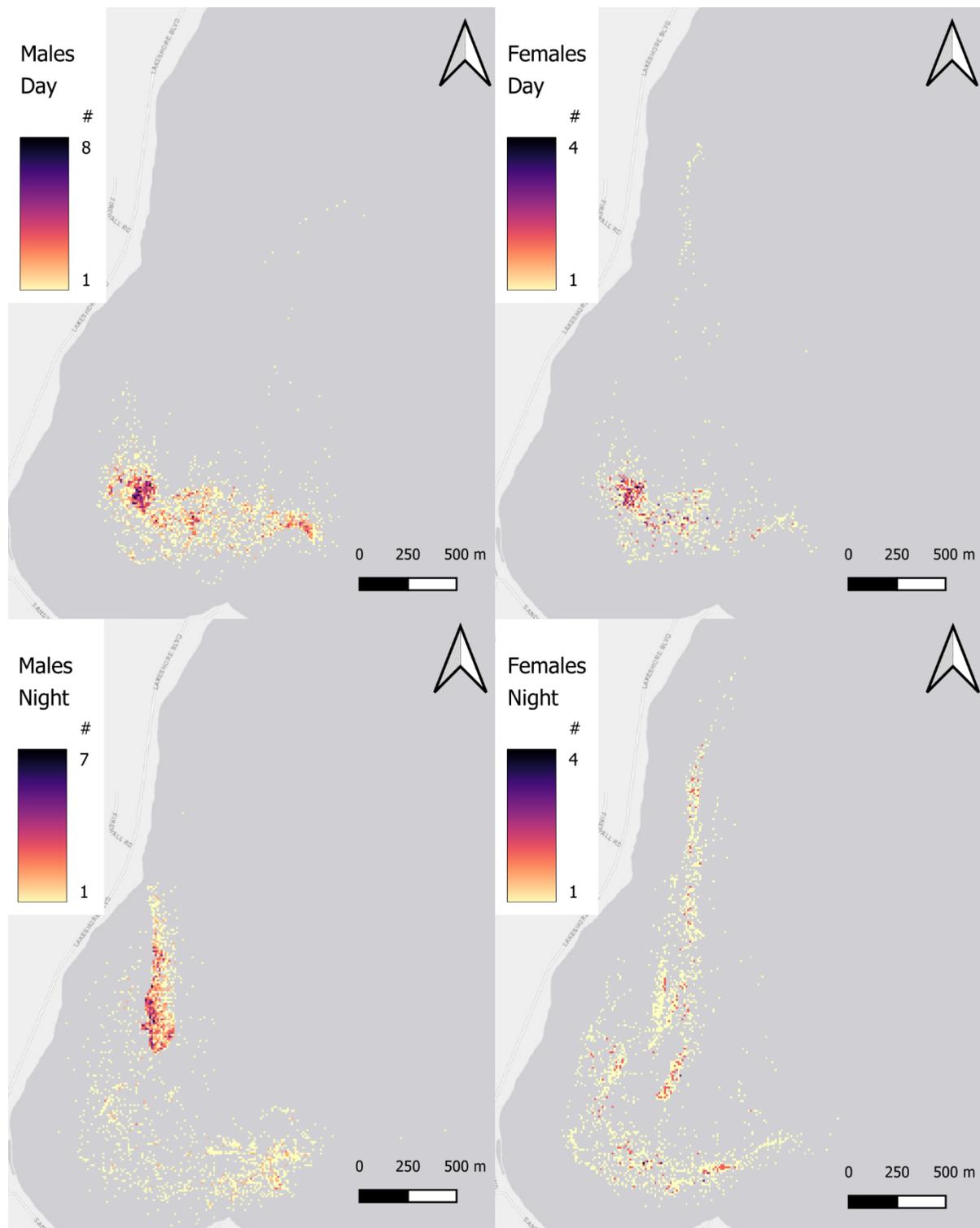
Fig. S13 Heatmaps depicting the number of individual male and female lake whitefish during the day (n = 15, 5) and night (n = 15, 5), respectively, from 12 – 18 November 2021. Total number of positions during the day and night for males was 4096 and 7180 and for females was 1825 and 3153, respectively.
