SEASONAL USE OF CHANNEL AND OFF-CHANNEL HABITATS AND DEPTH DISTRIBUTION OF WHITE STURGEON IN THE MARCUS AREA OF THE UPPER COLUMBIA RIVER DETERMINED USING AN ACOUSTIC TELEMETRY ARRAY

PHASE II
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Prepared For:

Toxics Cleanup Program, ERO
Department of Ecology
4601 N. Monroe Street
Spokane, WA 99205

By:

Jason G. McLellan[1], Dr. Stephen G. Hayes[2],
Matthew D. Howell[1], and Dr. R. Kirk Steinhorst[2]

[1]Fish Management Division, Region 1
Washington Department of Fish and Wildlife
2315 North Discovery Place
Spokane Valley, WA 99216

[2]Department of Statistics
University of Idaho
PO Box 441104
Moscow, ID 83844

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Executive Summary

An acoustic telemetry study of white sturgeon was conducted in 2009 and 2010 by the Washington Department of Fish and Wildlife (WDFW) within the Marcus region of the upper Columbia River. The Marcus area, located near Kettle Falls, Washington, is a known depositional area for sand-sized and finer industrial slag released from the smelter facility in Trail, British Columbia. The purpose of the study was to evaluate fine-scale movements and habitat utilization of upper Columbia River white sturgeon based on locational information provided from tagged fish. Both lateral and vertical positions of tagged fish were analyzed as part of this study.

The study was conducted in two phases. Phase I included implanting 21 adult sturgeon with pressure sensing acoustic transmitters, conducting instrumentation range tests using various acoustical tags, performing an evaluation of an optimum receiver array (using a Vemco VR2W Positioning System [VPS]), and deploying the final VPS array. A total of 301 adult white sturgeon within the Transboundary Reach of the upper Columbia River have been tagged with various types of Vemco (Halifax, NS) acoustic transmitter tags. The current study tracked the presence and positions of individual tagged sturgeon that entered the VPS receiver array deployed in the Marcus area during the course of this approximate one year period of data collection and monitoring.

Phase II of the study involved an approximate one year period of field data collection (June 10, 2009 to June 01, 2010) followed by reduction, manipulation, and detailed statistical analysis of the extensive data set. The statistical hypotheses, development of appropriate statistical and probabilistic approaches, and associated analyses addressed six primary study questions:

1. How many individual tagged sturgeon were positioned in the VPS array?

2. Did the number of individually positioned sturgeon vary by season, fish age, or gender?
3. Was there a difference in the amount of time spent and the number of positions in the original river channel versus outside of the original river channel by season?
4. Was there a difference in the amount of time spent and the number of positions in different areas within the array by season?
5. Were there specific movement, migration or congregation corridors for white sturgeon within the existing telemetry array?
6. Were there discernable patterns or spatial indications pertaining to the vertical position of the fish within the Marcus area?

Within the VPS array, 66 tagged adult sturgeon were positioned at some point during the period of data collection. There were no apparent differences in the number of white sturgeon positioned by season, fish length (surrogate for age), or gender. Position probabilities varied significantly across the study area, by season and tag family.

Position probability models were developed and used to provide occupancy estimates across the study area array. The models were used to assess seasonal variability in occupancy within 125 m x 125 m grid cells within and outside of the original river channel. Outcomes from the probabilistic models showed significant effects related to the tag family and grid cell location. Position probabilities were greatest during the spring and summer and lowest during winter and fall. Occupancy of grid cells in and out of the original river channel varied significantly by season. Sturgeon occupancy probabilities within the original river channel were greatest during spring (0.864) and winter (0.714) and lowest during summer (0.332) and fall (0.426). Sturgeon occupation within the study area was more concentrated in winter and spring and more disperse during summer and fall.

White sturgeon were recorded occupying a wide range of depths, but the vast majority (94.7%; n=153,974) of measurements were of depths between 10 and 30 m. The bottom depth within original river channel within the Marcus study area ranges from approximately 20 to 50 m at the full pool elevation of 393 m above mean sea level. The bottom depth outside of the original river channel (the “flats”) within the Marcus study area was approximately 10 m at the full pool elevation of 393 m MSL. Depth measurements generally corresponded with the bottom depth at the position of the measurement, suggesting a benthic orientation. There were no apparent diel patterns in seasonal depth use by tagged sturgeon. Overall, the VPS and the methods of statistical analysis used for this study provided a reasonable level of detail and discernment (i.e., based on use of 125 x 125 m grid cells) regarding habitat (channel versus off-channel) and depth use of white sturgeon within the Marcus area. Specifically, we were able to describe seasonal differences in the congregation positions of sturgeon within and outside of the original river channel, patterns in positioning by tag family and season, and depth use.

Acknowledgements

We gratefully acknowledge John Roland, Brendan Dowling, and Charles Gruenenfelder (Washington Department of Ecology) for assisting with project development, funding, final study design, and contracting. We also thank Mike Parsley (U.S. Geologic Survey [USGS]) for providing advice during project development, as well as the use of eight VR2W receivers. Charlee Capaul, Leslie King, Mitch Combs, Jim Meskan, Rex Gearhart (WDFW), and Hank Etue (Spokane Tribe of Indians) assisted with various activities associated with receiver/sync tag mooring construction, array deployment, downloads, and fish tagging. We also thank the staff at Vemco, particularly Jonathan Mulock, Dale Webber, and Frank Smith, for helping us with equipment testing, design of the final VPS array, and processing the downloaded data to provide the fish positions.

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Introduction

White sturgeon *Acipenser transmontanus* are native to the Columbia River and prior to dam construction generally had unrestricted access throughout the mainstem Columbia River as far upstream as Columbia Lake in British Columbia, Canada (Scott and Crossman 1973). Following dam construction, the white sturgeon population was fragmented into several small isolated populations due to a lack of fish passage for these large fish (North et al. 1993). One of these isolated populations occurs in the Columbia River upstream of Grand Coulee Dam (hereafter referred to as the Transboundary Reach). Recent stock assessment data indicates that the population in the Transboundary Reach consists of a moderate number of adult sturgeon, relative to other Columbia River reservoirs, with limited annual recruitment over the last 30 years. Recruitment is defined as the number of fish reaching one year of age. Without natural recruitment, the population is gradually declining in abundance. In response to increasing concerns over the threat of extinction, the Upper Columbia White Sturgeon Recovery Initiative (UCWSRI) was formed in 2000. The UCWSRI is an international organization with members from state, provincial, and federal fisheries agencies and First Nations tribes in British Columbia and Washington State. The Initiative produced an Upper Columbia White Sturgeon Recovery Plan (UCWSRP) that is compatible with the Canadian Species at Risk Act (SARA) and U.S. Endangered Species Act legislation (UCWSRI 2002). In 2006, the upper Columbia River population was listed as “Endangered” under SARA (Wood et al. 2007).

There are numerous factors suspected to limit natural recruitment of upper Columbia River white sturgeon; however, they can be narrowed into five general categories related to changes in flow patterns and turbidity, diminished habitat (primarily substrate) downstream of spawning areas, changes in the fish community resulting in increased predation, contaminants, and food availability (Gregory and Long 2008). There are several proposed mechanisms for recruitment failure under each of the potential limiting factors, which are either associated with direct mortality of embryos, larvae, and early juveniles or reduced growth, condition, and reproductive potential of older juveniles, sub-adults, and adults.

The Marcus area (rkm 1,135) of the upper Columbia River is heavily utilized by white sturgeon, as determined by previous biotelemetry and stock assessment (setline and gill net) investigations (Brannon and Setter 1992; Howell and McLellan 2007a, 2007b, 2008). In addition to the high concentrations of white sturgeon, the original Columbia River channel in the Marcus area is a deposition area for sand-sized water-granulated fumed slag released from the Teck Cominco (now Teck Metals Corporation) lead and zinc smelter in Trail, British Columbia (CH2M Hill 2006). Slag contains elevated levels of several trace elements, such as arsenic, cadmium, copper, lead, and zinc (Majewski et al. 2003). Smelter operations also historically discharged metal-enriched effluent wastes. Preliminary toxicity studies with larval and juvenile white sturgeon indicated LD50's at much lower concentrations of copper than similar aged rainbow trout (USFWS 2008). The effects of elevated trace elements on older life stages are unknown at this time; however, white sturgeon are long lived, thus increasing their risk of negative effects due to contaminants as a result of bioaccumulation (Beamesderfer et al. 1995). Previous studies indicated that copper can bioaccumulate in the eggs of upper Columbia River white sturgeon (Kruse and Webb 2006). Benthic feeding white sturgeon in the upper Columbia River also ingested slag particles. Parsley et al. (2010) examined the gut contents of 37 hatchery origin white sturgeon captured in upper Lake Roosevelt (rkm 1,120 to 1,170) that had been at large for 1–4 growing season and 78% contained slag particles, which was indicative of benthic feeding behavior. In addition, "all guts contained some material" and the primary prey taxa were "benthic in origin." Limited information was available regarding the fine-scale movement, congregation, and habitat preferences of white sturgeon that routinely use the Marcus area on a seasonal or year-round basis. Overall, specific sturgeon movements and interaction with known slag depositional areas has not been well characterized.

Biotelemetry is the remote detection and measurement of an animal function, activity, or condition (Merriam-Webster Online; www.Merriam-Webster.com). Biotelemetry often involves attaching a piece of equipment that communicates information regarding the organism (Winter 1996). Transmitters are devices that send a signal to be detected by receiving equipment (receiver). Two common types of transmitters used for underwater telemetry are ultrasonic, which send a low frequency acoustic (sound) signal through water that is received by a submerged hydrophone, and radio, which send a low radio signal through water and air that is received by an antenna (Winter 1996). Signals can be detected either actively or passively. Active signal detection usually requires an individual travel to the study area on a regular basis (weekly for example) and manually operates the receiver equipment. Passive signal detection is achieved when an autonomous receiver is deployed in the study area and transmitted signal are received whenever the organism is within range of the receiver.

An emerging technology within the field of biotelemetry is the acoustic positioning system. The basic idea of the positioning system is that a precise position (x, y, z coordinates) of an organism possessing an acoustic transmitter can be determined if the signal from the transmitter is detected by three or more receivers (Espinoza et al. 2011). Acoustic positioning systems have the potential to provide fine-scale (<5 m) position information for organisms that can used to examine habitat use and movements.

The original general objective of this project was to describe fine-scale (<5 m position accuracy) movements of white sturgeon juveniles (<110 cm FL), sub-adults (110-165 cm FL), and adults (>165 cm FL) within the Marcus area (rkm 1,135) of the upper Columbia River; however, as the project developed the specific objectives were refined. The project was conducted in two separate phases (Phase I and Phase II). The objective of Phase I, as outlined by McLellan and Howell (2009), was to determine the feasibility of using a Vemco (Halifax, NS) VR2W Positioning System (VPS) to determine fine-scale movements of white sturgeon. Phase I consisted of four specific activities, including:

- A series of range tests to determine optimum receiver spacing within the defined Marcus study area.
- A small Vemco VR2W Positioning System (VPS) experiment (study 1) to determine the feasibility of using a VPS to position white sturgeon within the Marcus area and optimize the configuration of a VPS array.
- Deployment of the final VPS array.
- Implanting 21 adult sturgeon with pressure sensing acoustic transmitters (also referred to as tags).

Phase II of the project, which is detailed in this report, included periodic downloads and positioning of the array over an approximately one year period and data analysis. The specific objective of Phase II was to address the following six study questions.

1. How many individual tagged sturgeon were positioned in the VPS array?
2. Did the number of individual sturgeon positioned vary by season, fish age, or gender?
3. Was there a difference in the amount of time spent and the number of positions in the original river channel versus outside of the original river channel by season?
4. Was there a difference in the amount of time spent and the number of positions in

different areas within the array by season?

5. Were there specific movement, migration or congregation corridors for white sturgeon within the existing telemetry array?
6. Were there discernable patterns or spatial indications pertaining to the vertical position of the fish within the Marcus area?

These study questions required the development of appropriate methods of data reduction, manipulation, and statistical evaluation to derive useful output from a large, complex dataset developed as part of this study effort. The discussion below summarizes the methods used to establish the VPS array and the statistical approaches used to analyze the data set generated by this project.

Methods

Study Area – Lake Roosevelt is the Columbia River reservoir that was created with the completion of Grand Coulee Dam (rkm 959) in 1941. At its full pool elevation (393 m above mean sea level [MSL]), the reservoir extends approximately 245 km upstream near the United States/Canada boundary (rkm 1,204) and has a surface area of approximately 33,000 ha (Figure 1). There is a 56 km free-flowing stretch of the Columbia River between the upper extent of Lake Roosevelt and Hugh Keeneleyside Dam in British Columbia. Grand Coulee Dam is operated for flood control, power production, and irrigation, with secondary considerations for recreation, fish, and wildlife. In general, the reservoir is drawn down 9–24 m in the spring and 2–4 m in the late summer/early fall.

This study was conducted in the Marcus area of Lake Roosevelt (rkm 1,138 – 1,144) (Figure 1). Study site characteristics consist of the original pre-impoundment Columbia River channel and the “flats” to the north and south of the channel, which were uplands prior to impoundment (Figure 2). Bottom depths within the original river channel and within our study area were generally between 20 and 50 m at the full pool elevation. Bottom depths on the “flats” at full pool elevation were generally 10 m. The study area encompassed the confluence of Kettle and Columbia rivers. During the study the daily mean reservoir elevation, measured at the Grand Coulee Dam forebay, ranged from 384 to 393 m above MSL, which was relatively narrow compared to the average range between 2001 and 2010 (381 to 393 m above MSL) (Columbia River Data Access in Real Time [DART], www.cbr.washington.edu/dart/dart.html) (Figure 3). The mean daily discharge, measured at the international border, ranged from 974 to 4,059 m^3/s, which was lower than the average range between 2001 and 2010 (1,637 to 4,548 m^3/s) (Columbia River DART) (Figure 4). The mean daily water temperature, measured at the international border, ranged from 3.1 to 20.2 ^oC, which was relatively similar to the average range between 2001 and 2010 (3.1 to 19.5 ^oC) (Columbia River DART) (Figure 5).

VPS Array – Using the information gathered during the range testing and test VPS, a final VPS array was designed in consultation with Vemco. The final array was deployed in the Marcus area on 10 and 11 June, 2009 (Figure 2) (McLellan and Howell 2009). The VPS array consisted of 24 VR2W’s spaced approximately 700 m apart and arranged in squares and triangles, with 14 synchronization tags placed near the center of each square or triangle.

The VR2W’s and synchronization tags were moored approximately 2 m above the reservoir bottom. The receiver and synchronization tag moorings consisted of a 35.6 cm L x 35.6 cm W x 20.3 cm H, 61.2 kg concrete anchor, a 2 m mooring line attached to the anchor, and a buoy line from the mooring line to a surface buoy. The 2 m mooring line was attached to the anchor, passed through the center of a 20.3 cm diameter trawl float, and had a 5.1 cm diameter stainless steel ring attached at the top. The trawl float acted to keep the mooring line suspended in the water column and the ring acted as a stop for the trawl float and a connection point for the buoy line. The VR2W's and synchronization tags were attached to the mooring lines below the trawl float.

A survey grade Trimble Pathfinder ProXH Global Positioning System (GPS) with a Zephyr antenna was used to determine the locations of VR2W and synchronization tags. Locations were recorded at the surface after the mooring was lowered to the bottom by pulling the buoy line taut and vertical, either through the center of a 66.0 cm diameter foam-filled mooring buoy or through a 7.62 cm open-face block clipped to the davit arm on the research boat. When the buoy was used, the line was secured in place using cleats mounted on the buoy. The GPS antenna was then mounted on top of the buoy and the boat was then slowly backed away so as not to disturb it. When the block was used, the boat operator maneuvered the boat so that the buoy line remained taut and vertical and the GPS antenna was fastened to the davit arm directly above the block. The GPS location was logged for 20 s via Bluetooth connection to a Trimble Recon field computer.

All of the receivers and synchronization tags in the VPS array were deployed on 10 and 11 June 2009. All of the receivers, with exception of one receiver that was lost, were retrieved, downloaded, and redeployed on 30 June, 13 and 14 August, and 03 November 2009, and 09 February 2010. The receivers were retrieved for downloading on 06 May 2010 and redeployed on 11 May 2010. The final retrieval and download of the receivers occurred on 01 June 2010. Synchronization tag locations were confirmed on 30 June 2009, 13 and 14 August, 04 November 2009, and 10 February and 11 May 2010. Each period between receiver deployment and download consisted of a "study". We considered the start of a study to be when we deployed the final receiver within the VPS on each occasion (Table 1). Thus, the end of a study was when the final receiver within the array was retrieved on each occasion. Study 1 consisted of the test VPS described in McLellan and Howell (2009). Thus, only studies 2 through 7 were included in this report. The detection data from each receiver recorded during each study was sent to Vemco, in the form of .vrl and RLD files, for calculation of tag locations and estimates of position error. Espinoza et al. (2011) described the method by which the tag positions and Horizontal Position Error (HPE) were calculated.

***Acoustic Tagged Sturgeon* –** The sturgeon targeted for positioning included any of the 301 sturgeon within the Transboundary Reach that possessed an active Vemco acoustic transmitter and that utilized the area within the VPS array at any time during the final six studies. A large scale acoustic telemetry study designed to determine the season movements and distribution of white sturgeon in the upper Columbia River, initiated in 2003, was ongoing throughout this study (Golder 2004, 2006; Howell and McLellan 2007a, 2007b, 2008; BC Hydro, unpublished data). The seasonal movement and distribution study was conducted using autonomous acoustic receivers (VR2W's) deployed between Grand Coulee Dam (rkm 959) in Washington and Hugh Keenleyside Dam (rkm 1,260) in British Columbia.

Among the 301 tagged sturgeon in the Transboundary Reach were the 21 affixed with acoustic transmitters during the first phase of this study (McLellan and Howell 2009). The transmitters implanted into these fish had pressure sensors for examining patterns in depth use. The other 280 sturgeon were implanted with transmitters during other studies to address other research questions. Four different tag families were represented among the 301 sturgeon affixed with an acoustic transmitter. The transmitters included V9-2L (146 db; 60-180 s ping delay; 537 d minimum life), V13-1L (147 db; 60-180 s ping delay; 1,123 d minimum life), V16P-4L (152 db; 170-310 s ping delay; 1,460 d minimum life), and V16-6H (160 db; 30-90 s ping delay;

3,650 d minimum life). A ping was a digitally coded acoustic signal emitted from a transmitter. A detection was a successful reception and recording of an individual ping by an individual receiver. A position represents the calculated location of a tag in 2-dimensional space (x, y) resulting from the detection of a single ping by three or more autonomous receivers.

Fish Position Analysis – Descriptive statistics were calculated for individual sturgeon positioned by study, month, season, tag family, fish size, and fish gender. We examined tag family because tags representing four different tag families had been implanted in to sturgeon within the Transboundary Reach. Seasons were defined as summer (11 June – 31 August 2009), fall (01 September – 30 November 2009), winter (01 December 2009 – 28 February 2010), and spring (01 March – 01 June 2010). Fish size categories, which were a surrogate for fish age, were small (<70 cm FL), medium (70-130 cm FL), and large (>130 cm FL). Fish gender was determined by gonad biopsy during acoustic transmitter implantation (McLellan and Howell 2009).

Position Probability and Occupancy Analysis – Three of the objectives were to estimate sturgeon occupancy inside and outside the river channel, by season; and to identify areas of "high occupancy" within the array (e.g. movement and migration corridors, congregation areas). It was suspected, however, that the probability of positioning a sturgeon within the acoustic array was not 1.0 throughout the array, and that the probability varied spatially and seasonally. Before using positions to estimate occupancy, we examined the validity of the assumption of uniform position probabilities of 1.0 across the array and between seasons. We identified position probability models within a 125 m x 125 m spatial grid and incorporated them into occupancy estimates across the array.

We estimated the proportion of use for each cell (occupancy) and calculated a confidence interval about the estimate, both with the correction for detection probability (adjusted) and without (naïve). We estimated seasonal occupancy in and out of the original river channel by assigning each grid cell to a river channel category, then estimating occupancy and confidence intervals for each of the categories. Cells with any portion inside (below) the 372 m bathymetric contour were categorized as within the original river channel. High occupancy areas were identified by isolating grid cells with the greatest occupancy's and non-overlapping confidence intervals. Details of the statistical methods for estimating position probabilities, occupancy, and comparing occupancy within and outside of the river channel are provided in Appendix A.

Depth Analysis – We examined patterns in season depth (m) use by calculating descriptive statistics and by mapping positions with associated depths over the existing bathymetric contours in the Marcus area using ArcGIS 9.3. Mean depth (m) of individual sturgeon with pressure sensor acoustic transmitters positioned within the VPS in each hour of the day and season were plotted to examine diel patterns in depth use. We also examined diel patterns in depth use for each season by plotting the mean depth (m) and associated standard deviation for each hour of the day. Each depth measurement for an individual fish within a season and hour of the day was treated as a subsample and the subsamples were averaged to provide the sample value to address concerns with pseudoreplication in the dataset (Hurlbert 1984). Pseudoreplication is an error in inferential statistics that occurs when samples are treated as independent when they are not independent.

Results and Discussion

Sturgeon Position Results (Questions 1 and 2) – A total of 66 individual sturgeon were positioned within the VPS array, which comprised approximately 21.9% of all of the tagged sturgeon within the Transboundary Reach over the course of the seven studies (Table 2;

Appendix B). The fish that were positioned ranged in length from 28.3 to 247.5 cm FL (Appendix B). The number of sturgeon positioned varied by study, ranging from a low of 39 during studies 2 and 5 and a high of 58 during study 4. The number of positions per individual sturgeon was highly variable with some positioned <5 times and others >10,000 times (Table 2; Appendix B). All four tag families implanted in white sturgeon within the Transboundary Reach were positioned in the VPS (Table 3; Appendix B). Generally, there was little variation in the number of individual sturgeon positioned seasonally, although there were fewer fish with V16-6H tags positioned overall. The number of positions (mean, median, maximum) per individual was associated with tag power so that higher power tags had the greatest number of positions.

The number of individual sturgeon positioned did not appear to vary seasonally by fish size (length), with the possible exception of medium length sturgeon during the winter (Table 4). The number of individuals positioned and total number of positions were lowest in the winter for the medium length group. The number of individual sturgeon positioned did not appear to vary seasonally by fish gender (Table 5).

Position Probability and Occupancy (Questions 3, 4, and 5) – Position probabilities varied significantly across the study area, by season and tag family (Table 6). Our seasonal models each contained significant effects for tag family and grid cell location. Position probabilities ranged from 0.10 to 0.40 (Figure 6 – Figure 9; Appendix C). Tags in family V16P-4L were most likely to be positioned, followed by family V9-2L, V13-1L, and V16-6H. Position probabilities were greatest during the spring and summer and lowest during winter and fall (Table 6). Sample sizes were large in each season/tag family group except for the “Above” and “Below” groups for tag family V9-2L (Table 6).

The sampling error of our occupancy estimator was low, the coefficient of variation on $\hat{\varphi}_i$ ranged from 0.4 to 1.0%, resulting in precise confidence interval estimates. Large sample sizes within most grid cells and the $\hat{N}$ term in denominator of the $\hat{\varphi}_i$ variance estimator produced the precise estimates (Table 7).

Occupancy of grid cells in and out of the original river channel varied significantly by season (Figure 6 – Figure 9). Sturgeon occupancy within the original river channel was greatest during spring (0.864) and winter (0.714) and lowest during summer (0.332) and fall (0.426) (Table 8). Occupancy also varied by season. Sturgeon occupation was more concentrated in winter and spring and more disperse during summer and fall (Figure 6 – Figure 9; Appendix D). Winter and spring occupancy was concentrated in 3 cells during winter and spring (Table 9; Figure 8; Appendix D), all within the original river channel. When position frequencies were adjusted for imperfect detection, over 31% occurred in grid cells 829 and 830 in winter and over 27% occurred in grid cells 829 and 783 during spring (Table 9). The set of 3 cells are contiguous. In contrast, summer and fall locations were more disperse; less than 3% occurred in a single grid cell during either season (Table 9).

Significant seasonal variation in occupancy of grid cells was likely related to water temperatures and reservoir elevation. More dispersed habitat use during the summer and fall, when water temperatures were warmest, were likely due to greater movement activity presumably associated with foraging. Reasons explaining the high use of the original river channel habitat during the winter were unknown; however, large aggregations of white sturgeon have been observed in other areas during winter months (Hildebrand et al., *in review*). Greater use of the original river channel during the spring corresponded with the Lake Roosevelt flood control drawdown, and the near de-watering of the off-channel “flats” habitat.

Patterns in Depth Use (Question 6) – White sturgeon were recorded occupying a wide range of depths (Table 10; Appendix E), but the vast majority of measurements were of depths between 10 and 30 m (Figure 10). The mean depths used by sturgeon appeared to vary seasonally, with depths increasing from summer to winter and then decreasing again in the spring (Table 11). The distribution of depth use was bimodal during the summer, with peaks at 10 and 23 m (Figure 11). Depth use during the winter was restricted to depths >10 m. The spatial distribution of the depth measurements indicated greater use of the Marcus area (the northern portion of the VPS array) during the summer and fall and more restricted use of the original Columbia River channel during the winter and spring (Figure 12 – Figure 15). The depth measurements of the tagged sturgeon generally corresponded with the current information about the maximum depths (bottom depth) within the study area (i.e. the sturgeon typically had a benthic orientation). For example, the deepest portion of the study area (>20 m) occurred within the original river channel and the depth measurements for positions within the original river channel were generally >20 m.

The depth use data from large white sturgeon that possessed transmitters with pressure sensors indicated that they were primarily oriented near the substrate within the Marcus area. For example, in the plots of individual positions with depth data there were few shallow (<5 m) depth measurements at positions where the reservoir was relatively deep (i.e. the original river channel). Most depth measurements were similar to our general knowledge of the bottom depth at the location of the VPS generated position. Gut contents of upper Columbia River hatchery white sturgeon that had been at large for 1-4 growing seasons, which included fish captured within the Marcus area, were primarily composed of benthic organisms and a high proportion (79%) contained slag (Parsley et al. 2010). Their results suggested that upper Columbia River white sturgeon between the age 1 and 5 were oriented near the bottom, at least during the time of the study (October).

The distributions of the depth measurements corresponded with the habitat use data. The bimodal distribution of depth data during summer corresponded with the diverse use of habitat. The peak in depth use around 10 m was indicative of the use of the flats habitat and the peak around 23 m was indicative of the use of the original river channel. The distribution of depth measurements >10 m during the winter was consistent with the observed high use of the original river channel.

There were no apparent diel (a 24 hr period that included a day and adjoining night) patterns in seasonal depth use by sturgeon with pressure sensing tags positioned within the VPS (Figure 16 and Figure 17). This was in contrast to white sturgeon in the lower Columbia River, which used significantly shallower depths at night (Parsley et al. 2008). The reasons for the differences are unknown; however, they could be related to fish sizes (lengths) and study area characteristics. The fish with pressure sensors (depth) in our study were large (163-248 cm FL) adults (sexually mature), whereas the fish in the Parsley et al. (2008) study were relative small (50-122 cm FL) juveniles (immature). The Marcus area is a reservoir environment, unlike the lower Columbia River which was potentially more productive, riverine, and experienced a tidal influence (Parsley et al. 2008).

Conclusions

Overall, the VPS was an adequate tool for determining habitat use of individual white sturgeon (differentiated based on gender, size, and tag type) within the Marcus area at the scale of 125 x 125 m grid cells. During this study, we were able to describe seasonal differences in the occupancy of sturgeon within and outside of the original river channel, patterns in positioning by tag family and season, and depth use. Results and findings from this latest sturgeon telemetry study also will support study development to examine fine-scale movement rates and patterns in other portions of the upper Columbia River system.

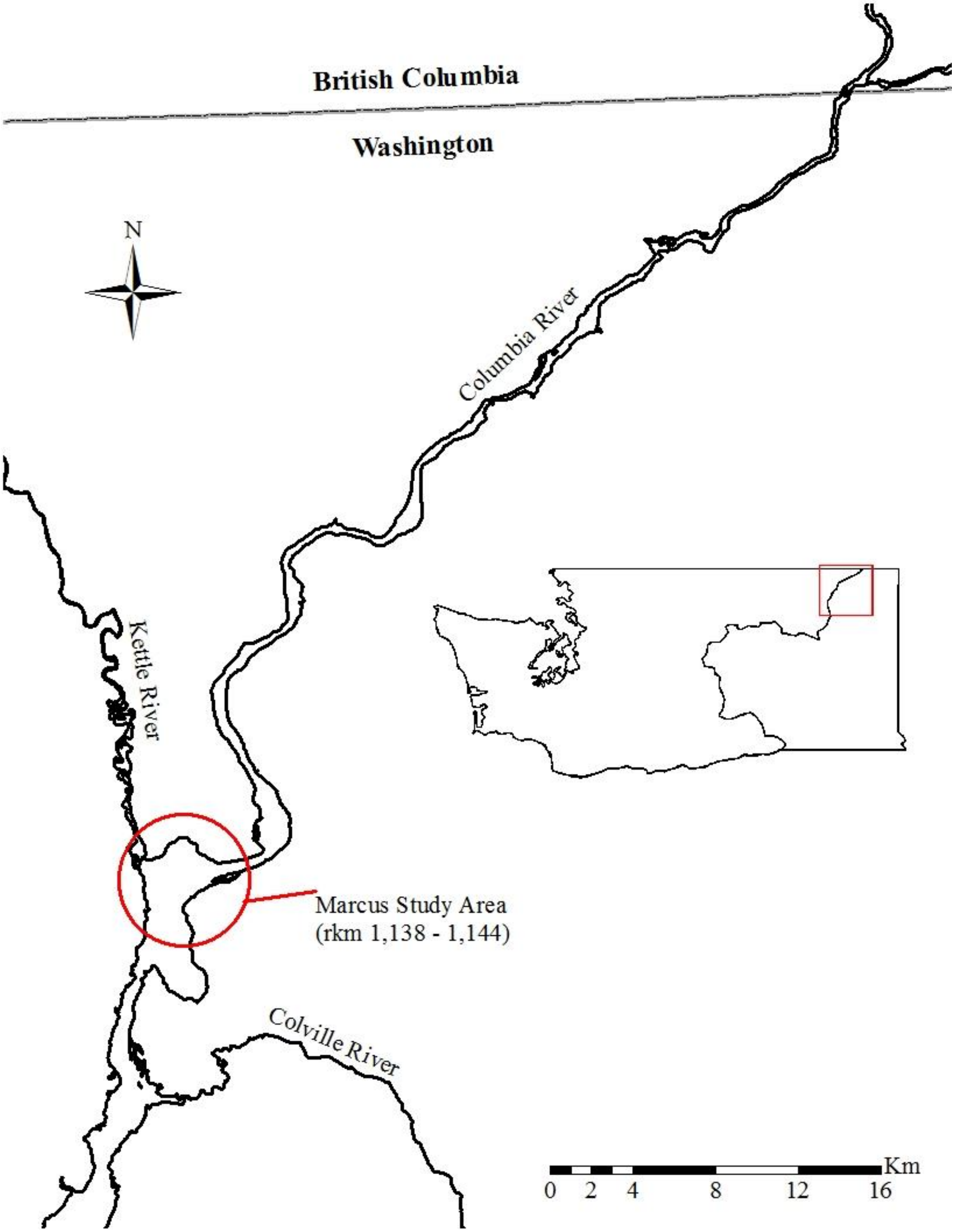

Figure 1. The location of the VR2W Positioning System (VPS) within upper Columbia River.

