Investigating Patterns in Spatial Distribution and Diversity of Submerged Aquatic Vegetation in the San Marcos River from 2013 to 2019

by

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A directed research report submitted to the Geography Department of
Texas State University in partial fulfillment
of the requirements for the degree of
Master of Applied Geography
with a specialization in Geographic Information Science

August 2021

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I. Introduction

The headwaters of the San Marcos River are fed by the San Marcos Springs (SMS), creating a unique groundwater-dependent ecosystem whose endurance faces both anthropogenic and natural challenges. The SMS ecosystem, located in the Edwards Plateau region of Texas, represents a microcosm for springs across the planet (Perkin 2017). The second largest spring system in Texas, the SMS has historically exhibited the greatest flow dependability and environmental stability of any spring system in the southwestern United States (United States Fish and Wildlife Service, 1996). Because of the demands placed on aquifers by human population growth, spring-fed river ecosystems like the San Marcos are threatened by a number of different anthropogenic disturbances such as agricultural practices, impoundment and flood control projects, siltation from erosion, groundwater pumping, recreational activities, pollution, and the introduction of non-native species (Bowles 1993). The introduction of exotic species into aquatic habitats of the San Marcos River poses significant threats to native and endemic species through predation, competition, hybridization, and habitat modification (Bowles 1993). Before 1930, several dams were constructed along the San Marcos River (Bradsby 1994) which altered flow rates and allowed for non-native, accidentally and intentionally introduced submerged aquatic vegetation (SAV) to establish (Jenkins et al. 1986), leading to a subsequent decrease in native population (Stanton 1992). Understanding spatial patterns in the distribution of native and invasive species over time is important to the mitigation of negative impacts. Identifying these patterns associated with SAV to help guide restoration and conservation efforts is the primary aim of this research.

In 2006, the United States Fish and Wildlife Service brought together stakeholders from across the region to initiate a collaborative process to develop a plan to contribute to the recovery of federally listed (threatened and endangered) species that live in the Comal and San Marcos river-springs ecosystems and that are dependent on the Edwards Aquifer. This collaboration was known as the Edwards Aquifer Recovery Implementation Program (EARIP). The EARIP recommended the application and adoption of an Incidental Take Permit (ITP) and the development of the Habitat Conservation Plan (HCP) to support the adoption of the ITP. The Edwards Aquifer Authority (EAA) previously created a long-term monitoring program with the purpose of assessing water quality, water quantity, habitats, and biological monitoring for several federally listed species in the Comal and San Marcos springs and river systems. In 2012 these monitoring efforts came fully under the purview of the Edwards Aquifer Habitat Conservation Plan (EAHCP) (EAA 2012).

Over this time period the EAA tracked changes in 26 different types of submerged aquatic vegetation (SAV) within the San Marcos River at three different sites, and since the implementation of the EAHCP, the data also includes native vegetation plantings and removal of non-native vegetation since 2013 (EAA 2012). Texas wild-rice (*Zizania texana)* is one species of SAV monitored as part of the EAHCP and is a federally listed endangered species endemic to the San Marcos River (Poole 1999). Endemic species occupy a specific geographic niche and are found only in specific localities (Meriam-Webster 2019). Submerged aquatic vegetation fulfills a significant role in aquatic ecosystems as it provides cover and food for a wide range of species (Fynn 2014) including the endangered fountain darter (*Etheostoma fonticola*), a fish species endemic to the San Marcos and Comal rivers (Schenck 1976), and also protected and managed by the EAHCP. The fountain darter's physical habitat structure is primarily determined by submerged aquatic vegetation (Schneck 1976). Thus, in addition to understanding how SAV coverage has changed over time relative to TWR, it is also important to monitor for its contributions to habitat suitability of the fountain darter. Quantitatively measuring change and observing spatial patterns and trends in the data can help inform management decisions involving native vegetation restoration and conservation, through native planting and invasive removal efforts. Although there is existing research which examines quantitative trends in the amounts of SAV at these sites over time (BIO-WEST 2020), it is primarily focused on year-to-year total areal coverage measurement comparisons and does not examine changes in the spatial patterns in the distribution of SAV.

This directed research investigates patterns and trends in the spatial distribution and diversity of SAV in three sections of the San Marcos River during the period of 2013-2019. Specifically, this project explores the following research questions:

1. **What are the absolute areal coverage amounts and relative proportions of the different SAV species in the three long term biological goal reaches in the San Marcos River for the years 2013-2019?**
2. **Where are there highest and lowest areas of planting and removal of SAV?**
3. **Where are the areas of highest diversity over time of natives and invasives?**
4. **Where are the areas of predominantly Texas wild-rice and where have those contracted and expanded over time?**

This is a GIS-focused research project using mapping and spatial analysis techniques to explore changes in and visualize the data over the subject years for management purposes. Measuring spatial and temporal changes in SAV and providing visual representation of the patterns is important in informing management decisions involving native vegetation restoration and non-native vegetation management by helping to evaluate outcomes and in the allocation of resources. This research does not intend to provide a causation of why this vegetation is changing, but rather to describe the patterns of how the vegetation is changing and provide digital data-sets that may be useful to EAHCP stakeholders managing and protecting the San Marcos River. Because different external factors can affect the abundance of SAV species from year to year, it is difficult to attribute causation directly, but a general trend in the data would seem to support that conservation efforts in native planting and invasive removal are successful.

II. Materials and Methods

This directed research project investigated changes in spatial distribution and diversity of SAV in three study reaches of the San Marcos River. The specific objectives were to measure absolute areal coverage amounts and relative proportions of SAV of the study years and to investigate spatial trends in planting and removal of SAV, the dispersion of Texas wild-rice-dominant stands of SAV, and native and invasive SAV species.

Data

The entirety of the data is a secondary data set collected as part of the EAHCP's bio-monitoring program, conducted by BIO-WEST, Inc. and the Habitat Conservation Plan habitat crew members with the Meadow Center for Water and the Environment. Summary results of these data are available publicly via the EAA's website through annual reports and the raw data can be requested from them as well. The EAA provided geographic datasets including shapefiles and file geodatabases of data including polygons for planting, removal, and measured spatial extent of SAV for the years 2013-2020, as well as polygons of the reach boundaries for the three study areas used in this project. The HCP collects data in April and October each year; this research used the April data. Vegetation was mapped using a Trimble Geoexplorer 6000 and a Trimble Tempest External Antenna which is capable of sub-meter accuracy. Stands of vegetation were mapped down to a spatial resolution of 0.5m x 0.5m point, anything less than 0.5m was not mapped due to GPS accuracy. For the reach boundaries, a file geodatabase containing a feature dataset which had all the study reaches for both the Comal and San Marcos river systems; for these purposes only San Marcos River data were used. The planting polygons included a single shapefile containing polygons for all reaches for all years; the same was done for removal polygons. The SAV extent data included shapefiles for each reach for each year. All datasets were projected to in the NAD 1983 UTM Zone 14N coordinate system.

Study Area

Three reaches are used for measuring change in the submerged aquatic vegetation in the San Marcos Springs ecosystem as part of the EAHCP bio-monitoring program (EAA 2012), including Spring Lake Dam (SLD), City Park (CP), and the Interstate 35 (I35) reach (Figure 1).

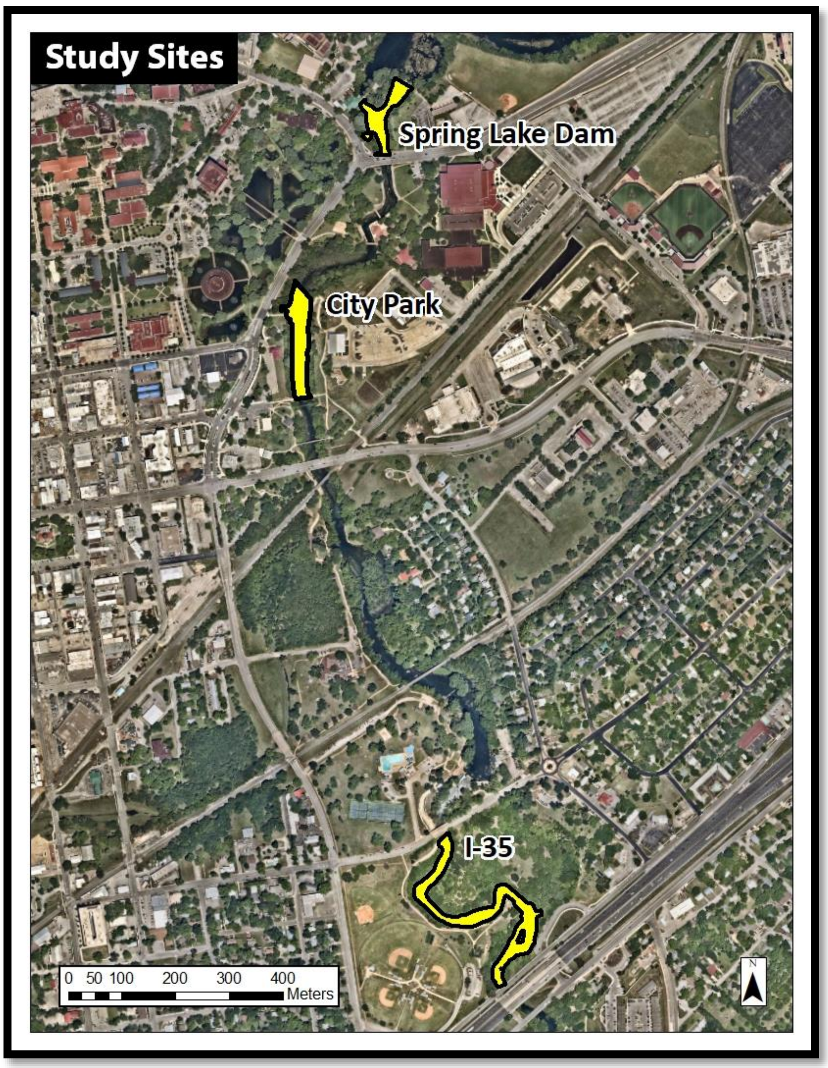

Figure 1: Location of surveyed sites.

Data Preparation

Esri ArcGIS Pro software was used for all spatial analyses. Many of the repetitive steps for data manipulation were scripted using Python 3 and the arcpy library. The IDE PyCharm was the software used for scripting. The data for SAV removal, planting, and extent was in three shapefiles for all reaches and all years. The end objective was polygon feature classes and rasters for each species of SAV for each year.

The data analyses followed this general sequence: (1) The first step involved clipping the removal/planting data by each of the reach boundaries to eliminate any portions of the data not within reach boundaries, this was necessary for subsequent raster calculations. (2) After clipping, the Select by Attributes tool was used to select all species for a single year and creating individual feature classes of planting/removal by year. (3) Each individual species was then selected by name using the Select by Attributes tool and a new feature class for each species for each year was created. (4) Next, the Dissolve analysis tool was used to create a single polygon for each species from multipart polygons; no dissolve field was used as no aggregation of features was needed. (5) The Union tool was used with the appropriate reach boundary to combine the planting/removal data with the reach polygons to be able to perform binary raster calculations. (6) A value field was added to each feature and was calculated as either 1 for polygons of planting or removal, or 0 for values which did not correspond to areas of planting or removal. (7) Finally, the Polygon to Raster tool was used on these feature classes to obtain a raster of each species by reach by year, with a value of 1 assigned for areas corresponding to planting or removal of SAV.

Areal Coverage, Relative Proportions, and Percent Change

The polygons created via data manipulation each correspond to a particular species in a particular reach in a particular year and contain a 'shape' field corresponding to an area-based measurement which is calculated automatically by the software with units specified in the map documents to square meters. These area values populated tables for areal coverage by species/reach/year and were then aggregated across years and reaches. Relative proportions for each species were calculated by dividing the area of a particular species' polygons by the total areal coverage in that reach for that year. Percent change between years was calculated at the species level and by reach using Eq. (1).

$$\frac{a_y - a_x}{a_x} \qquad \begin{array}{l} a_x = \text{areal covereage of original year} \\ a_y = \text{areal coverage of following year} \end{array} \tag{1}$$

Raster Calculations

The areas of highest and lowest concentrations of plantings and removals of SAV were aggregated with raster addition for each reach. The individual binary rasters for planting/removal of each species for all years were added together. The resulting final raster displayed cumulative totals with higher values corresponding to areas of many overlapping locations of planting/removal and lower values indicating fewer overlapping locations of these activities.

Raster addition was also used as a step in looking at trends in the concentration of natives and invasives over time. For each reach, all the individual binary rasters of the existing extent of each species for all years were summed. Similarly, the output raster had higher values corresponding to areas of overlapping natives/invasives and lower values indicating fewer overlapping natives and invasives.

To examine areas of predominantly Texas wild-rice, raster addition was used with an additional step to convert binary raster values to values which correspond to the year that TWR was present in that location. Simple binary rasters were created for each reach for each year. Then, the

Reclassify tool from the Spatial Analysis toolkit was used to reassign the binary value of 1 to the corresponding value for each year by increasing order of magnitude (Table 1) and create seven new reclassified rasters.

Table 1 – Raster reclassification values

Raster Value	Year
0	No TWR Mapped
1	2013
10	2014
100	2015
1000	2016
10000	2017
100000	2018
1000000	2019

These seven rasters were summed using the Raster Calculator tool, and a single output raster was created. Individual pixel values in the output raster can be used to determine which years TWR was present in that location, e.g., a pixel value of 111 would indicate that TWR was present in that spatial location for the years 2013, 2014 and 2015 (1 + 10 + 100 = 111), whereas a pixel value of 101 would indicate that TWR was only present for the years 2013 and 2015 (1 + 100 = 101). Because the output raster would contain 119 unique classes or combinations of pixel values, visualizing this output cohesively is difficult. The creation of the final raster dataset with 119 classes is not intended for cartographic display of all the classes simultaneously, but to provide a digital data-set that can be queried for years of interest to examine spatial presence or absence over single years or any combination of multiple years. In addition to the coded output raster, a simple binary summation was created on the individual binary rasters for each reach for all years. The output raster had pixel values ranging from 1-7 corresponding to the number of years TWR was present at a given spatial location. These simple sum rasters are more easily visualized and interpreted, but do not give information as to which specific years TWR was present at a location.

Heat Maps

A heat map for each year for each reach provides an effective way to examine trends in the distribution of native and invasive species. Developing heat maps requires converting the sum rasters for species extents back to polygons with the Raster to Polygon tool, with the value of the raster assigned to a field in the output polygon. A polygon fishnet was generated using the Create Fishnet tool, with the extent set to each reach and a cell size of 0.5 meters x 0.5 meters. This fishnet was clipped to the individual reach boundaries. A spatial join was then used to join the sum-raster-polygon to the clipped fishnet. Finally, the Feature to Point tool was run on this joined feature class, which converted each individual 0.5 meters x 0.5 meters cell into a point with the same values from the input polygon cell. The point layer was then symbolized as a heat map with the weight field set the sum raster value.

III. Results and Discussion

Because there are many different factors which can affect the coverage of SAV species from year to year, this research does not intend to provide a causation of why this vegetation is changing, but rather to describe the patterns of how the vegetation is changing.

Changes to Native and Invasive SAV

The absolute areal coverage amounts in square meters and percent change of natives and invasives in each reach over the study years can be seen in figures 2-7. Tables 2-7 contain absolute areal coverage of each species in each reach over the study years as well as percent change over time.