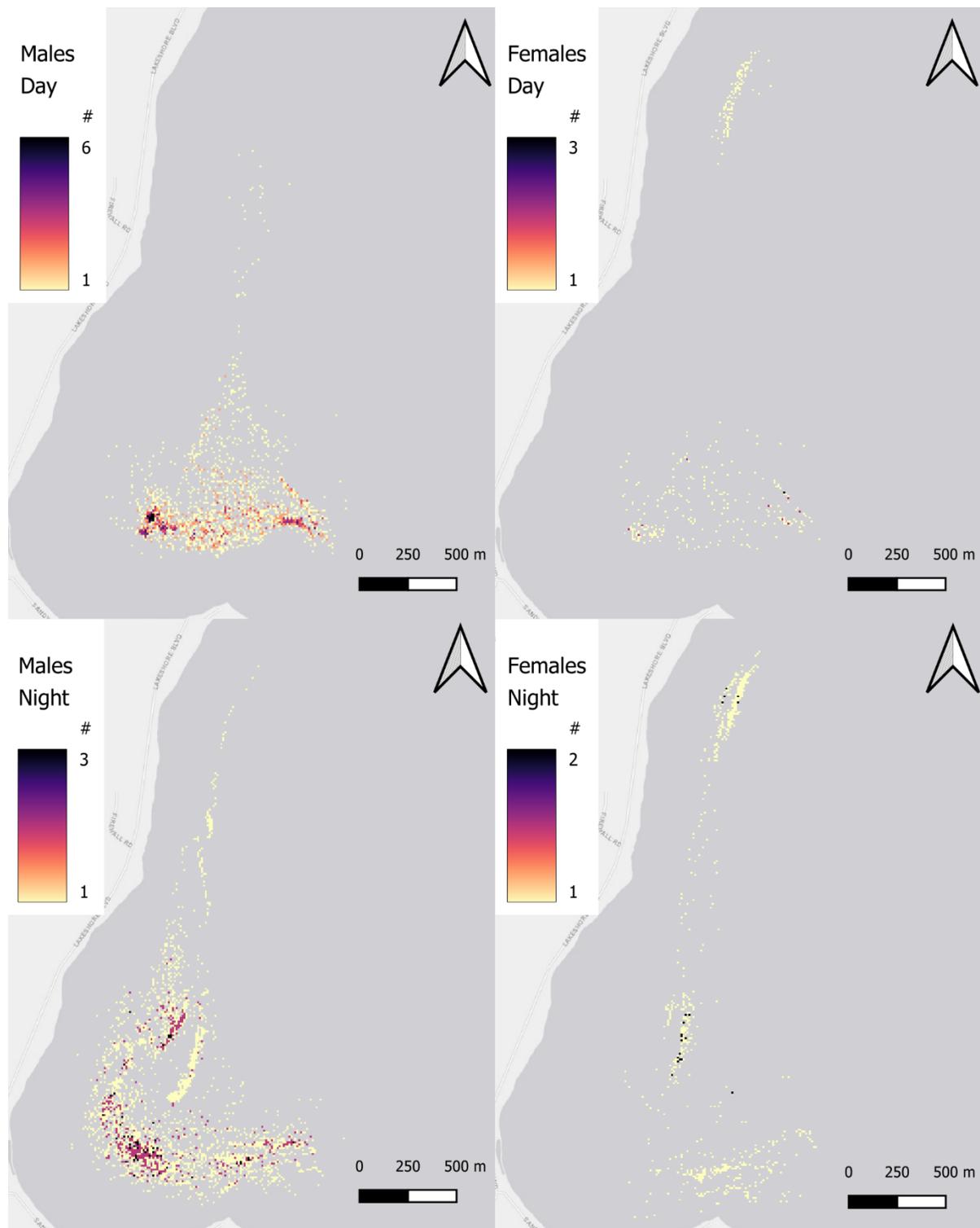
Fig. S14 Heatmaps depicting the number of individual male and female lake whitefish during the day (n = 15, 7) and night (n = 15, 7), respectively, from 19 – 25 November 2021. Total number of positions during the day and night for males was 4045 and 5536 and for females was 2122 and 3485, respectively.