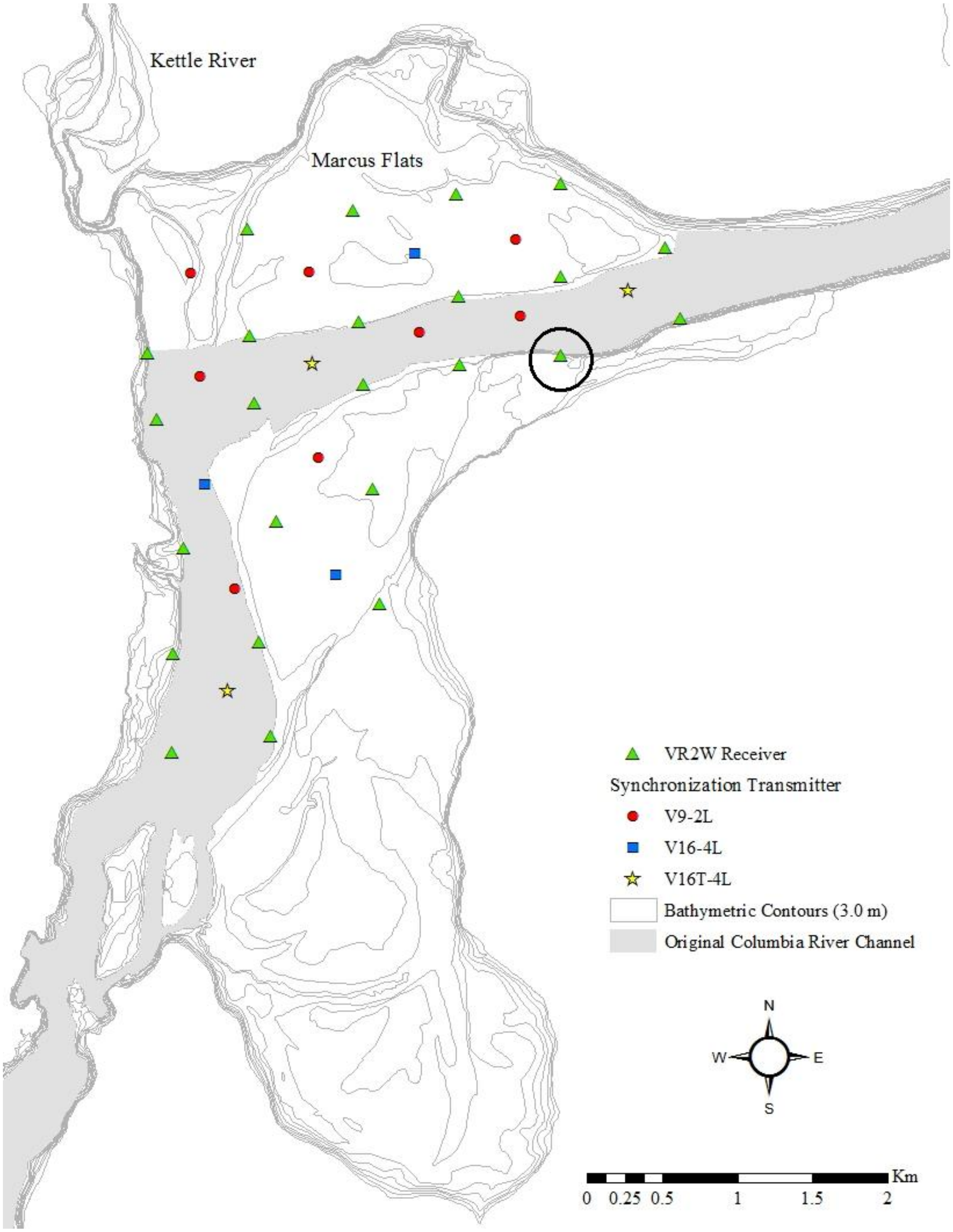

Figure 2. Configuration of VR2W receivers and synchronization transmitters in the Vemco Positioning System (VPS) array deployed in the Marcus area of Lake Roosevelt on 10 and 11 June 2009 and operated until 01 June 2010. The receiver within the black circle was not retrieved until spring 2010 and thus was not included in the data analysis. The original river channel was defined for the study area as all depths below the 372 m above mean sea level elevation. Columbia River flow was east to west.

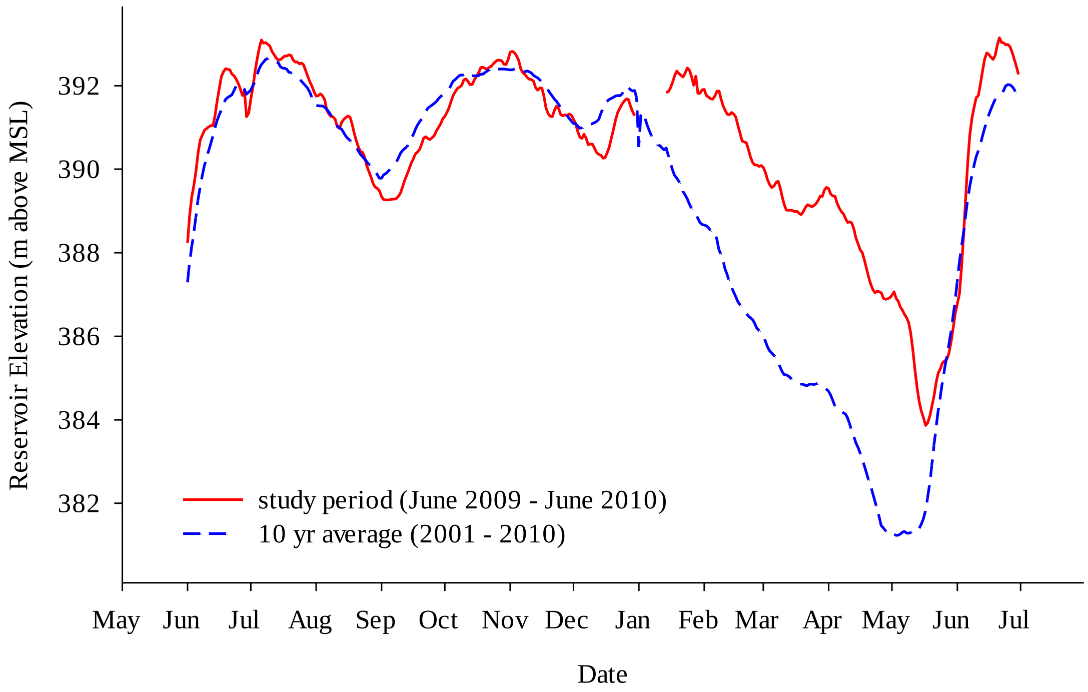

Figure 3. The daily mean reservoir surface elevation (m above mean sea level [MSL]) of Lake Roosevelt measured at the forebay of Grand Coulee Dam during the study period (June 2009 – June 2010) and the 10 year average over the same time period (June – June).

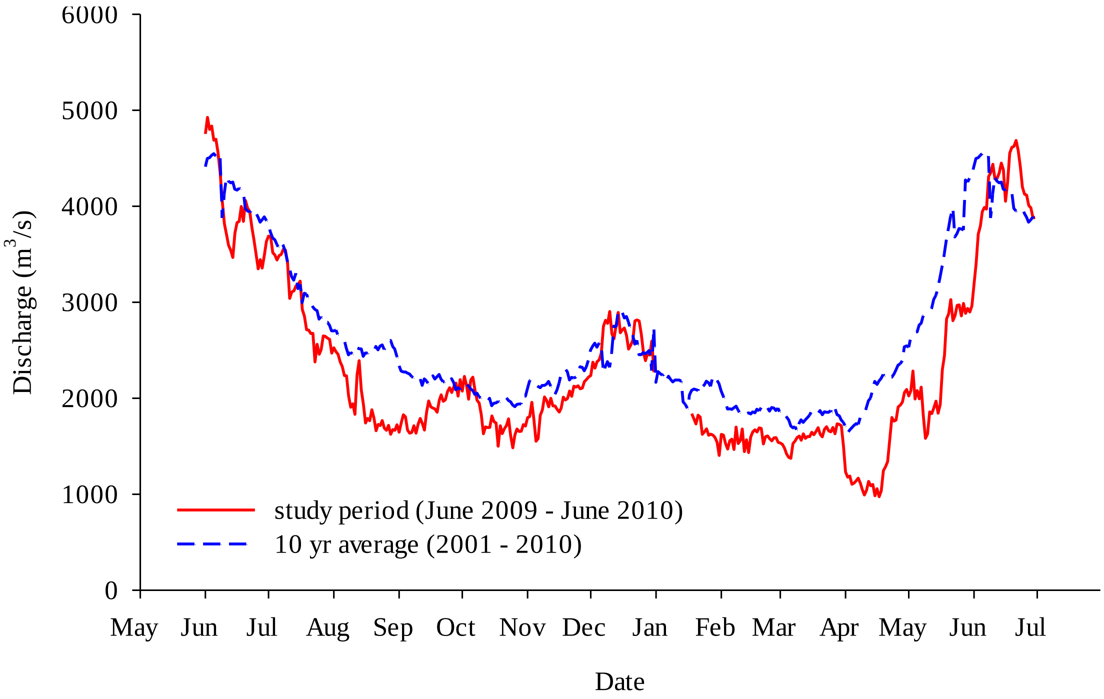

Figure 4. The daily mean discharge (m^3/s) of the Columbia River measured at the U.S./Canada border during the study period (June 2009 – June 2010) and the 10 year average over the same time period (June – June).

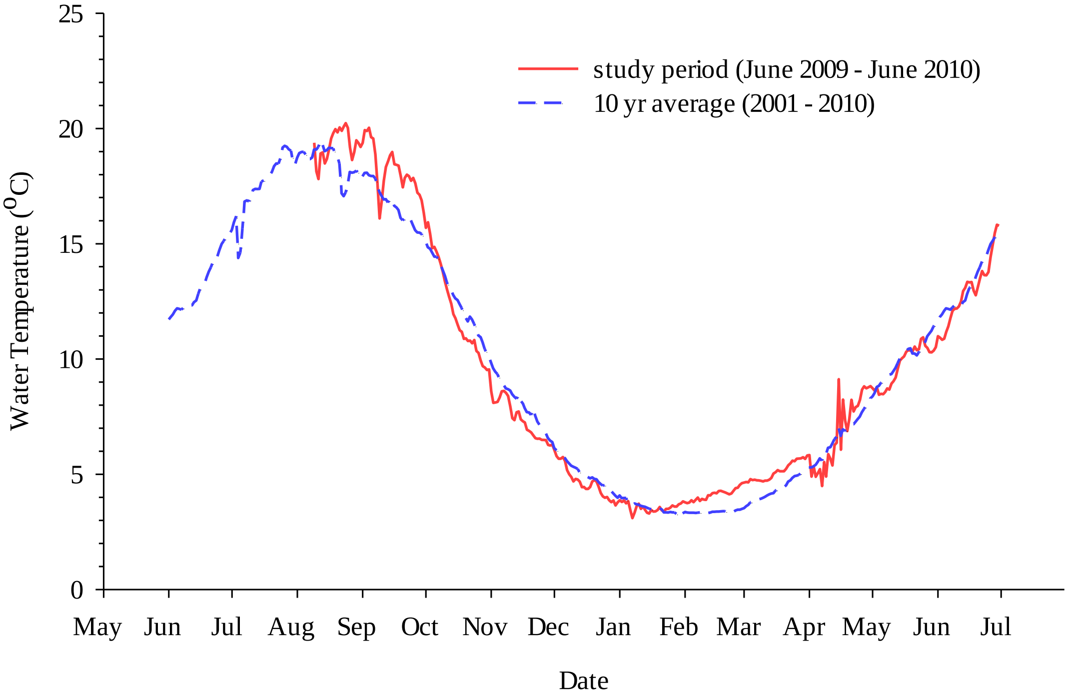

Figure 5. The daily mean water temperature (^{o}C) of the Columbia River measured at the U.S./Canada border during the study period (June 2009 – June 2010) and the 10 year average over the same time period (June – June).

Table 1. Start and end dates and times for each VPS study. The start of a study was when the final receiver within the VPS was deployed on each occasion and the end was when the final receiver within the array was retrieved. Study 1 was a test array (McLellan and Howell 2009) and was not included.

Study	Start Date/Time (hh:mm:ss)	End Date/Time (hh:mm:ss)
2	11 Jun 2009 14:10:00	30 Jun 2009 10:00:00
3	30 Jun 2009 11:00:00	14 Aug 2009 16:00:00
4	14 Aug 2009 16:00:01	03 Nov 2009 19:18:43
5	03 Nov 2009 19:18:44	09 Feb 2010 16:43:16
6	09 Feb 2010 16:43:16	6 May 2010 12:41:33
7	11 May 2010 10:15:57	01 Jun 2010 13:47:24

Table 2. Descriptive statistics of white sturgeon positioned in the VPS array between 11 June 2009 and 01 June 2010.

	No. of Tags			No. of Positions per Tag					
Study	Positioned	Available	Proportion Positioned (%)	Median	Mean	SD	Min	Max	Total No. of Positions
2	39	282	13.8	681	1,543	2,722	4	15,794	60,179
3	47	291	16.2	633	1,390	2,289	1	12,528	65,350
4	58	301	9.3	1,045	3,310	5,837	1	29,096	192,004
5	39	301	13.0	1,021	3,564	7,702	1	44,316	139,011
6	51	301	16.9	879	6,689	12,625	1	67,410	341,163
7	43	301	14.3	329	1,626	3,025	1	18,566	69,897
Total	66	301	21.9	773	3,132	7,139	1	67,410	867,604

Table 3. Descriptive statistics of white sturgeon positioned in the VPS array between 11 June 2009 and 01 June 2010 by tag family, month, and season.

Tag Family	Jun-09	Jul-09	Aug-09	Summer	Sep-09	Oct-09	Nov-09	Fall	Dec-09	Jan-10	Feb-10	Winter	Mar-10	Apr-10	May-10	Jun-10	Spring	Total
V13-1L																		
n	19	18	20	22	17	14	11	19	11	10	10	11	14	16	16	8	19	22
median	368	162	63	1,289	276	274	27	363	66	120	441	706	136	132	190	2	678	2,030
mean	12,06	874	687	2,381	1,299	1,194	564	2,369	491	436	1,605	2,347	1,352	486	718	49	2,031	7,353
sd	15,27	1,712	15,19	3,488	2,506	2,281	1,006	4,705	876	766	2,705	4,213	2,706	813	1,269	125	3,794	14,173
min	4	1	2	6	1	5	1	1	1	1	3	5	1	2	2	1	1	21
max	5,820	6,348	6375	12,486	8,753	7,211	2,676	18,420	2,367	2,238	7,125	11,730	8,347	2,741	4,701	359	12,850	53,252
V16-6H																		
n	4	4	5	5	6	3	3	6	3	3	3	3	3	4	4	1	6	6
median	3,759	2,622	1,629	7,932	5,766	13,555	6,232	11,278	6,075	7,401	18,123	30,263	28,125	5,627	3,776	136	21,770	52,728
mean	6,072	4,417	2,744	11,134	5,591	11,151	8,416	15,374	7,834	9,241	14,079	31,154	26,132	7,234	6,515	136	22,254	62,484
sd	6,748	5,489	2,790	9,818	3,320	6,406	5,047	14,029	4,256	5,380	12,399	20,354	3,595	7,371	8,608		20,482	53,575
min	974	228	334	3,905	34	3,891	4,828	34	4,739	5,023	162	11,260	21,982	512	76	136	322	82,88
max	15,794	12,194	7,190	28,322	9,516	16,007	14,187	36,533	12,688	15,300	23,951	51,939	28,288	17,172	18,430	136	52,690	141,162
V16P-4L																		
n	13	18	15	20	16	15	15	18	16	16	16	16	16	16	19	16	19	21
median	681	855	596	2,028	952	1,298	1,130	2,925	924	889	3,351	5,573	4,503	2,293	1,895	73	8,171	17,261
mean	985	985	975	2,258	1,271	1,890	1,156	3,668	945	904	3,000	4,849	3,989	2,289	1,843	80	7,197	15,501
sd	827	656	959	1,807	965	1,623	733	2,682	602	524	1,205	1,998	1,590	1,185	1,260	62	3,417	9,561
min	103	177	218	218	29	38	37	29	38	117	122	1,087	83	440	4	4	37	37
max	2,558	2,753	3,876	6,629	3,245	5,085	2,529	9,702	2,170	2,085	4,028	7,655	5,794	4,141	4,069	183	13,386	30,949
V9-2L																		
n	3	2	4	5	7	12	4	13	7	3	7	8	7	8	7	3	11	17
median	43	53	2	44	3	8	57	10	8	45	90	50	55	21	6	2	55	20
mean	60	53	18	71	89	113	136	194	40	46	135	170	119	31	12	2	106	319
sd	47	43	33	109	208	276	201	447	65	10	151	227	174	37	15	1	155	604
min	24	22	1	1	1	1	2	1	1	37	1	2	1	1	1	1	2	2
max	113	83	67	263	559	953	428	1,512	181	57	387	613	491	114	43	2	493	1,866

Table 4. Descriptive statistics for each size class (small <70 cm fork length [FL]; medium 70-130 cm FL; large >130 cm FL) of white sturgeon positioned within the VPS array between 11 June 2009 and 01 June 2010 by season.

Size Group	No. of Tags	No. of Positions per Tag					Total No. of
Season	Positioned	Median	Mean	SD	Min	Max	Positions
Small							
Summer	5	44	71	109	1	263	356
Fall	13	10	194	447	1	1,512	2,528
Winter	8	50	170	227	2	613	1,361
Spring	11	55	106	155	2	493	1,170
Medium							
Summer	19	405	1,495	2,044	6	8,153	28,411
Fall	17	296	956	1,652	1	6,654	16,259
Winter	9	249	473	487	5	1,433	4,254
Spring	17	308	846	1,401	1	5,852	14,388
Large							
Summer	28	2,942	4,457	5,695	218	28,322	124,797
Fall	26	4,160	7,193	8,643	29	36,533	187,020
Winter	21	5,990	9,171	11,498	1,087	51,939	192,600
Spring	27	8,395	10,906	11,344	37	52,690	294,460

Table 5. Descriptive statistics for each gender of white sturgeon positioned within the VPS array between 11 June 2009 and 01 June 2010 by season. Gender was determined by gonad biopsy.

Gender Season	No. of Tags Positioned	No. of Positions per Tag					Total No. of Positions
		Median	Mean	SD	Min	Max	
Female							
Summer	15	3,084	4,946	6,765	352	28,322	74,188
Fall	16	3,005	5,930	8,733	34	36,533	94,882
Winter	13	5,920	10,246	14,477	1,271	51,939	133,200
Spring	16	8,283	11,091	13,881	37	52,690	177,456
Males							
Summer	8	495	1,679	2,310	218	6,629	13,434
Fall	6	4,579	4,325	3,931	29	9,702	25,949
Winter	5	5,771	5,316	2,661	1,087	7,655	26,582
Spring	7	7,220	7,038	3,868	2,660	13,386	49,267
Unknown							
Summer	29	405	2,274	3,444	1	12,486	65,942
Fall	34	137	2,499	5,945	1	27,929	84,976
Winter	20	262	1,922	3,918	2	11,730	38,433
Spring	32	241	2,603	5,928	1	24,973	83,295

Table 6. Seasonal position probabilities estimated for grid cell groups and tag families using logistic regression. Grid groups formed by combining 125 x125 m cells based on magnitude of grid cell effect on position probability.

Grid Cell Group	Tag Family	Number of Observations (detections/positions)	Estimated position probability
Summer			
Above	V16-6H	919	0.23182
Average	V16-6H	180,699	0.16512
Below	V16-6H	715	0.13631
Above	V16P-4L	205	0.38010
Average	V16P-4L	54,865	0.28665
Below	V16P-4L	219	0.24280
Above	V13-1L	563	0.24126
Average	V13-1L	154,449	0.17245
Below	V13-1L	227	0.14258
Above	V9-2L	16	0.26289
Average	V9-2L	247	0.18945
Below[1]	V9-2L	0	-
Fall			
Above	V16-6H	543	0.18026
Average	V16-6H	275,433	0.12766
Below	V16-6H	490	0.11076
Above	V16P-4L	163	0.33368
Average	V16P-4L	108,096	0.24996
Below	V16P-4L	260	0.22098
Above	V13-1L	186	0.20722
Average	V13-1L	164,202	0.14817
Below	V13-1L	196	0.12896
Above	V9-2L	52	0.23438
Average	V9-2L	4,259	0.16924
Below[1]	V9-2L	0	-
Winter			
Above	V16-6H	1,280	0.17550
Average	V16-6H	174,928	0.13438
Below	V16-6H	440	0.09976
Above	V16P-4L	9,081	0.32555
Average	V16P-4L	163,013	0.26038
Below	V16P-4L	2,214	0.20082
Above	V13-1L	287	0.19336
Average	V13-1L	98,369	0.14882
Below	V13-1L	2,059	0.11095
Above	V9-2L	268	0.25216
Average	V9-2L	1157	0.19739
Below	V9-2L	7	0.14933
Spring			
Above	V16-6H	2,968	0.22261
Average	V16-6H	489,336	0.13113
Below	V16-6H	16,524	0.11375
Above	V16P-4L	477	0.40413
Average	V16P-4L	268,665	0.26332
Below	V16P-4L	6,694	0.23312
Above	V13-1L	381	0.25329
Average	V13-1L	128,945	0.15166
Below	V13-1L	3,969	0.13197
Above	V9-2L	13	0.30917
Average	V9-2L	916	0.19084
Below	V9-2L	1	0.16707

[1] Position probability was not estimated for V9-2L tag in “Below Average” grid group because no encounter histories were observed in this group during summer.

Table 7. Sample sizes by season for number of tags, number of encounter histories, number of positions/detections, number of grid cells occupied, and number of grid cells used to model position probability. Overall detection rate is pooled over tag families.

Season	Tags	Encounter Histories	Positions	Detections	Overall Detection Rate (%)	Grid Cells Occupied	Grid Cells Modeled (% obs. dropped)
Summer	50	39,734	72,859	320,265	18.53	672	631 (0.06)
Fall	55	45,114	87,572	466,308	15.81	686	636 (0.05)
Winter	37	37,937	84,842	368,261	18.72	374	332 (0.05)
Spring	54	74,613	159,557	759,332	17.36	462	400 (0.03)

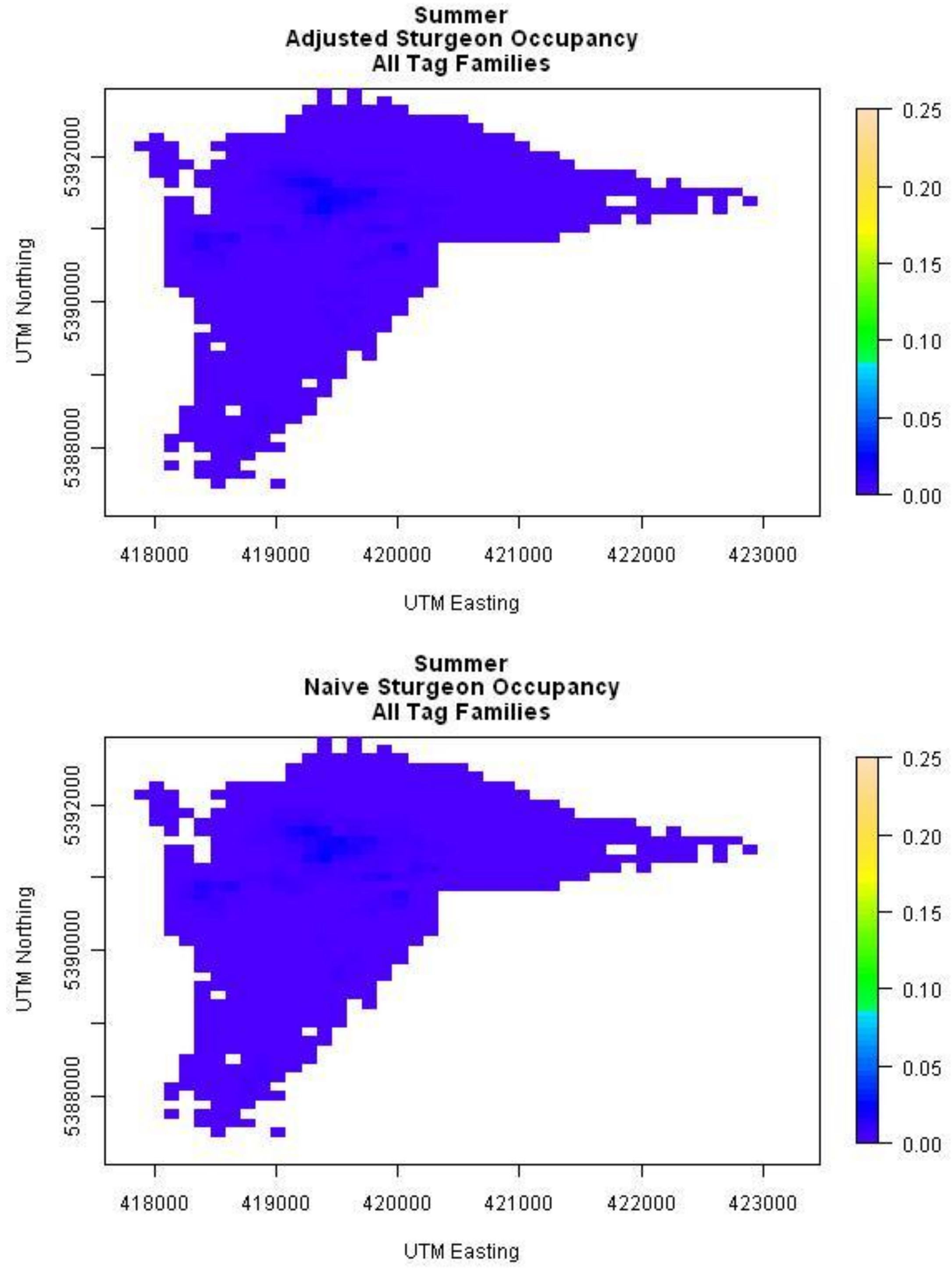

Figure 6. Adjusted and naïve occupancy for summer season, all tag families combined.

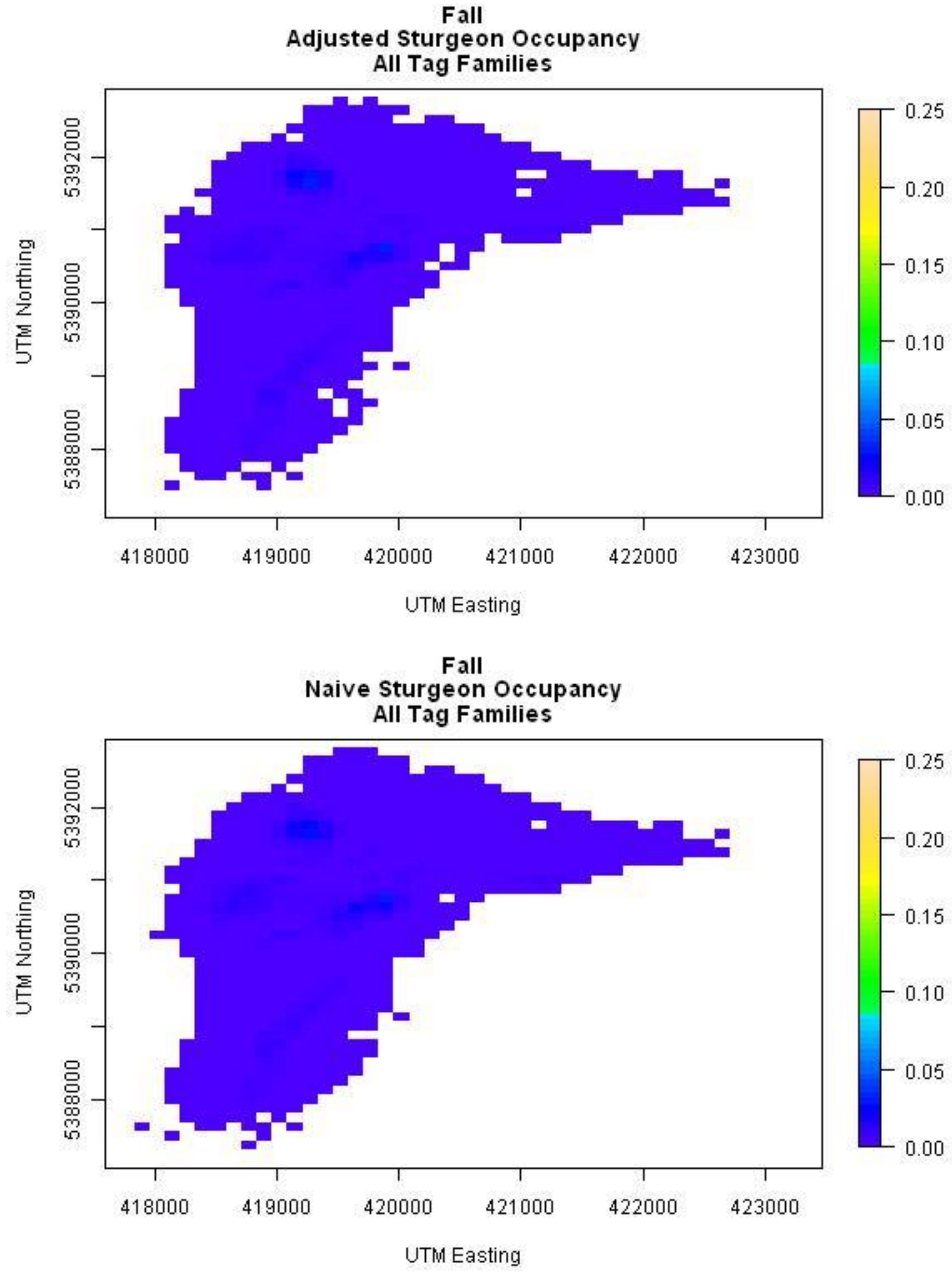

Figure 7. Adjusted and naïve occupancy for fall season, all tag families combined.