Table 2 – CP Existing Extent Areal Coverage (m^2)

Species	2013	2014	2015	2016	2017	2018	2019	Cumulative
Bacopa	0	0	0	2	1	0	0	0
Cabomba	1	0	0	0	0	2	41	40
Ceratophyllum	0	0	0	0	0	0	3	3
Ceratopteris	0	0	0	0	0	3	14	14
Colocasia	201	0	0	0	0	0	0	-201
Eicchornia	32	0	0	0	0	0	9	-23
Emory Sedge	0	0	0	0	0	0	3	3
Heteranthera	0	5	16	4	0	1	1	1
Hydrilla	2666	1747	1098	748	919	422	214	-2452
Hydrocotyle	0	0	0	14	2	1	0	0
Hygrophila	1034	507	640	679	228	294	335	-698
Ludwigia repens	1	7	5	5	3	54	94	93
M. heterophyllum	0	1	0	0	0	0	1	1
Nasturtium	21	17	43	7	0	3	4	-17
Potamogeton	483	159	107	151	164	176	382	-101
Sagittaria	74	122	128	129	146	164	46	-28
Vallisneria	6	5	5	0	0	3	0	-6
Zizania (TWR)	353	551	1345	1605	2218	1969	1924	1571
Totals	4870	3120	3387	3344	3681	3093	3071	-1799

Table 3 – CP Existing Extent Percent Change

Species	2014	2015	2016	2017	2018	2019	Cumulative
Bacopa				-69%	-16%	18%	-70%
Cabomba	-100%			-100%		1563%	3293%
Ceratophyllum							
Ceratopteris						389%	389%
Colocasia	-100%						-100%
Eicchornia	-100%						-72%
Emory Sedge							
Heteranthera		205%	-77%	-100%		-31%	-81%
Hydrilla	-34%	-37%	-32%	23%	-54%	-49%	-92%
Hydrocotyle				-86%	-58%	-85%	-99%
Hygrophila	-51%	26%	6%	-66%	29%	14%	-68%
Ludwigia repens	552%	-27%	-9%	-29%	1468%	74%	8355%
M. heterophyllum		-100%					-100%
Nasturtium	-19%	159%	-83%	-100%		37%	-82%
Potamogeton	-67%	-32%	41%	9%	7%	118%	-21%
Sagittaria	64%	5%	1%	13%	13%	-72%	-38%
Vallisneria	-8%	-6%	-100%			-100%	-100%
Zizania (TWR)	56%	144%	19%	38%	-11%	-2%	446%
Totals	-36%	9%	-1%	10%	-16%	-1%	-37%

Table 4 – I35 Existing Extent Areal Coverage (m^2)

Species	2013	2014	2015	2016	2017	2018	2019	Cumulative
Acmella	4	0	41	0	0	0	4	0
Alternanthera	0	0	10	8	0	0	0	0
Cabomba	93	134	162	105	50	96	54	-39
Ceratophyllum	46	7	1	0	0	0	3	-43
Colocasia	58	78	35	0	0	0	0	-58
Heteranthera	2	1	2	1	1	5	11	10
Hydrilla	72	295	781	35	58	62	181	109
Hydrocotyle	2	0	0	1	22	1	11	9
Hygrophila	20	512	349	419	398	786	675	655
Ludwigia repens	2	64	19	57	152	232	190	188
Justicia	6	0	0	0	0	0	0	-6
Nasturtium	2	46	46	0	0	0	21	19
Nuphar	0	23	23	41	18	41	44	44
Potamogeton	0	0	0	0	17	0	0	0
Sagittaria	8	212	212	328	433	552	381	373
Zizania (TWR)	133	360	424	178	256	549	743	610
Zizaniopsis	0	0	5	0	0	0	0	0
Totals	450	1734	2112	1172	1404	2325	2320	1870

Table 5 – I35 Existing Extent Percent Change

Species	2014	2015	2016	2017	2018	2019	Cumulative
Acmella	-100%		-100%				-9%
Alternanthera			-25%	-100%			-100%
Cabomba	44%	21%	-35%	-53%	93%	-44%	-42%
Ceratophyllum	-84%	-89%	-100%				-93%
Colocasia	34%	-55%	-100%				-100%
Heteranthera	-23%	53%	-29%	-2%	288%	115%	581%
Hydrilla	309%	164%	-95%	64%	7%	191%	151%
Hydrocotyle	-100%			1673%	-95%	952%	395%
Hygrophila	2440%	-32%	20%	-5%	98%	-14%	3249%
Ludwigia repens	2492%	-70%	199%	167%	53%	-18%	7624%
Justicia	-100%						-100%
Nasturtium	1797%	0%	-100%				767%
Nuphar		0%	79%	-57%	135%	7%	95%
Potamogeton					-100%		-100%
Sagittaria	2674%	0%	54%	32%	28%	-31%	4873%
Zizania (TWR)	170%	18%	-58%	44%	115%	35%	458%
Zizaniopsis			-100%				-100%
Totals	285%	22%	-44%	20%	66%	0%	416%

Table 6 – SLD Existing Extent Areal Coverage (m^2)

Species	2013	2014	2015	2016	2017	2018	2019	Cumulative
Bacopa	0	0	0	1	0	0	2	2
Cabomba	0	0	3	0	0	0	4	4
Ceratophyllum	0	33	0	0	0	0	0	0
Ceratopteris	0	0	0	0	0	1	2	2
Eicchornia	0	0	0	0	11	0	0	0
Heteranthera	0	1	0	1	0	0	1	1
Hydrilla	592	152	194	14	3	0	0	-592
Hydrocotyle	55	84	81	60	67	135	129	75
Hygrophila	99	79	62	54	53	24	55	-45
Ludwigia repens	31	1	0	0	0	20	10	-22
Nasturtium	1	8	0	0	0	1	0	-1
Pistia	0	0	0	0	19	0	0	0
Potamogeton	296	180	108	38	124	200	131	-166
Sagittaria	55	60	12	10	12	14	29	-26
Vallisneria	150	110	63	1	1	3	0	-150
Totals	1281	707	524	178	289	398	363	-918

Table 7 – SLD Existing Extent Percent Change

Species	2014	2015	2016	2017	2018	2019	Cumulative
Bacopa			95%	-100%			381%
Cabomba			-100%			1146%	34%
Ceratophyllum		-100%					-100%
Ceratopteris						46%	46%
Eicchornia					-100%		-100%
Heteranthera		-100%		-100%			167%
Hydrilla	-74%	28%	-93%	-80%	-100%		-100%
Hydrocotyle	54%	-4%	-26%	12%	101%	-4%	137%
Hygrophila	-21%	-22%	-13%	-3%	-55%	131%	-45%
Ludwigia repens	-97%	-100%				-51%	-69%
Nasturtium	456%	-100%				-100%	-100%
Pistia					-100%		-100%
Potamogeton	-39%	-40%	-64%	223%	62%	-35%	-56%
Sagittaria	8%	-79%	-22%	26%	11%	115%	-47%
Vallisneria	-27%	-43%	-99%	-8%	441%	-100%	-100%
Totals	-45%	-26%	-66%	62%	38%	-9%	-72%

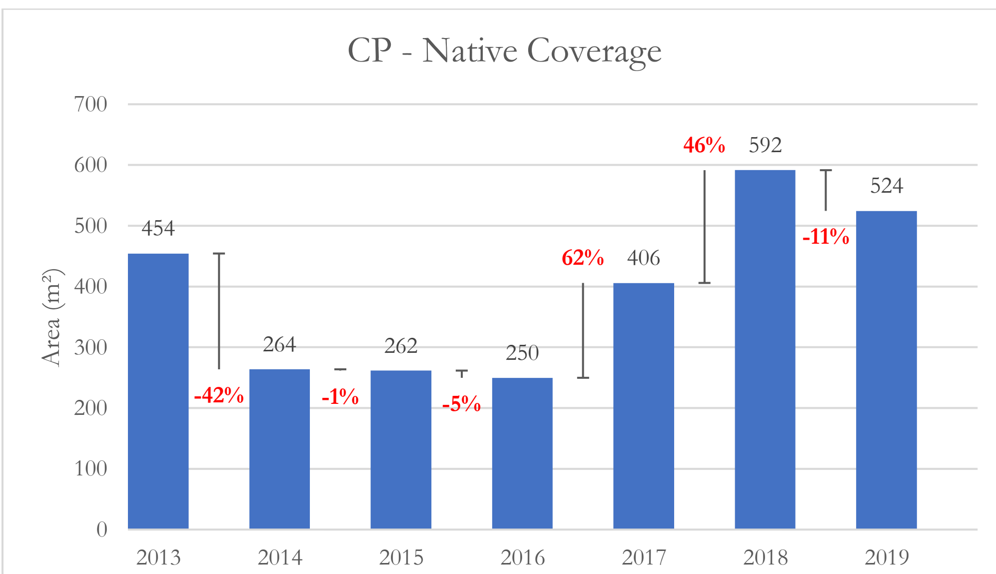

Figure 2 – CP Native Existing Extent Areal Coverage and Percent Change (m^2)

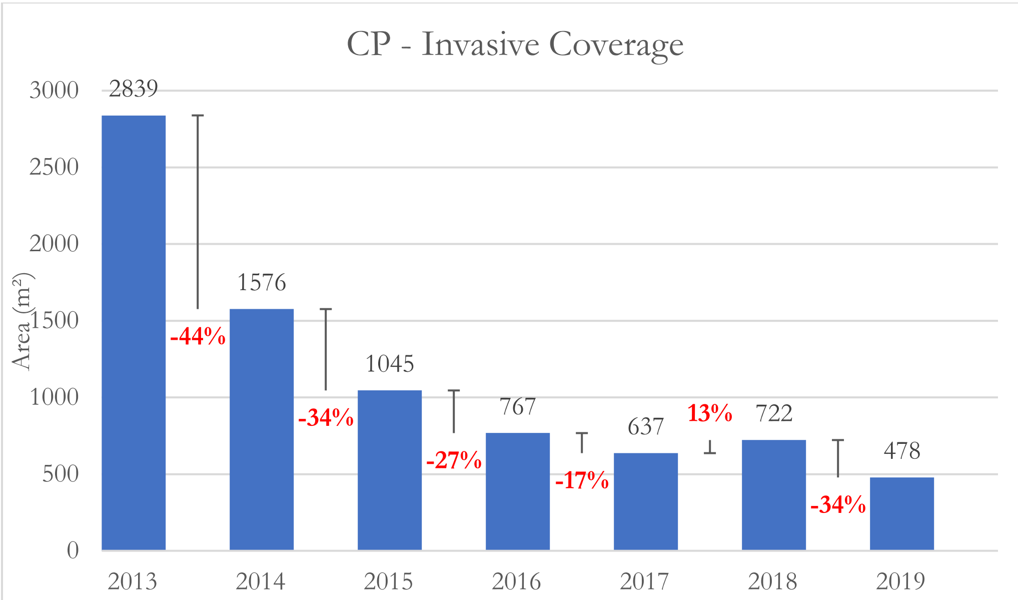

Figure 3 – CP Invasive Existing Extent Areal Coverage and Percent Change (m^2)

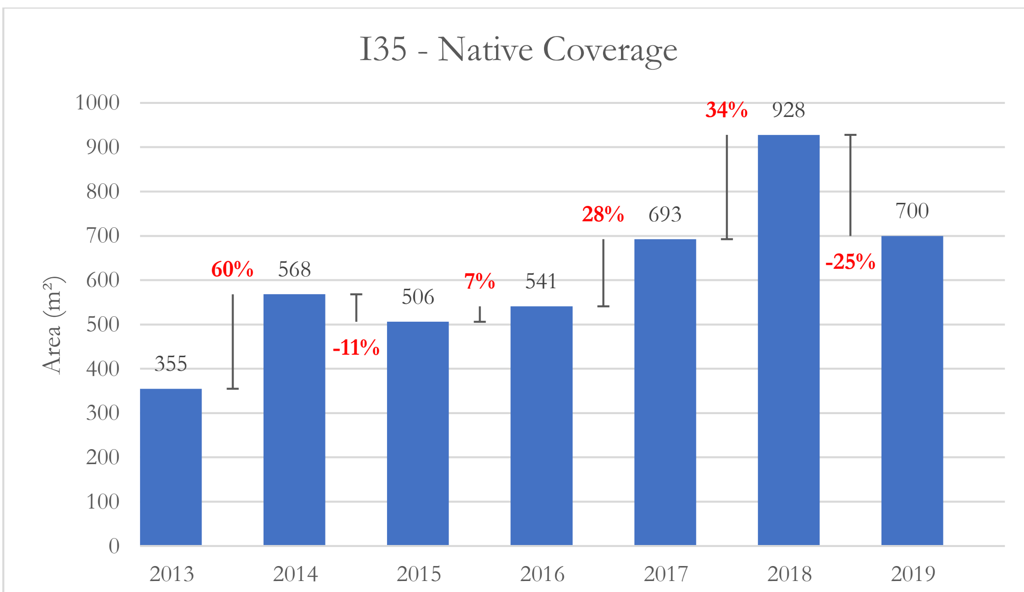

Figure 4 – I-35 Native Existing Extent Areal Coverage and Percent Change (m^2)

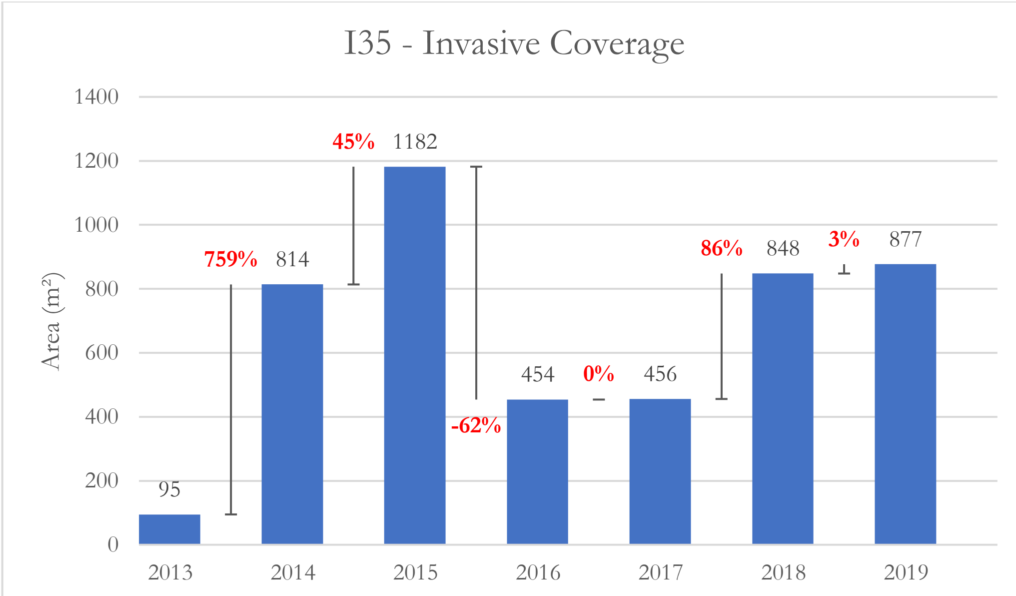

Figure 5 – I-35 Invasive Existing Extent Areal Coverage and Percent Change (m^2)

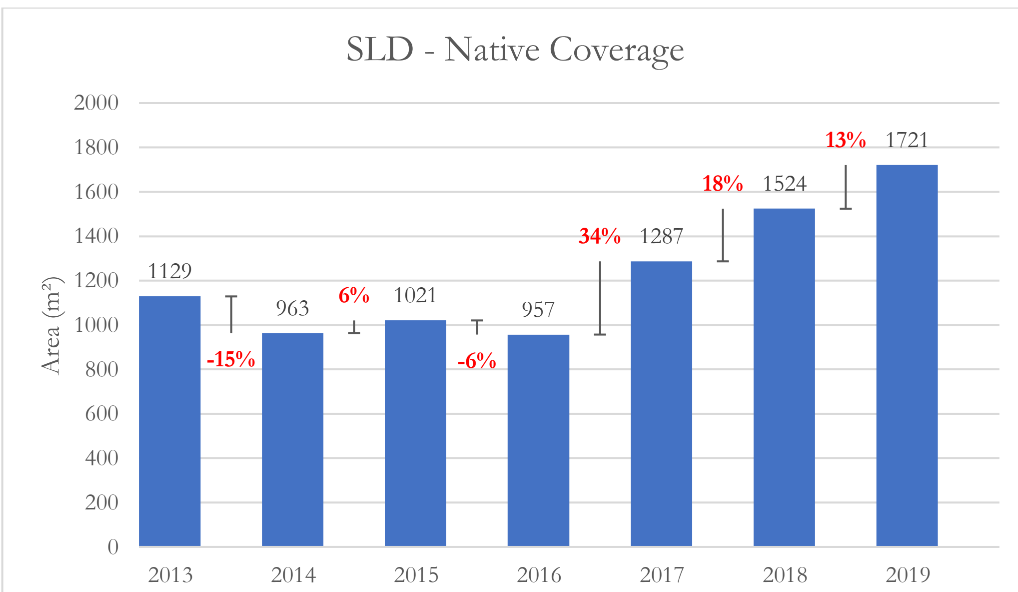

Figure 6 – SLD Native Existing Extent Areal Coverage and Percent Change (m^2)