Fig. S15 Heatmaps depicting the number of individual male and female lake whitefish during the day (n = 15, 7) and night (n = 15, 7), respectively, from 26 November – 02 December 2021. Total number of positions during the day and night for males was 2955 and 2632 and for females was 1645 and 2465, respectively.
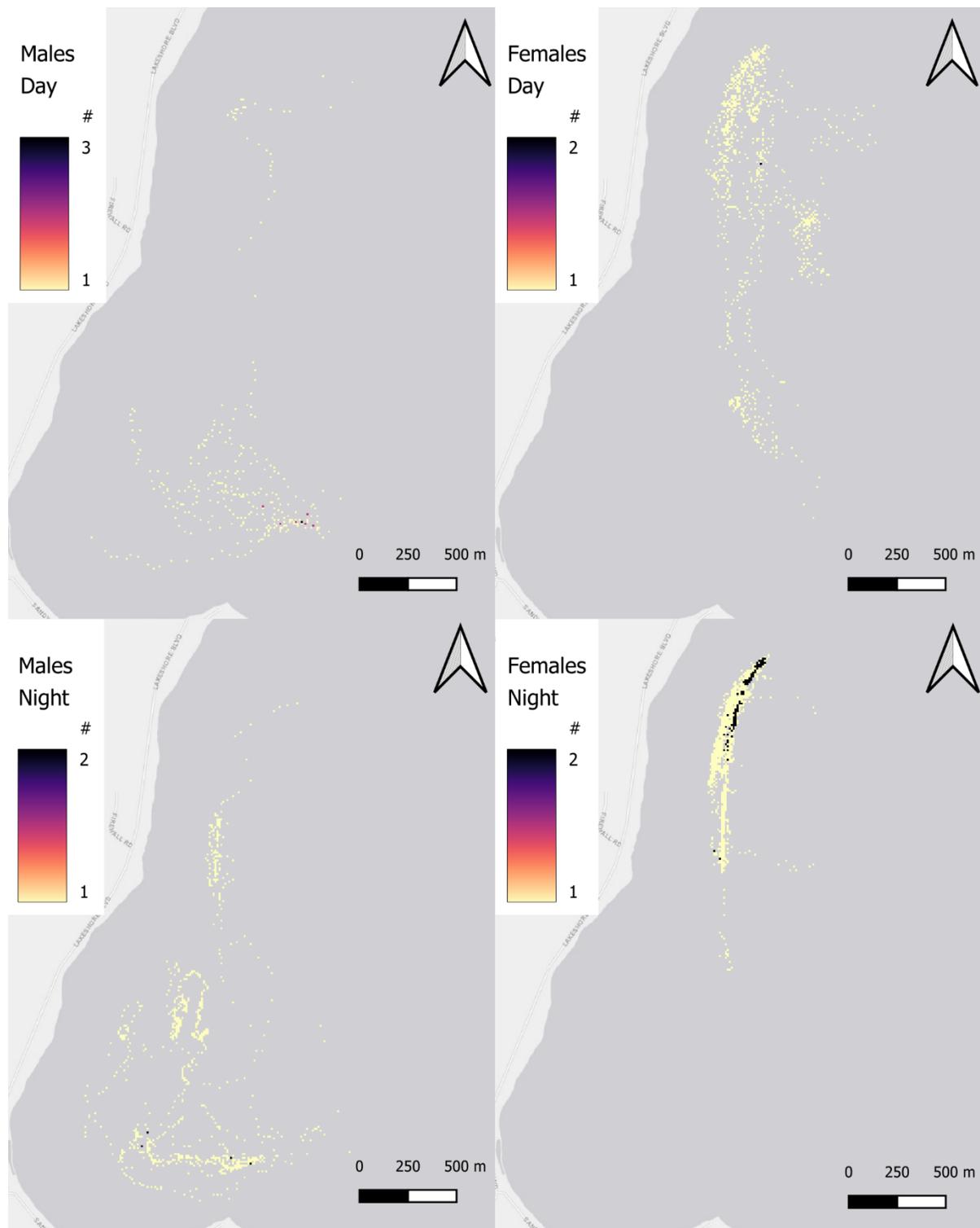
Fig. S16 Heatmaps depicting the number of individual male and female lake whitefish during the day (n = 15, 5) and night (n = 15, 5), respectively, from 03 – 09 December 2021. Total number of positions during the day and night for males was 3524 and 3594 and for females was 1421 and 2709, respectively.