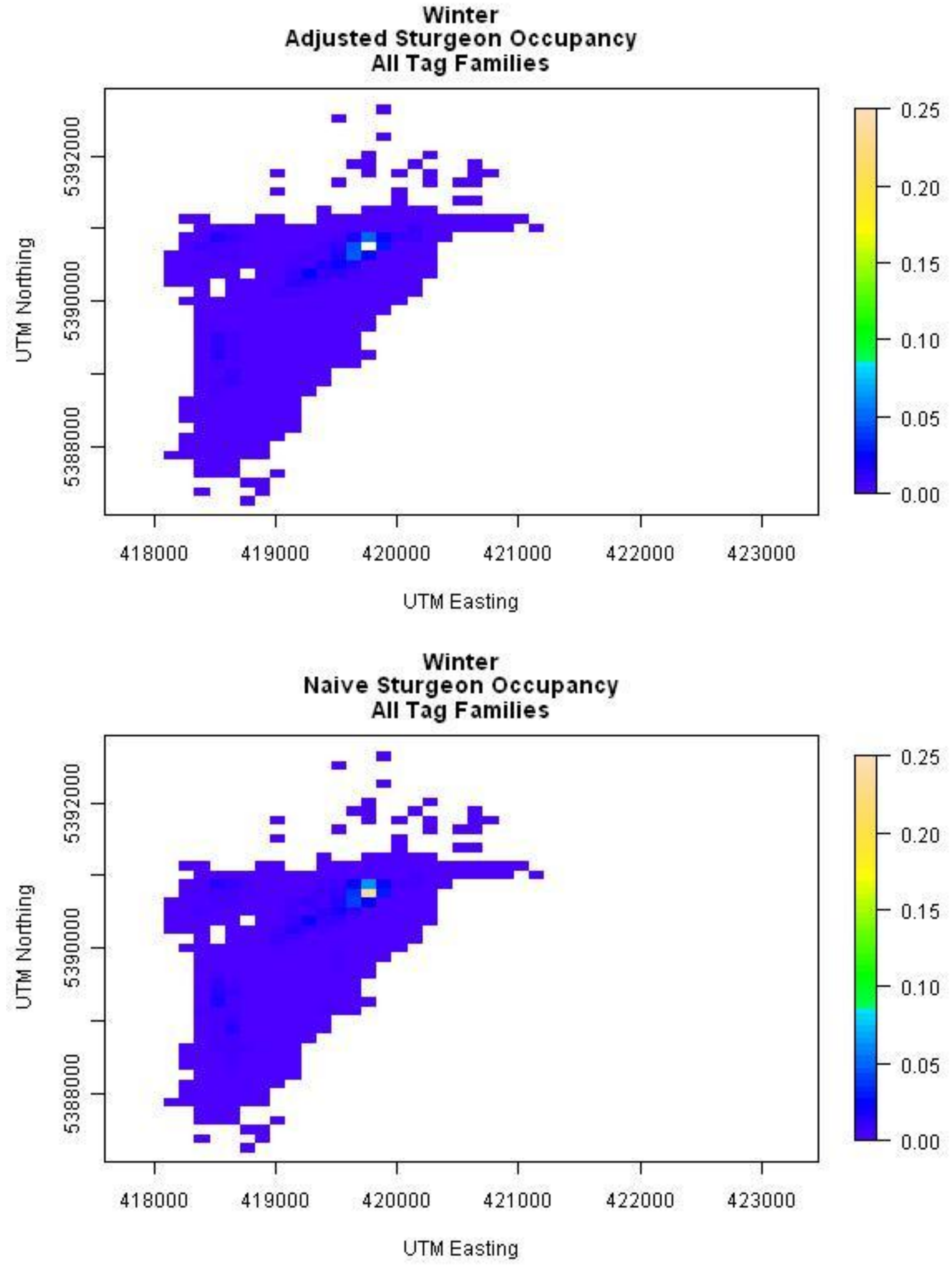

Figure 8. Adjusted and naïve occupancy for winter season, all tag families combined.

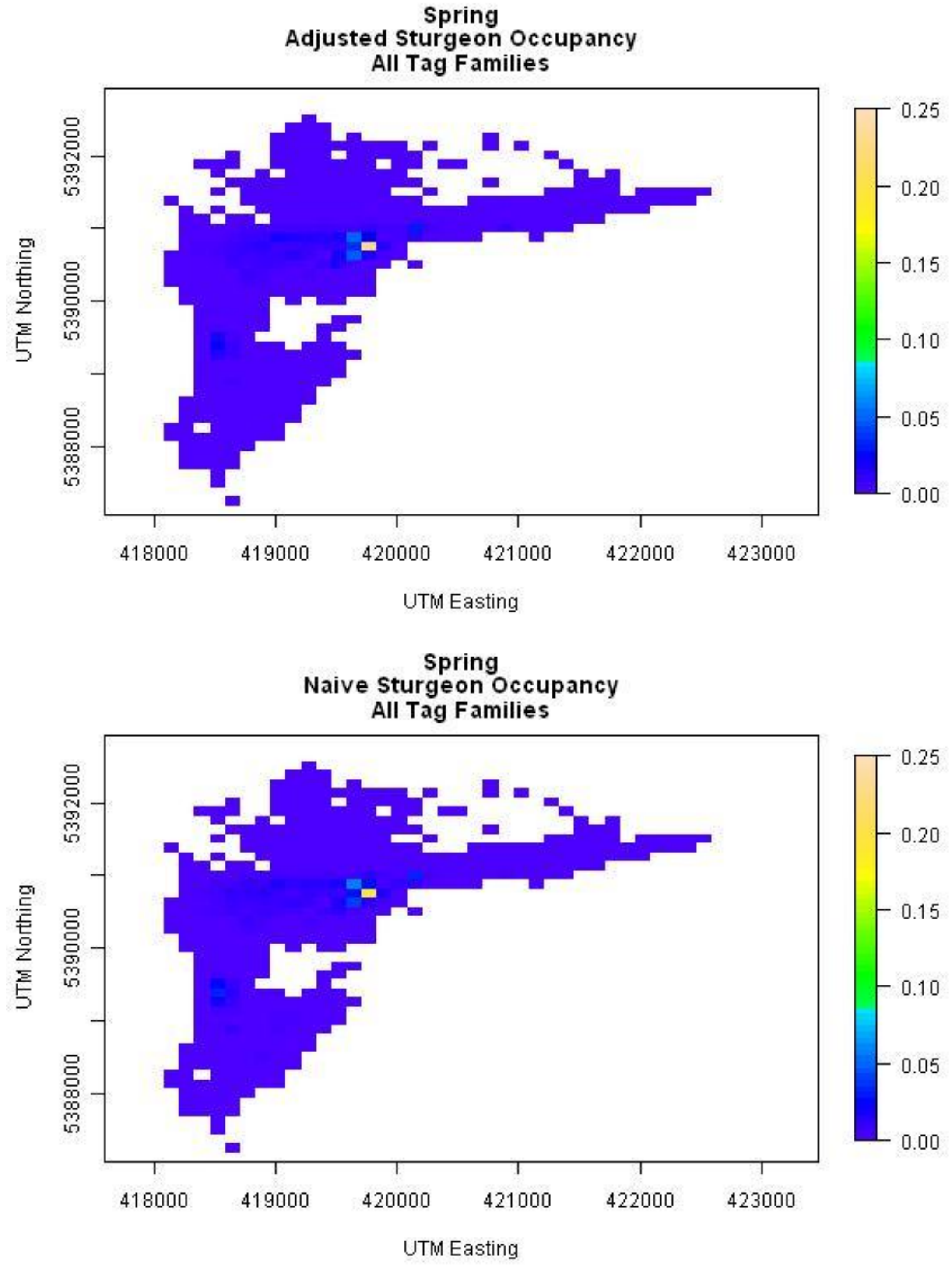

Figure 9. Adjusted and naïve occupancy for spring season, all tag families combined.

Table 8. Occupancy estimates, 95% confidence intervals, and naïve occupancy for sturgeon inside and outside the original river channel, by season.

Season	Channel Habitat	Occupancy Estimate	95% CI	Naïve Occupancy	Number of Grid Cells
Summer	In	0.332	0.332 – 0.332	0.351	269
	Out	0.668	0.668 – 0.669	0.649	403
Fall	In	0.426	0.426 – 0.426	0.444	282
	Out	0.574	0.574 – 0.575	0.556	404
Winter	In	0.714	0.711 – 0.716	0.730	203
	Out	0.286	0.285 – 0.287	0.270	171
Spring	In	0.864	0.862 – 0.865	0.865	258
	Out	0.136	0.136 – 0.137	0.135	204

Table 9. Grid cells with greatest sturgeon occupancy estimates, by season. Southeast corner of grid cell locations are given in UTM coordinates, Zone 11.

Season	Occupancy	95% CI	Grid Number	UTM Easting	UTM Northing
Summer	0.024	0.024 – 0.024	590	419150	5390250
	0.020	0.020 – 0.021	996	420275	5388125
Fall	0.028	0.028 – 0.029	876	419900	5390750
	0.028	0.028 – 0.028	648	419275	5391625
Winter	0.263	0.261 – 0.266	829	419775	5390750
	0.049	0.048 – 0.050	830	419775	5390875
Spring	0.223	0.221 – 0.224	829	419775	5390750
	0.050	0.049 – 0.051	783	419650	5390875

Table 10. Fork length (FL; cm) and gender (M=male; F=female) and descriptive statistics of depth (m) for the 21 individual white sturgeon affixed with an acoustic transmitters with depth sensors and positioned within the VPS between 11 June 2009 and 01 June 2010.

Fish ID	Tag Code	FL (cm)	Sex	n	Median	Mean	SD	Min	Max
46	16347	216.5	M	1,876	10.9	13.5	5.8	7.3	28.5
47	16348	223.0	F	1,607	12.1	13.2	4.1	1.2	29.7
48	16349	188.0	F	4,565	18.8	19.1	4.4	4.9	32.1
49	16350	196.0	M	238	24.9	24.1	3.4	10.9	33.4
50	16351	202.0	F	5,638	24.3	23.1	5.3	1.2	34.0
51	16352	198.5	F	14,268	21.8	21.0	3.5	9.7	32.8
52	16353	178.0	F	8,388	27.9	26.8	5.1	9.1	38.2
53	16354	202.5	F	6,834	29.1	24.9	7.9	4.2	40.6
54	16355	181.5	M	15,014	19.4	19.6	4.7	4.9	37.0
55	16356	233.0	F	21	19.4	19.3	1.5	17.0	21.8
56	16357	206.5	F	9,559	15.8	16.3	2.5	8.5	29.1
57	16358	244.0	F	10,214	15.8	15.4	3.4	1.8	28.5
58	16359	200.0	F	11,862	22.4	22.3	5.1	8.5	35.8
59	16360	187.0	M	7,003	27.9	26.5	4.9	3.0	37.6
60	16361	165.0	M	15,620	26.7	25.6	4.6	8.5	32.8
61	16362	163.0	F	9,409	26.1	22.7	6.5	3.0	35.2
62	16363	162.5	M	2,384	17.0	16.8	2.3	8.5	26.7
63	16364	178.0	M	10,282	23.0	22.3	3.0	2.4	32.1
64	16365	179.5	M	5,268	15.8	17.9	5.1	4.9	30.9
65	16366	237.4	F	11,586	17.6	17.7	4.1	4.2	31.5
66	16367	247.5	F	10,993	17.6	16.4	3.2	3.6	29.7

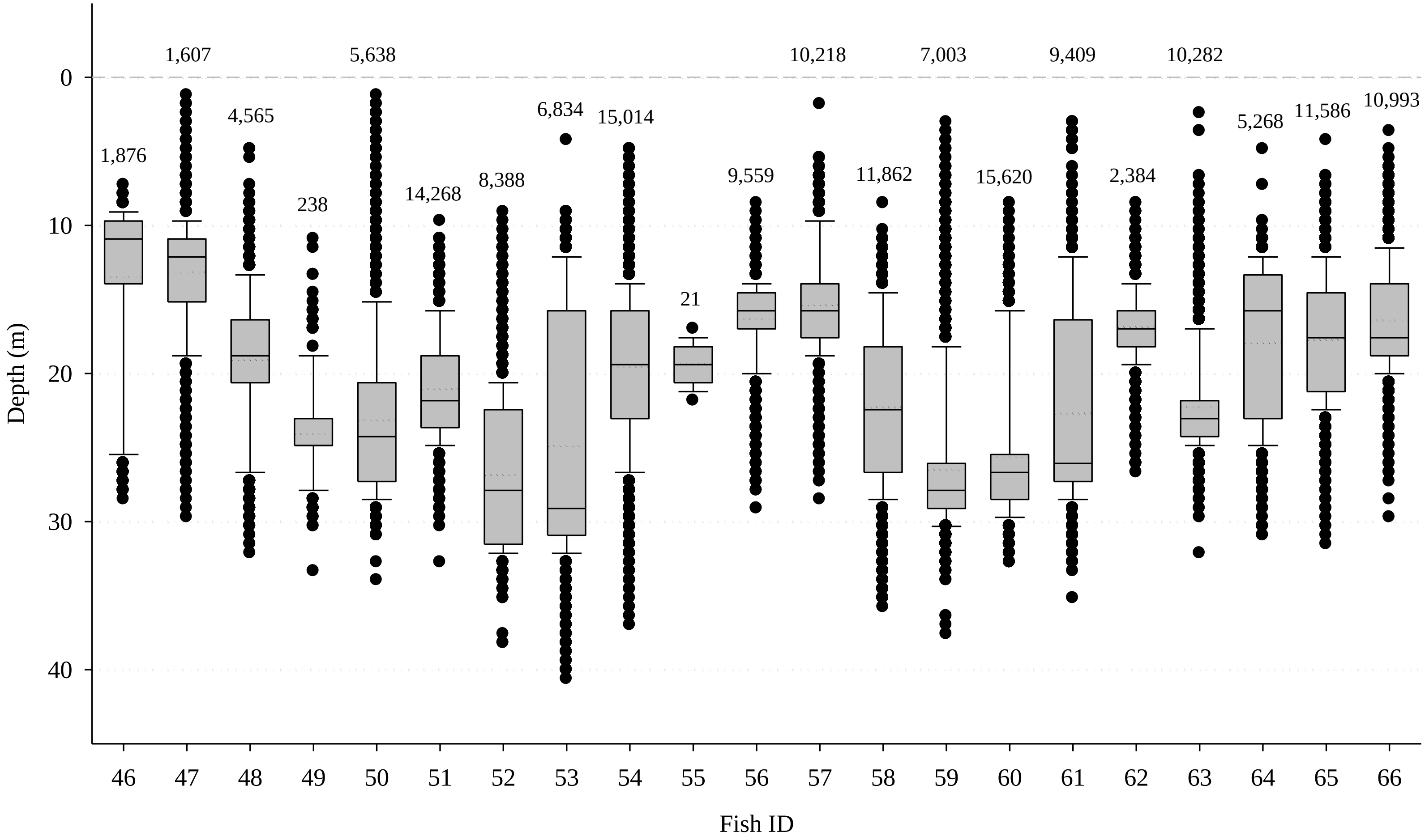

Figure 10. Box blots of depth (m) for each white sturgeon that possessed an acoustic tag with a pressure sensor and was positioned within the VPS array. Boxes indicate the 25th and 75th percentiles, whiskers indicate the 10th and 90th percentiles, the solid line is the median, the dotted line is the mean, the solid dots represent outliers, and the numbers indicate the sample sizes.

Table 11. Descriptive statistics of depth (m) for the 21 white sturgeon affixed with acoustic transmitters with pressure sensors and positioned within the VPS between 11 June 2009 and 01 June 2010. In order to account for pseudoreplication, depth measures within each strata were considered subsamples and the mean of the subsamples for each individual fish were considered the sample values (Hurlbert 1984).

Month/Season	n	Median	Mean	SD	Min	Max
Jun-09	13	11.8	12.8	4.0	8.6	23.7
Jul-09	18	16.7	17.2	3.9	12.3	26.5
Aug-09	15	16.5	17.7	4.3	12.5	25.1
Summer	20	16.3	17.0	4.2	12.5	25.7
Sep-09	16	15.6	15.8	2.7	12.0	21.2
Oct-09	15	18.7	19.9	4.2	14.5	26.1
Nov-09	15	20.9	21.7	5.3	13.8	30.2
Fall	18	17.4	18.1	3.7	12.1	24.1
Dec-09	16	22.9	23.0	6.0	13.9	33.6
Jan-10	16	25.1	24.1	5.8	14.8	34.2
Feb-10	16	25.5	24.6	5.1	15.7	32.0
Winter	16	24.5	24.1	5.3	15.5	31.8
Mar-10	16	23.2	23.9	4.9	15.1	31.0
Apr-10	16	23.0	22.6	4.2	14.9	29.0
May-10	19	18.3	17.2	3.4	10.6	21.9
Jun-10	16	17.4	16.6	4.2	8.8	22.1
Spring	19	20.9	21.2	4.3	13.1	27.7
Total	21	19.6	20.2	4.2	13.2	26.8

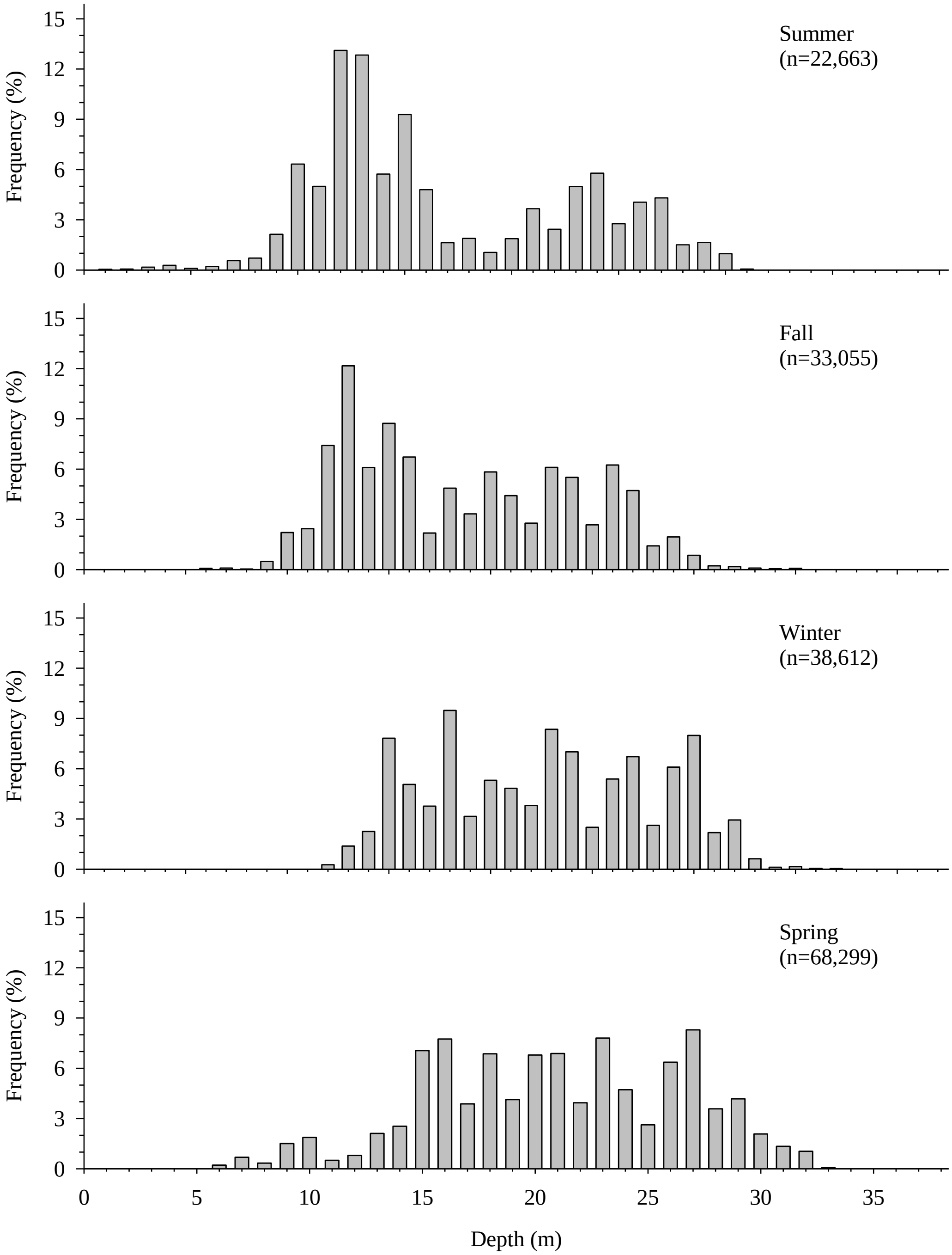

Figure 11. Frequency distributions of seasonal depth (m) measurements for the 21 white sturgeon with acoustic transmitters with pressure sensors and positioned within the VPS between 11 June 2009 and 01 June 2010.

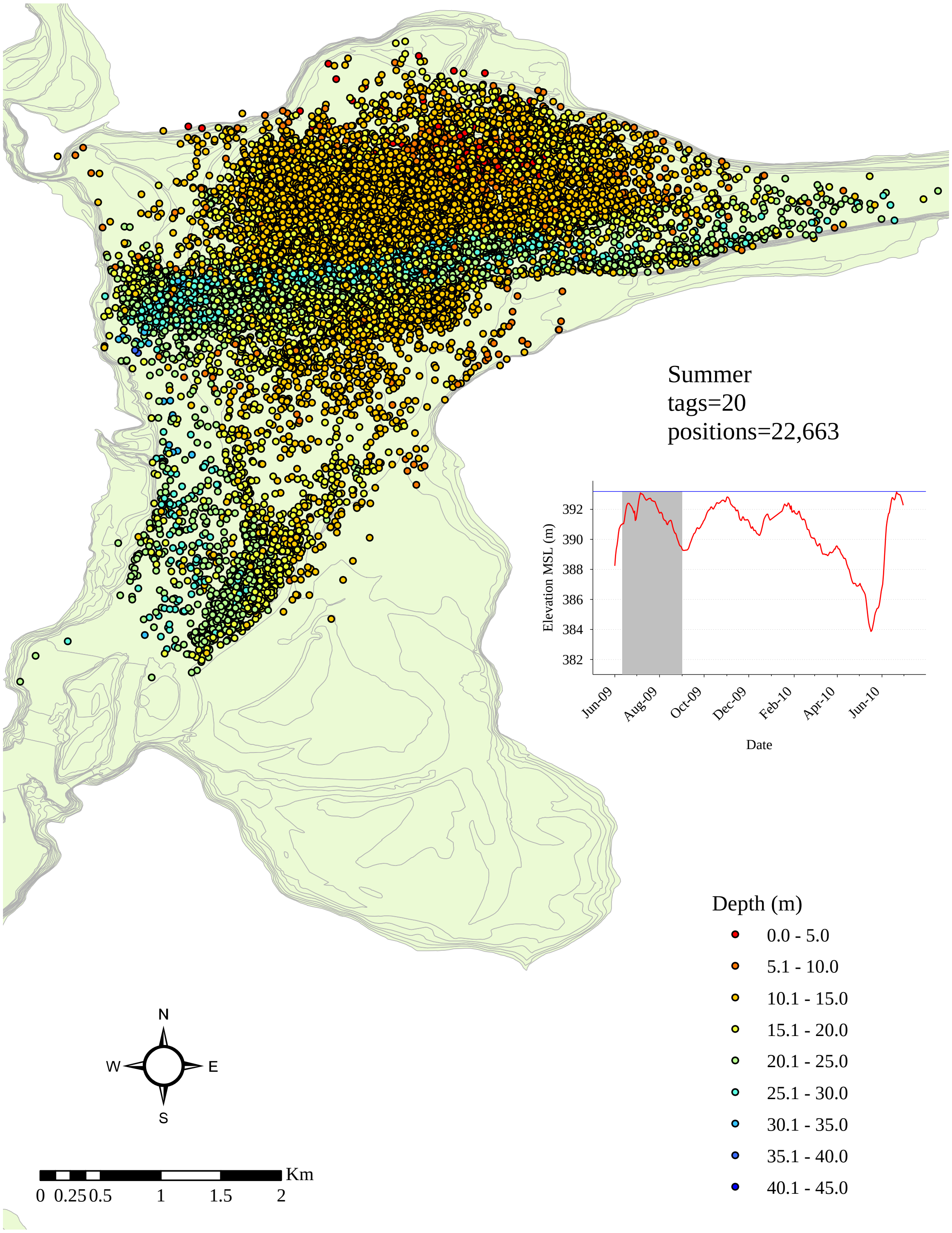

Figure 12. White sturgeon positions and associated depth (m) measurements within the VPS array during the summer. The bathymetric contours (gray lines) are in 3.0 m (10 ft) increments from the full pool elevation of 393.2 m (1,290 ft) above mean sea level (MSL) down to 371.9 m (1,220 ft) above MSL. The inset graph indicates reservoir surface elevation (m; red line) during the summer (gray box) relative to the full pool elevation (blue line).

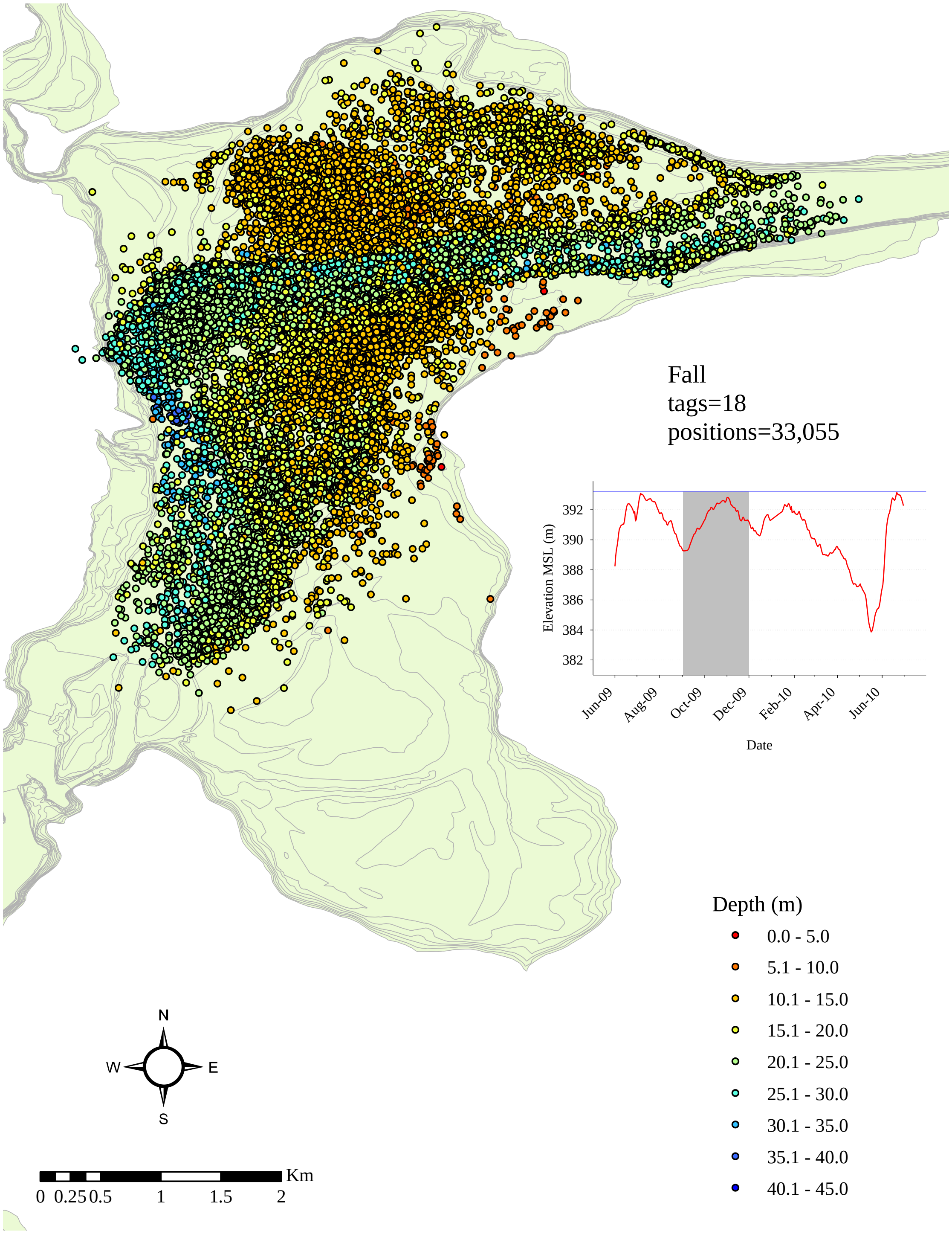

Figure 13. White sturgeon positions and associated depth (m) measurements within the VPS array during the fall. The bathymetric contours (gray lines) are in 3.0 m (10 ft) increments from the full pool elevation of 393.2 m (1,290 ft) above mean sea level (MSL) down to 371.9 m (1,220 ft) above MSL. The inset graph indicates reservoir surface elevation (m; red line) during the fall (gray box) relative to the full pool elevation (blue line).

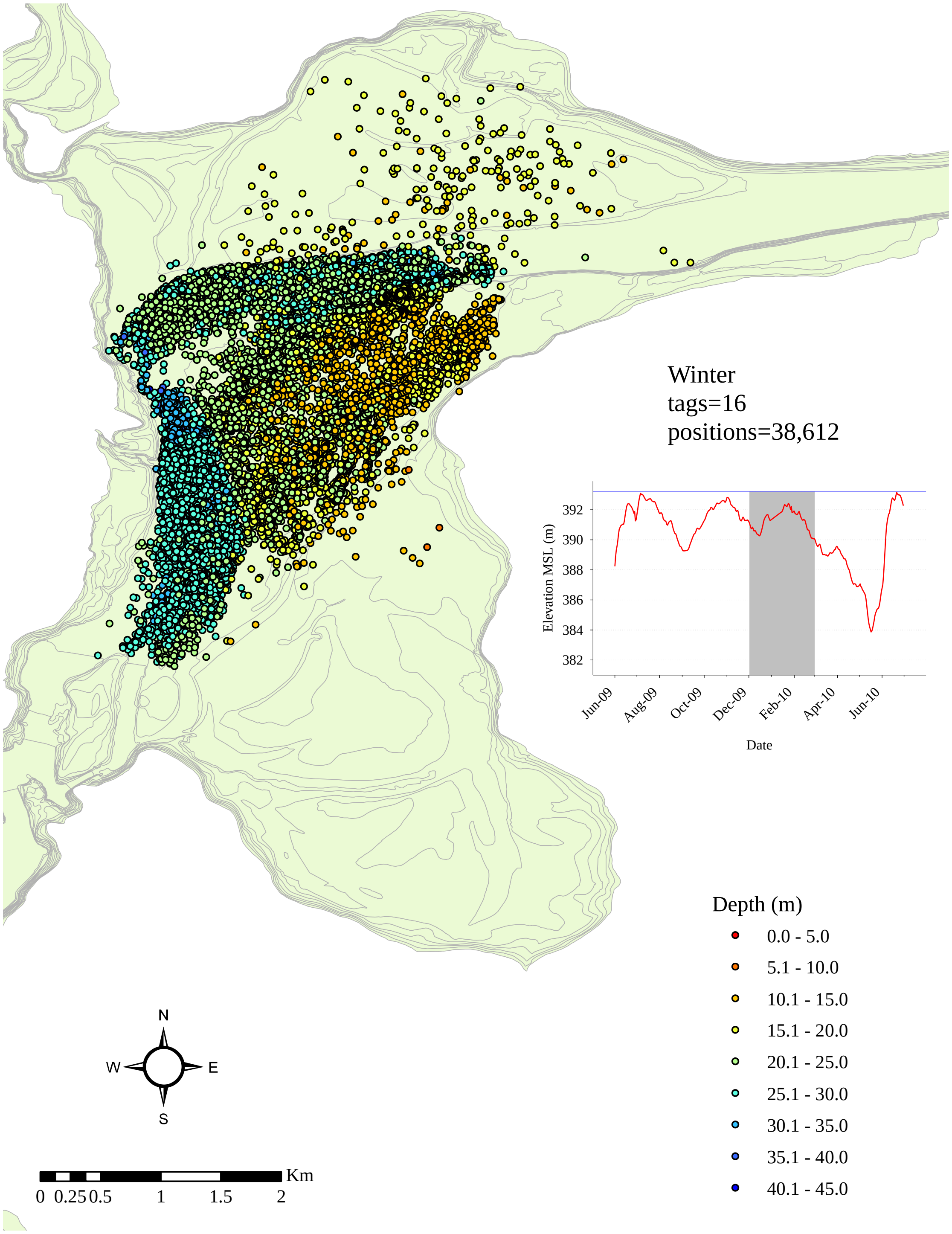

Figure 14. White sturgeon positions and associated depth (m) measurements within the VPS array during the winter. The bathymetric contours (gray lines) are in 3.0 m (10 ft) increments from the full pool elevation of 393.2 m (1,290 ft) above mean sea level (MSL) down to 371.9 m (1,220 ft) above MSL. The inset graph indicates reservoir surface elevation (m; red line) during the winter (gray box) relative to the full pool elevation (blue line).