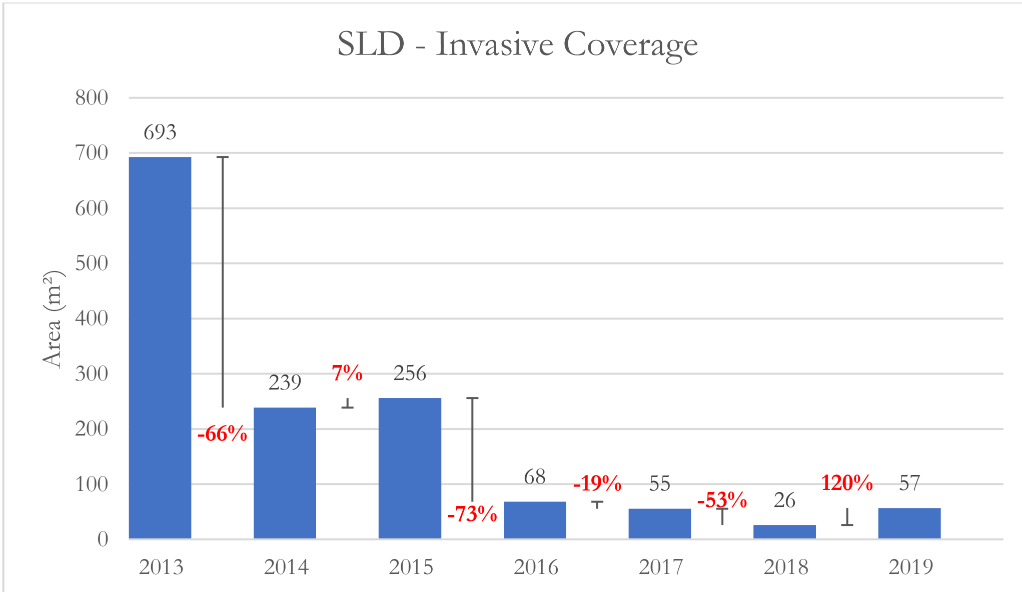

Figure 7 – SLD Invasive Existing Extent Areal Coverage and Percent Change (m^2)

Over the study years, total SAV coverage decreased by 1799m^2/37% and 918m^2/72% in the CP and SLD reaches, respectively (Tables 2, 3, 6, 7), but this is in part due to a large reduction in the amount of hydrilla (2452m^2/92% and 592m^2/100%)—an invasive species targeted for removal—and is an indication of successful removals efforts as part of the bio-monitoring program. Total SAV coverage increased at the I35 site over the study years by 1870m^2/416%, including large gains in TWR (610m^2/459%) and Sagittaria (373m^2/4860%), which were targeted species for planting (Tables 4-5).

Patterns in SAV Removal and Planting Activities

Raster summation for the study years resulted in areas of extent and concentration of SAV removal and plantings at the three sites (Figures 8-10). Darker areas correspond to areas of overlap of SAV in that spatial location over the years and indicate that these areas had concentration of SAV planting or removal. For removals, darker areas could correspond to stands which continue to thrive despite removal efforts. Darker areas of planting species might indicate areas where planting efforts have been less successful in establishing native species which propagate on their own. However, this research did not examine if there exists overlap or areas of coincidence of planting or removal with the measured extent of native and invasive SAV to support this conjecture. It might be interesting for future research to explore possible spatial autocorrelation.

Table 8 – CP SAV Removal (m^2)

Species	2014	2015	2016	2017	2018	2019	Totals
Hydrilla	678	788	22	213	505	23	2229
Hygrophila	349	160	75	472	406	0	1462
Nasturtium	0	35	0	3	0	0	38
Veg Mat	0	281	188	33	55	0	557
Totals	1027	1264	285	720	966	23	4285

Table 9 – CP SAV Planting (m^2)

Species	2014	2015	2016	2017	2018	2019	Totals
Cabomba				34	61		95
Heteranthia	71	56	1				129
Hydrocotyle			0	0			0
Ludwigia	123	76	4	59	163		426
Potamogeton		3	12	100	306		422
Sagitaria	67	69		78	9		223
TWR	499	625	16		4	25	1169
Totals	761	829	32	272	543	25	2463

Table 10 – I35 SAV Removal (m^2)

Species	2016	2017	2018	2019	Totals
Hydrilla	477	205	147	828	1657
Hygrophila	522	224	449	1196	2391
Veg Mat		83	26	109	218
Totals	999	513	621	2133	4267

Table 11 – I35 SAV Planting (m^2)

Species	2016	2017	2018	2019	Totals
Cabomba	17	19	55		91
Hydrocotyle	146	28	18		193
Ludwigia	159	57	49		265
Potamogeton	56	67	71		194
Sagitaria	101	17	97		215
TWR	111	174	86	44	416
Totals	591	363	376	44	1374

Table 12 – SLD SAV Removal (m^2)

Species	2014	2017	2018	2019	Totals
Cutgrass	3				3
Hydrilla	2	20	11	7	41
Hygrophila		88	78		167
Veg Mat		405	1991		2397
Watercress				2	2
Water Hyacinth			49		49
Totals	5	514	2130	10	2658

Table 13 – SLD SAV Planting (m^2)

Row Labels	2017	2018	Totals
Cabomba	7	17	24
Hydrocotyle	8		8
Ludwigia	39	31	70
Sagitaria	1	47	48
Totals	55	95	150

SAV removal in the SLD site was concentrated primarily in the center and northern parts of the site (Figure 8). Most of the removal occurred in 2018, constituting approximately 2130m^2 (Table 12). Total area removed for other years in SLD was 528m^2 (Table 12). CP SAV removal occurred throughout a large portion of the site with higher concentrations occurring in the central area (Figure 9). Removal was consistently high except for 2016 and 2019. SAV removal at I35 was primarily concentrated in the southern section of the site near the I-35 interstate crossing and the amount removed was consistently high—more than 500m^2 (Table 10)—for all years in which removal occurred (2016-2018) (Figure 10). SAV planting at SLD was concentrated in the center of the reach and only occurred in 2017 (55m^2) and 2018 (95m^2) (Figure 8, Table 13). In CP, like SAV removal, planting occurred over a large portion of the site. 2014, 2015, and 2018 were years of high areas of planting, at 760, 829, and 543m^{2}of SAV planted, respectively (Figure 9, Table 9). I35 SAV planting occurred in the middle and southern sections of the site (Figure 10, Table 11). The amount of planted SAV decreased over time from 591m^2 in 2016 to 44 m^2 in 2019 (Table 11).

The ideal trend would be an overall decreased area of removal activities and a corresponding decreased coverage of invasive SAV. The plantings supplement areas of removal to encourage native plant growth and thus a primary goal includes increased coverage of native SAV.

Figure 8 – SAV Removal and Planting, SLD - Numeric values correspond to the number of years SAV has been actively modified through removal or planting at this location in the SLD reach.

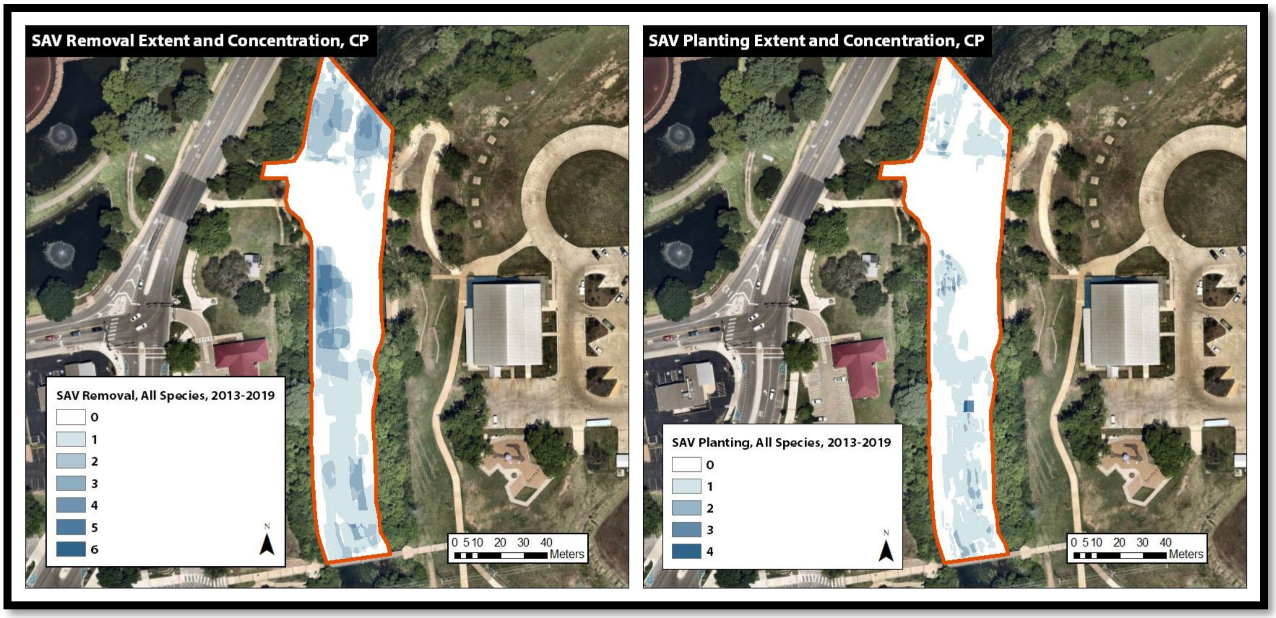

Figure 9 – SAV Removal and Planting, CP - Numeric values correspond to the number of years SAV has been actively modified through removal or planting at this location in the CP reach.

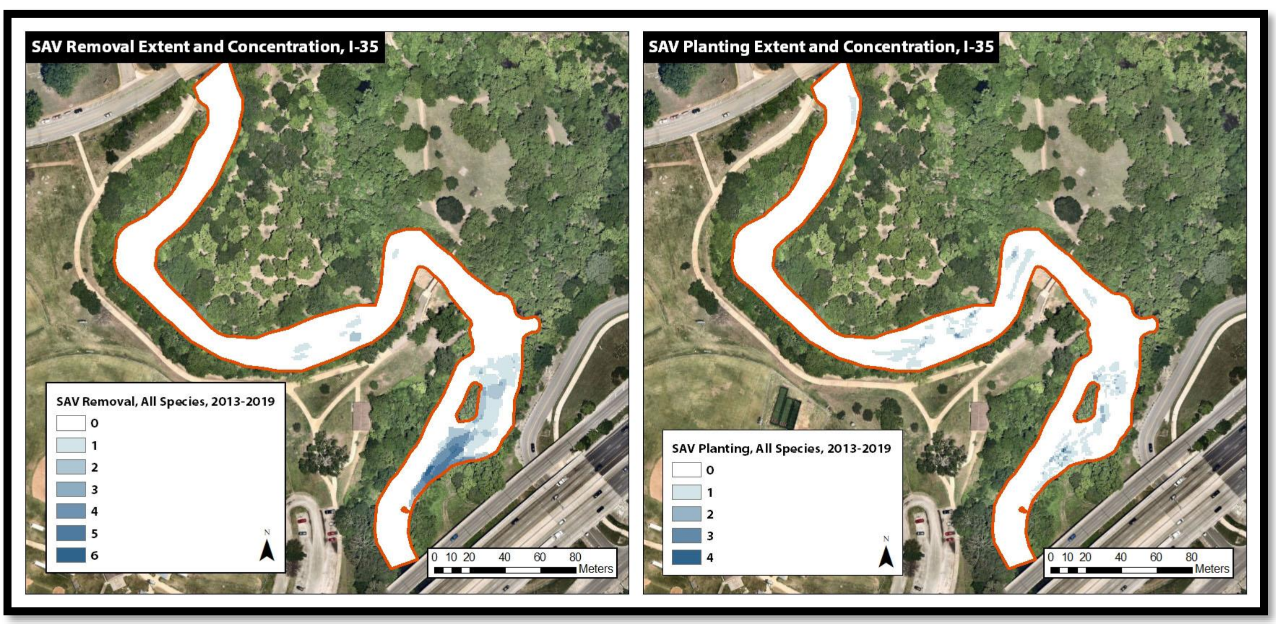

Figure 10 – SAV Removal and Planting, I-35 - Numeric values correspond to the number of years SAV has been actively modified through removal or planting at this location in the I35 reach.

Native and Invasive Diversity Heatmaps

Heatmaps were created to show the concentration of natives and invasives over time (Figures 11-22). These heatmaps are used to visualize the magnitude of the concentration of SAV in a spatial location, with areas of lower concentration in the darker red hues and areas of higher concentration in lighter yellow. Ideally, we would see an overall reduction in intensity and size in the darker values in the invasive maps at each site over time which would correlate with an overall reduction in SAV at those locations and, conversely, an increase and size in intensity in the darker values in the native maps which would correspond to an increase in size and density of native species in those locations. These maps can help to visualize trends in native and invasive distribution and can be a tool in evaluating conservation efforts.