Fig. S17 Heatmaps depicting the number of individual male and female lake whitefish during the day (n = 9, 5) and night (n = 9, 5), respectively, from 10 – 16 December 2021. Total number of positions during the day and night for males was 2936 and 4948 and for females was 374 and 1082, respectively.

Fig. S18 Heatmaps depicting the number of individual male and female lake whitefish during the day (n = 3, 2) and night (n = 3, 2), respectively, from 17 − 23 December 2021. Total number of positions during the day and night for males was 324 and 1101 and for females was 971 and 2569, respectively.
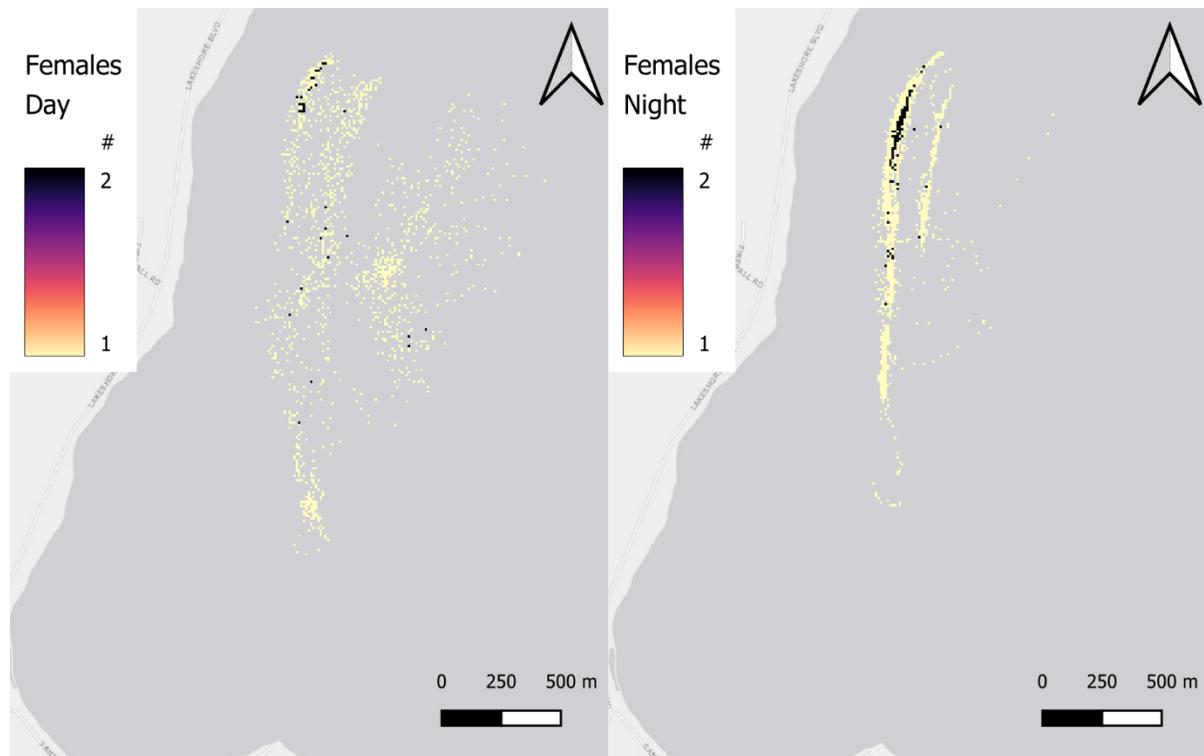
Fig. S19 Heatmaps depicting the number of individual female lake whitefish during the day (n = 3) and night (n = 3), respectively, from 24 – 30 December 2021. Total number of positions for females was 969 during the day and 3495 during the night.