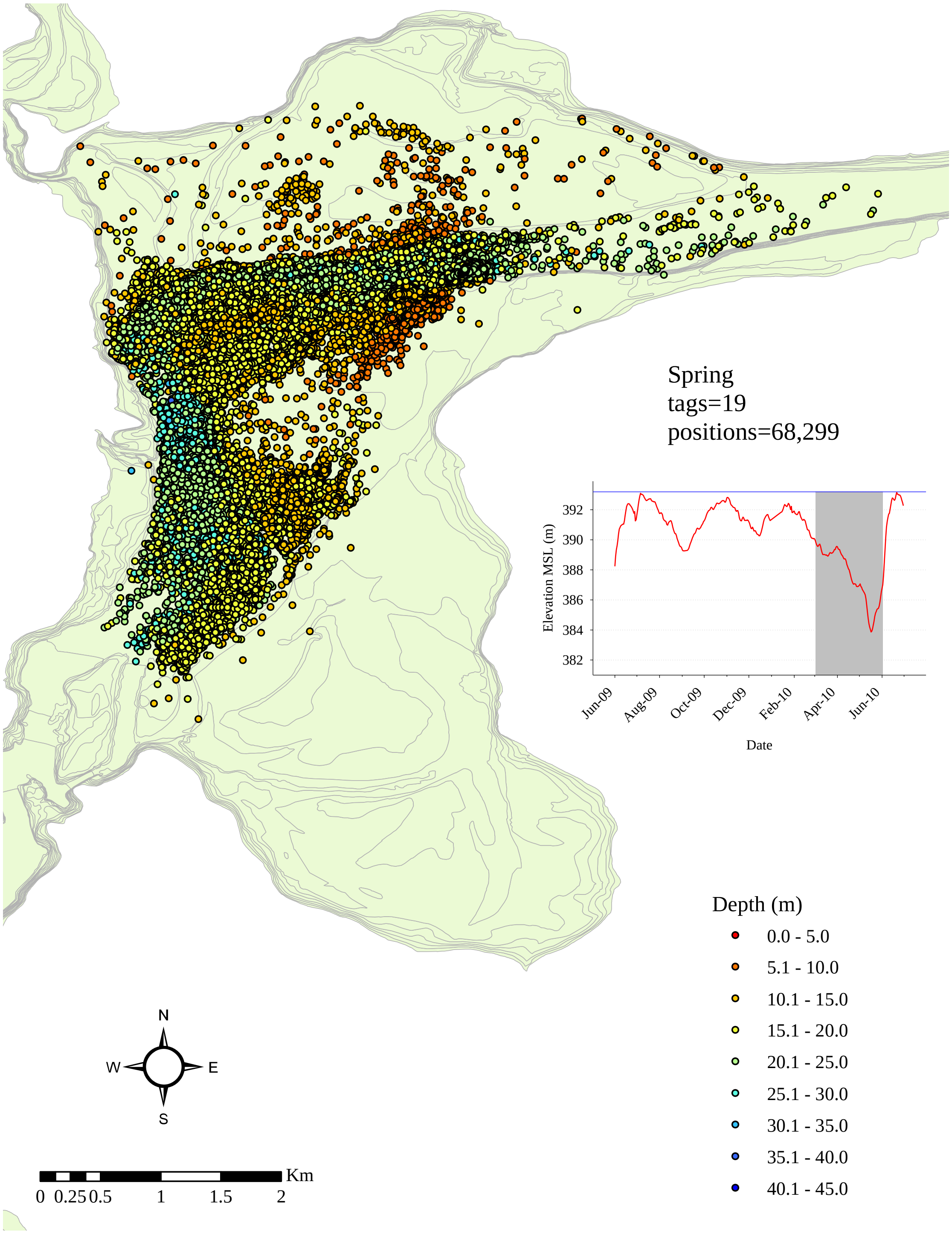

Figure 15. White sturgeon positions and associated depth (m) measurements within the VPS array during the spring. The bathymetric contours (gray lines) are in 3.0 m (10 ft) increments from the full pool elevation of 393.2 m (1,290 ft) above mean sea level (MSL) down to 371.9 m (1,220 ft) above MSL. The inset graph indicates reservoir surface elevation (m; red line) during the spring (gray box) relative to the full pool elevation (blue line).

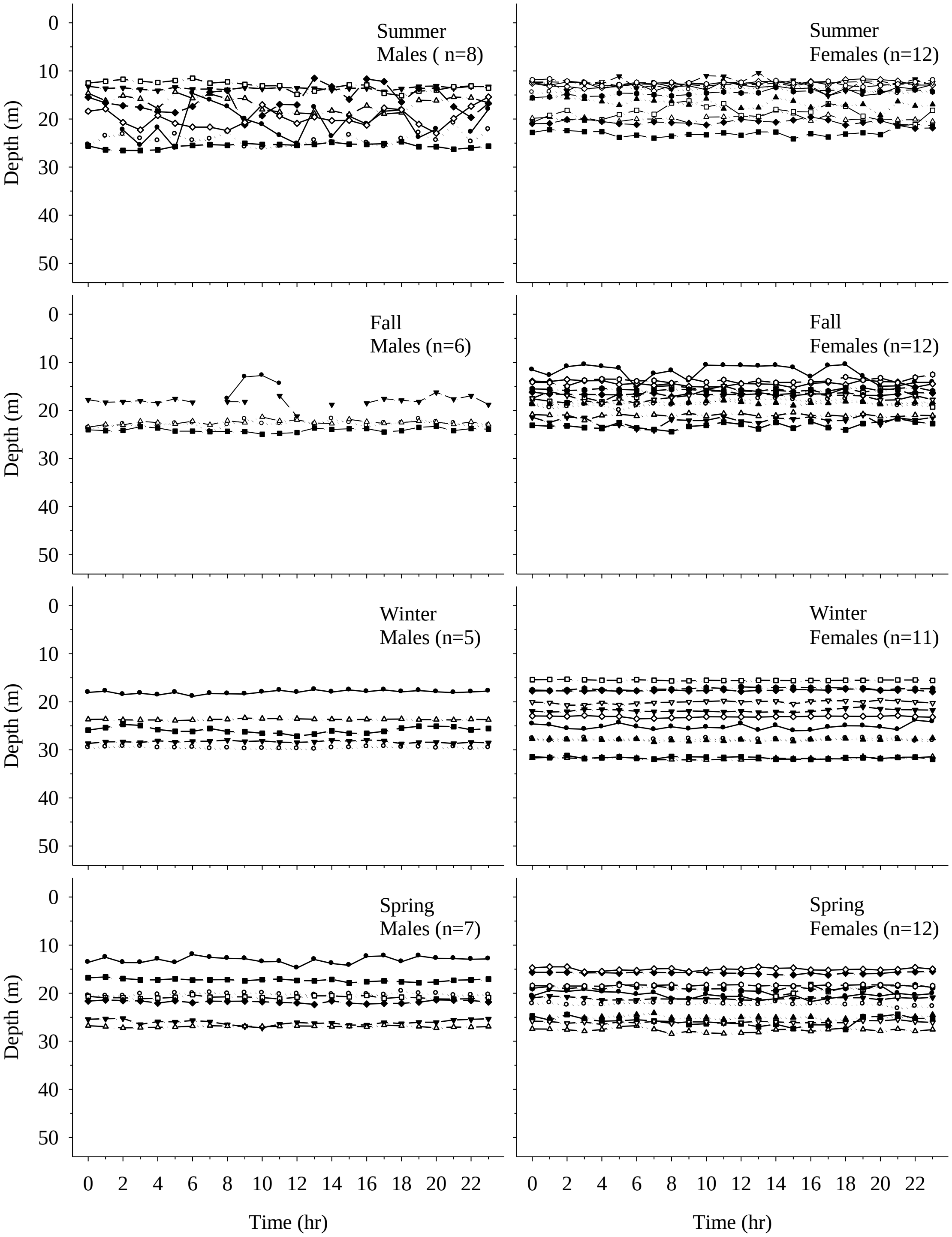

Figure 16. Mean depth (m) by hour of the day, gender, and season for each individual white sturgeon that was affixed with an acoustic transmitter with a pressure sensor and was positioned within the VPS between 11 June 2009 and 01 June 2010. Each symbol represents a different individual in each graph.

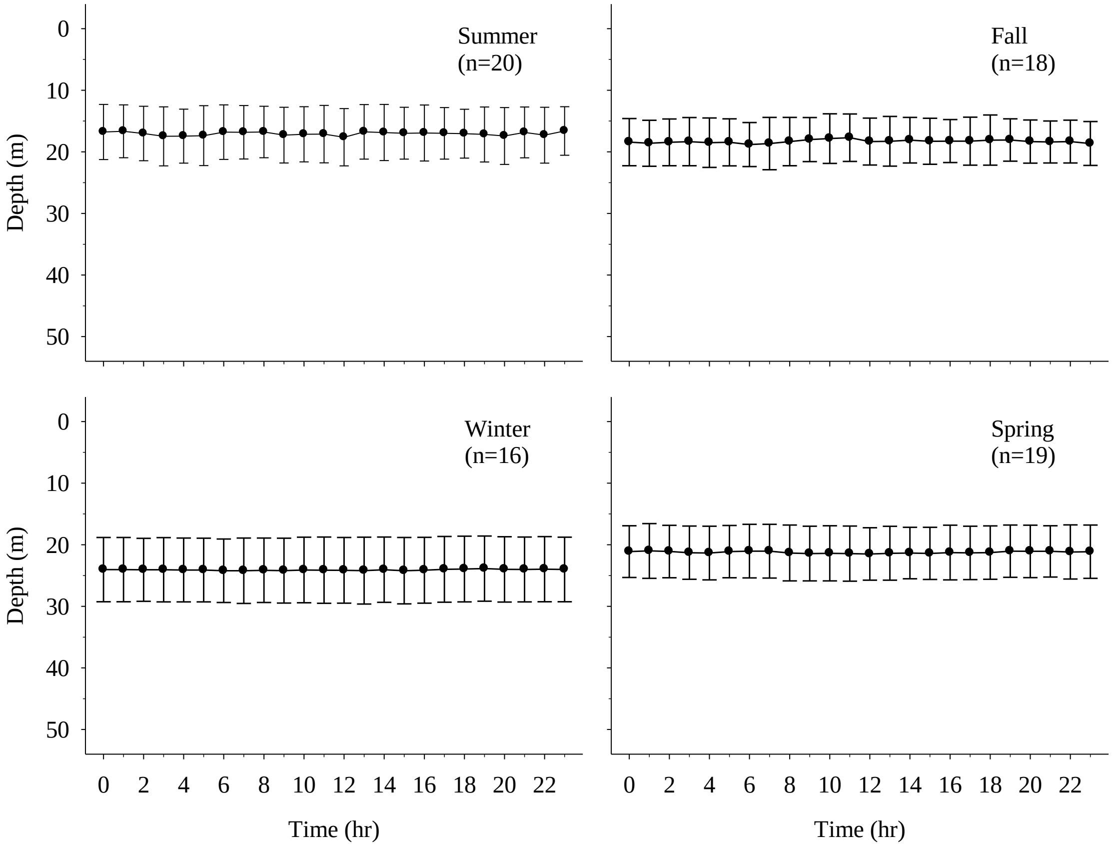

Figure 17. Mean depth (m) and standard deviation by hour of the day and season of white sturgeon with affixed with acoustic transmitters with pressure sensors and positioned within the VPS between 11 June 2009 and 01 June 2010. In order to account for pseudoreplication, depth measures within each strata were considered subsamples and the mean of the subsamples for each individual fish were considered the sample values (Hurlbert 1984).

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Appendix A.

Detailed Methods of Statistical Analysis for Position Probabilities and Occupancy

Three of the objectives were to estimate sturgeon occupancy inside and outside the river channel, by season; and to identify areas of "high occupancy" within the array (e.g. movement and migration corridors, congregation areas). It was suspected, however, that the probability of positioning a sturgeon within the acoustic array was less than 1.0, and that the probability varied spatially and seasonally. Before using positions to estimate occupancy, we examined the validity of the assumption of uniform position probabilities of 1.0 across the array and between seasons. We identified tenable position probability models and incorporated them into occupancy estimates across the array.

We estimated the proportion of transmitter pings that resulted in positions, as a function of position within the array and tag power. The proportion was interpreted as a measure of the array's ability to convert transmitter pings into positions. Specifically, we estimated the probability of positioning a fish, given a ping was transmitted. We interpreted this estimate as the probability of positioning a fish, given it was present.

We estimated the proportion of transmitter pings that resulted in positions by defining an "encounter history", a period of time that included positioned and un-positioned pings. All encounter histories began and ended with positions so we could associate them within geographic boundaries. The temporal limit of the encounter history was defined by transmitter type because each type had different ping delays. We suspected the variance of position probability would be positively related to the distance each fish traveled during an encounter history, therefore we limited interval length so each transmitter was expected to deliver 5 pings per encounter history.

For each season, we estimated the probability of position, given presence, using logistic regression. The binary response was position/non-position given presence of fish during an encounter history (*y*=0,1). All encounter histories began with a position, so to model the probability of position given presence, we excluded the initial position in each encounter history from the response vector. We modeled the effect of tag type and fish position within the array on probability of position. Since transmitter signal power varied with tag type, we expected to observe different position probabilities for each tag type.

The effect of fish position within the array was modeled by first generating a spatial grid that included all positions made by the acoustic array. Encounter histories were then assigned to a grid cell within the array. Since we could not assign a grid cell to un-positioned pings (*y*=0), we calculated the geometric center (i.e. centroid) of each encounter history using position coordinates. We then assigned a grid cell id to all pings in the encounter history, based on the grid cell location of the centroid.

Grid cell size selection represented a trade-off between maximizing inferential scale and minimizing variance of grid cell effect estimation. A small grid cell size would provide high resolution for spatial inference, but reduce the number of encounter histories per grid cell, increasing sampling error. In addition, as grid cell size is reduced, it is more likely that positions made within an encounter history occur in >1grid cell. We generated a square grid (125 m^2) that contained 2,209 cells. Grid cell sizes less than 125 m^2 resulted in >15% of cells with <10 positions. After choosing the grid size, we omitted encounter histories with positions >65.5 m from the centroid. This filter reduced sampling error associated with estimating grid cell effects and removed the effects of rapidly swimming fish or erroneously positioned fish.

During summer and fall, sturgeon were positioned in >670 different grid cells, so initial logistic regression models contained over 650 grid cell effect estimates. Final logistic regression models were formed by grouping grid cells after comparing position odds for each grid cell to the average odds for all grid cells. The comparison allowed us to identify cells with greater than average, and less than average, position probabilities. We identified cells with odds ratios >1.35 as having "above average" position probabilities, and those with odds <0.74 as having "below average" position probabilities. We formed 3 groups on the basis of these odds ratios (below average, average, and above average).

We incorporated position probabilities into estimates of grid cell use, by tag type, for all positions made during the study. Given that there were g cells covering the detection array, we wanted to estimate the proportion of use for each cell and find a confidence interval about the estimate. Let $C_1, C_2, \ldots, C_g$ be the counts for each of the g cells. $(C_1, C_2, \ldots, C_g) \sim \text{Poisson}(\lambda_1, \lambda_2, \ldots, \lambda_g)$. That is, counts in cells are Poisson processes with parameters $\lambda_1, \lambda_2, \ldots, \lambda_g$. In a finite time interval, T, there were N fish observed in the g cells, i.e., $N = \sum_{i=1}^{g} C_i$. If we condition on N, then $(C_1, C_2, \ldots, C_g)|N \sim$ multinomial$(N, \varphi_1, \varphi_2, \ldots, \varphi_g)$, where $\varphi_I = \lambda_i / \sum \lambda_k$.

In our case, we did not observe C_i directly due to varying detectability among the cells. What we observed instead was $(n_1, n_2, \ldots, n_g)$ where the distribution of n_i given that there were C_i fish occurrences in the i^{th} cell was binomial. That is, $n_i|C_i \sim$ binomial (C_i, π_i). The usual estimator of π_i is n_i/C_i. We didn't know C_i, but from logistic regression we estimated of π_i, $\hat{\pi}_i$ say. Setting $\hat{\pi}_i = n_i/C_i$ we get an estimate of C_i as $\hat{C}_i = \dfrac{n_i}{\hat{\pi}_i}$. We calculated an unbiased estimate of C_i as $\hat{C}_i = n_i\hat{\theta}_i$ (Steinhorst and Samuel 1989, p. 421) instead of $\hat{C}_i = \dfrac{n_i}{\hat{\pi}_i}$. Now having $(\hat{C}_1, \hat{C}_2, \ldots, \hat{C}_g)$, we obtained $\hat{\varphi}_i = \dfrac{\hat{C}_i}{\hat{N}}$ where $\hat{N} = \sum_{k=1}^{g} \hat{C}_k$. That is, the estimated proportions $(\hat{\varphi}_1, \hat{\varphi}_2, \ldots, \hat{\varphi}_g)$ were found by dividing the detectability corrected counts by the estimated total number of fish observances, $\hat{N}$, giving us $\hat{\varphi}_i = \dfrac{\hat{C}_i}{\hat{N}} = \dfrac{n_i\hat{\theta}_i}{\hat{N}}$.

We conditioned our estimate on $\hat{N}$, to find the variance of $\hat{\varphi}_i$ as $\dfrac{1}{\hat{N}^2}\operatorname{var}(\hat{C}_i) = \dfrac{1}{\hat{N}^2}\operatorname{var}(n_i\hat{\theta}_i)$. The exact variance of a product is given by Goodman (1960) and its estimate is $s^2_{\hat{C}_i} = \hat{\theta}_i^2 s^2_{n_i} + n_i^2 s^2_{\hat{\theta}_i} - s^2_{n_i} s^2_{\hat{\theta}_i}$, where $s^2_{n_i} = \hat{C}_i\hat{\pi}_i(1-\hat{\pi}_i)$ and $s^2_{\hat{\theta}_i} = e^{-2\underline{x}_i'\underline{\hat{\beta}} - 2\underline{x}_i'\hat{\Sigma}\underline{x}_i}(e^{\underline{x}_i'\hat{\Sigma}\underline{x}_i} - 1)$ (from Steinhorst and Samuel 1989, p. 421). Finally, we obtained the confidence interval as $\hat{\varphi}_i \pm 2s_{\hat{\varphi}_i} = \hat{\varphi}_i \pm 2\dfrac{s_{\hat{C}_i}}{\hat{N}}$. Logistic regression modeling and interval estimation were performed using SAS (PROC LOGISTIC, PROC IML, DATA STEP; SAS Institute 2003).

We estimated $\hat{\varphi}_i$ and 95% confidence intervals for each grid cell using the above estimators. We estimated seasonal occupancy in and out of the original river channel by assigning each grid cell to a river channel category, then estimating $\hat{\varphi}_i$ and 95% confidence intervals for each of the 2 categories. Cells with any portion inside (below) the 372 m bathymetric contour were categorized as within the original river channel. We compared occupancy estimates among grid cells using image plots (function *image.plot()*; R Development Core Team 2010). We identified high occupancy areas by isolating grid cells with the greatest $\hat{\varphi}_i$ ‘s and non-overlapping 95% confidence intervals.

Appendix A - Literature Cited

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Appendix B.

Table B-1. Specific information on each white sturgeon positioned within the VPS array between 11 June 2009 and 01 June 2010. FL=fork length at the time of tagging; Sex codes: F=female, M=male, U=undetermined; Deployment date=the date the fish was released with the transmitter; rkm=river kilometer of the release (Columbia River).

Fish ID	Tag Family	Tag Code	FL (cm)	Sex	Origin	Deployment Date	rkm	No. Positions
1	V13-1L	5069	77.3	U	hatchery	4-Jun-2008	1,140.6	442
2	V13-1L	5070	70.5	U	hatchery	4-Jun-2008	1,140.6	21
3	V13-1L	5071	80.2	U	hatchery	4-Jun-2008	1,140.6	2,579
4	V13-1L	5072	98.3	U	hatchery	4-Jun-2008	1,140.6	916
5	V13-1L	5073	110.6	U	wild	4-Jun-2008	1,140.6	1,533
6	V13-1L	5074	97.9	U	hatchery	4-Jun-2008	1,140.6	3,627
7	V13-1L	5075	101.4	U	wild	4-Jun-2008	1,140.6	9,357
8	V13-1L	5076	96.5	U	hatchery	4-Jun-2008	1,140.6	1,202
9	V13-1L	5077	74.2	U	hatchery	4-Jun-2008	1,140.6	405
10	V13-1L	5078	92.7	U	hatchery	4-Jun-2008	1,140.6	20,659
11	V13-1L	5079	95.7	U	hatchery	4-Jun-2008	1,140.6	4,322
12	V13-1L	5080	95.0	U	hatchery	4-Jun-2008	1,140.4	472
13	V13-1L	5082	118.4	U	wild	17-Jun-2008	1,140.5	662
14	V13-1L	5083	87.1	U	hatchery	5-Jun-2008	1,173.3	2,527
15	V13-1L	5087	114.6	U	wild	17-Jun-2008	1,140.5	33
16	V13-1L	5090	82.5	U	hatchery	10-Jun-2008	1,168.4	3,724
17	V13-1L	5091	118.3	U	wild	17-Jun-2008	1,141.2	149
18	V13-1L	5092	92.8	U	hatchery	19-Jun-2008	1,185.2	5,191
19	V13-1L	5094	154.0	U	wild	28-Apr-2009	1,138.5	53,252
20	V13-1L	5095	141.0	U	wild	28-Apr-2009	1,139.6	43,986
21	V13-1L	5096	197.0	U	wild	29-Apr-2009	1,141.4	1,226
22	V13-1L	5097	117.5	U	wild	29-Apr-2009	1,142.4	5,491
23	V16-6H	5100	137.3	U	wild	19-Aug-2008	1,076.6	38,394
24	V16-6H	5101	218.7	F	wild	21-Aug-2008	1,071.2	8,288
25	V16-6H	5102	200.0	F	wild	21-Aug-2008	1,068.2	11,985
26	V16-6H	5103	211.5	F	wild	28-Apr-2009	1,140.5	108,012
27	V16-6H	5104	159.4	M	wild	30-Apr-2009	1,142.9	67,061
28	V16-6H	5108	214.0	F	wild	4-Sep-2009	1,095.2	141,162
29	V9-2L	5124	35.0	U	hatchery	8-May-2008	1,112.8	1,866
30	V9-2L	5129	37.3	U	hatchery	8-May-2008	1,112.8	8
31	V9-2L	5137	34.0	U	hatchery	8-May-2008	1,112.8	1,775
32	V9-2L	5140	36.1	U	hatchery	8-May-2008	1,019.1	10
33	V9-2L	5142	37.2	U	hatchery	8-May-2008	1,071.6	88
34	V9-2L	5156	36.8	U	hatchery	8-May-2008	1,112.8	10
35	V9-2L	5163	36.0	U	hatchery	8-May-2008	1,019.1	46
36	V9-2L	5170	36.5	U	hatchery	8-May-2008	1,071.6	13
37	V9-2L	5176	36.2	U	hatchery	8-May-2008	1,112.8	717
38	V9-2L	5180	33.5	U	hatchery	8-May-2008	1,071.6	170
39	V9-2L	5184	34.0	U	hatchery	8-May-2008	18.9[a]	2
40	V9-2L	5191	32.1	U	hatchery	8-May-2008	18.9[a]	65
41	V9-2L	5192	35.8	U	hatchery	8-May-2008	1,112.8	2
42	V9-2L	5193	28.3	U	hatchery	8-May-2008	1,019.1	3
43	V9-2L	5194	34.5	U	hatchery	8-May-2008	1,112.8	608
44	V9-2L	5197	36.4	U	hatchery	8-May-2008	1,071.6	12
45	V9-2L	5209	30.7	U	hatchery	8-May-2008	1,071.6	20
46	V16P-4L	16347	216.5	M	wild	28-Apr-2009	1,138.3	3,766
47	V16P-4L	16348	223.0	F	wild	28-Apr-2009	1,138.5	3,228
48	V16P-4L	16349	188.0	F	wild	28-Apr-2009	1,139.6	8,946
49	V16P-4L	16350	196.0	M	wild	28-Apr-2009	1,139.6	469
50	V16P-4L	16351	202.0	F	wild	28-Apr-2009	1,139.6	11,231
51	V16P-4L	16352	198.5	F	wild	28-Apr-2009	1,140.5	28,387
52	V16P-4L	16353	178.0	F	wild	29-Apr-2009	1,140.8	17,261
53	V16P-4L	16354	202.5	F	wild	29-Apr-2009	1,140.8	13,694
54	V16P-4L	16355	181.5	M	wild	29-Apr-2009	1,141.9	29,837
55	V16P-4L	16356	233.0	F	wild	29-Apr-2009	1,142.4	37
56	V16P-4L	16357	206.5	F	wild	29-Apr-2009	1,142.4	19,851
57	V16P-4L	16358	244.0	F	wild	29-Apr-2009	1,142.4	20,074
58	V16P-4L	16359	200.0	F	wild	29-Apr-2009	1,142.6	24,393
59	V16P-4L	16360	187.0	M	wild	29-Apr-2009	1,142.6	14,055
60	V16P-4L	16361	165.0	M	wild	29-Apr-2009	1,142.6	30,949
61	V16P-4L	16362	163.0	F	wild	29-Apr-2009	1,142.6	18,427
62	V16P-4L	16363	162.5	M	wild	29-Apr-2009	1,142.6	4,772
63	V16P-4L	16364	178.0	M	wild	30-Apr-2009	1,140.0	20,952
64	V16P-4L	16365	179.5	M	wild	30-Apr-2009	1,140.0	10,432
65	V16P-4L	16366	237.4	F	wild	30-Apr-2009	1,142.2	23,485
66	V16P-4L	16367	247.5	F	wild	30-Apr-2009	1,142.2	21,265

[a] Released in the Spokane River.

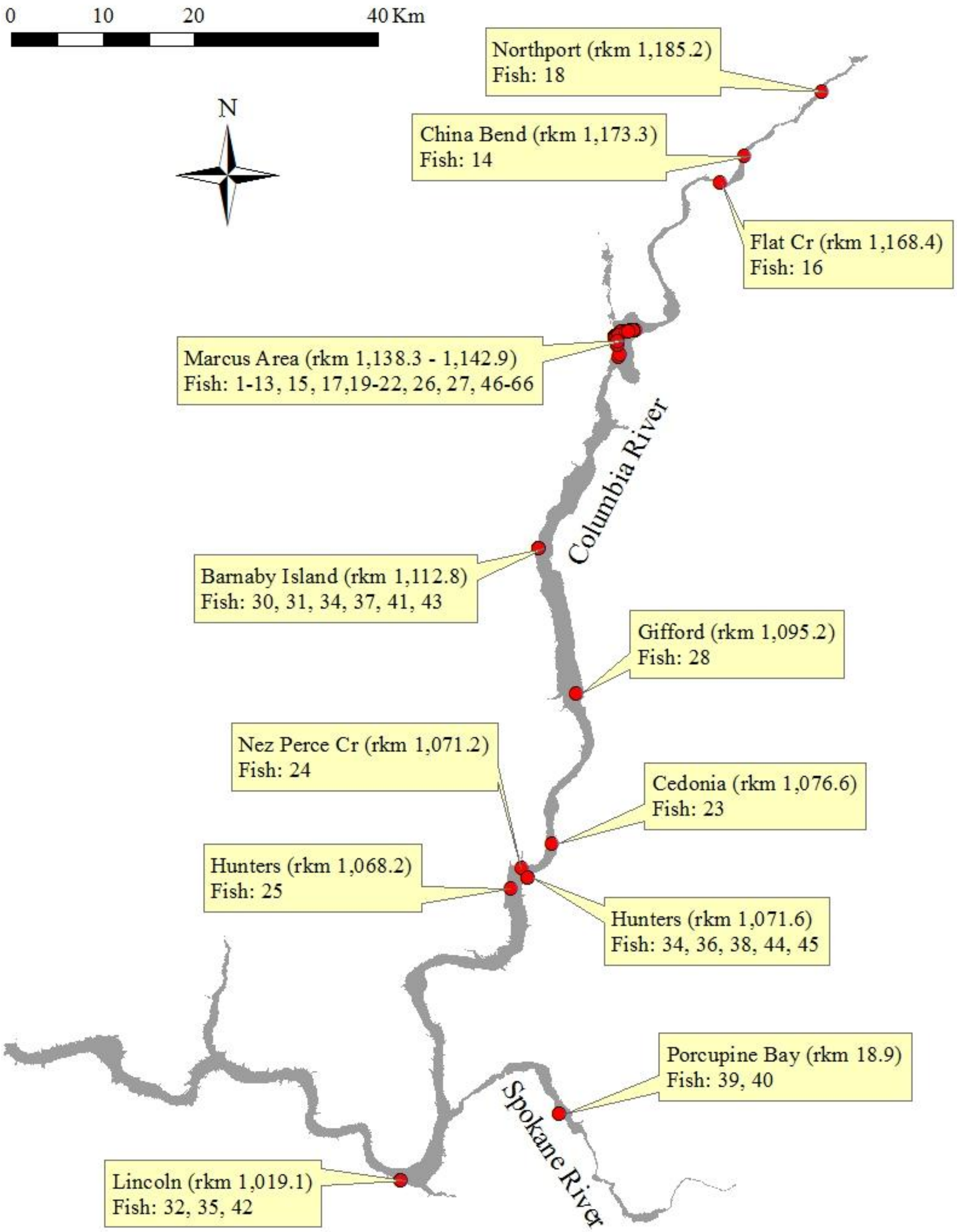


Figure B-1. The release locations of the white sturgeon that were detected within the VR2W Positioning System (VPS) that was deployed in the Marcus area between 11 June 2009 and 01 June 2010.

Appendix C.