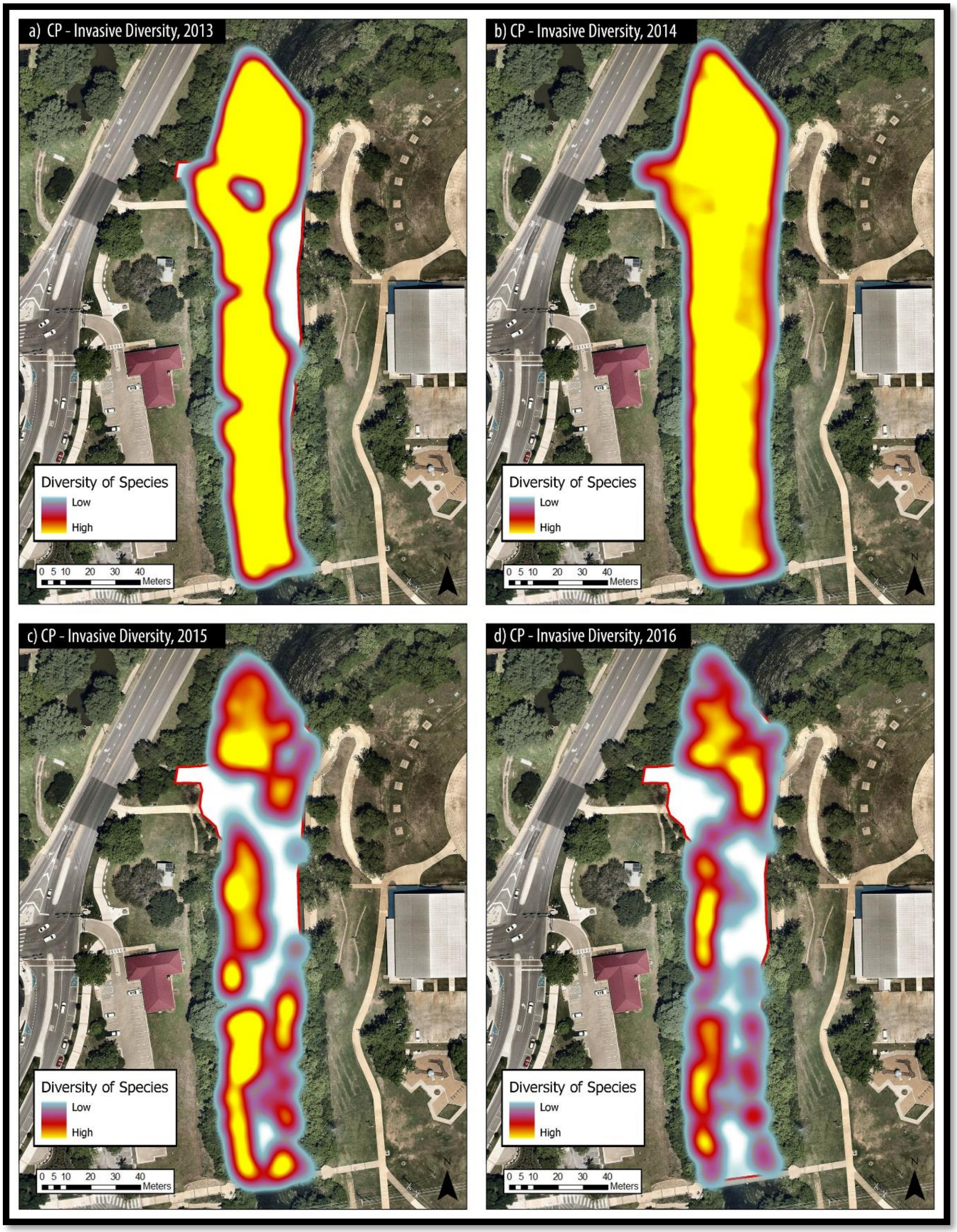

Figure 11 – CP Invasive Diversity

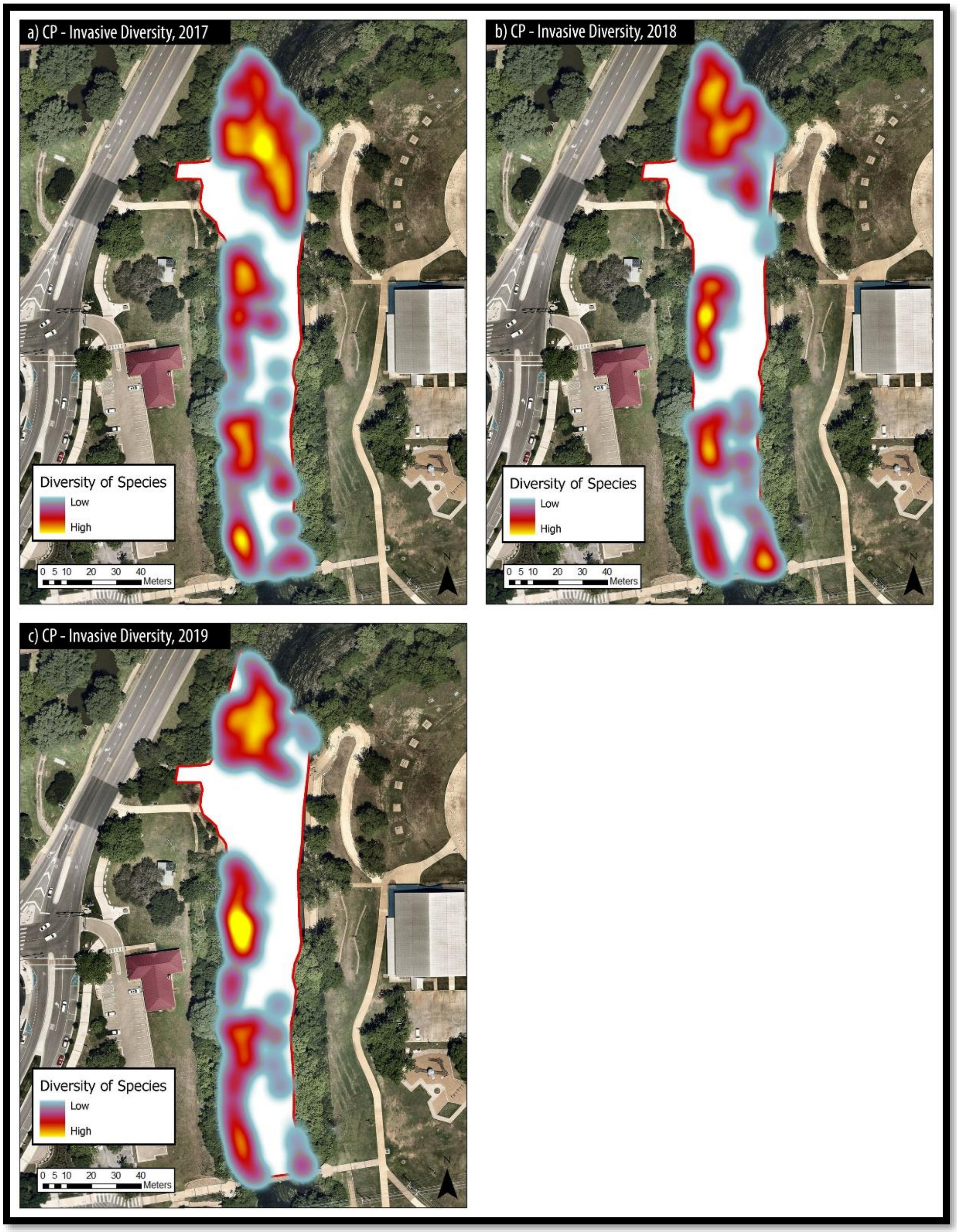

Figure 12 – CP Invasive Diversity

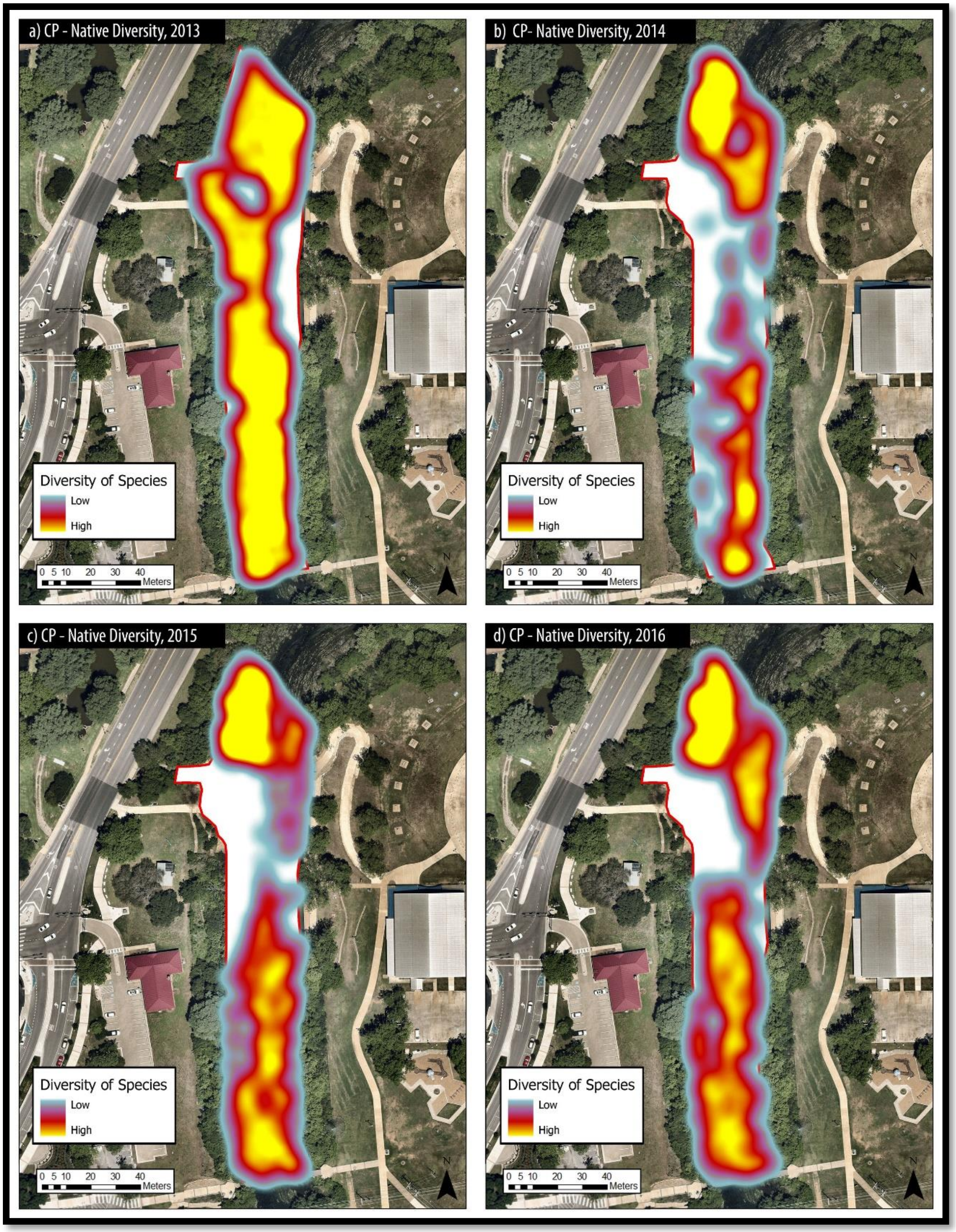

Figure 13 – CP Native Diversity

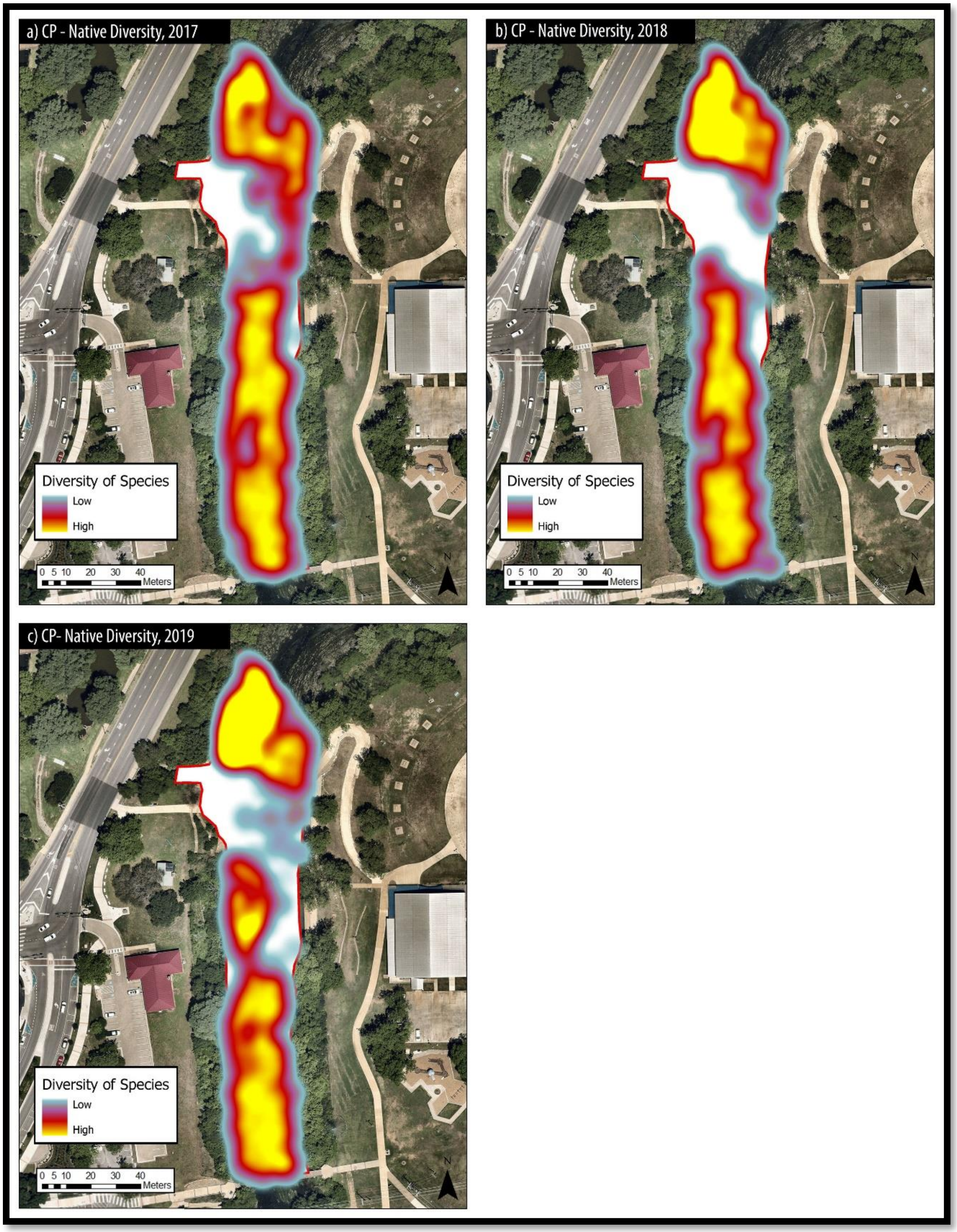

Figure 14 – CP Native Diversity

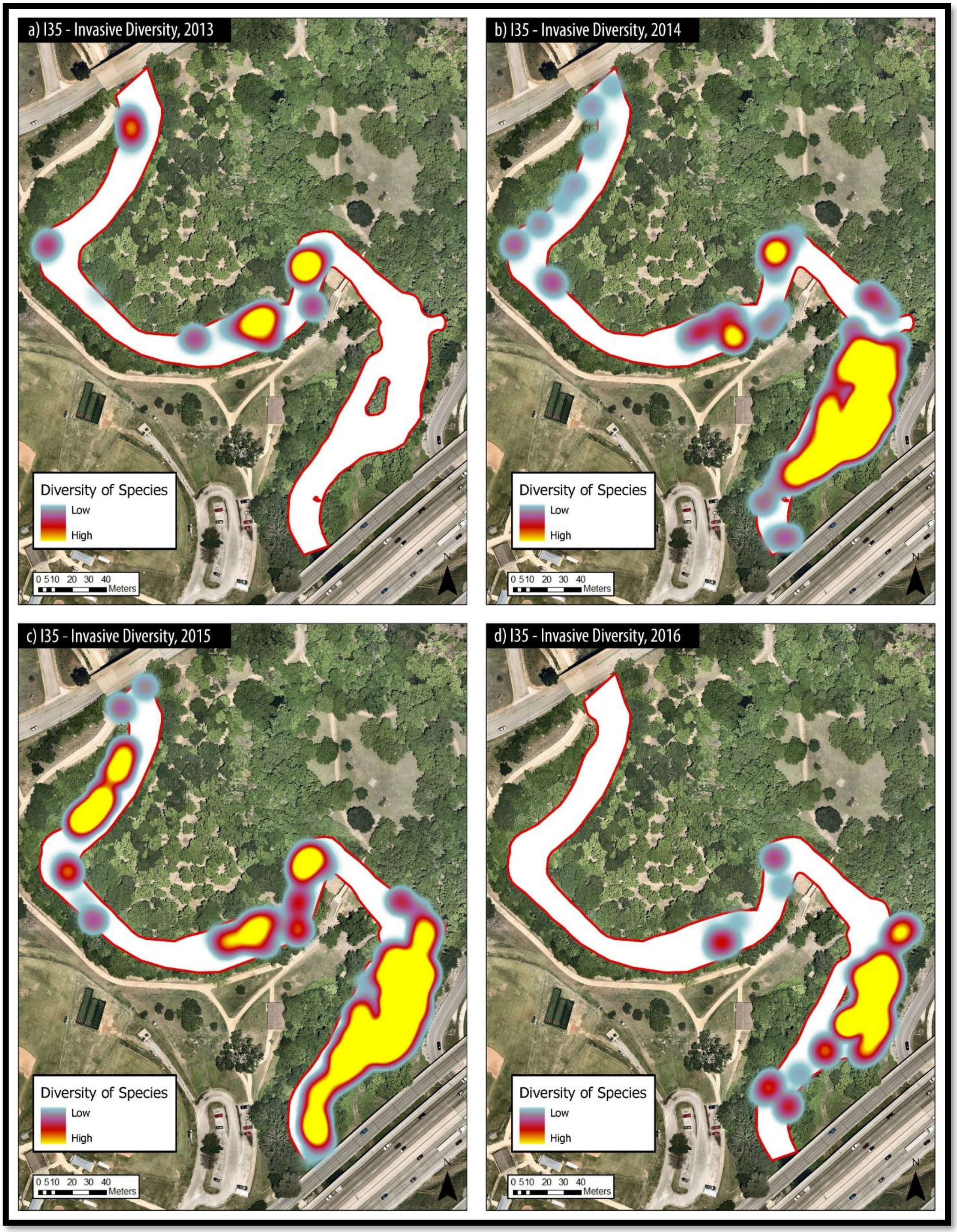

Figure 15 – I35 Invasive Diversity

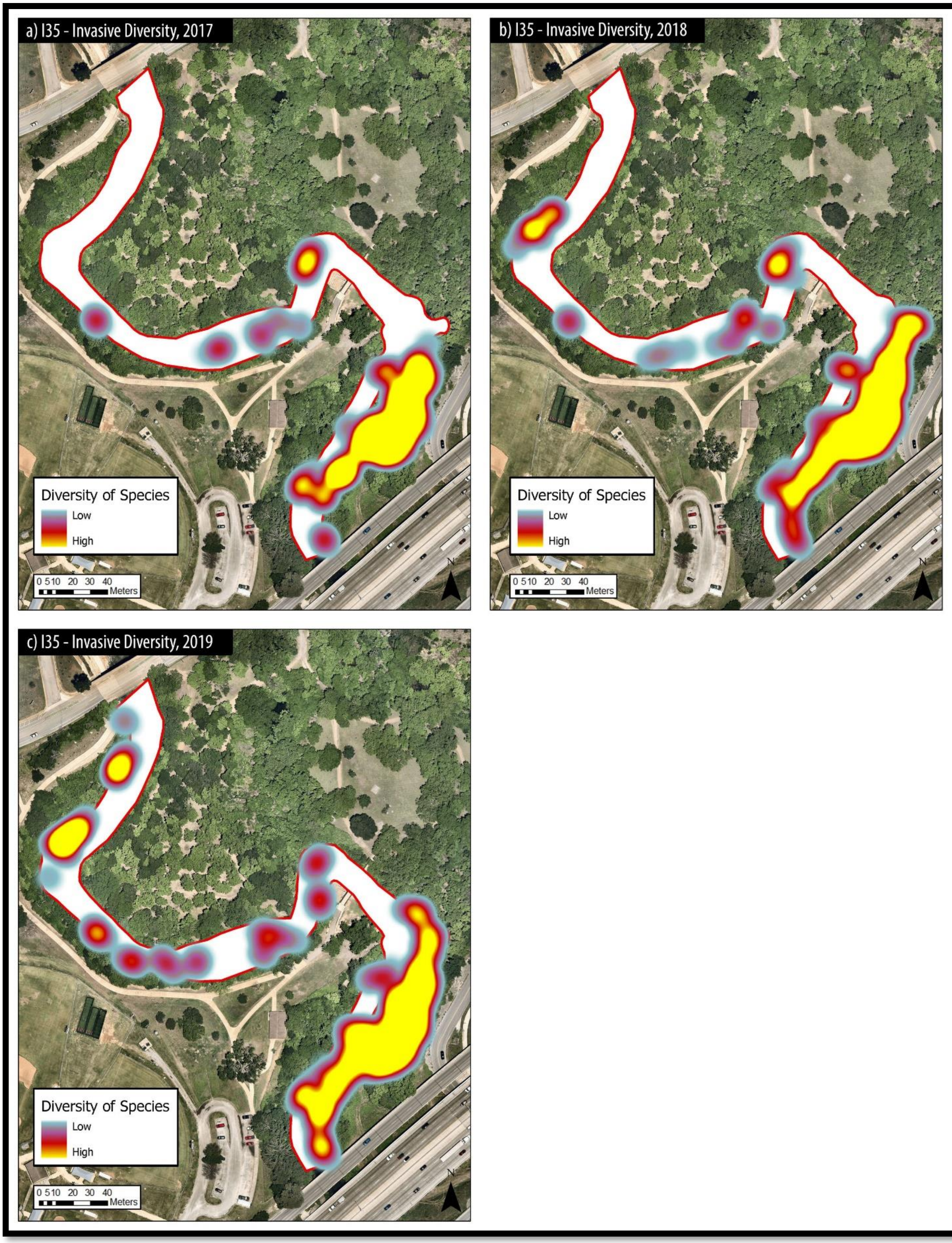

Figure 16 – I35 Invasive Diversity

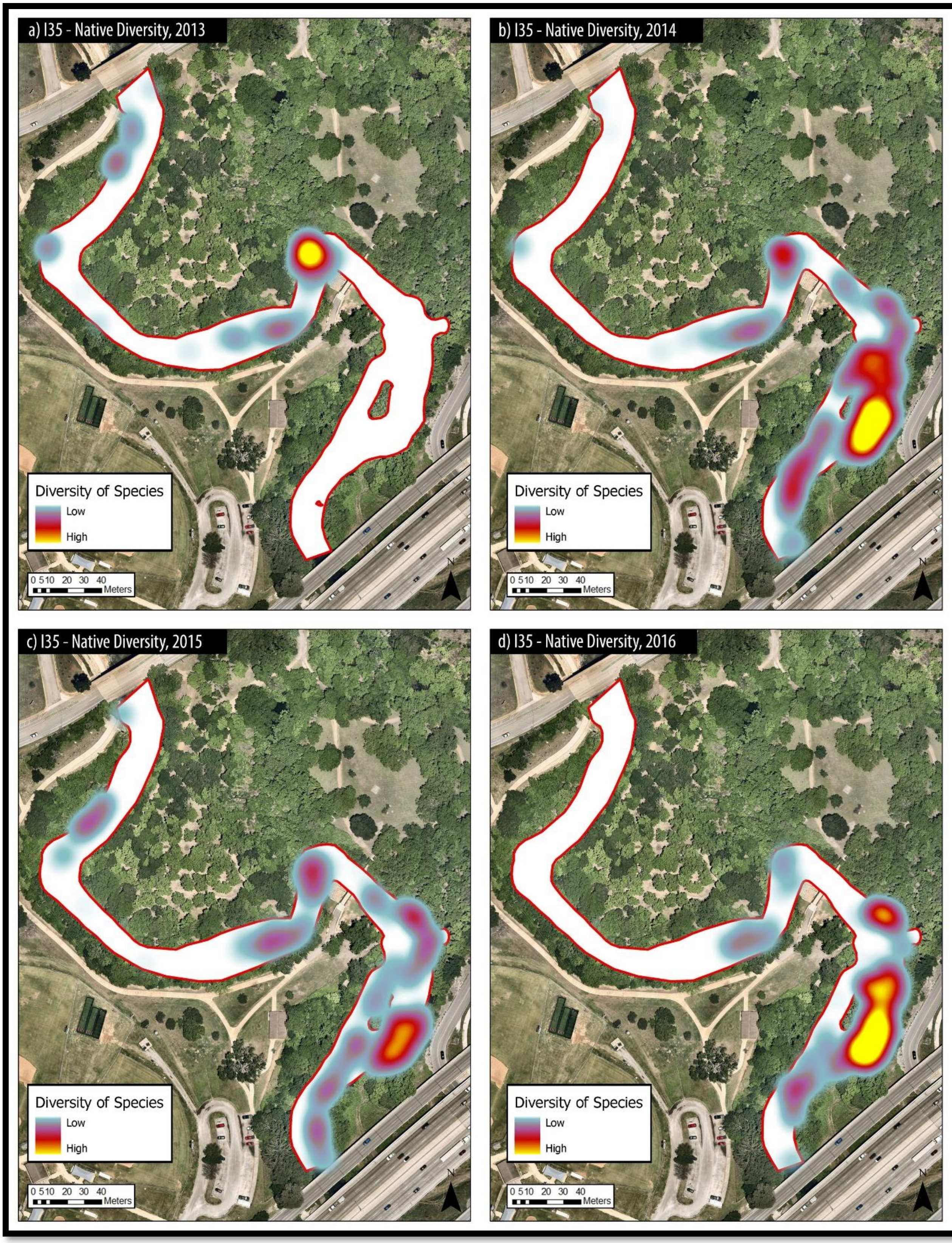

Figure 17 – I35 Native Diversity

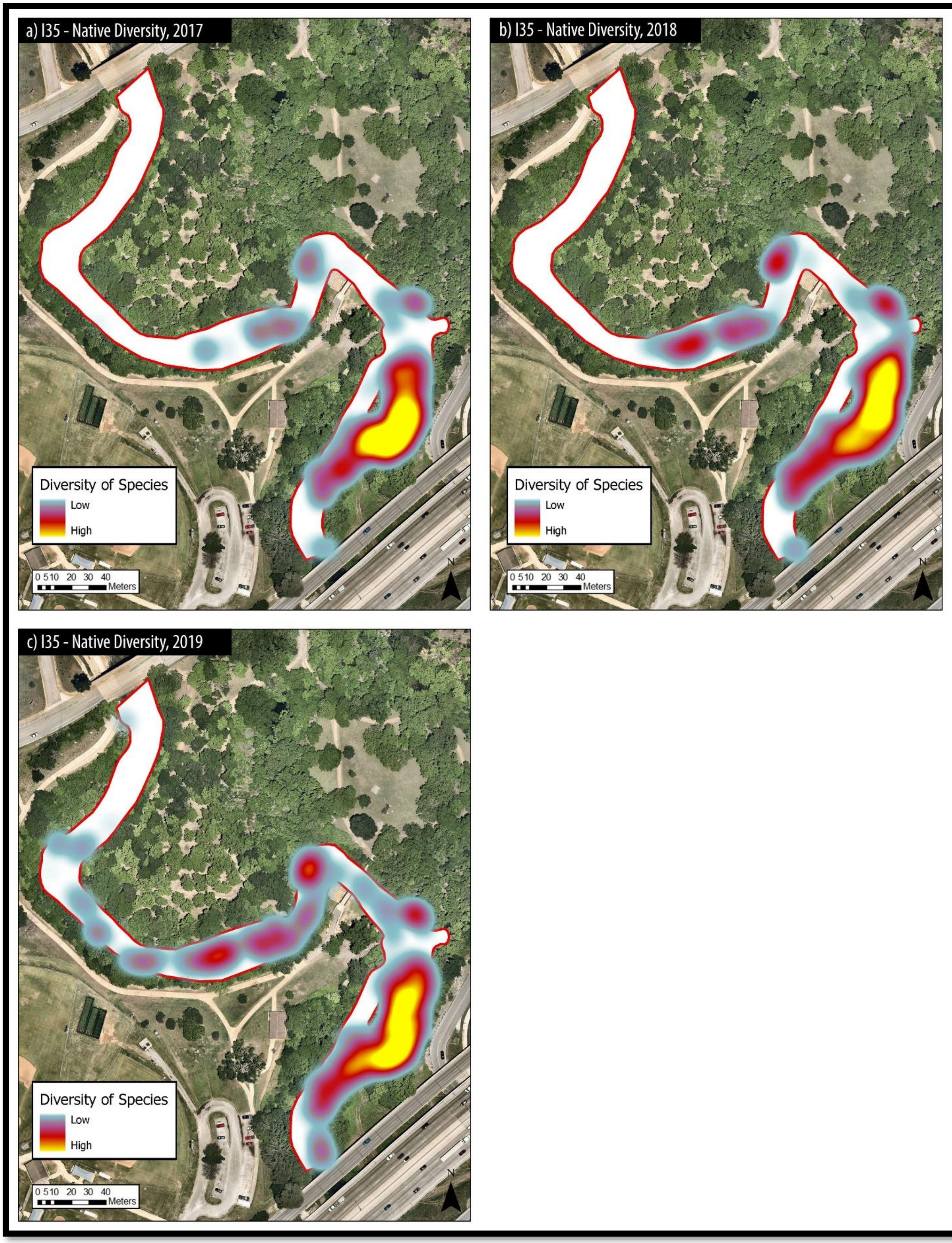

Figure 18 – I35 Native Diversity

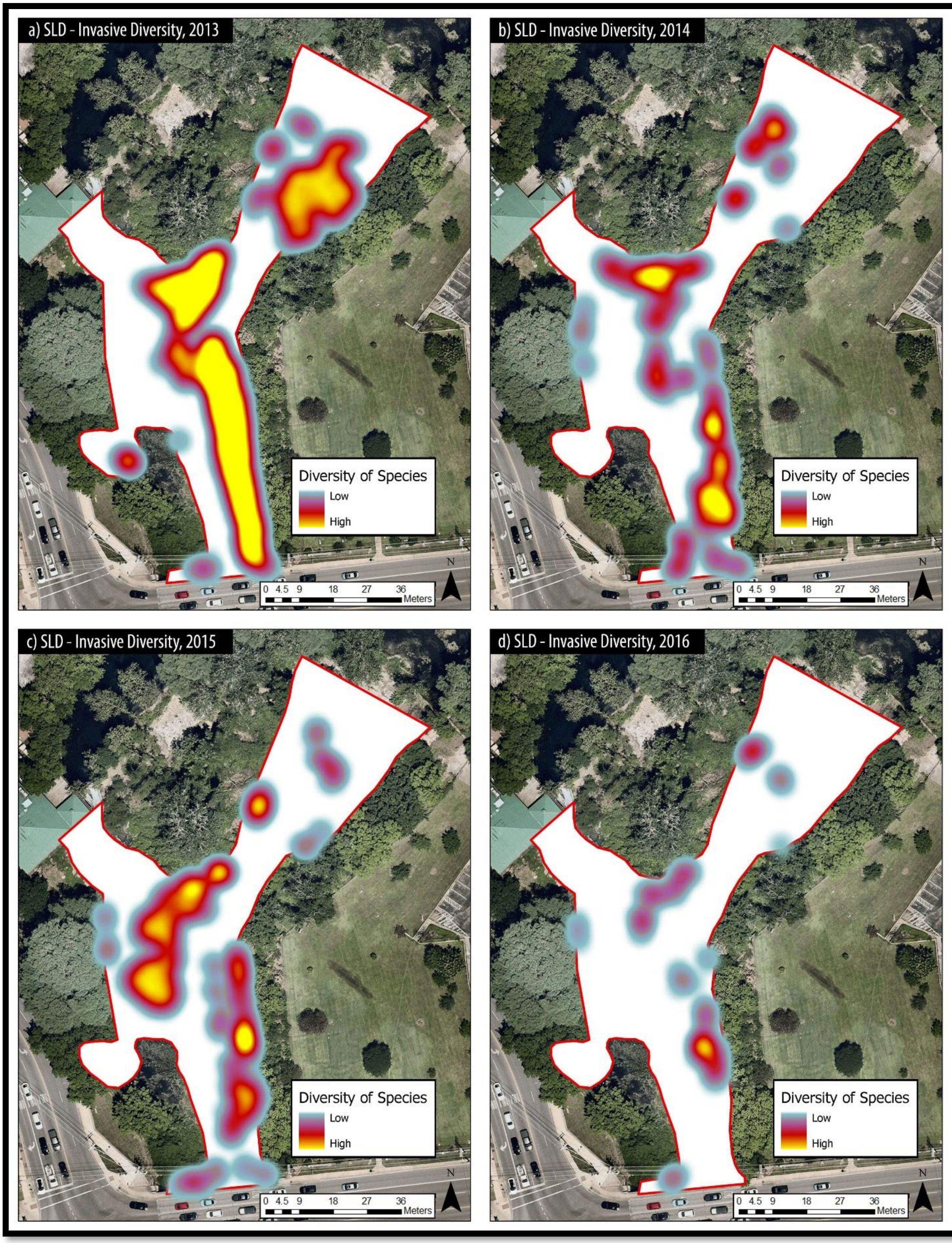

Figure 19 – SLD Invasive Diversity

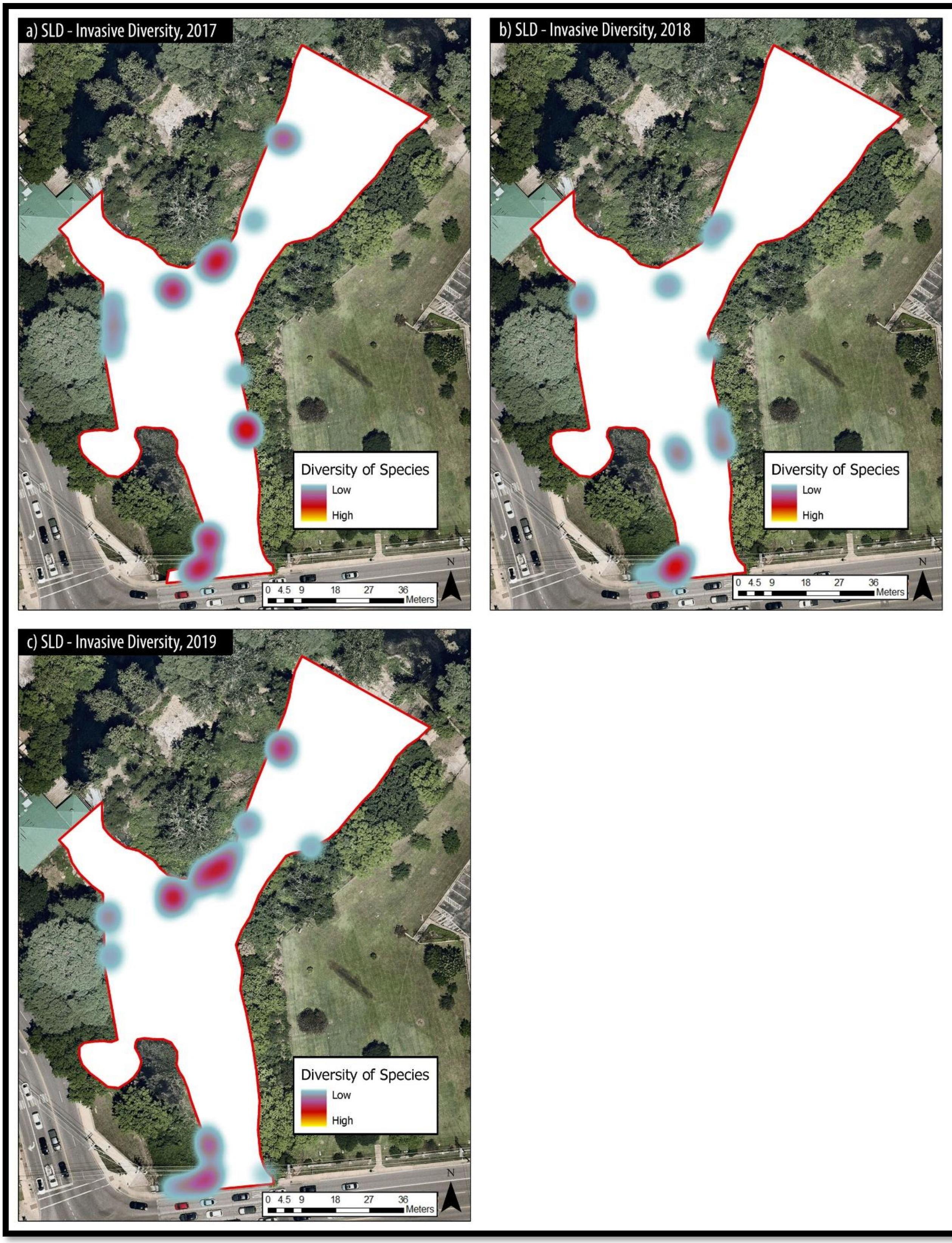

Figure 20 – SLD Invasive Diversity

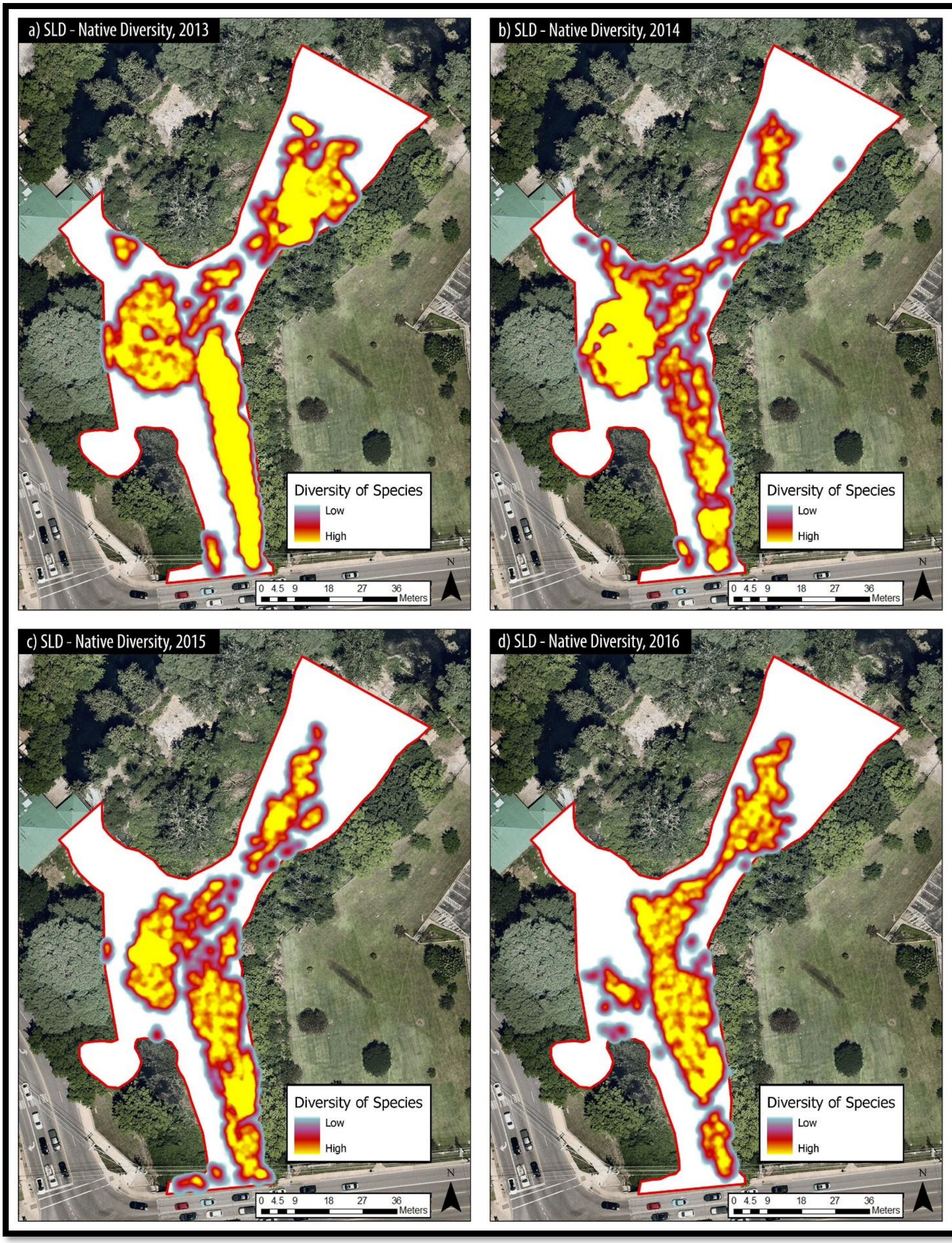

Figure 21 – SLD Native Diversity

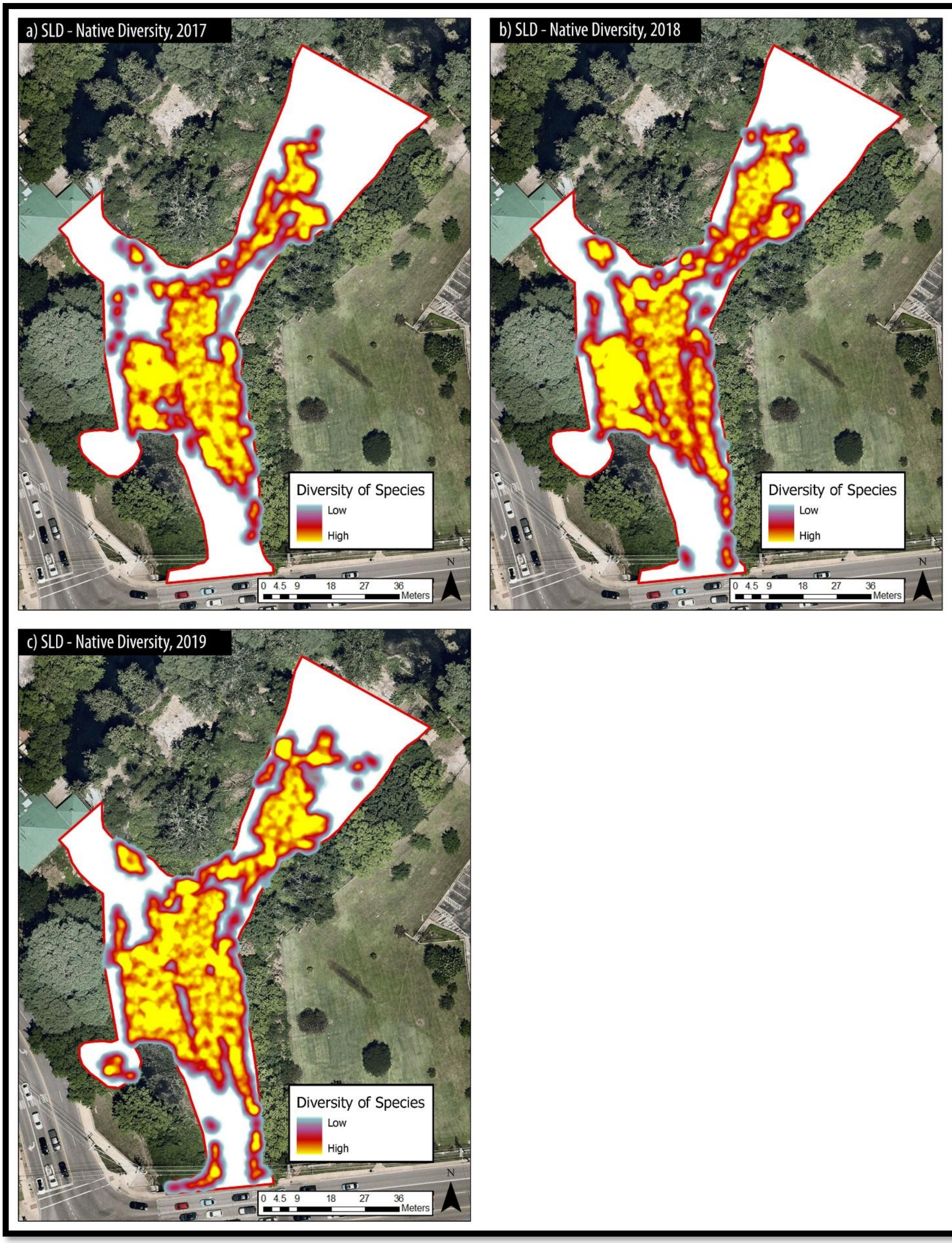

Figure 22 – SLD Native Diversity

CP invasive diversity was originally concentrated across much of the site, with a high area of diversity in the northern most part of the site (Figure 11). Over time, diversity decreased and was concentrated along the western edge and to the north of the study site (Figure 12). CP native diversity was