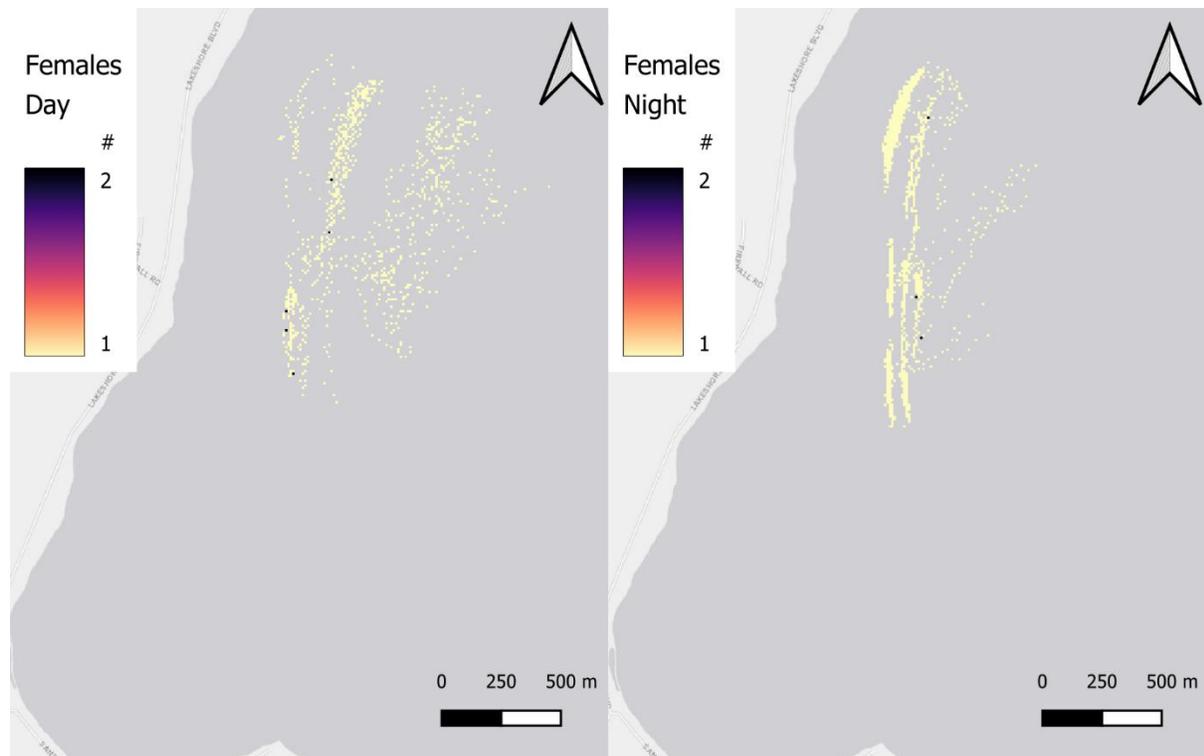
Fig. S20 Heatmaps depicting the number of individual female lake whitefish during the day (n = 3) and night (n = 3), respectively, from 31 December 2021 – 06 January 2022. Total number of positions for females was 1045 during the day and 4098 during the night.
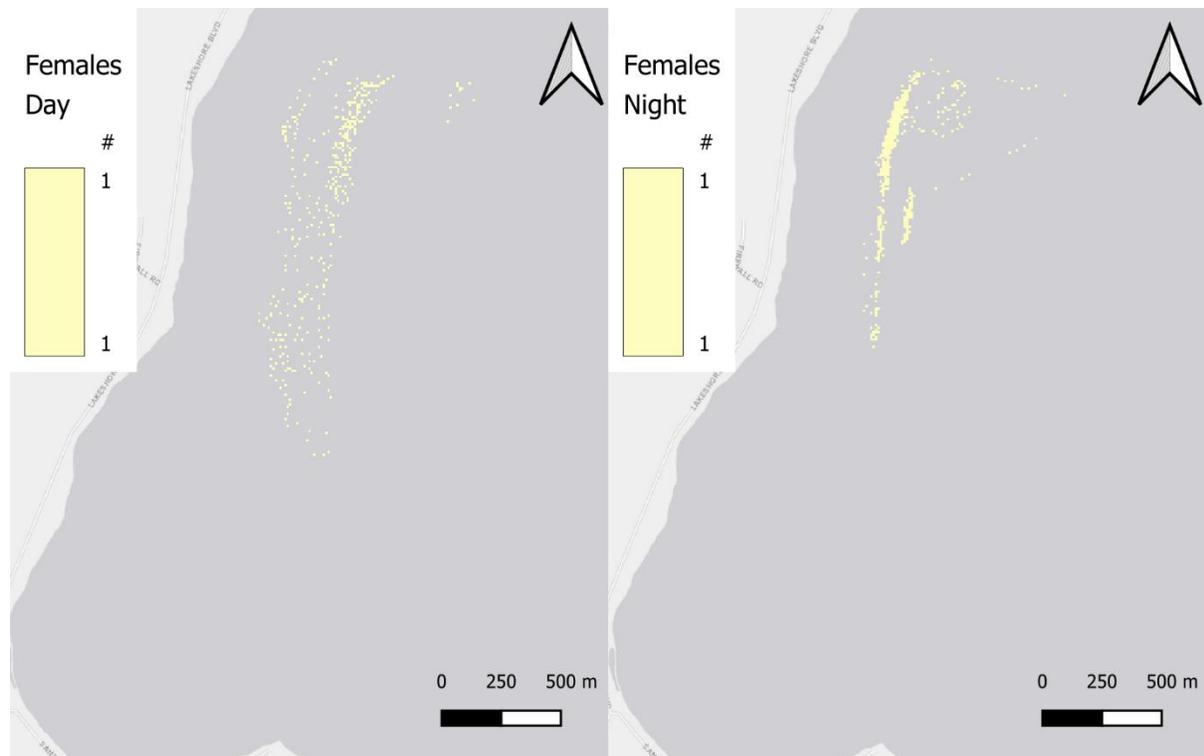
Fig. S21 Heatmaps depicting the number of individual female lake whitefish during the day (n = 2) and night (n = 2), respectively, from 07 – 13 January 2022. Total number of positions for females was 421 during the day and 2186 during the night.
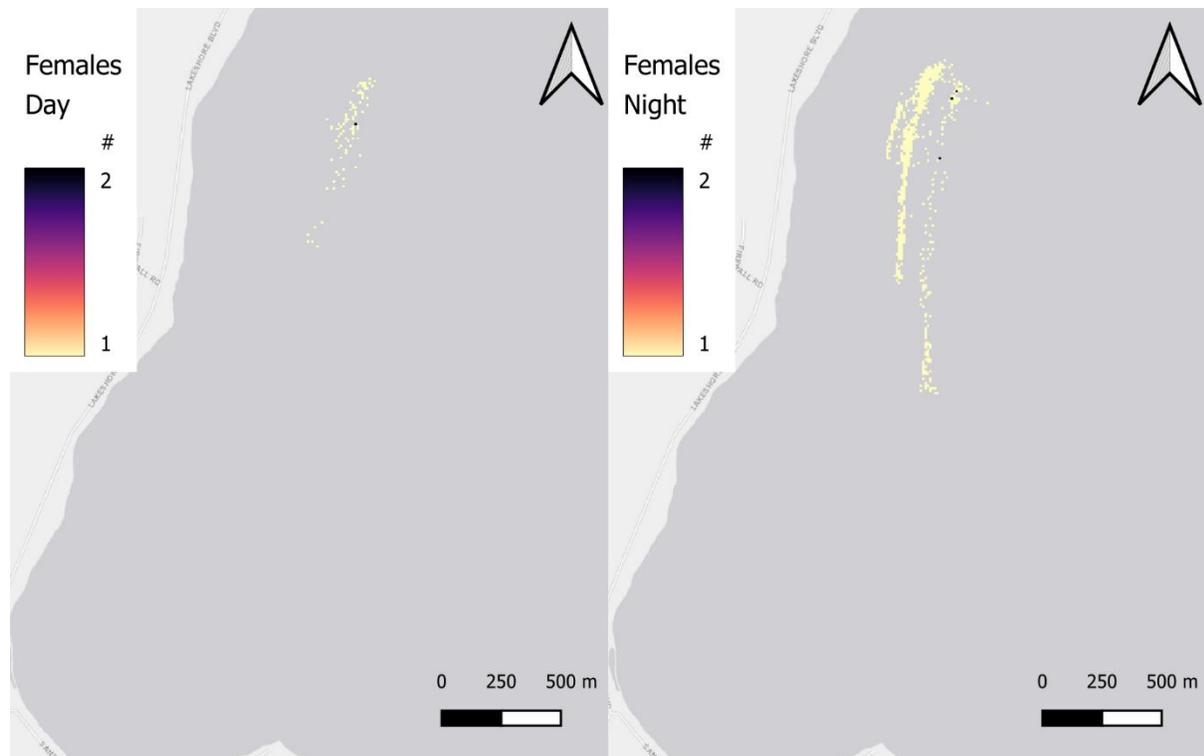
Fig. S22 Heatmaps depicting the number of individual female lake whitefish during the day (n = 2) and night (n = 3), respectively, from 14 – 18 January 2022. Total number of positions for females was 94 during the day and 1195 during the night.