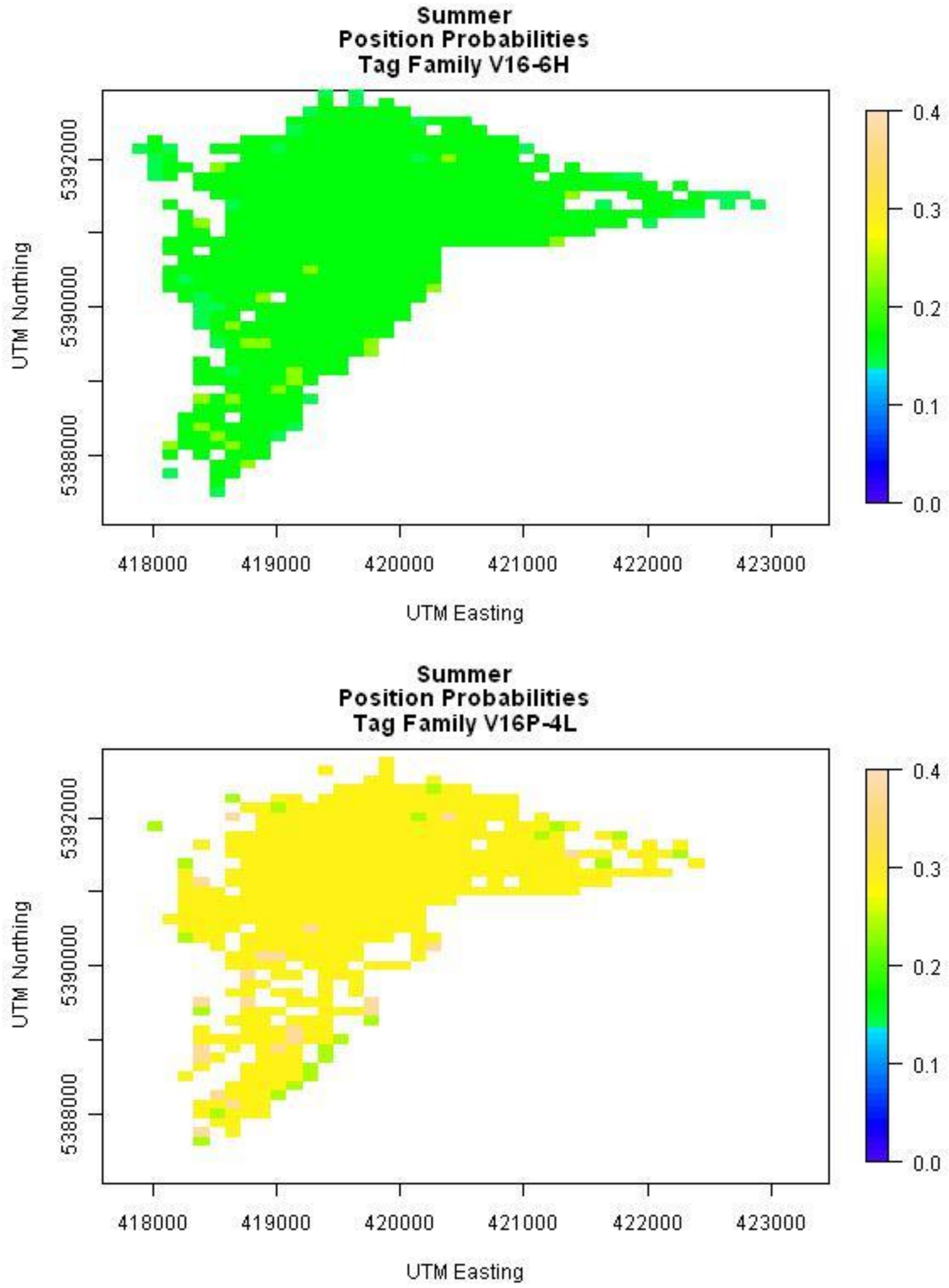


Figure C-1. Summer position probabilities ($\hat{\pi}_i$) predicted by logistic regression for V16-6H and V16P-4L tag families.

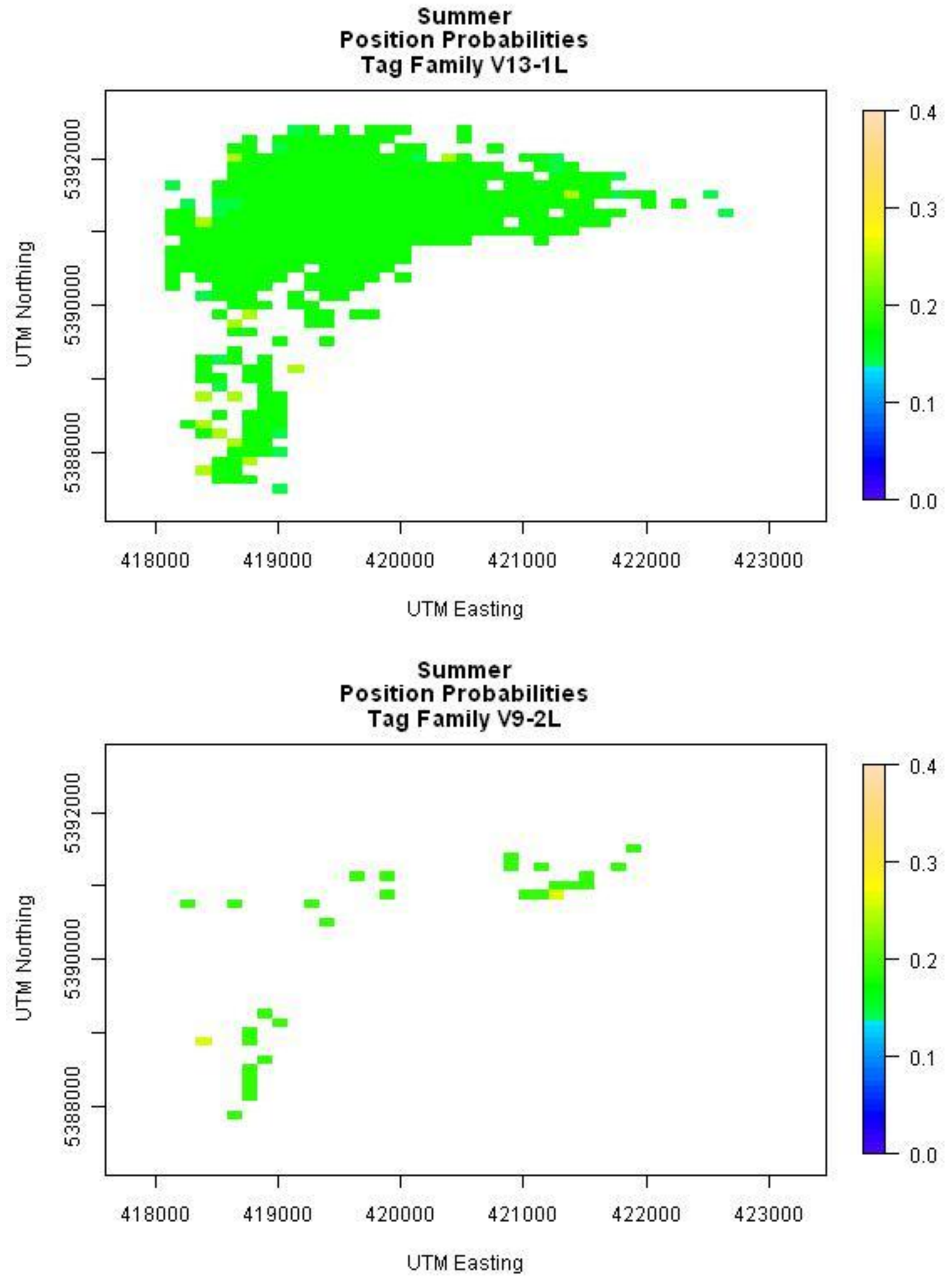


Figure C-2. Summer position probabilities ($\hat{\pi}_i$) predicted by logistic regression for V13-1L and V9-2L tag families.

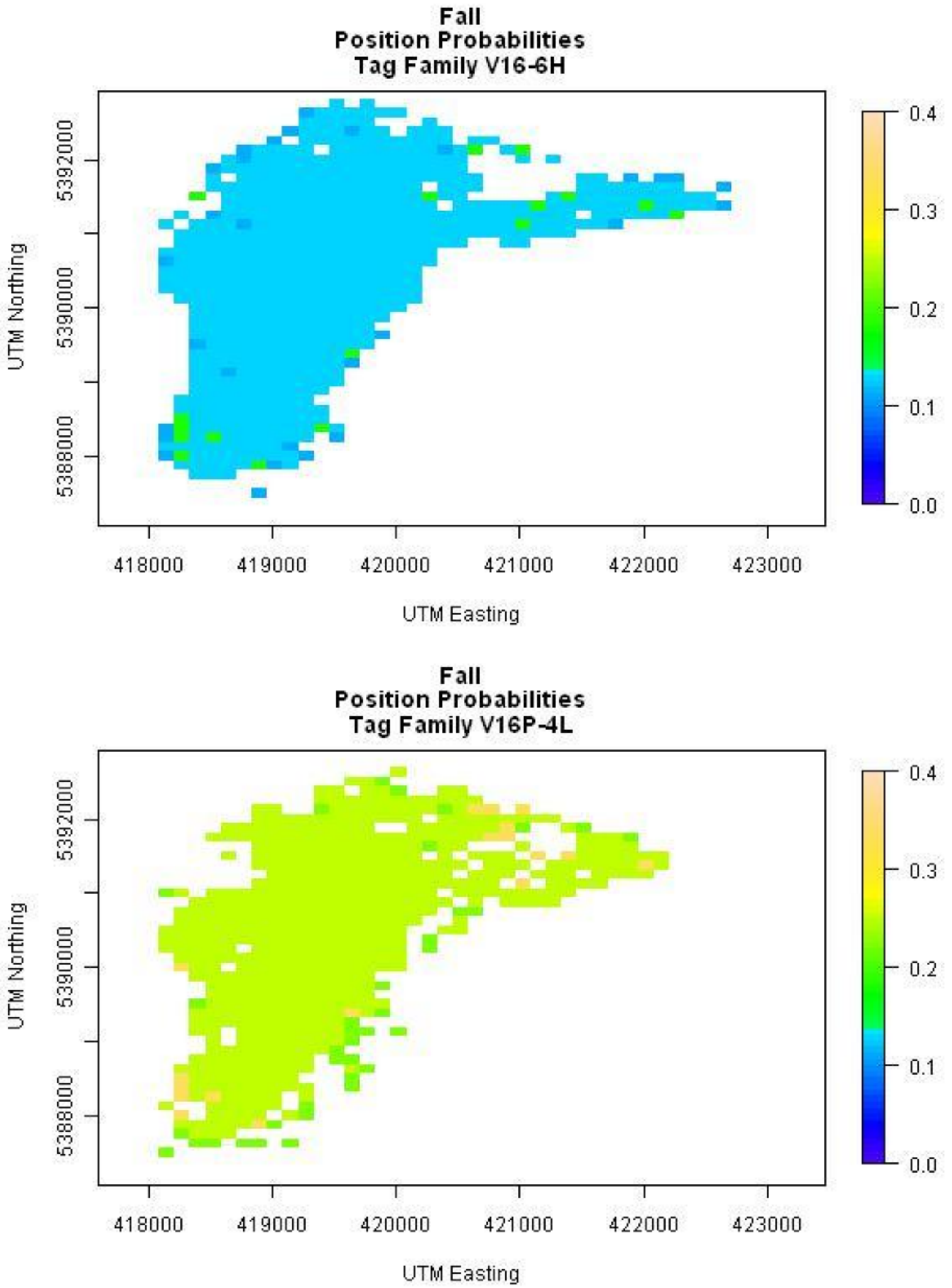
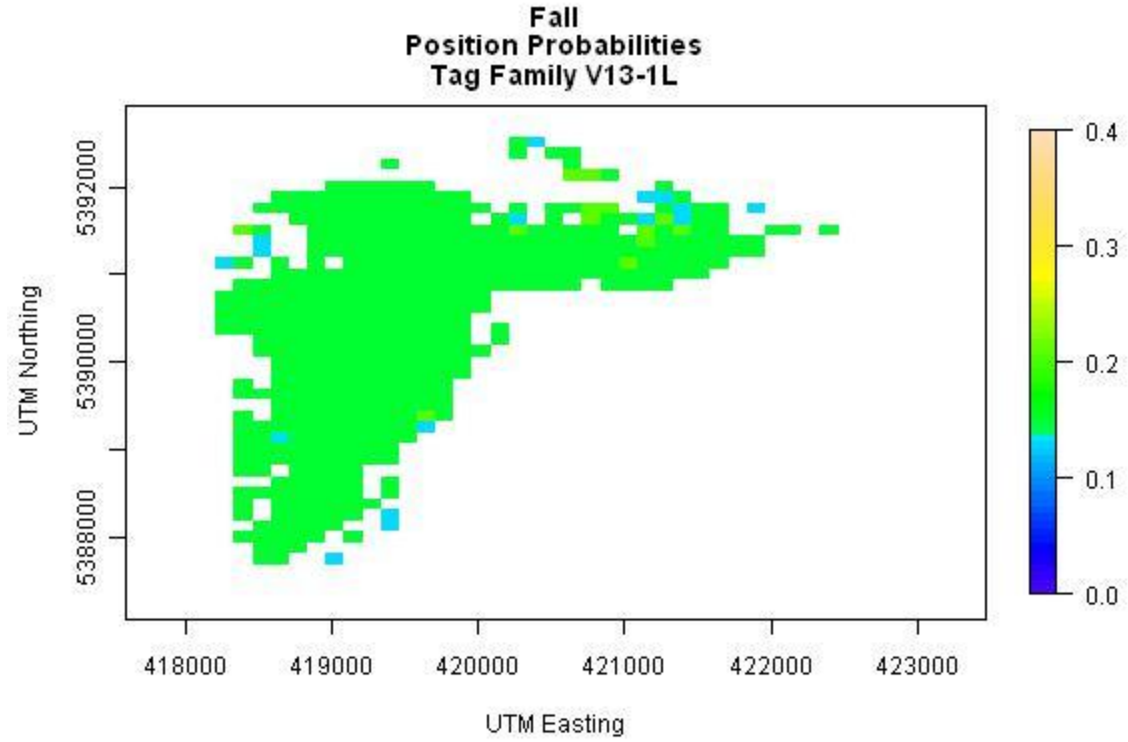


Figure C-3. Fall position probabilities ($\hat{\pi}_i$) predicted by logistic regression for V16-6H and V16P-4L tag families.



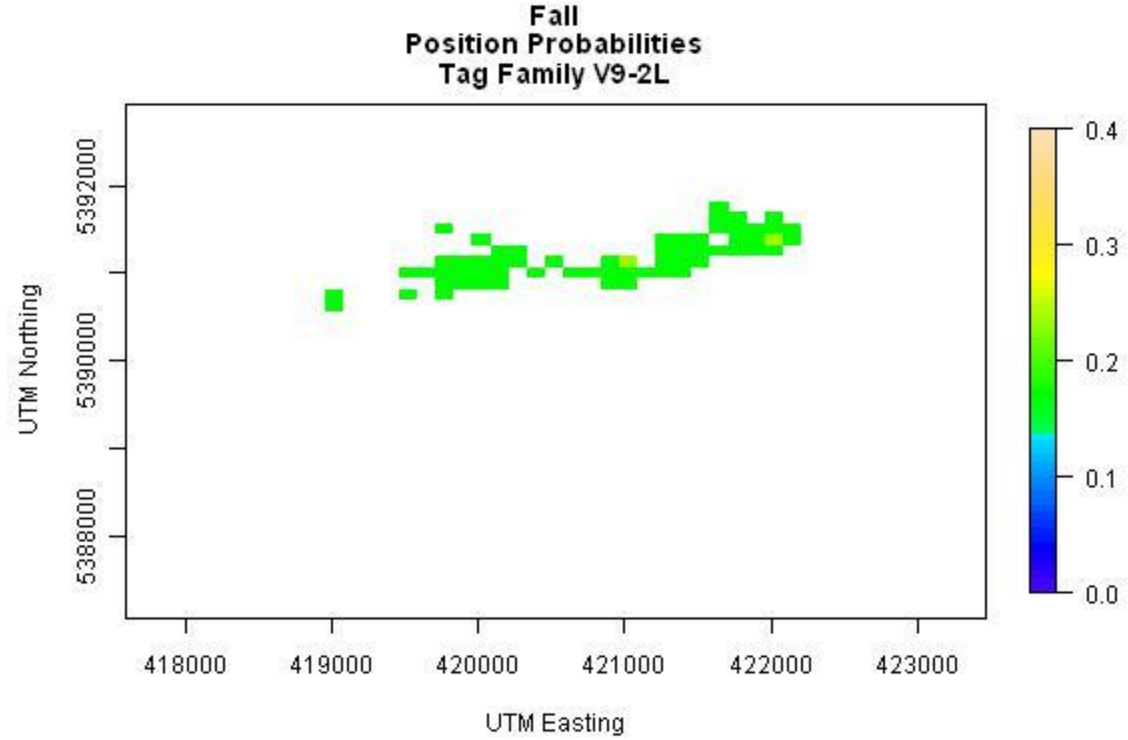


Figure C-4. Fall position probabilities ($\hat{\pi}_i$) predicted by logistic regression for V13-1L and V9-2L tag families.

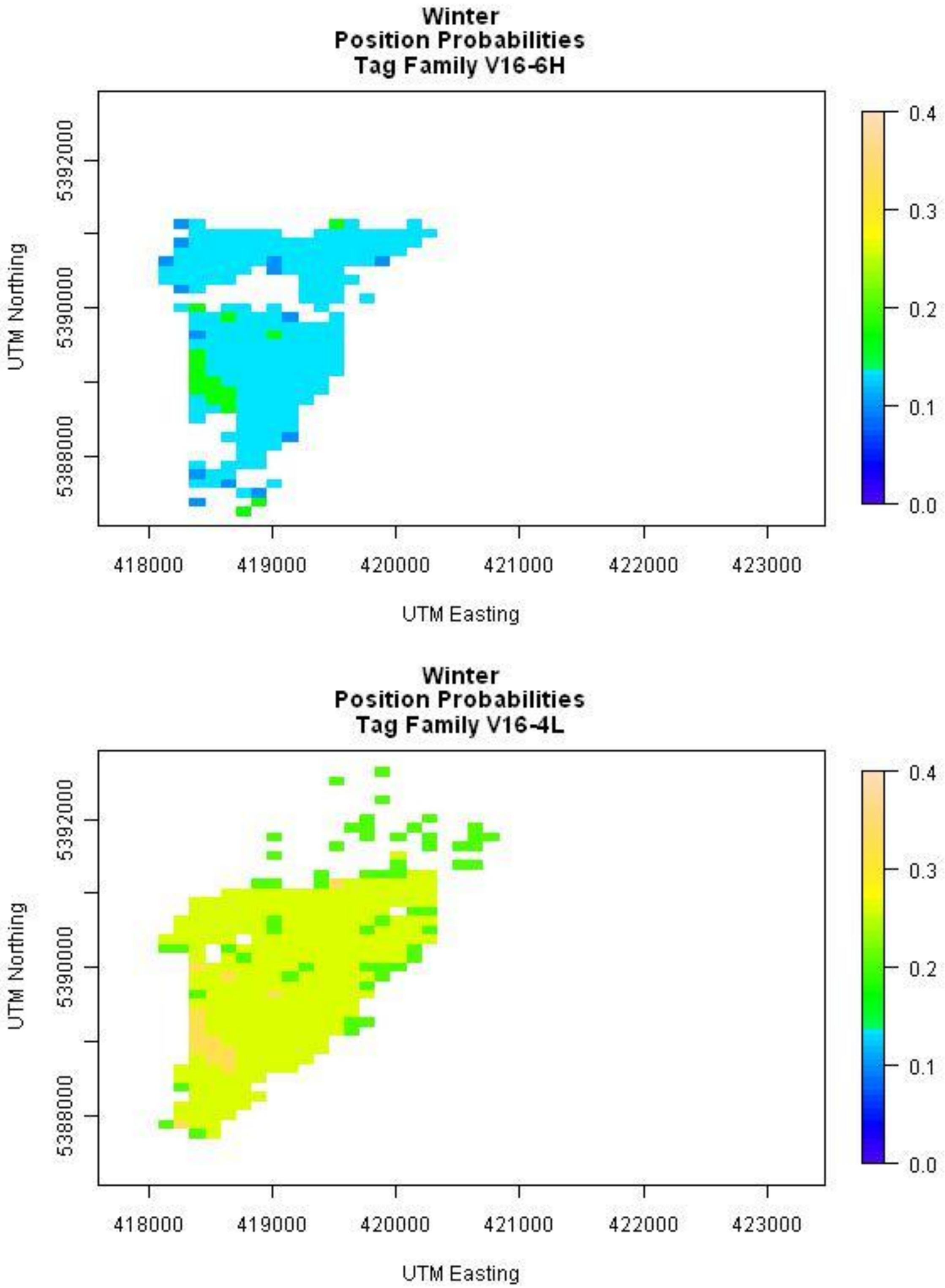
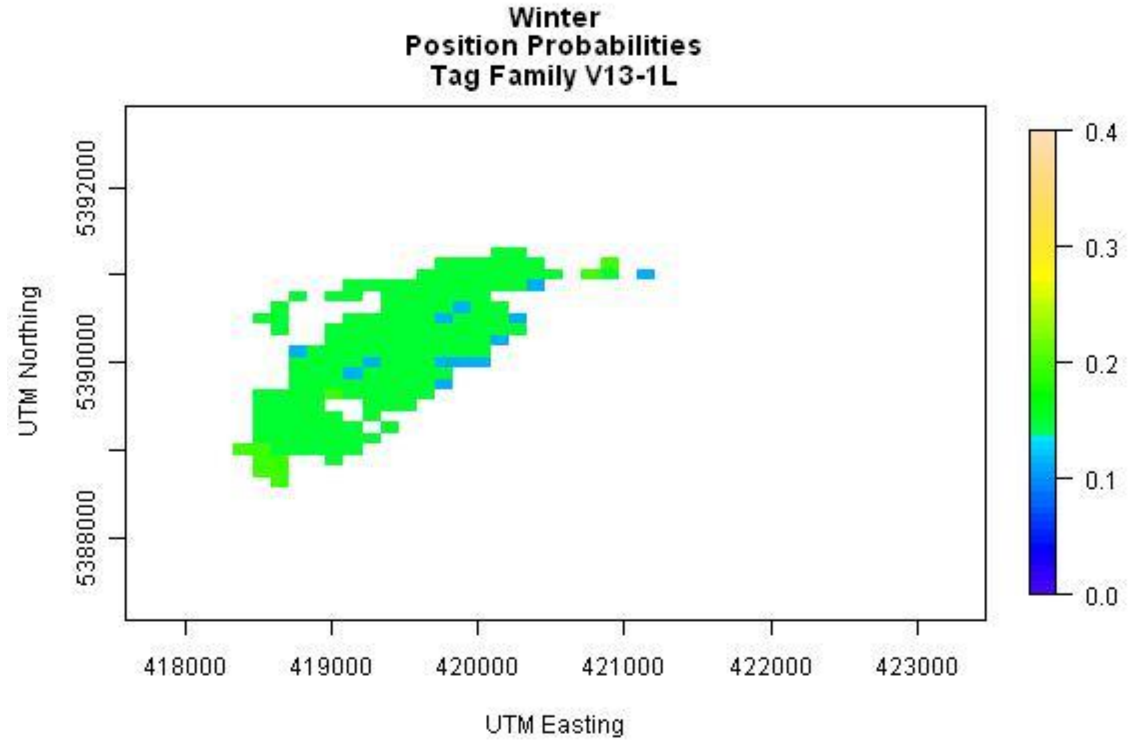


Figure C-5. Winter position probabilities ($\hat{\pi}_i$) predicted by logistic regression for V16-6H and V16P-4L tag families.



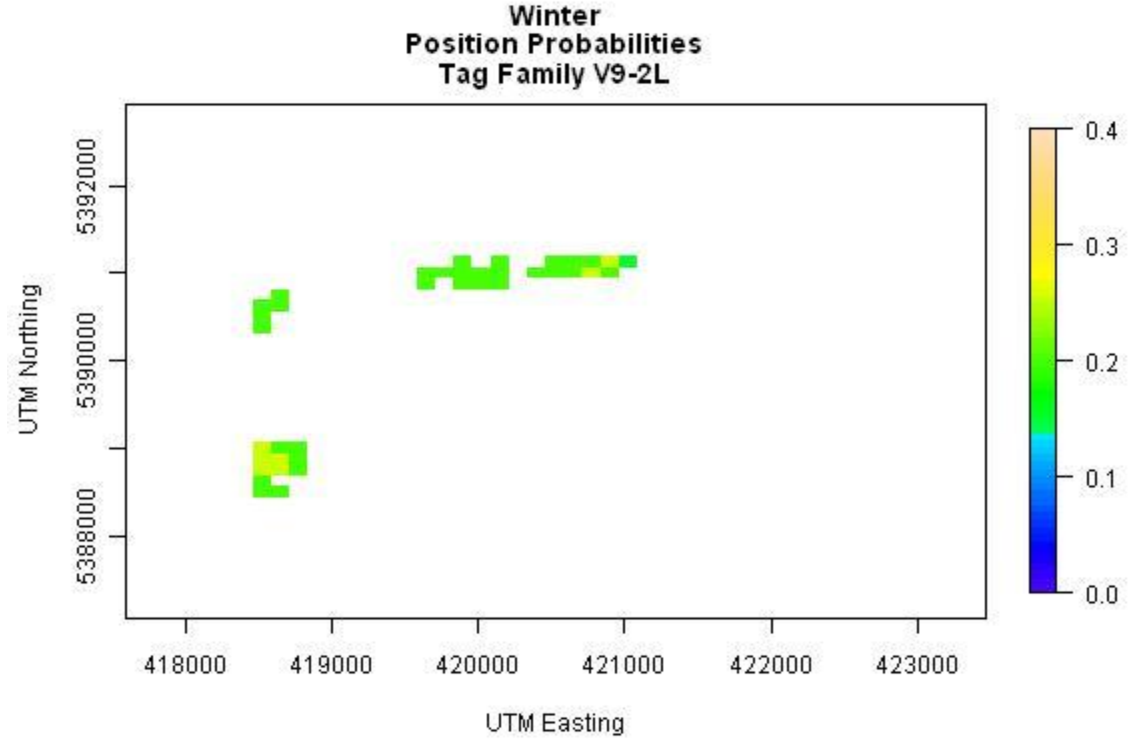


Figure C-6. Winter position probabilities ($\hat{\pi}_i$) predicted by logistic regression for V13-1L and V9-2L tag families.

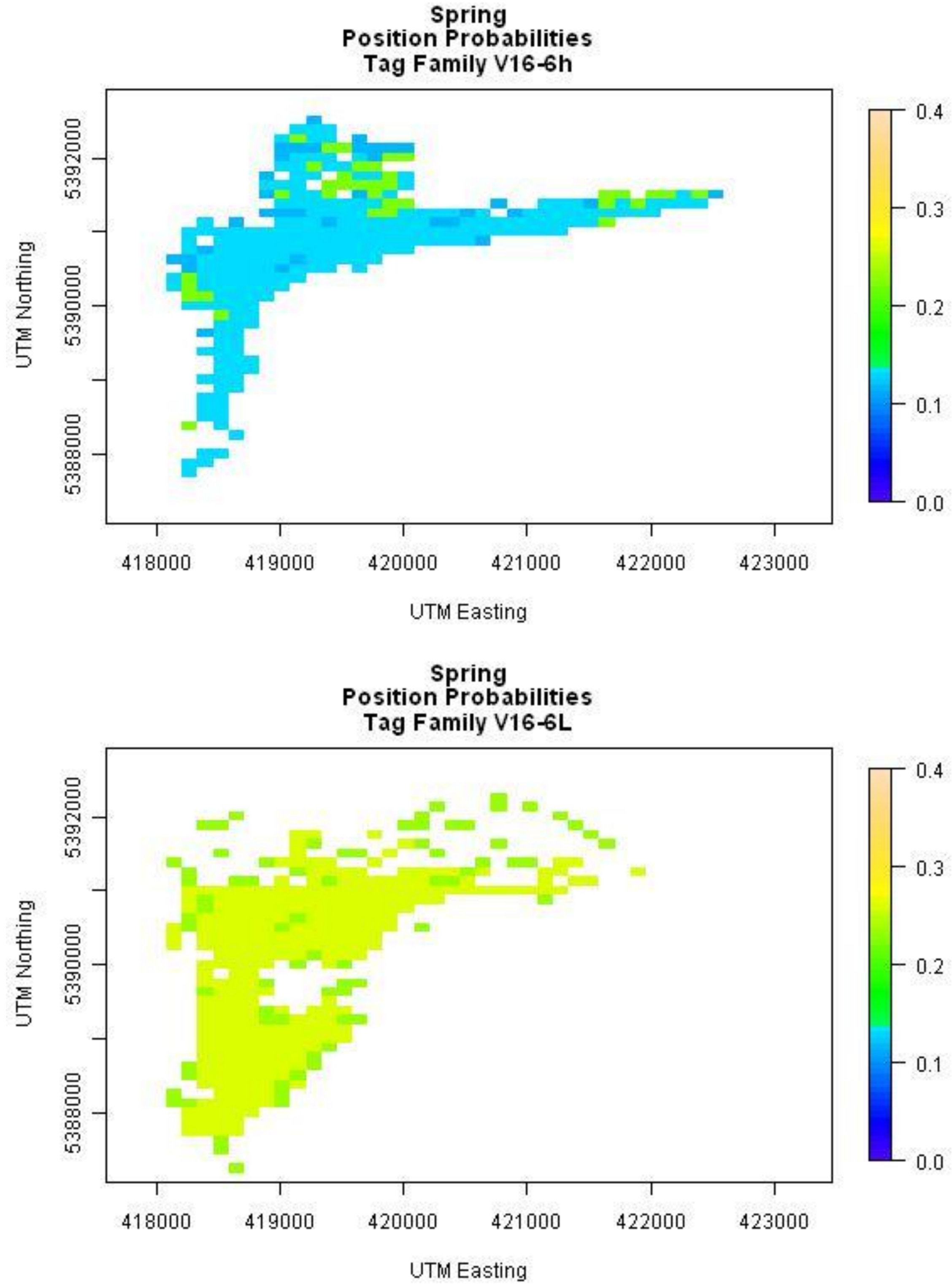
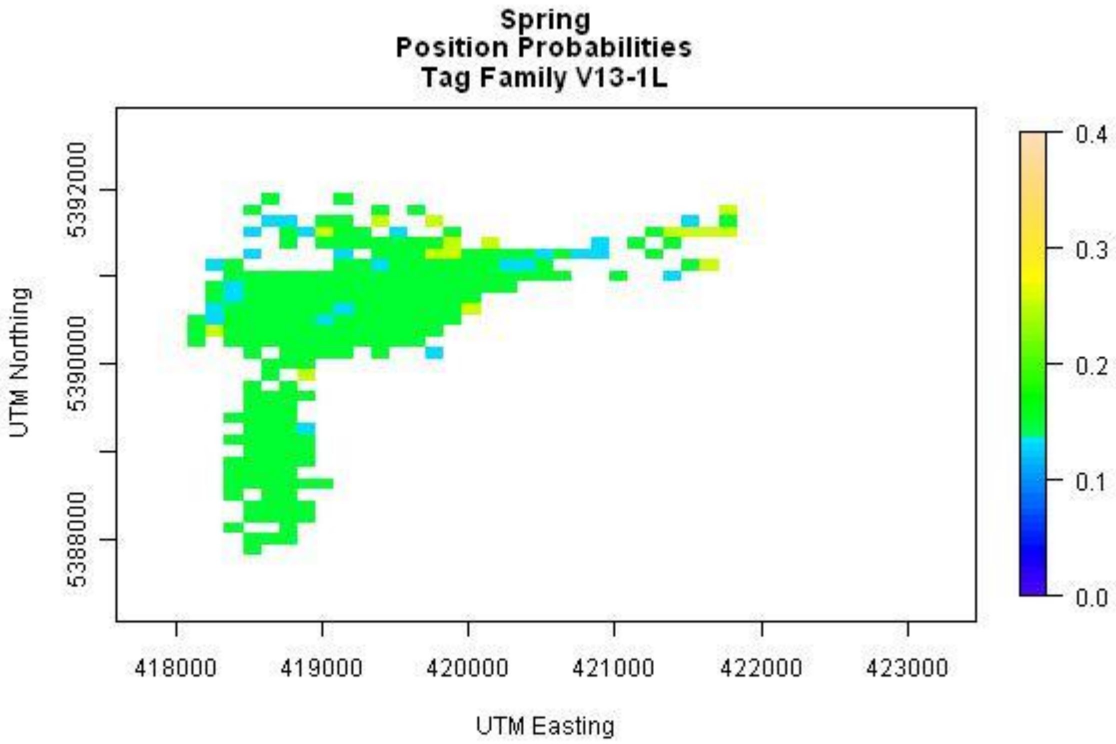


Figure C-7. Spring position probabilities ($\hat{\pi}_i$) predicted by logistic regression for V16-6H and V16P-4L tag families.