uniform across much of the reach beginning in 2013 and remained uniform except for one area absent natives in the upper middle quadrant (Figures 13-14). I35 invasive diversity was sparse in 2013 and concentrated towards the middle of the site; invasive diversity expanded considerably in the southern portion of the site over subsequent years (Figures 15-16). Native diversity at I35 was also located primarily in the center of the site beginning in 2013. Similarly, native diversity occurred heavily in the southern area of the site in the following years (Figures 17-18). Invasive diversity at the SLD site was concentrated in the northern and eastern parts of the site (Figure 19). Over time, invasive diversity contracted in the eastern and northern areas and expanded in the middle section before decreasing in all areas of the site by 2019 (Figure 20). Native diversity was dispersed uniformly over large portions of the site beginning in 2014 and remained mostly consistent with some expansion to the western part of the site over time (Figures 21-22).

Distribution of Texas wild-rice

Figures 23, 24, and 25 show the binary raster maps for TWR at each site for each year. Red polygons represent areas where TWR was present. Figures 26, 27, and 28 are the summation raster maps for each site. The pixel values in these maps range from 1-7 and correspond to the number of years TWR was present at a given location. These values do not imply any sequence of persistence year to year except for 7 which indicates presence 2013 – 2019 for a given location. A value of ‘2’ only indicates presence for 2 of the 7 years, but the years are not specific to the binary presence and could be any combination of years. Using this more simplified binary raster addition approach, TWR was present more frequently along the eastern edge of the SLD site, with stands that were present for fewer years more prevalent along the central western region (Figure 26). In CP, TWR was frequently present in the south-central area and in small sections or the northern part of the site and consistently absent in the upper central reach between the two hardened bank access recreational areas on either side of the river (Figure 27). TWR persistence over time was less pronounced in the I35 site, with few areas of high frequency, and most of the concentrations being in the 1–4-year range and located in the central and southern areas of the reach (Figure 28).