Appendix S10 Swimming depth and lake depth plots

There were instances where lake depth was shallower than swimming depth for Fish ID 4283

and Fish 4287. This error could potentially be due depth tag accuracy or potential error

introduced when interpolating the depth contours or collecting depth while in the field.

Specifically, V16P-4X tags rated for 68 m, like those used in our study, have accuracy of +/- 3.4

m (Innovasea-Fish-Tracking-69khz-tags-data-sheet-0621.pdf). Between Fish ID 4283 and 4287,

there were no instances where lake depth was shallower than swimming depth by more than 2.27

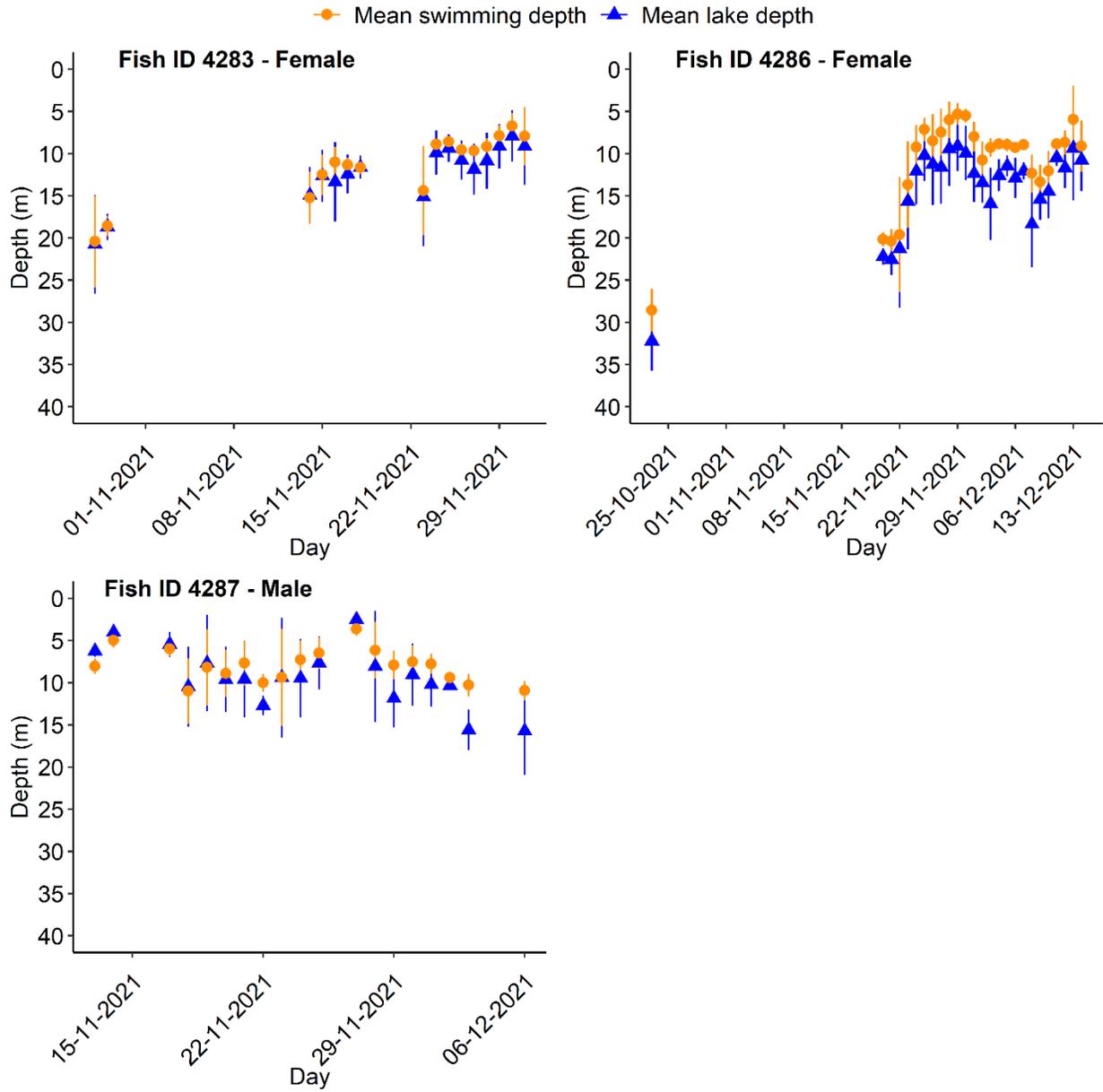m. All lake depths were deeper than swimming depth for Fish ID 4286.