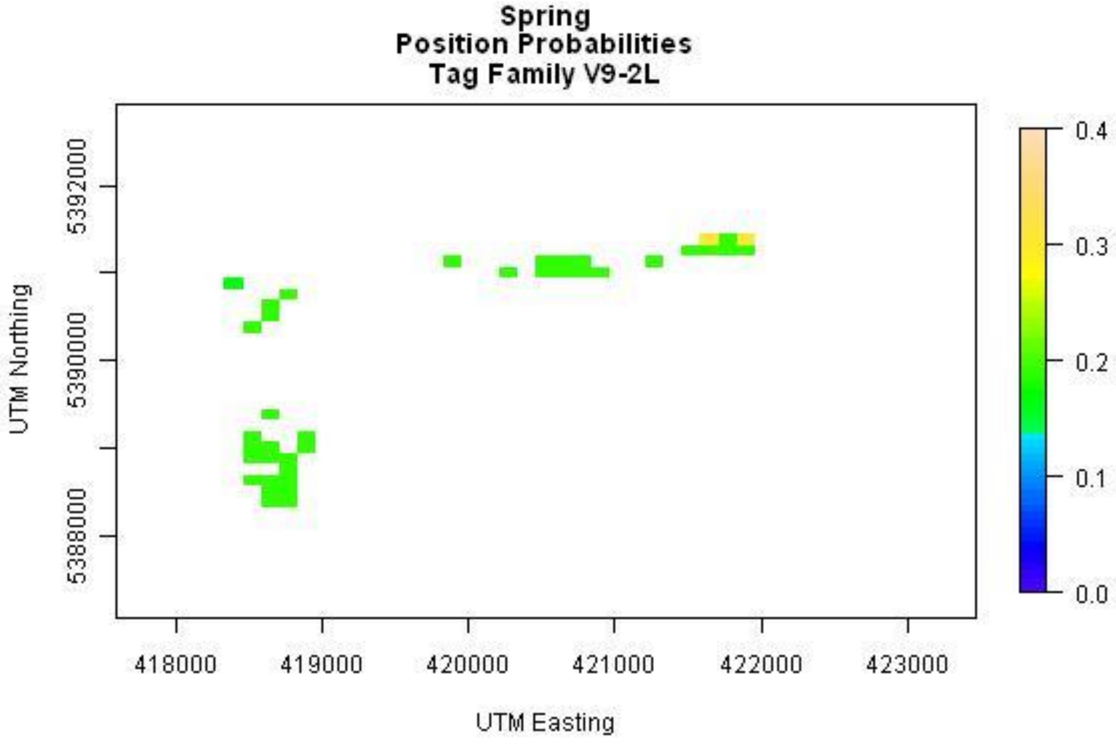
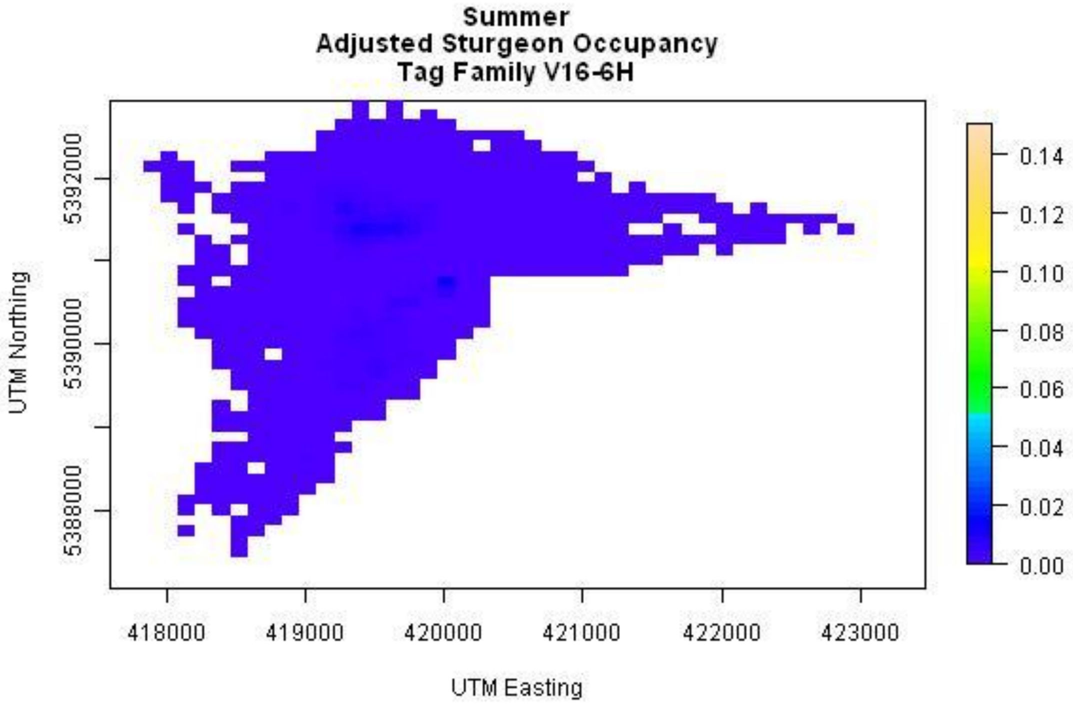


Figure C-8. Spring position probabilities ($\hat{\pi}_i$) predicted by logistic regression for V13-1L and V9-2L tag families.

Appendix D.



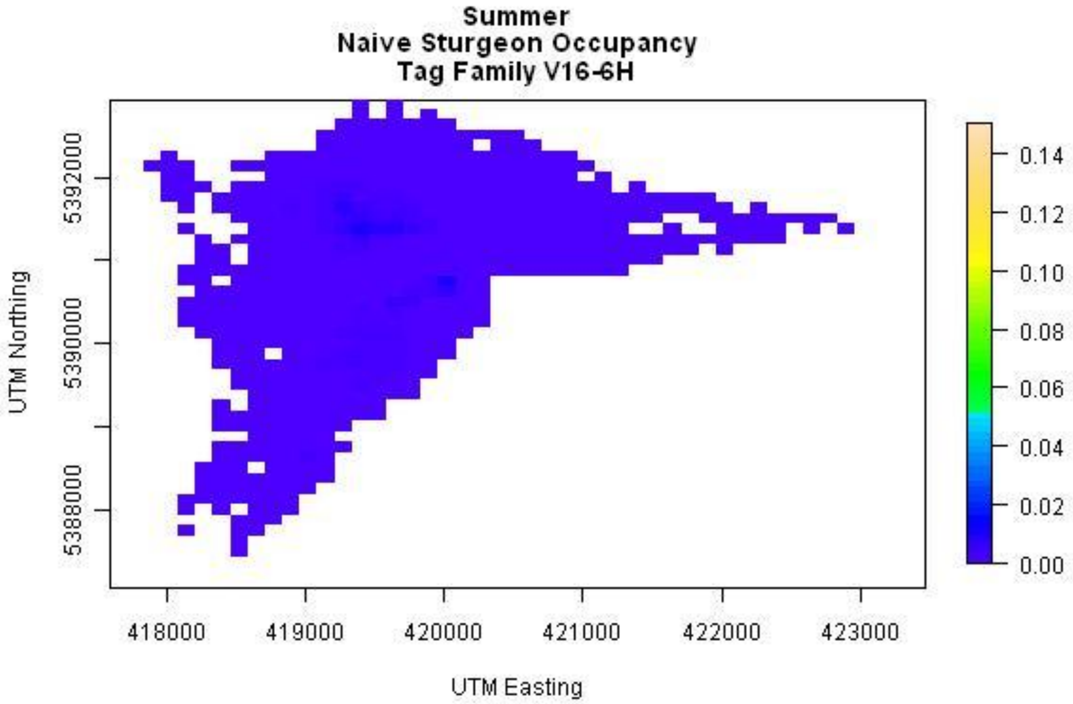


Figure D-1. Adjusted and naïve occupancy for summer season and V16-6H tag family.

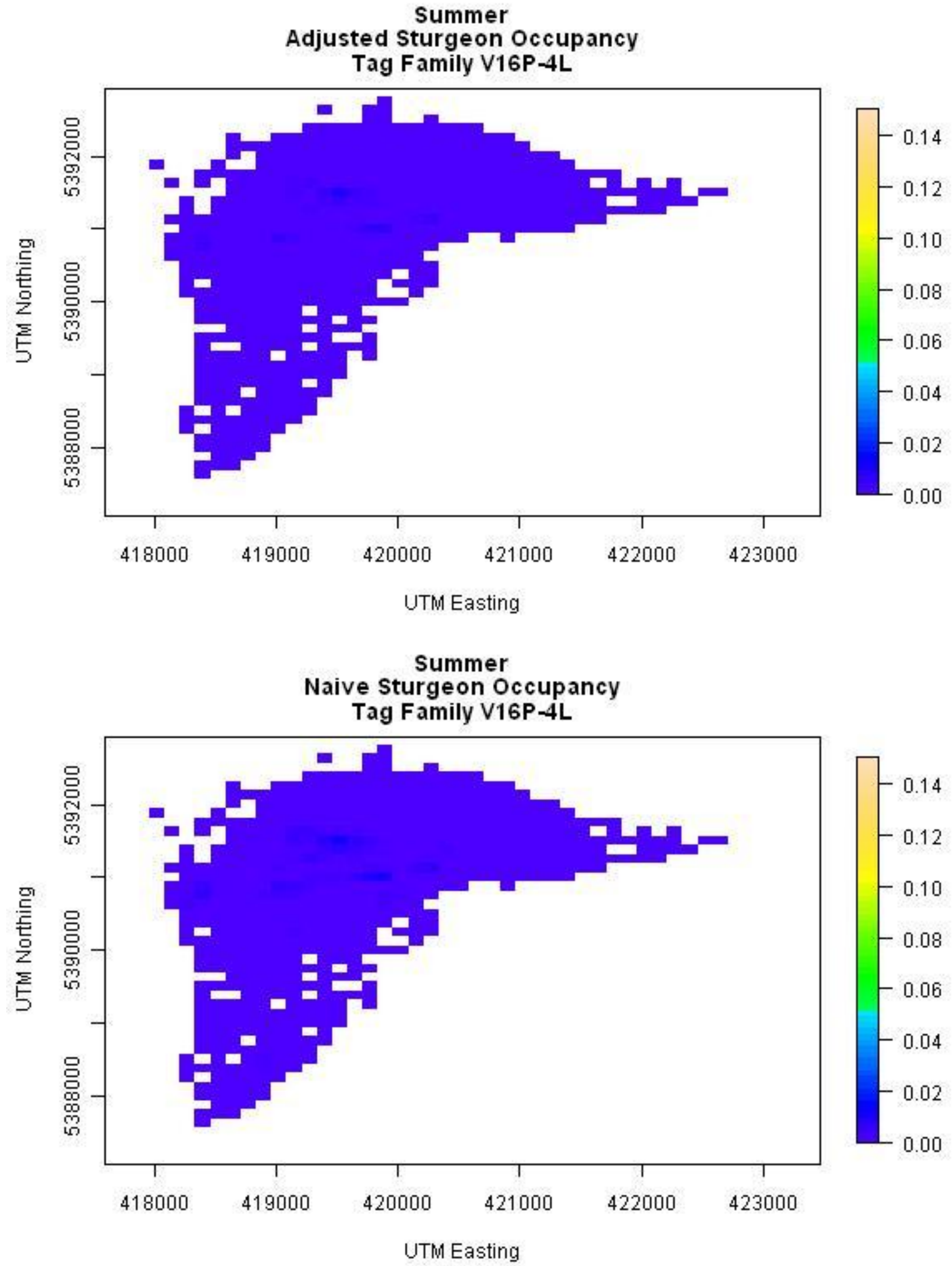


Figure D-2. Adjusted and naïve occupancy for summer season and V16P-4L tag family.

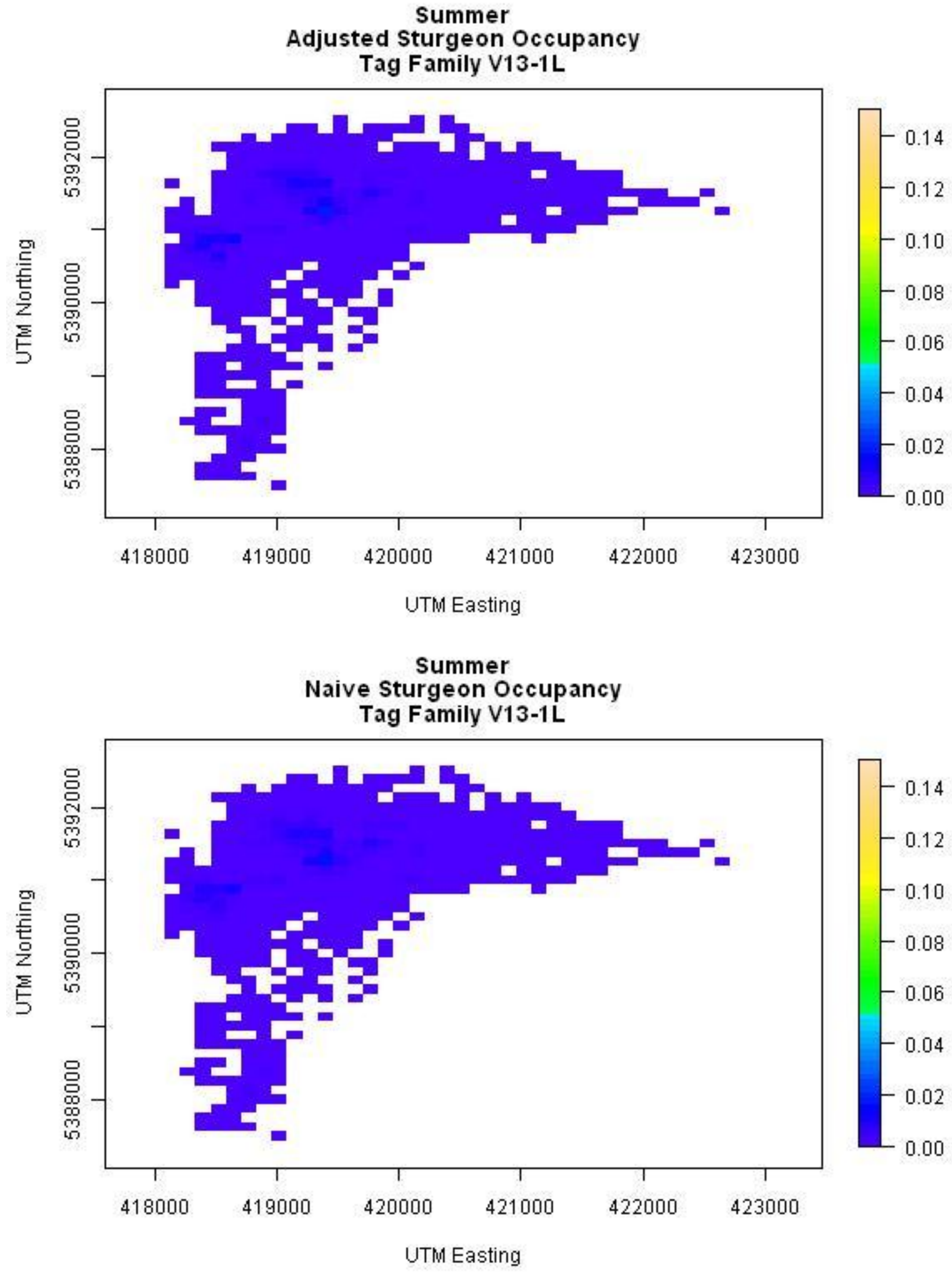


Figure D-3. Adjusted and naïve occupancy for summer season and V13-1L tag family.

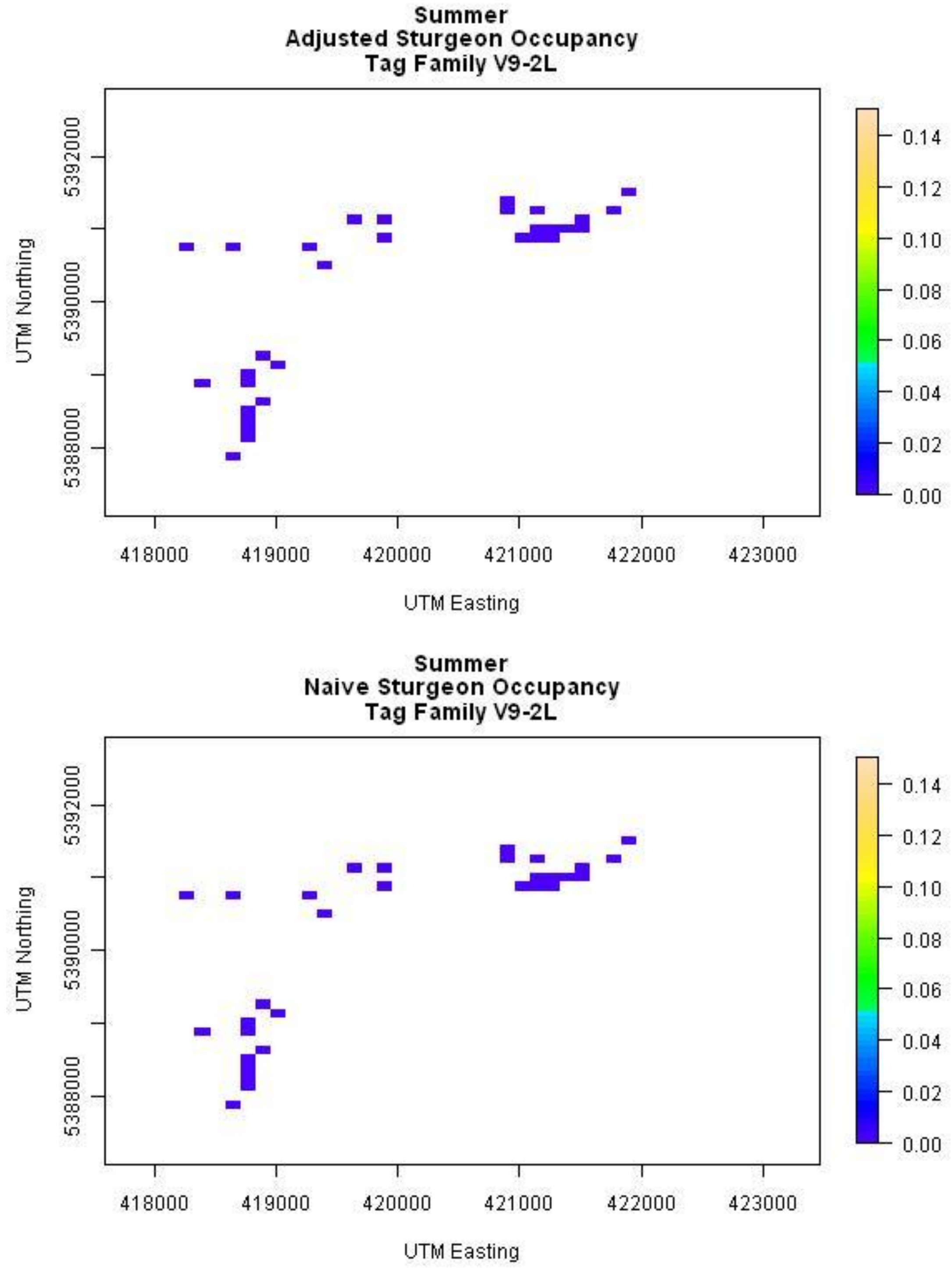


Figure D-4. Adjusted and naïve occupancy for summer season and V9-2L tag family.

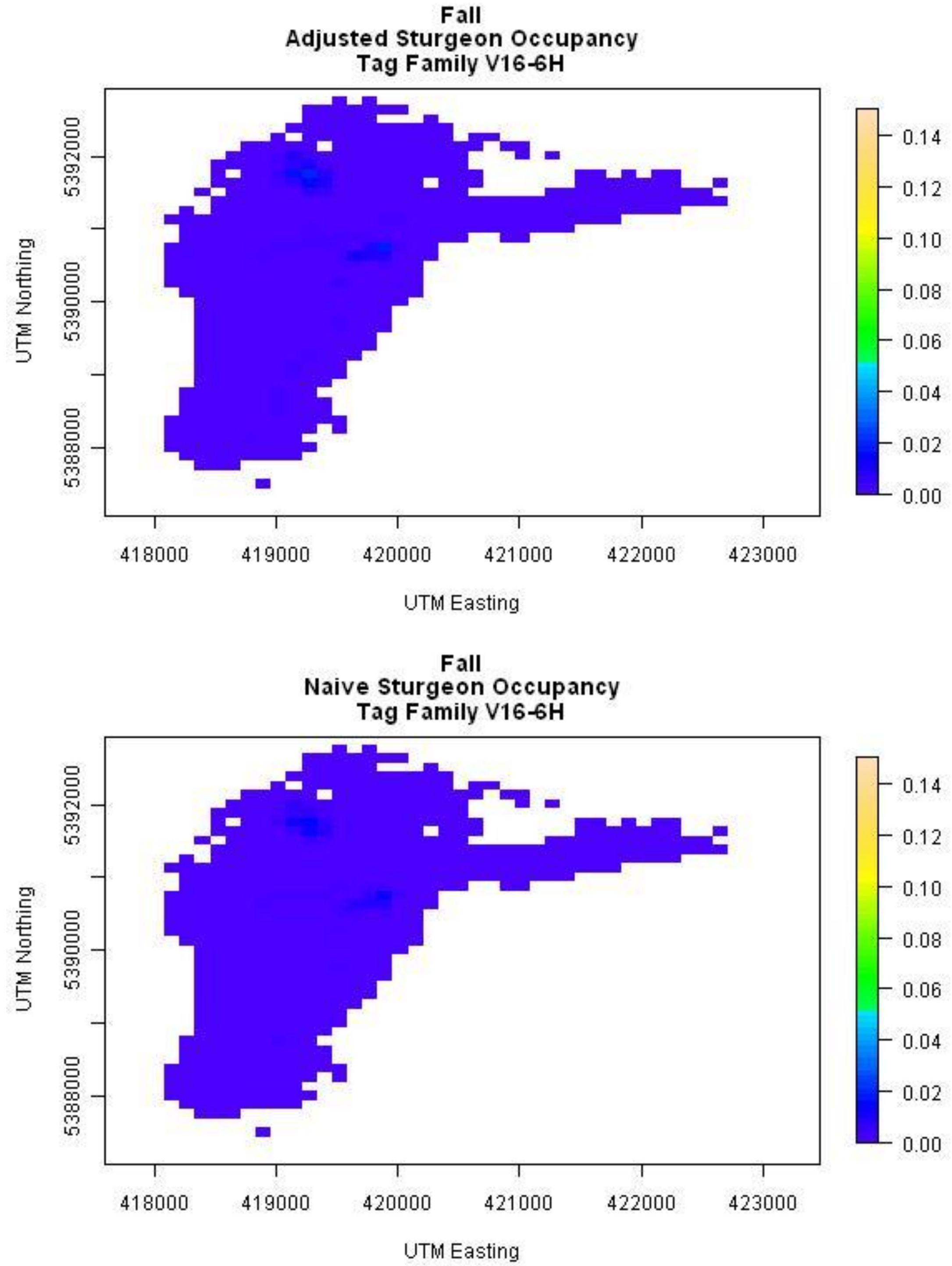


Figure D-5. Adjusted and naïve occupancy for fall season and V16-6H tag family.

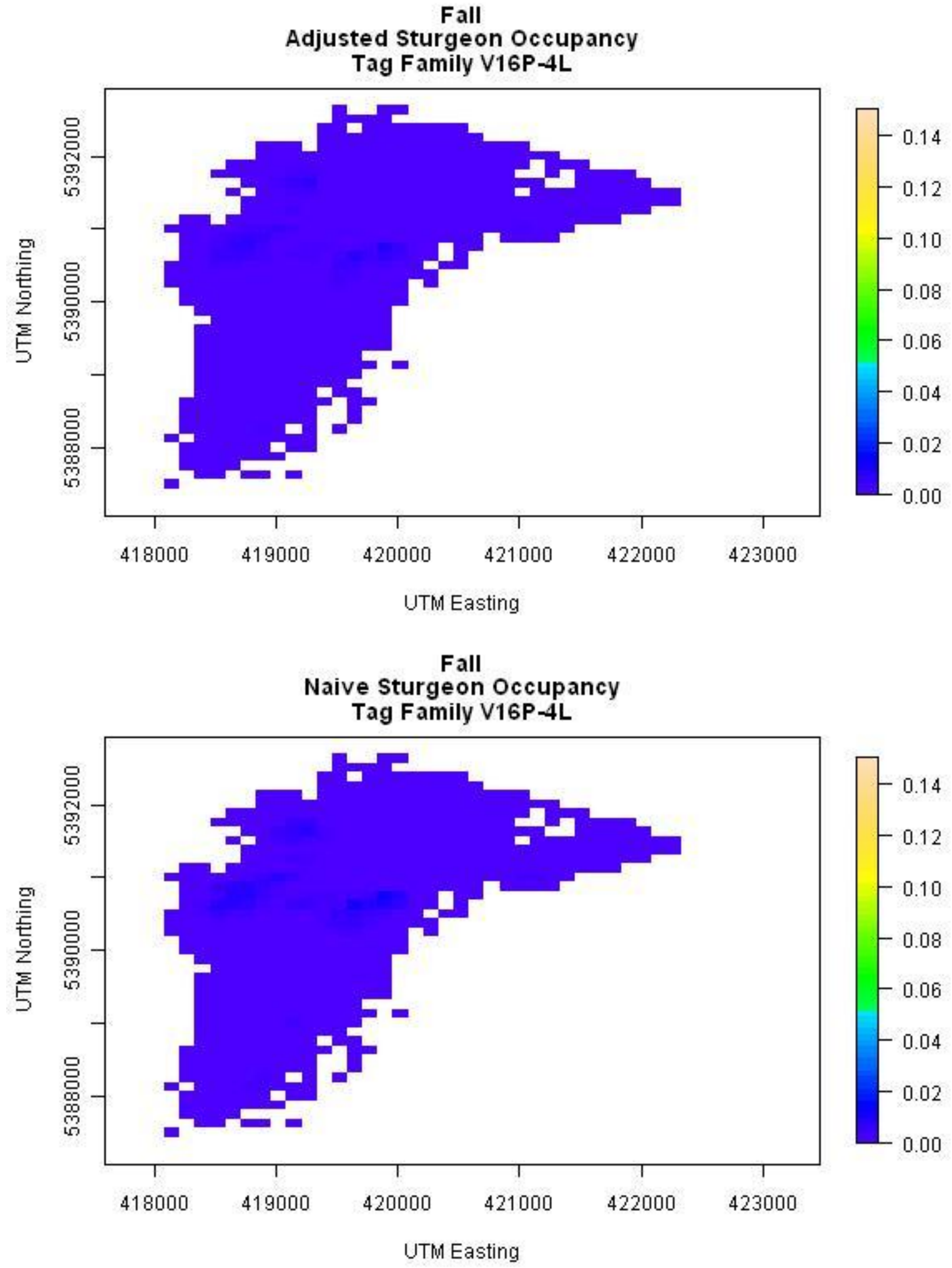


Figure D-6. Adjusted and naïve occupancy for fall season and V16P-4L tag family.

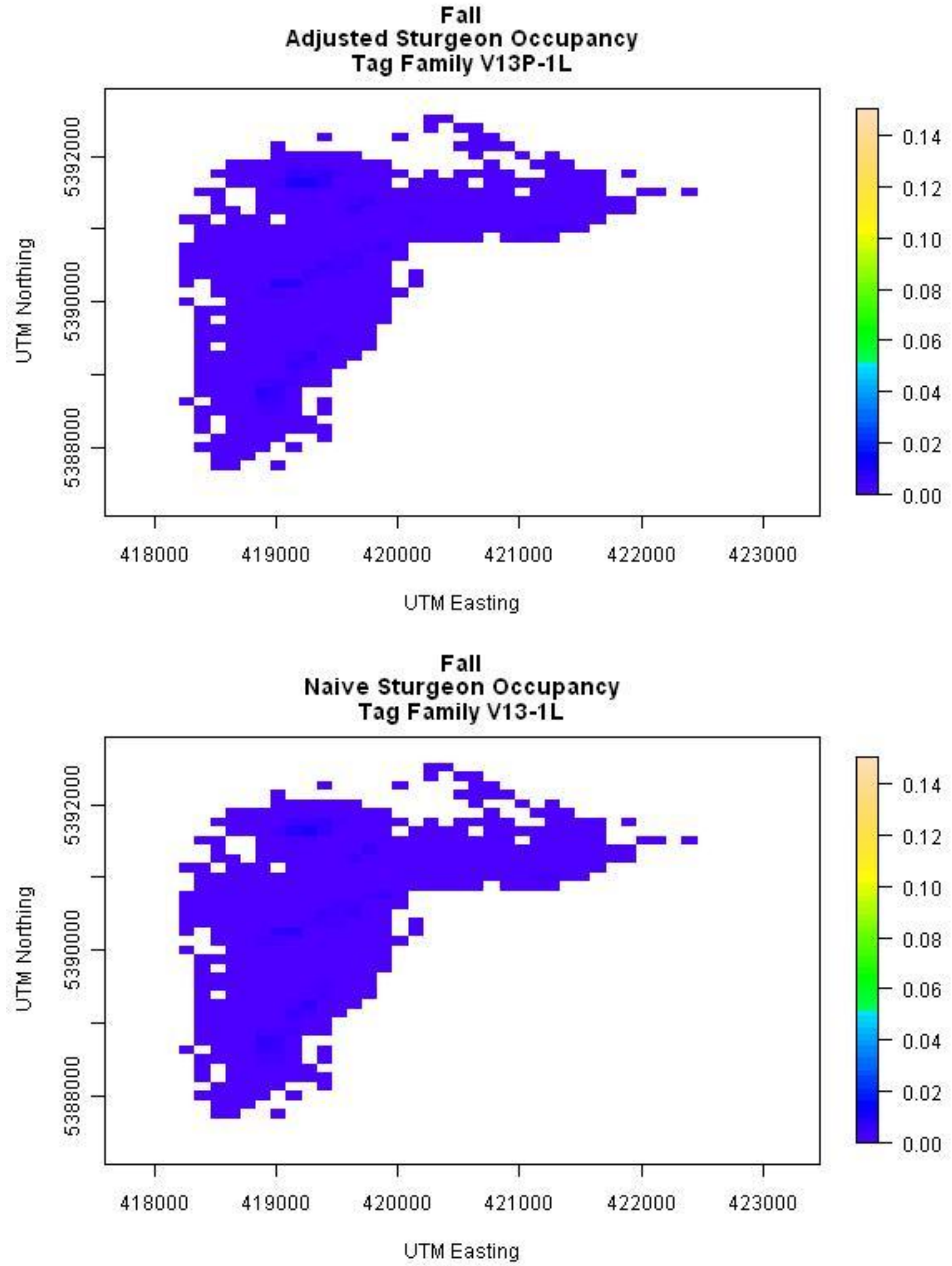


Figure D-7. Adjusted and naïve occupancy for fall season and V13-1L tag family.