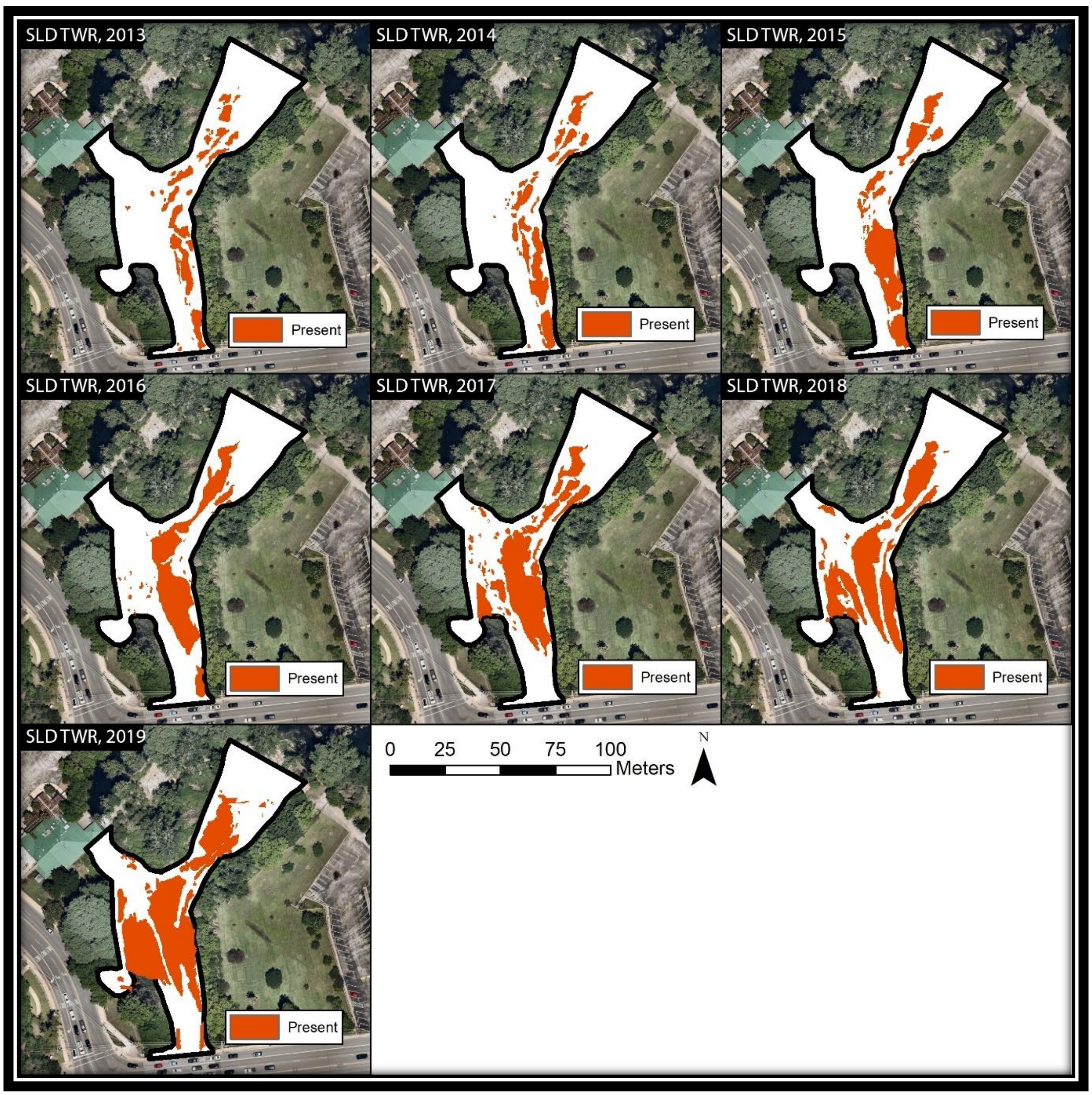

Figure 23 – TWR Presence, SLD

Figure 24 – TWR Presence, CP

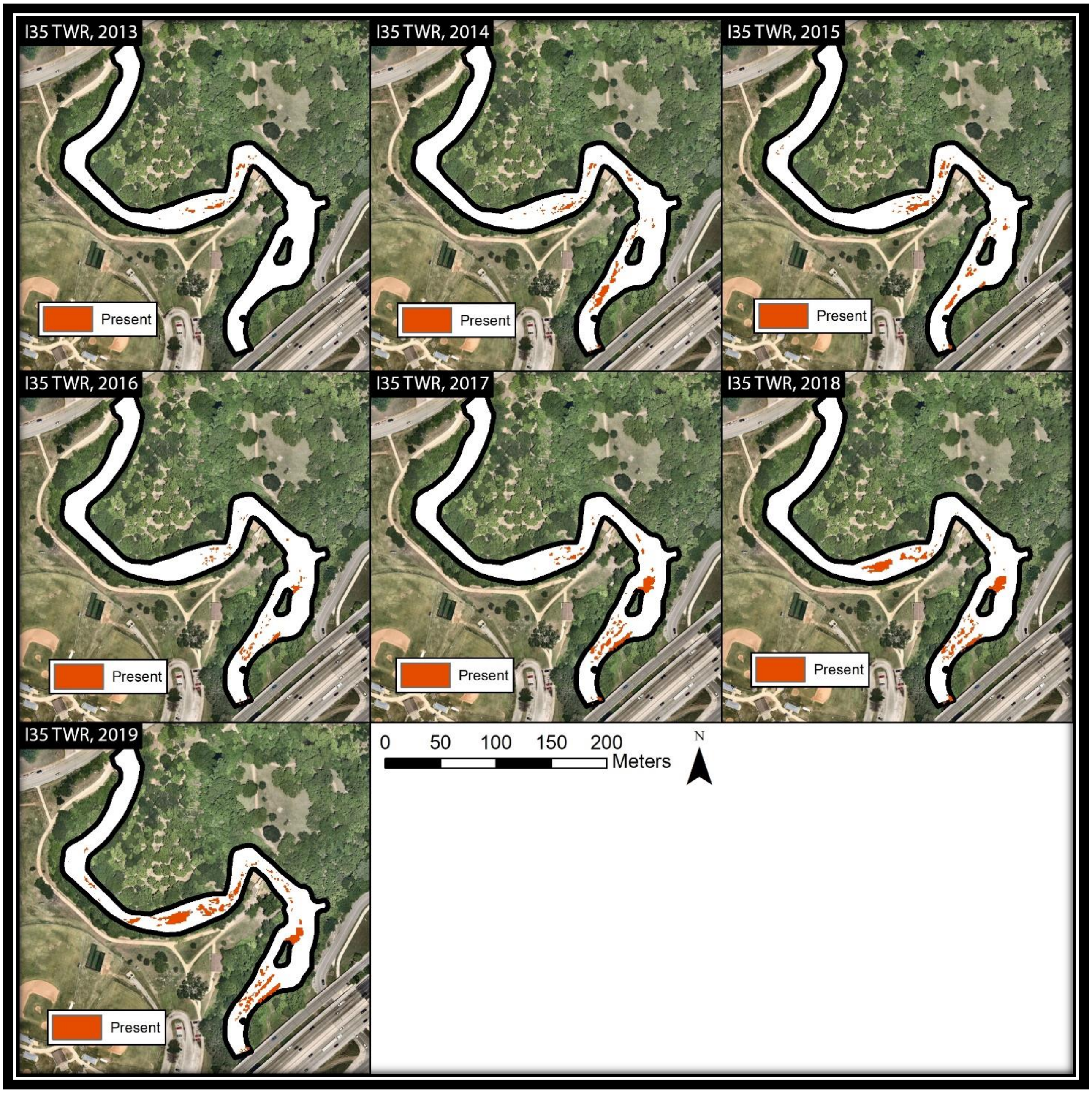

Figure 25 – TWR Presence, I35

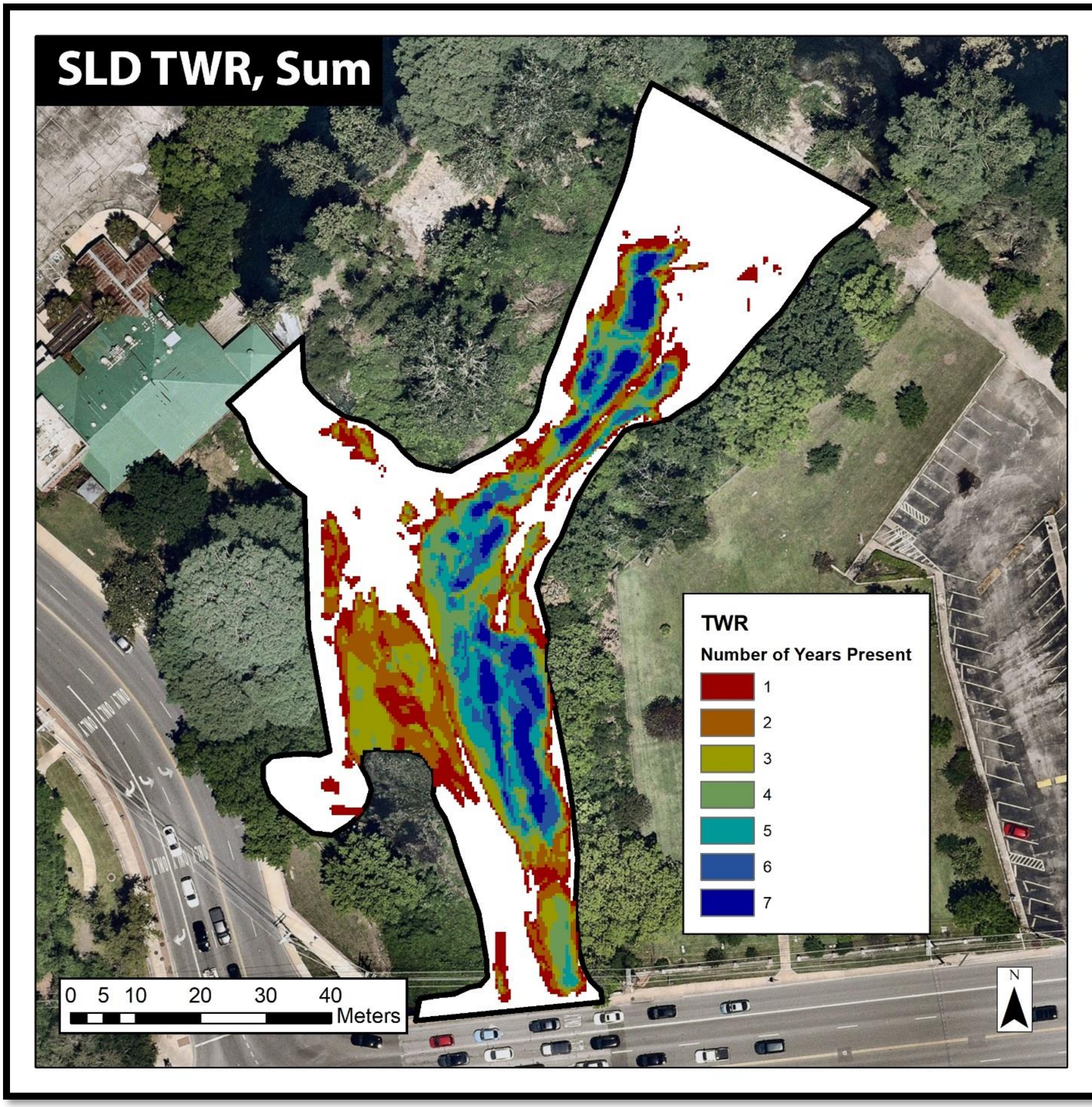

Figure 26 – TWR Concentration Over Time, SLD – Values correspond to the number of years TWR was present.

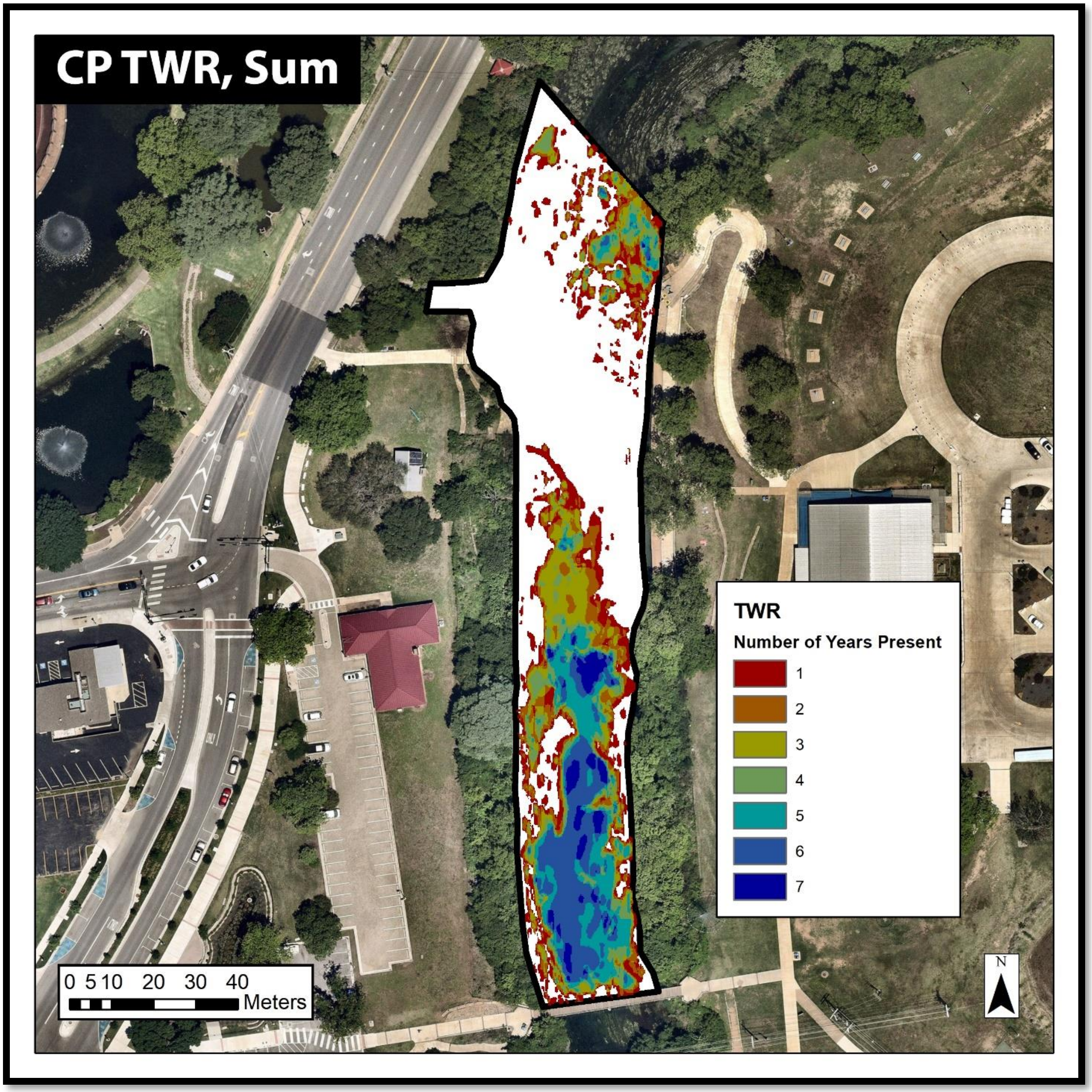

Figure 27 – TWR Concentration Over Time, CP - Values correspond to the number of years TWR was present.

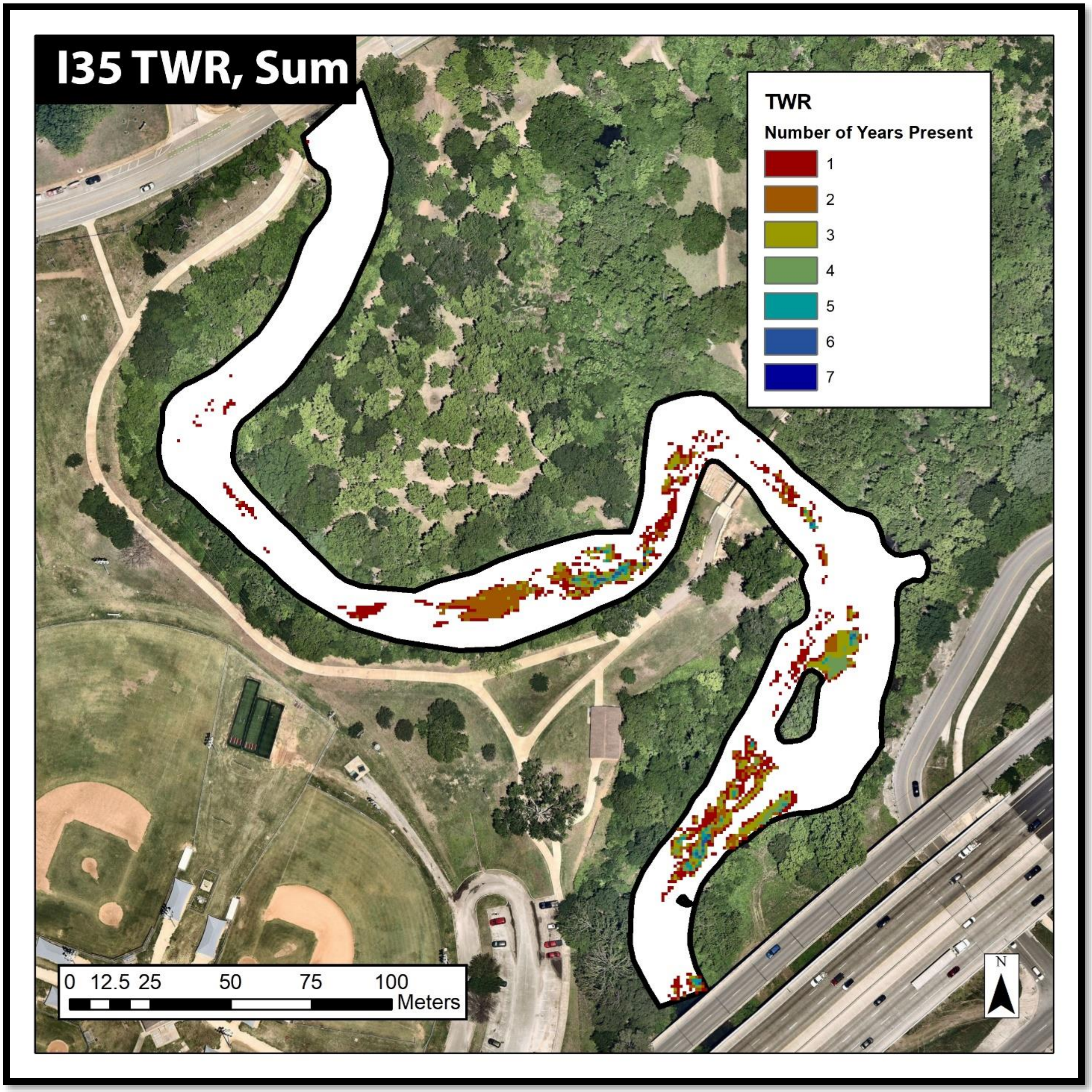

Figure 28 – TWR Concentration Over Time, I35 - Values correspond to the latest year in which TWR was present.