Figure S23. Mean daily swimming (orange circle) and lake (blue triangle) depth (m) for three fish implanted with depth tags (females 4283 and 4286 and male 4287). Note that the x-axes are not common among plots. Shows means and standard deviations measured for each 24-hour period.
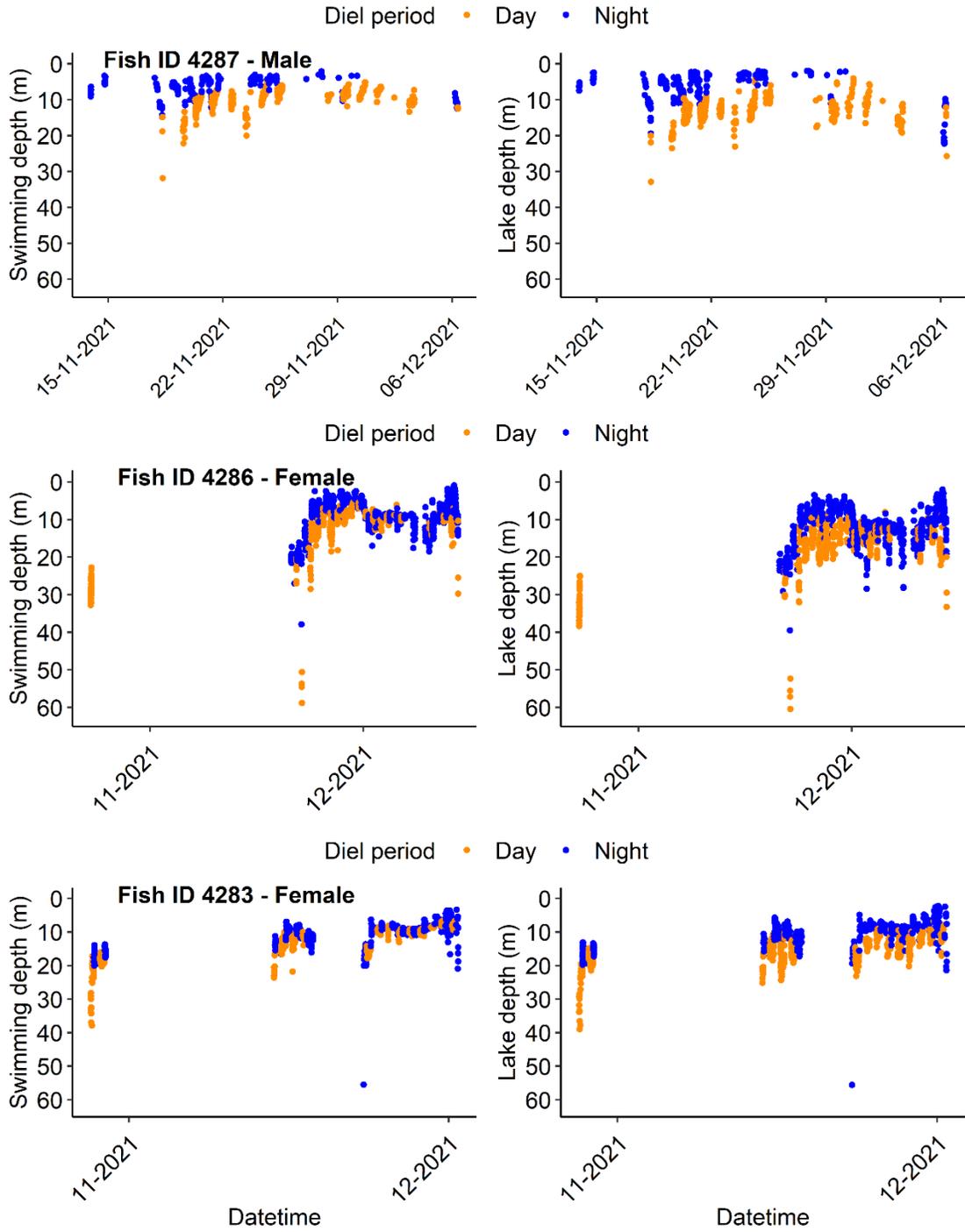
Figure S24. Swimming and lake depths (m) for three fish implanted with depth tags (females 4283 and 4286 and male 4287) for the day (orange) and night (blue). Note that the x-axes are not common among plots. Shows raw values for each individual.
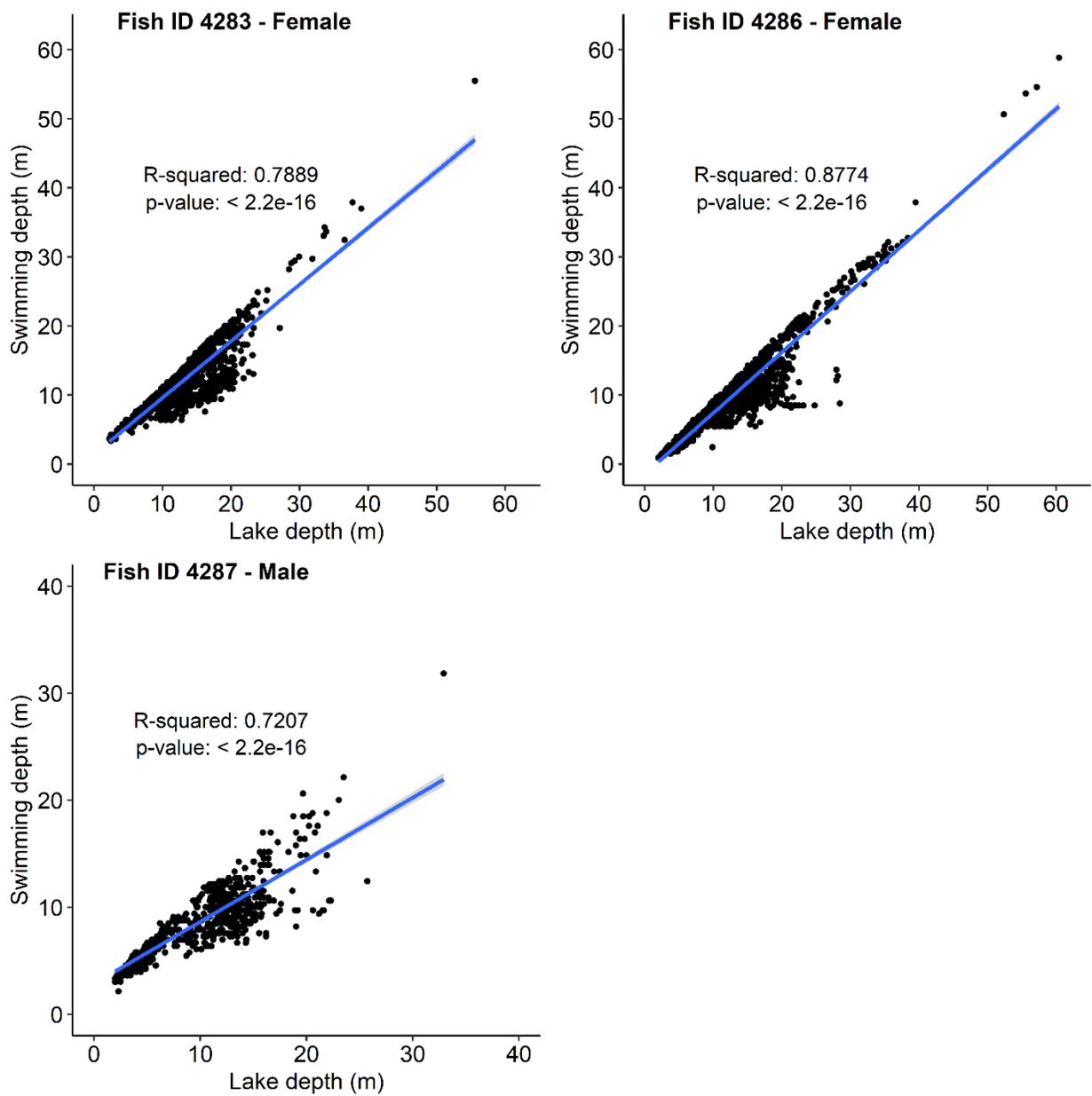
Figure S25. Linear regressions comparing the relationship between lake depth and swimming depth at each position for three fish implanted with depth tags (females 4283 and 4286 and male 4287). R^2 and p-values are provided in each plot.

Appendix S11 Mean horizontal rate of movement in each activity stage

Table S4. Summary table mean horizontal rate of movement (m s^{-1}) for males and females during the day (MD and FD, respectively) and night (MN and FN, respectively) between 15 October 2021 and 22 December 2021 for each stage of activity.

Stages of activity	Mean horizontal rate of movement (m s^{-1})
Pre-activity	MD – 0.291 (± 0.14)
	FD – 0.285 (± 0.15)
	MN – 0.175 (± 0.12)
	FN – 0.105 (± 0.08)
Escalation	MD – 0.244 (± 0.11)
	FD – 0.261 (± 0.12)
	MN – 0.165 (± 0.12)
	FN – 0.102 (± 0.09)
Peak activity	MD – 0.184 (± 0.11)
	FD – 0.203 (± 0.11)
	MN – 0.221 (± 0.18)
	FN – 0.139 (± 0.11)
De-escalation	MD – 0.132 (± 0.10)
	FD – 0.152 (± 0.11)
	MN – 0.118 (± 0.12)
	FN – 0.109 (± 0.10)
Post-activity	MD – 0.284 (± 0.08)
	FD – 0.250 (± 0.11)
	MN – 0.265 (± 0.09)
	FN – 0.07 (± 0.06)