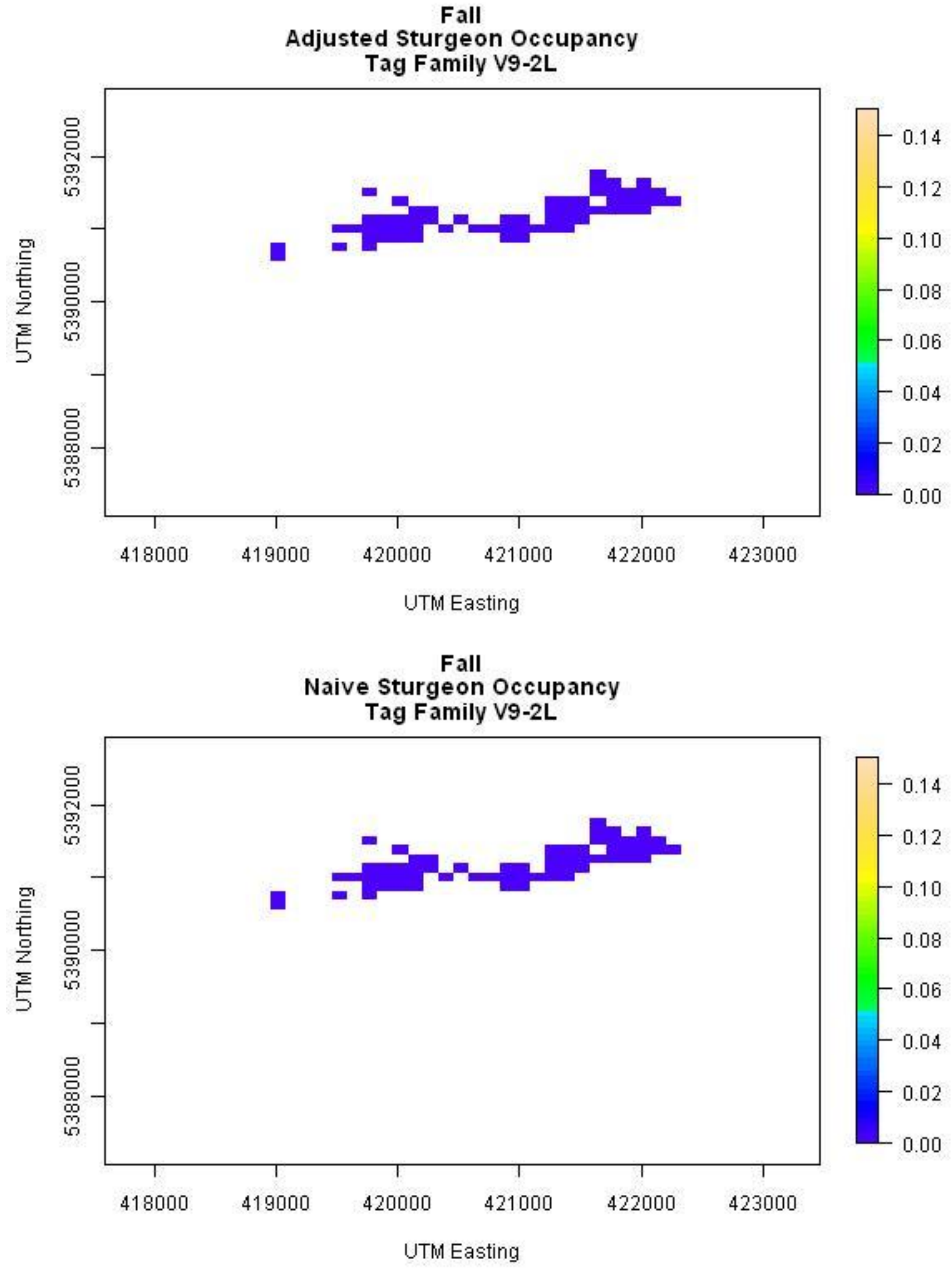
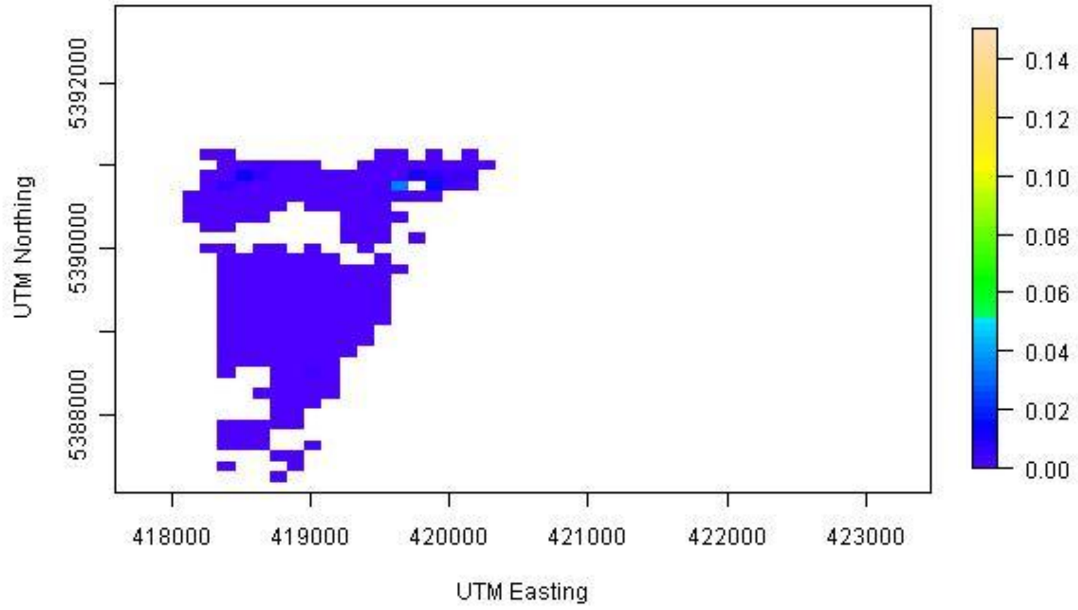


Figure D-8. Adjusted and naïve occupancy for fall season and V9-2L tag family.


Winter
Adjusted Sturgeon Occupancy
Tag Family V16-6H

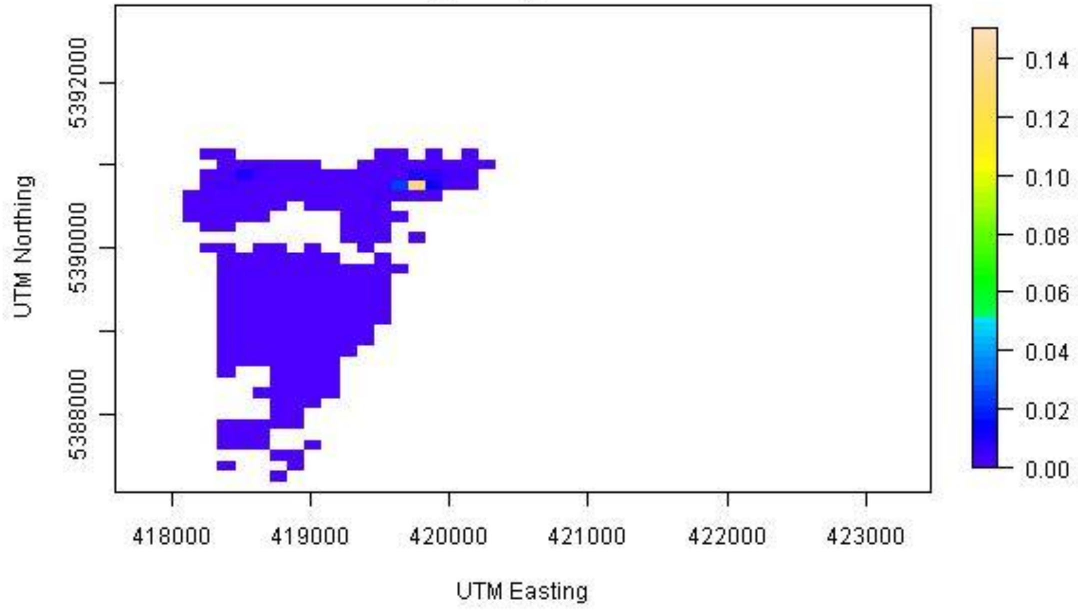

Winter
Naive Sturgeon Occupancy
Tag Family V16-6H

Figure D-9. Adjusted and naïve occupancy for winter season and V16-6H tag family.

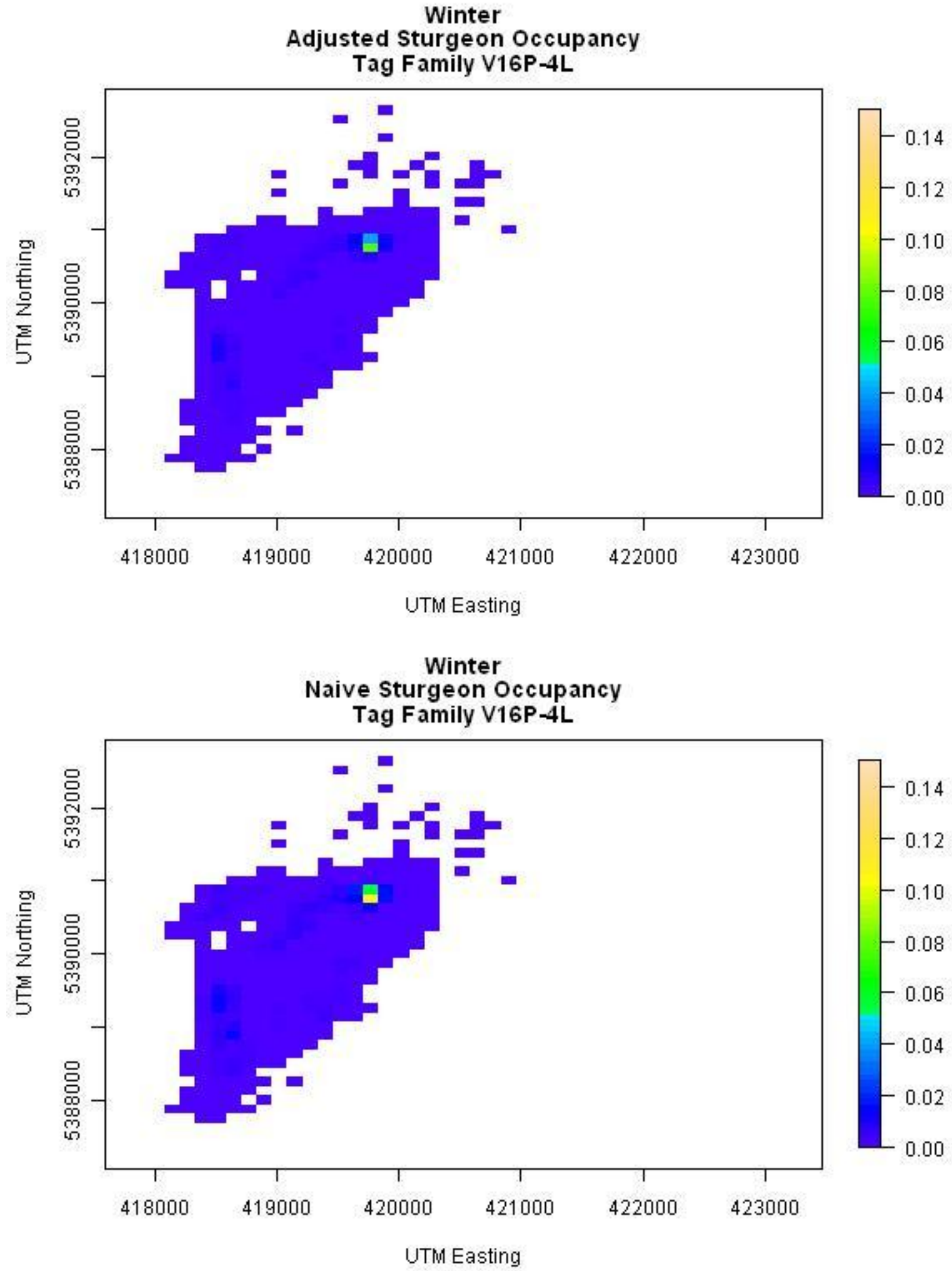


Figure D-10. Adjusted and naïve occupancy for winter season and V16P-4L tag family.

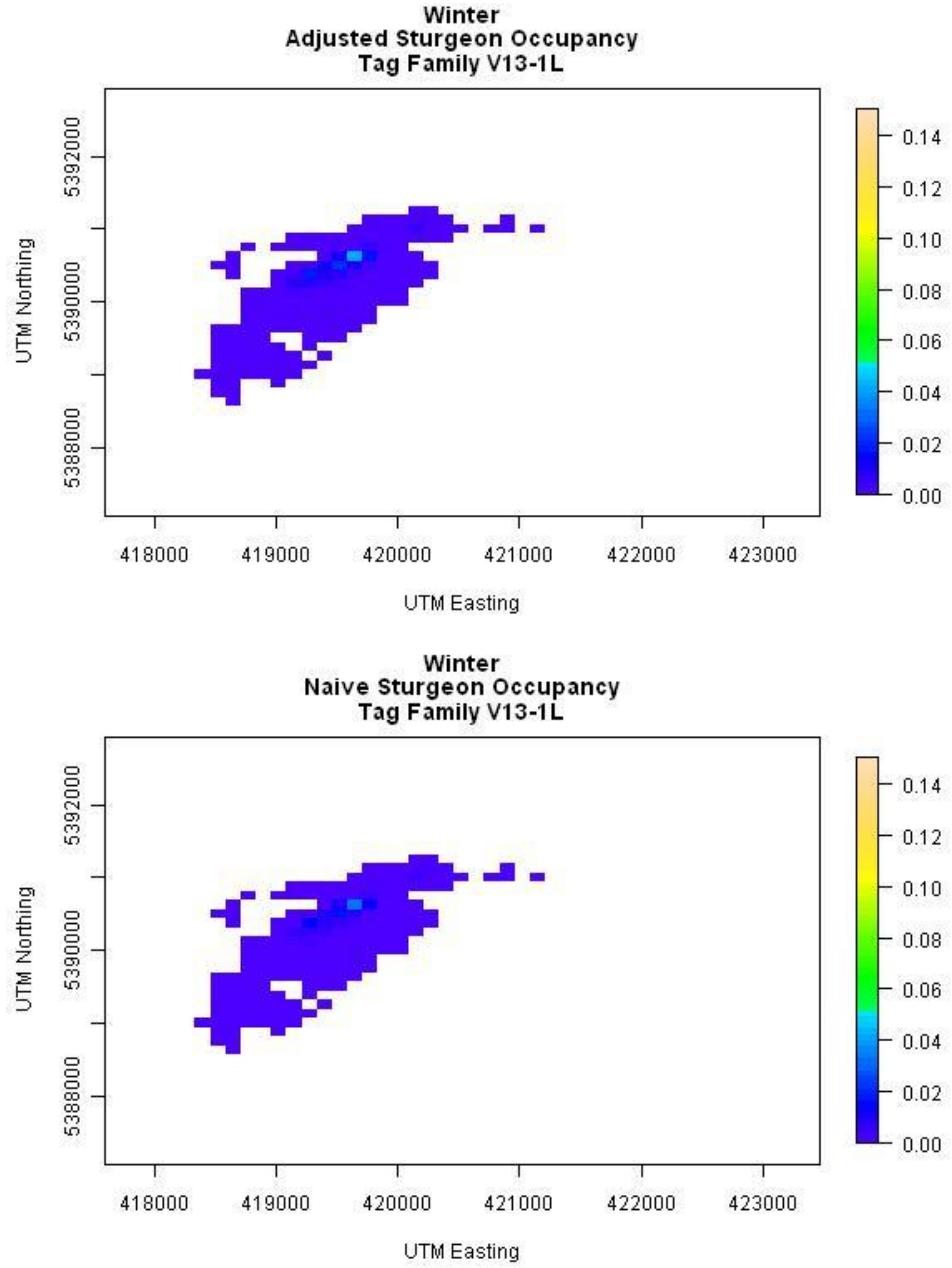


Figure D-11. Adjusted and naïve occupancy for winter season and V13-1L tag family.

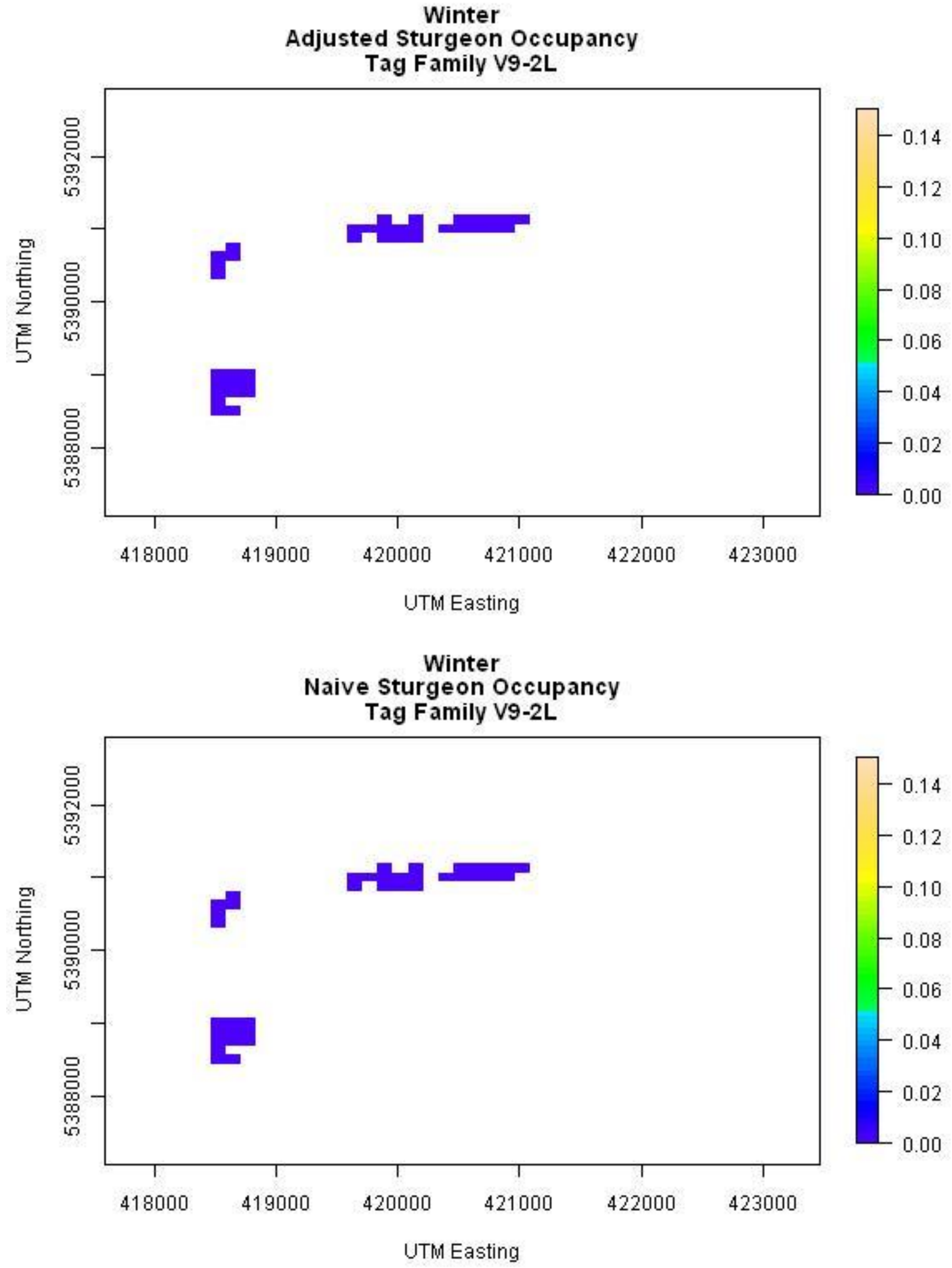


Figure D-12. Adjusted and naïve occupancy for winter season and V9-2L tag family.

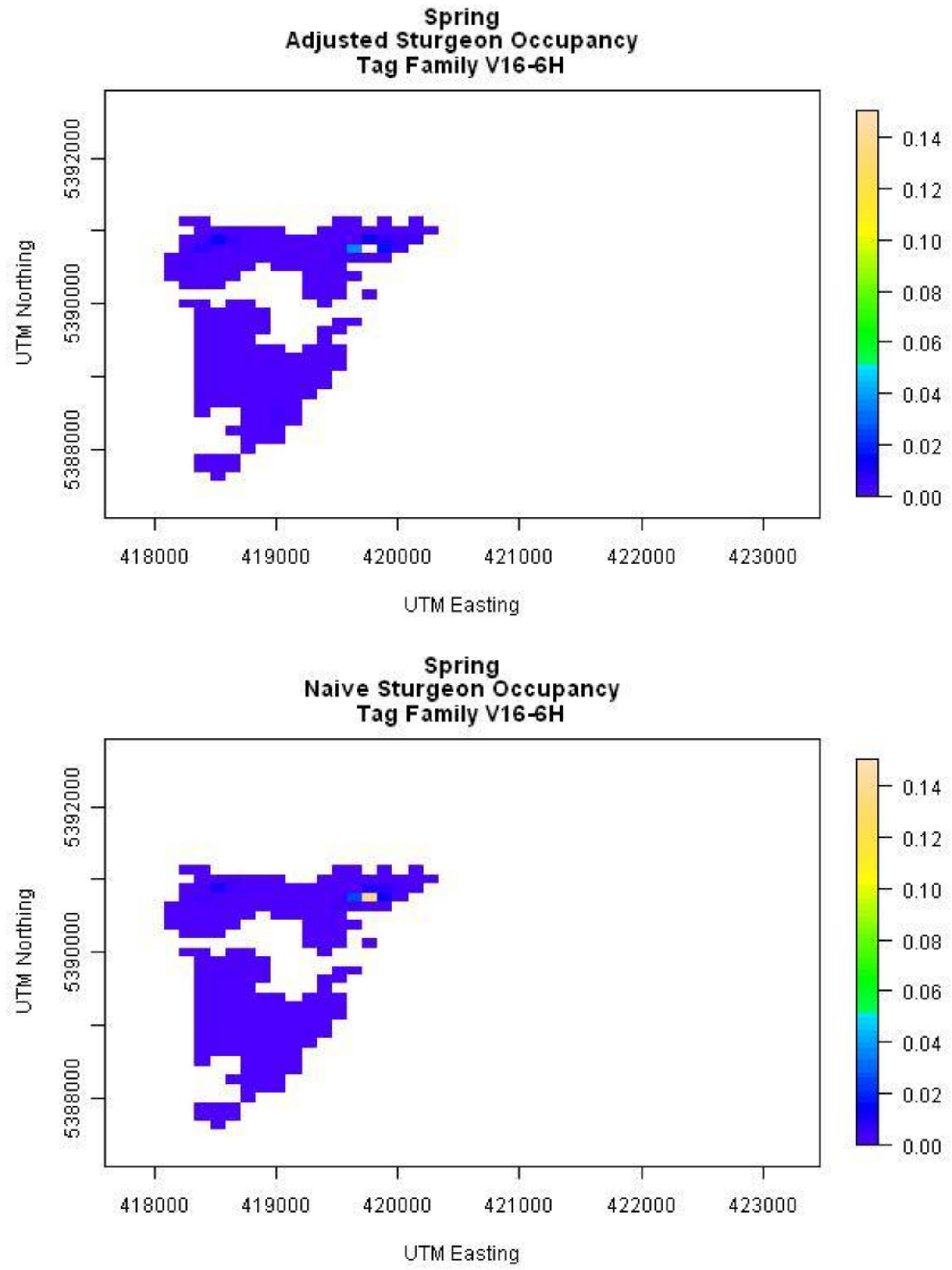
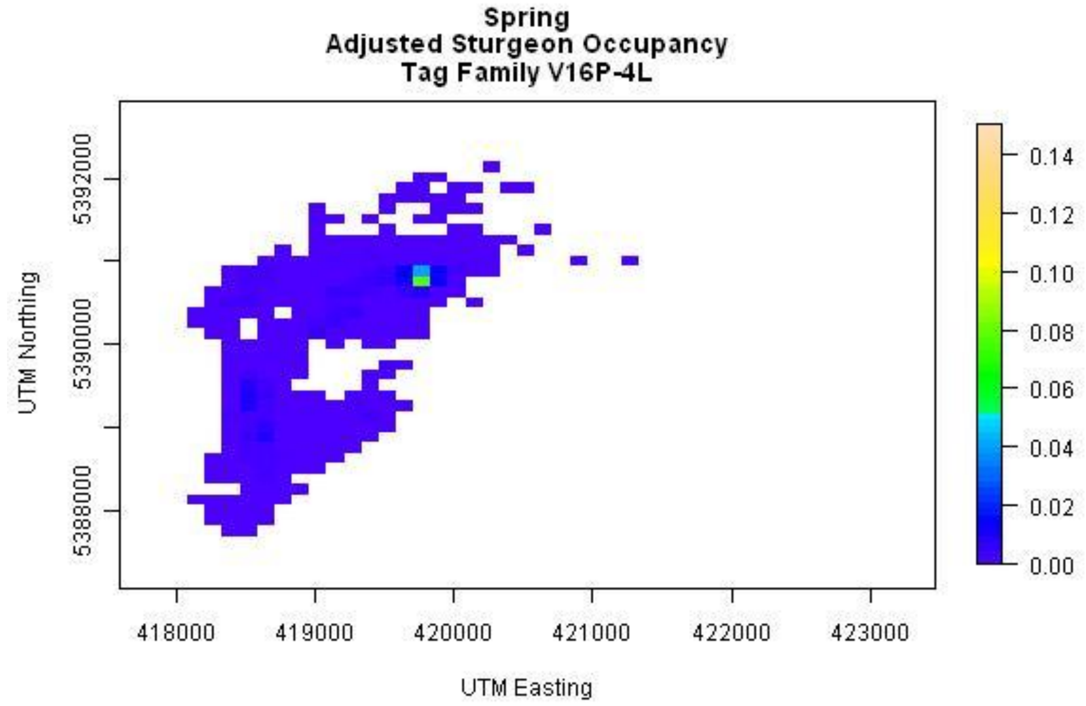
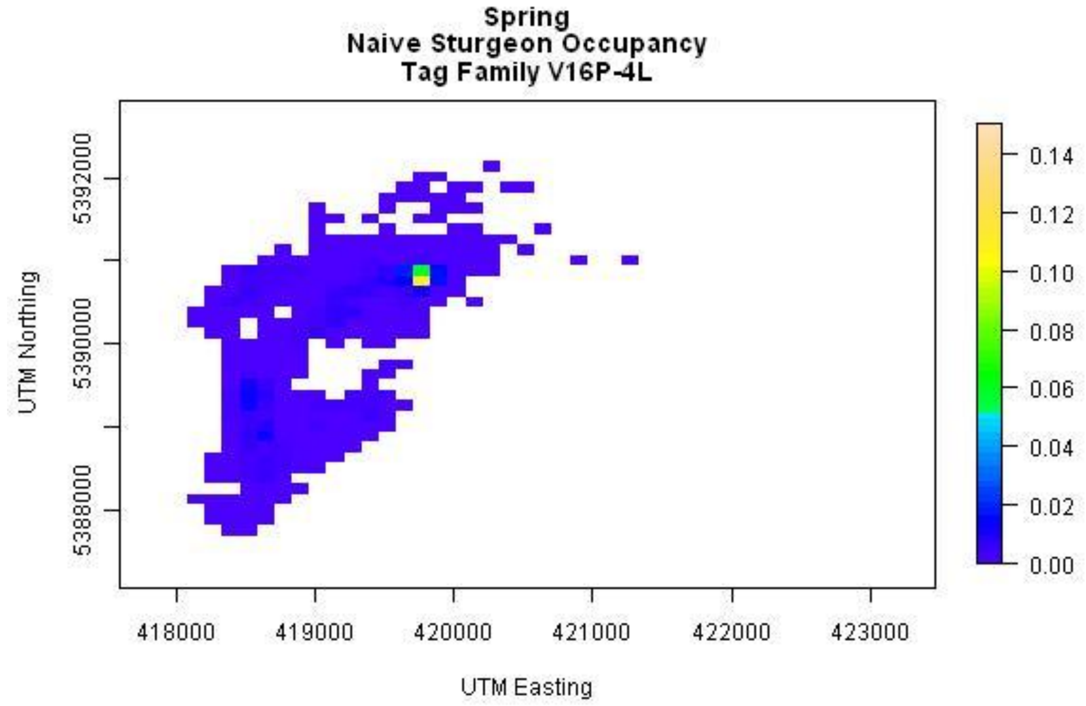


Figure D-13. Adjusted and naïve occupancy for spring season and V16-6H tag family.



Spring
Adjusted Sturgeon Occupancy
Tag Family V16P-4L



Spring
Naive Sturgeon Occupancy
Tag Family V16P-4L

Figure D-14. Adjusted and naïve occupancy for spring season and V16P-4L tag family.

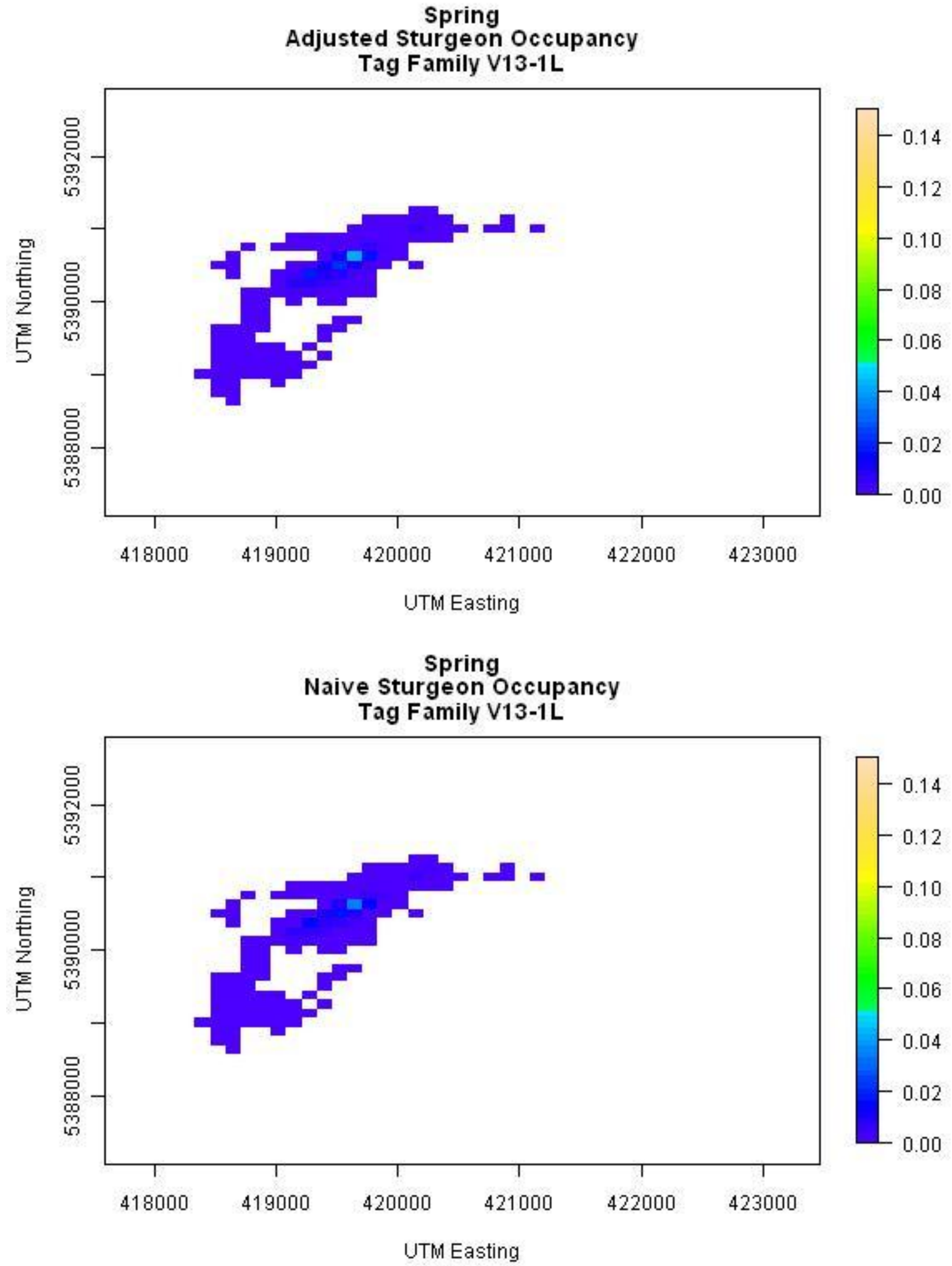


Figure D-15. Adjusted and naïve occupancy for spring season and V13-1L tag family.

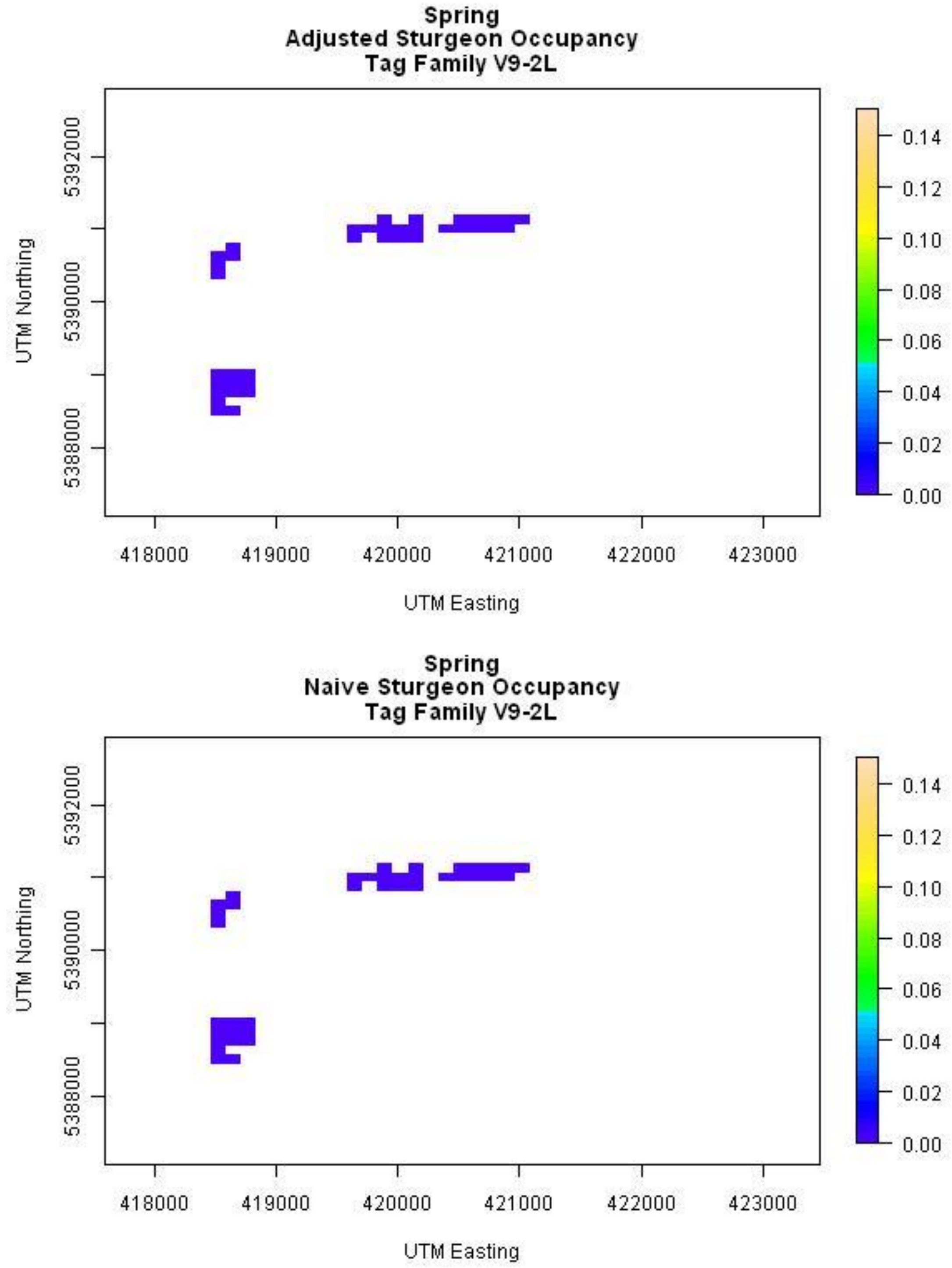


Figure D-16. Adjusted and naïve occupancy for spring season and V9-2L tag family.

Appendix E.

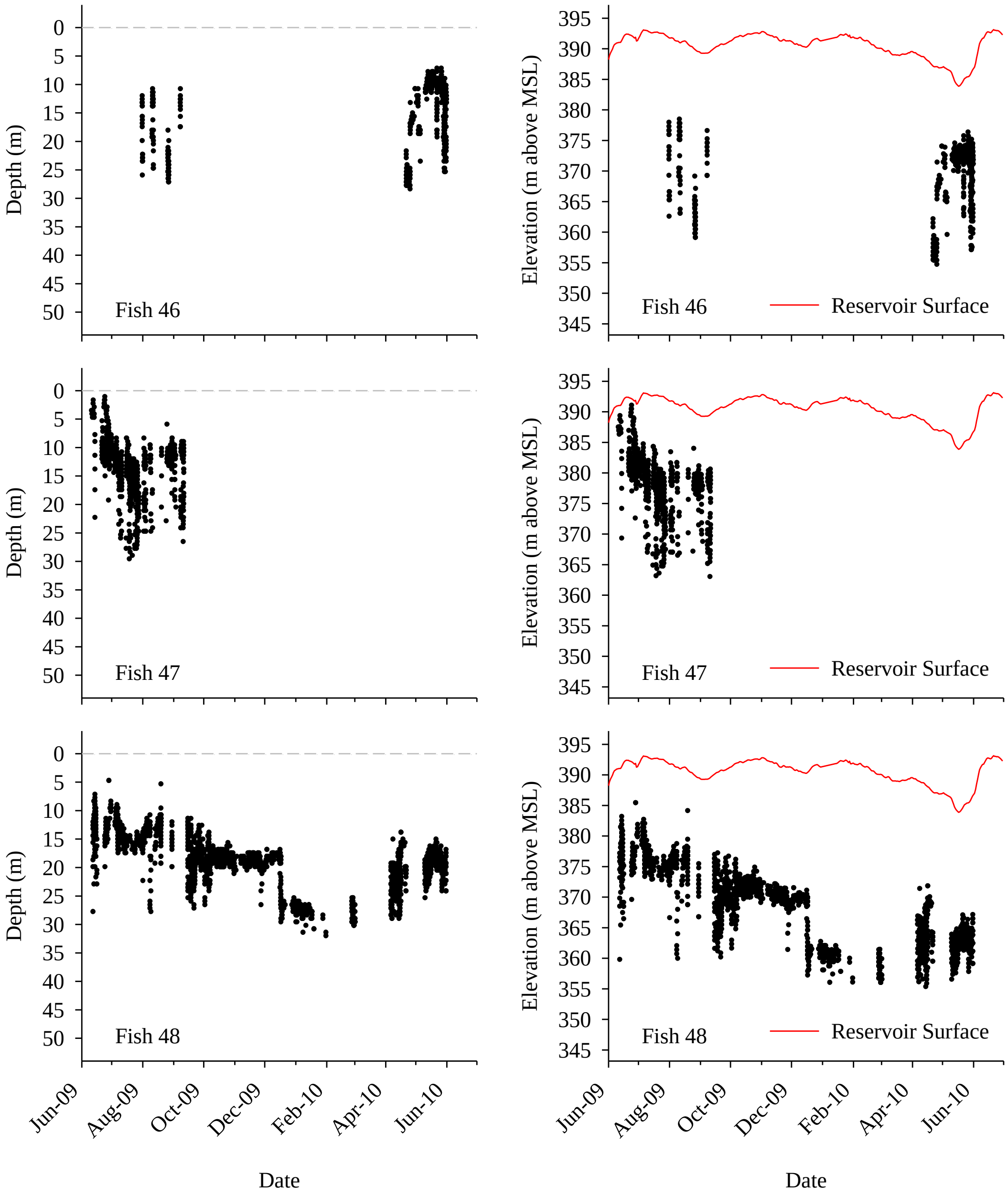


Figure E-1. Absolute depth (m) and elevation above mean sea level (MSL) relative to the reservoir surface for white sturgeon no. 46, 47, and 48.

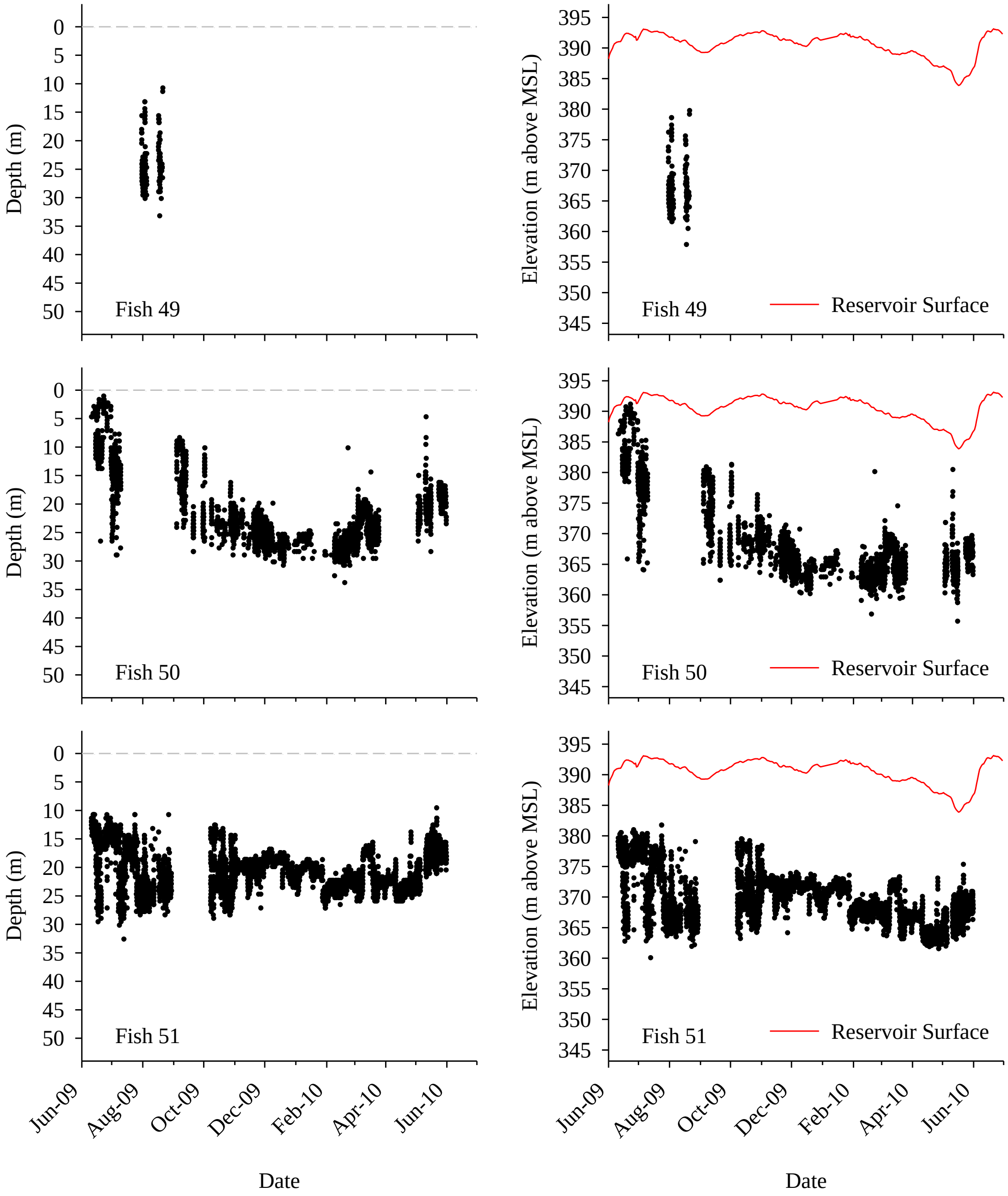


Figure E-2. Absolute depth (m) and elevation above mean sea level (MSL) relative to the reservoir surface for white sturgeon no. 49, 50, and 51.

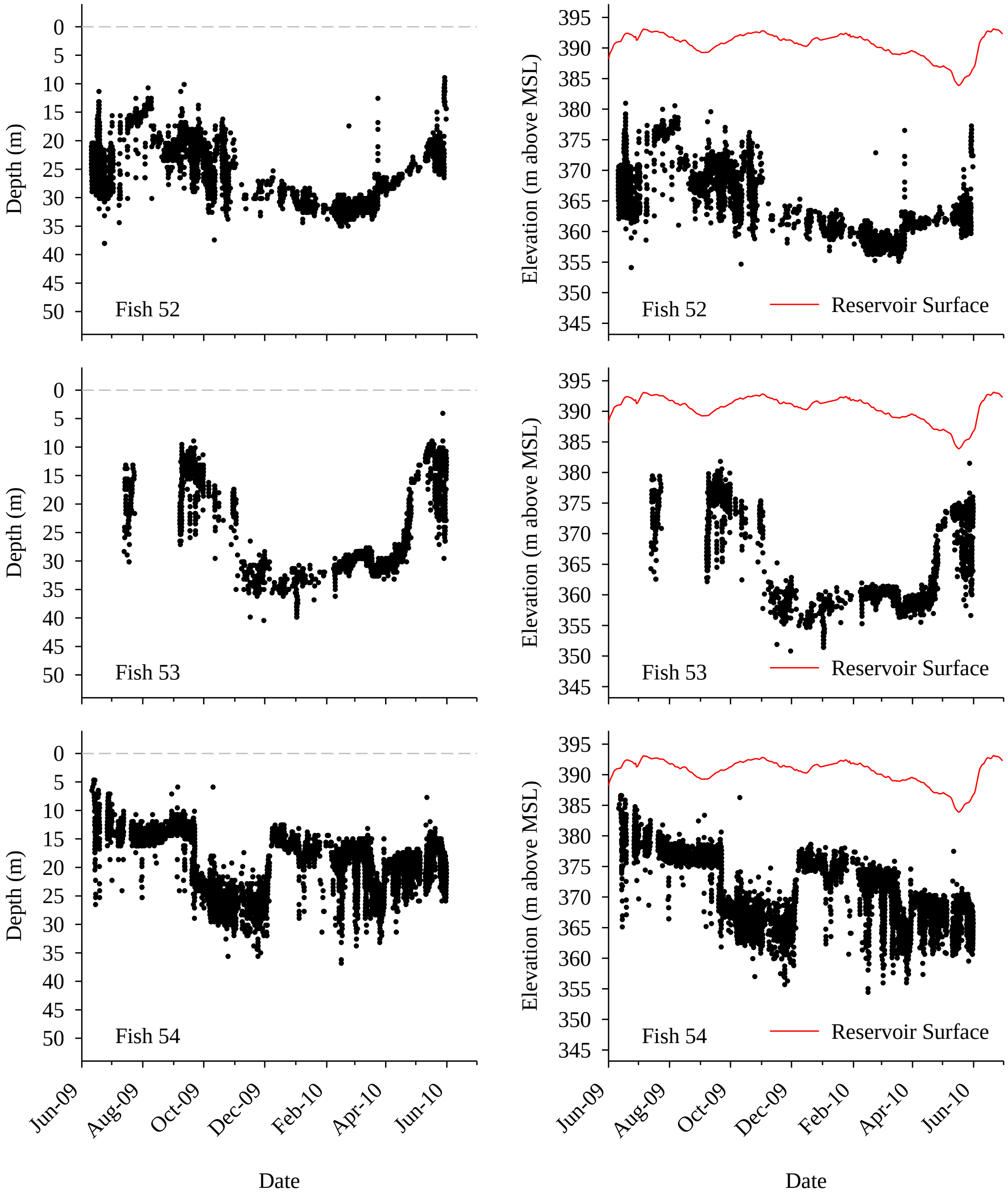


Figure E-3. Absolute depth (m) and elevation above mean sea level (MSL) relative to the reservoir surface for white sturgeon no. 52, 53, and 54.

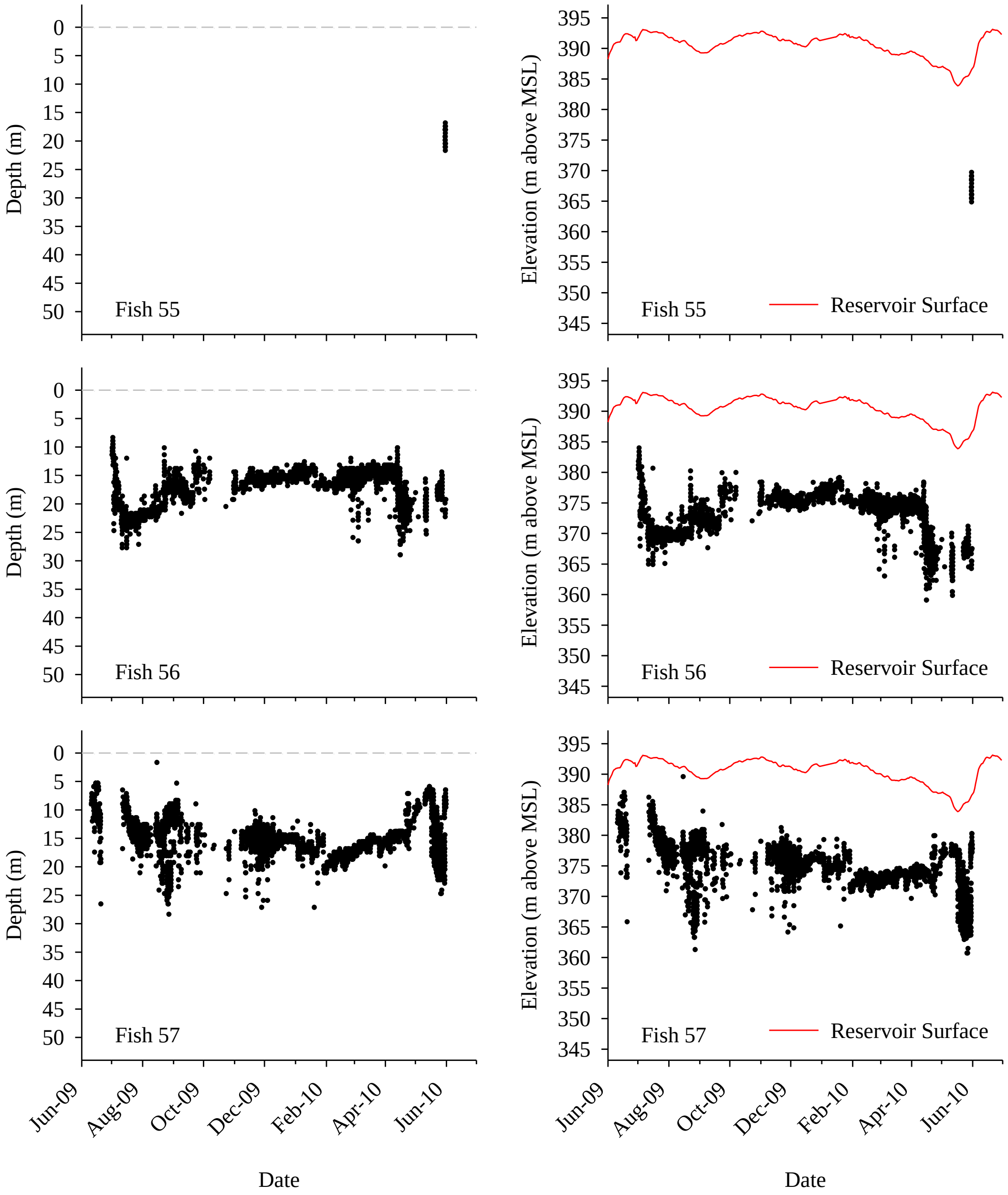


Figure E-4. Absolute depth (m) and elevation above mean sea level (MSL) relative to the reservoir surface for white sturgeon no. 55, 56, and 57.

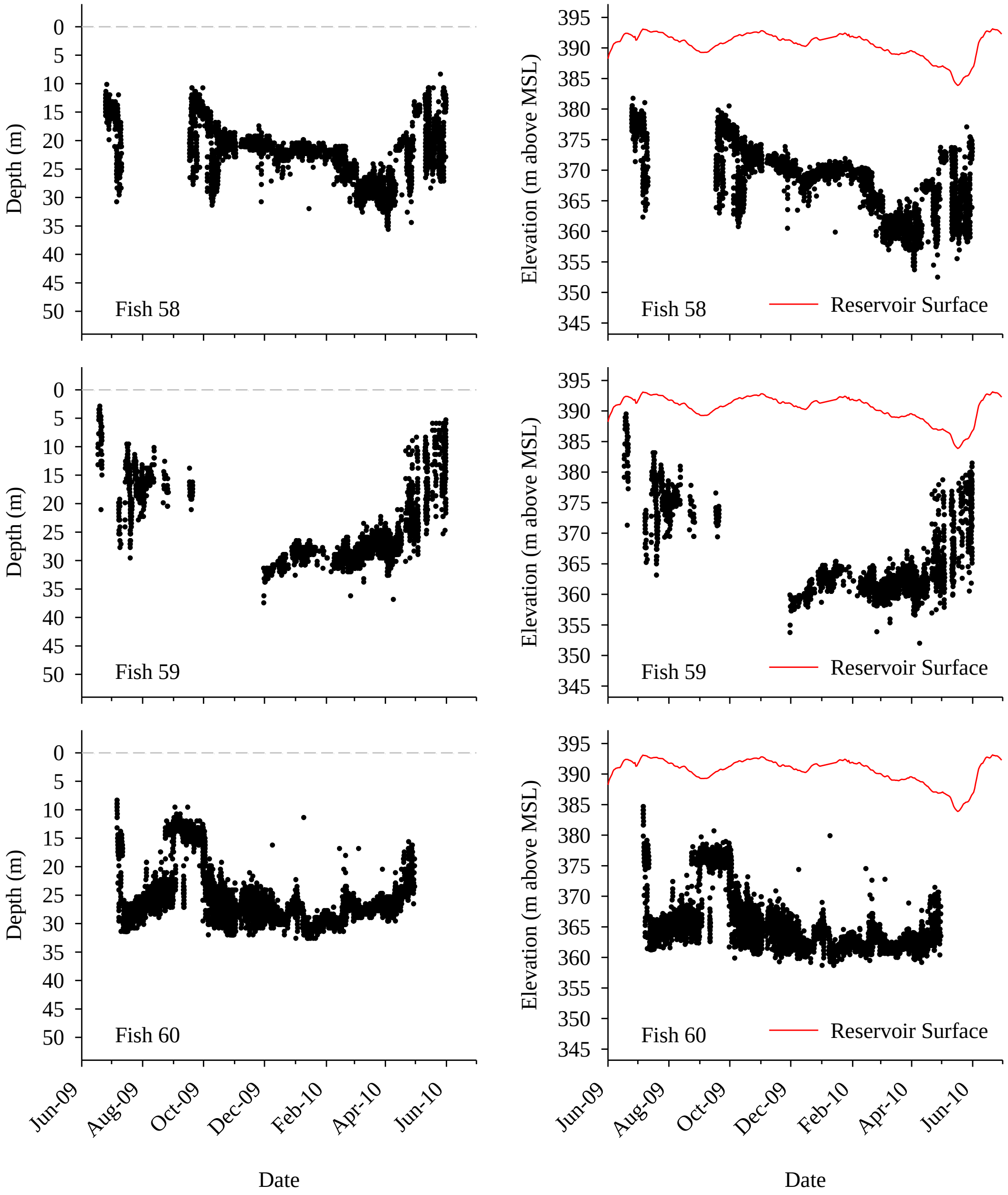


Figure E-5. Absolute depth (m) and elevation above mean sea level (MSL) relative to the reservoir surface for white sturgeon no. 58, 59, and 60.

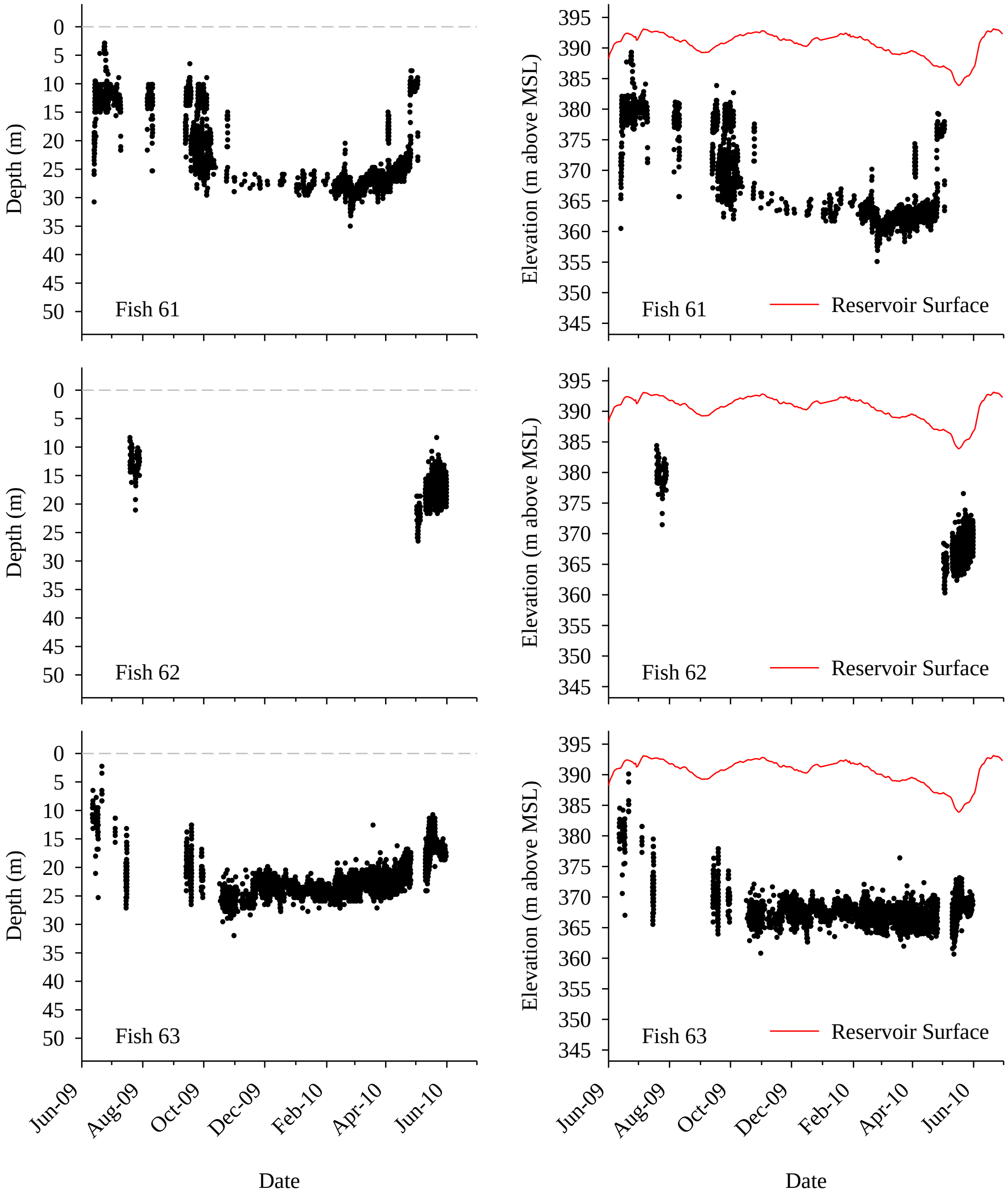


Figure E-6. Absolute depth (m) and elevation above mean sea level (MSL) relative to the reservoir surface for white sturgeon no. 61, 62, and 63.

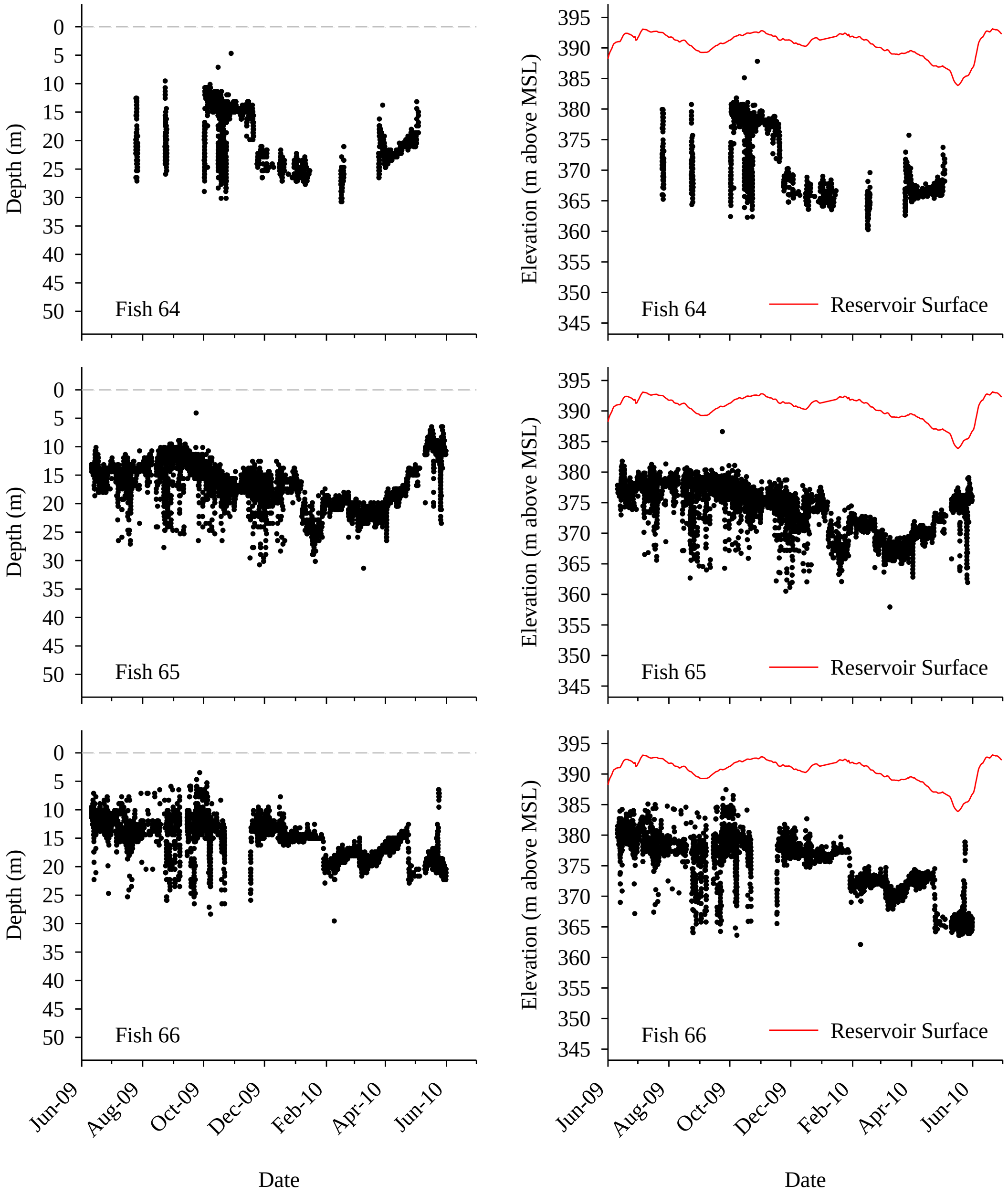


Figure E-7. Absolute depth (m) and elevation above mean sea level (MSL) relative to the reservoir surface for white sturgeon no. 64, 65, and 66.