An output raster was created for the reclassified order of magnitude rasters, but visualization of this data is difficult due to there being a high number of unique values of data to display--119 for CP (Figures 29, 31, 32). Output maps of the three sites were created using this method for display purposes (Figures 30, 32, 34). The intended use of this analysis is not as a map of all the possible presence absence combinations for the seven years per se, but it is an important digital information product nonetheless due to its use in SAV management activities for the data that can be derived via query from different combinations of pixel values. A query for a single magnitude value, i.e., 1 (2013), 100 (2014), 1,000 (2015), 10,000 (2016) will tell you where it was present in only that year and no other year – which could be useful for mapping yearly new growth patterns or tracking TWR planting success (and failure). It can be useful for looking at where TWR has been persistent for longer periods at a given location, where it has expanded, or where it has contracted year to year on account of different pressure such as flood scouring or recreation. Tracking these patterns, particularly persistent or new expansion year to year, could be useful for genetics applications. Future years can continue to be added to this raster map using increasing magnitudes, i.e., 2020 will be 10,000,000, and so one.

The place these two raster addition approaches (binary presence absence and recoded magnitudes for each year) provide conformity is that a value of 7 displayed on Figure 27 corresponds to the value 1,111,111 on Figure 30, illustrating that at that location TWR has been present for the full time period from 2013-2019.

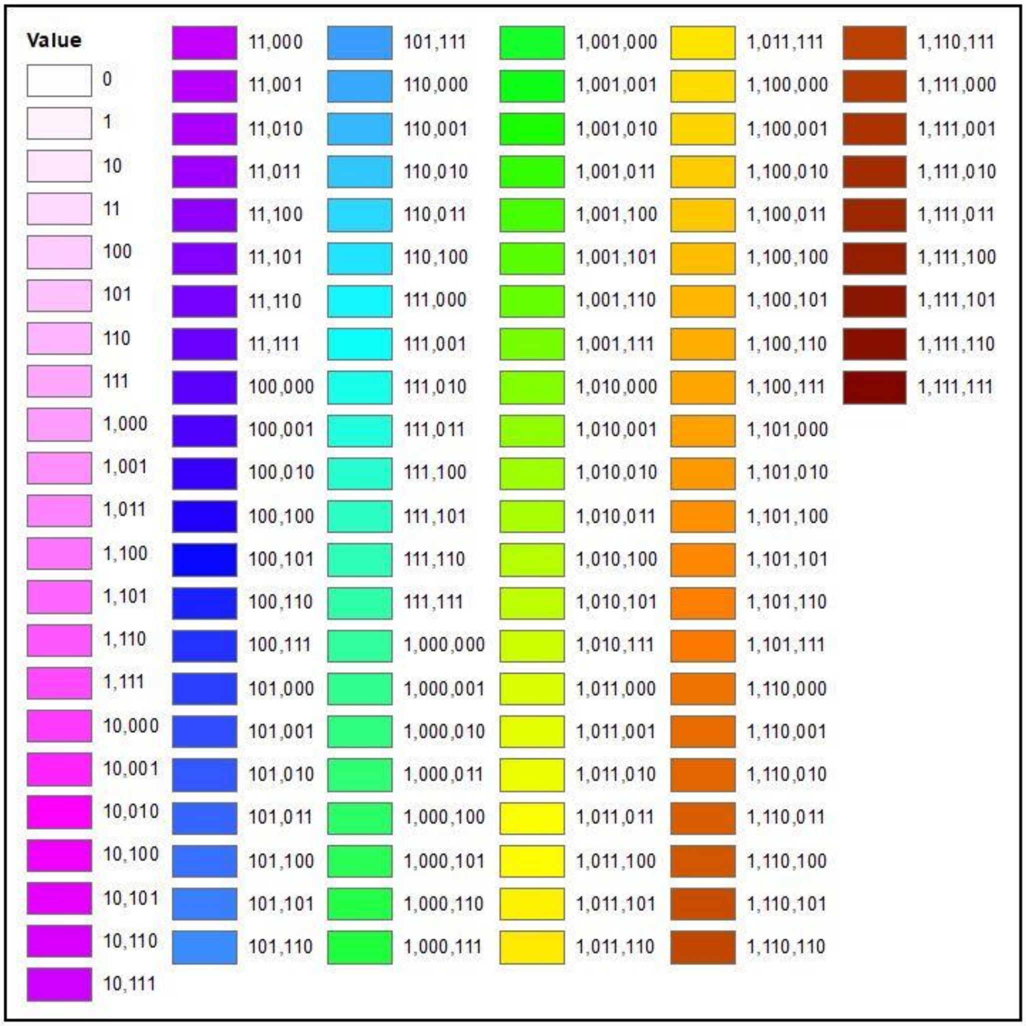

Figure 29 – Symbolizing CP TWR presence with unique values. A value of 1 in each order of magnitude corresponds to the year TWR was present at that location, i.e., 1 = 2013, 10 = 2014, 100 = 2015, 1,000 = 2016, 10,000 = 2017, 100,000 = 2018, 1,000,000 = 2019. For example, when interpreting the values, a '1' implies TWR was only present at that site in 2013, whereas a value of '1011' would have been present for the years 2013, 2014 and 2016.

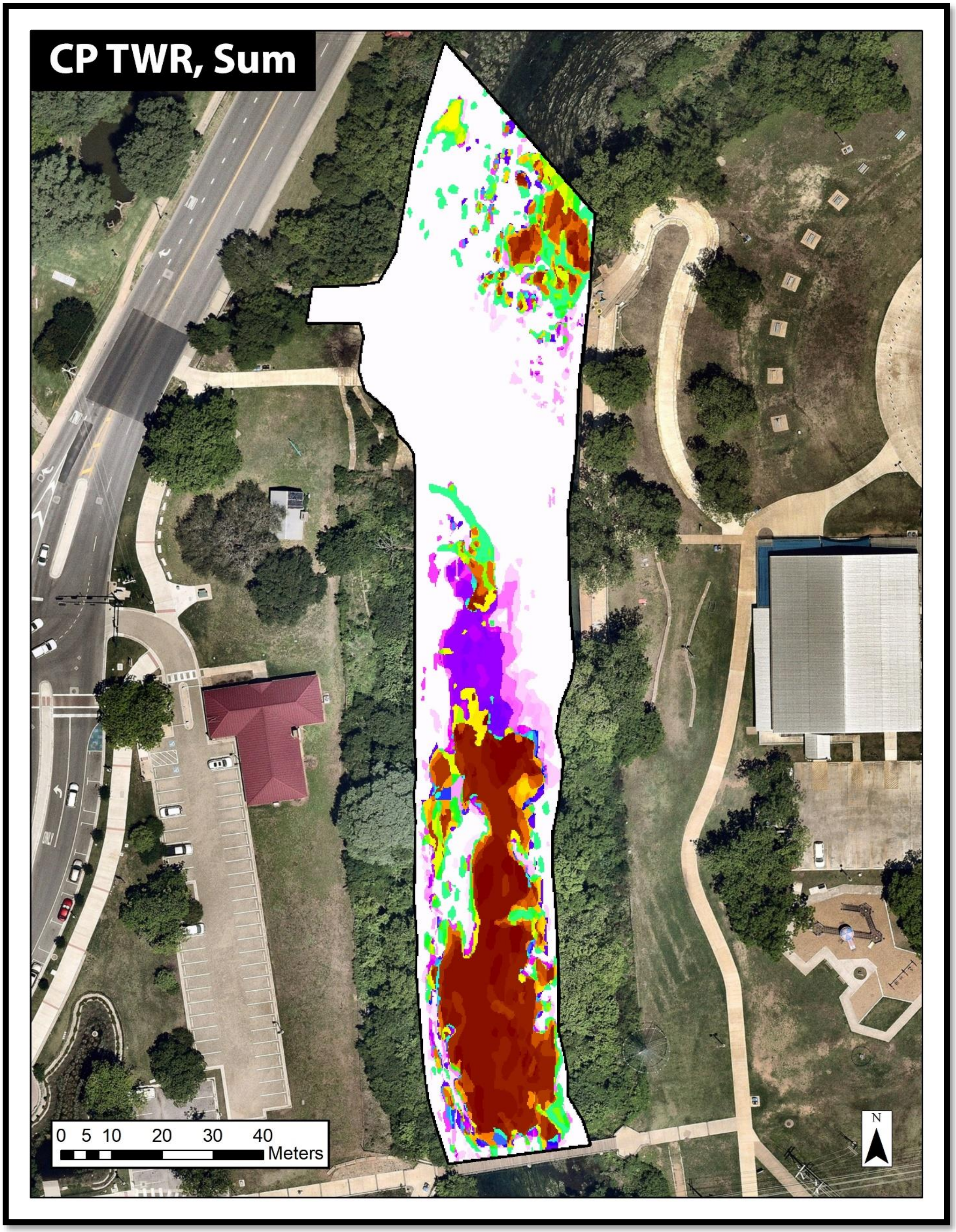

Figure 30 –CP TWR spread/contraction over time with unique values

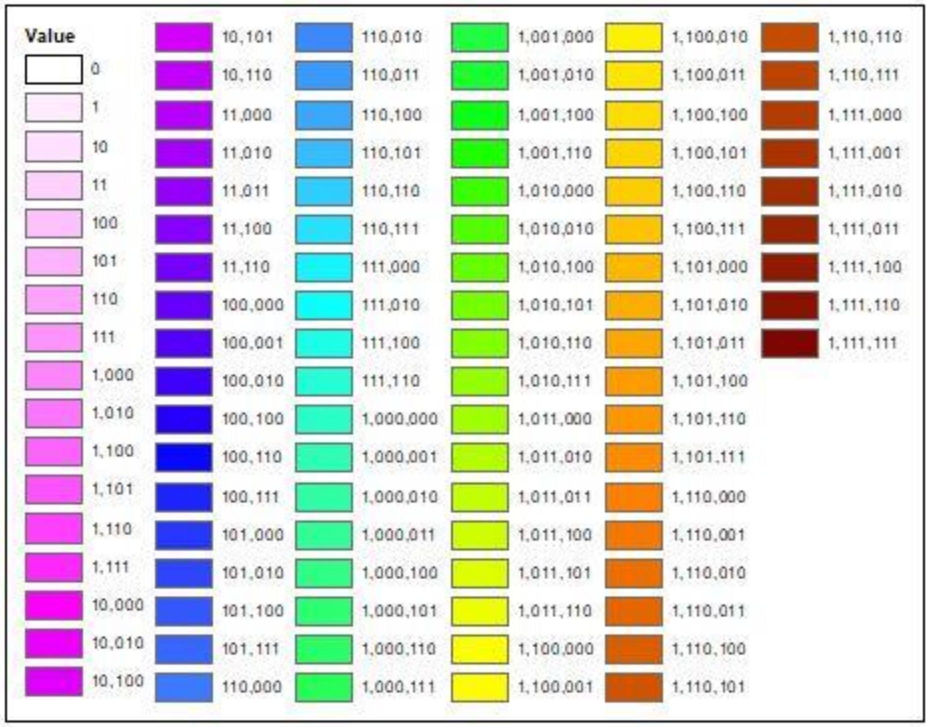

Figure 31 – Symbolizing I35 TWR presence with unique values. A value of 1 in each order of magnitude corresponds to the year TWR was present at that location, i.e., 1 = 2013, 10 = 2014, 100 = 2015, 1,000 = 2016, 10,000 = 2017, 100,000 = 2018, 1,000,000 = 2019. For example, when interpreting the values, a '1' implies TWR was only present at that site in 2013, whereas a value of '1011' would have been present for the years 2013, 2014 and 2016.

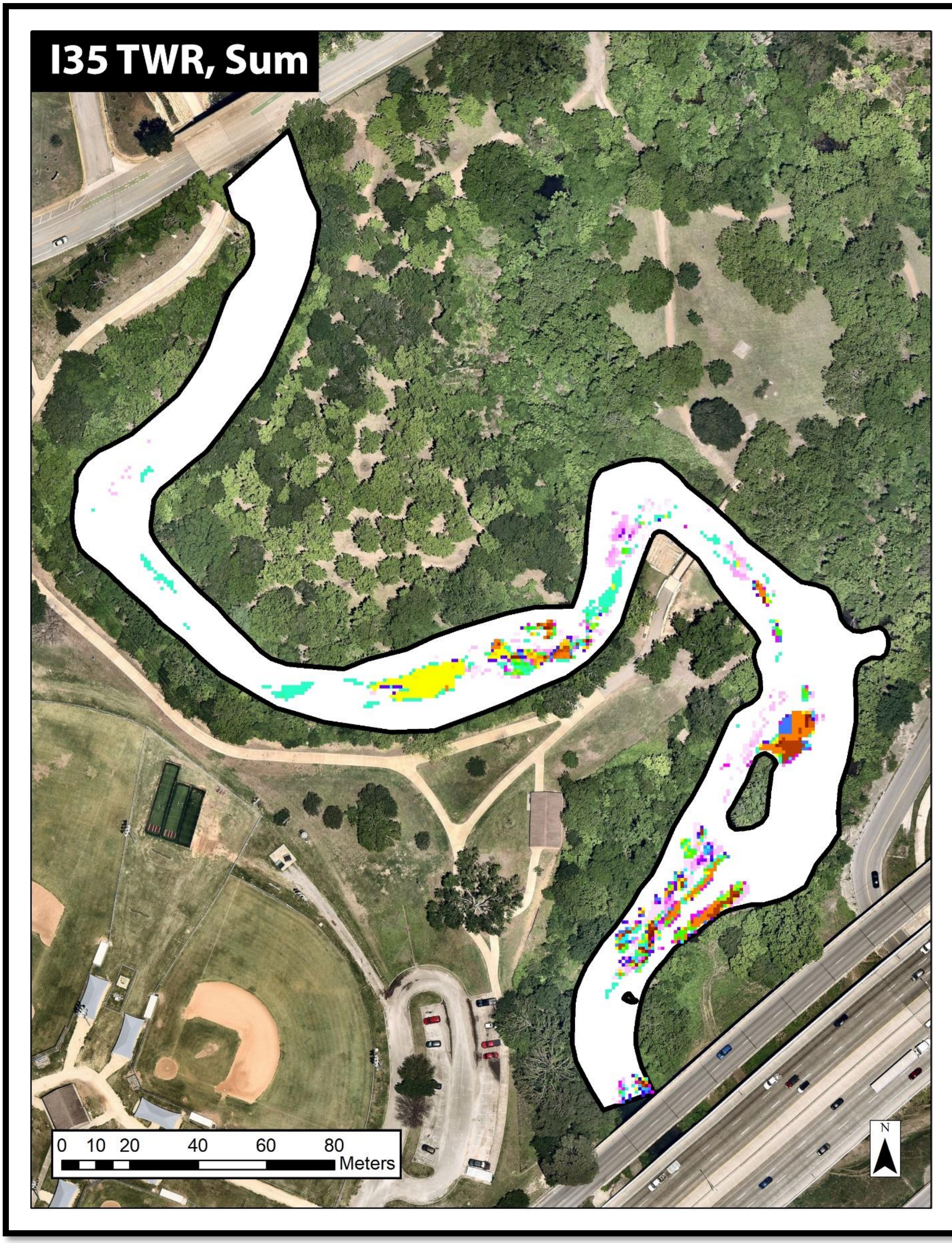

Figure 32 – I35 TWR spread/contraction over time with unique values

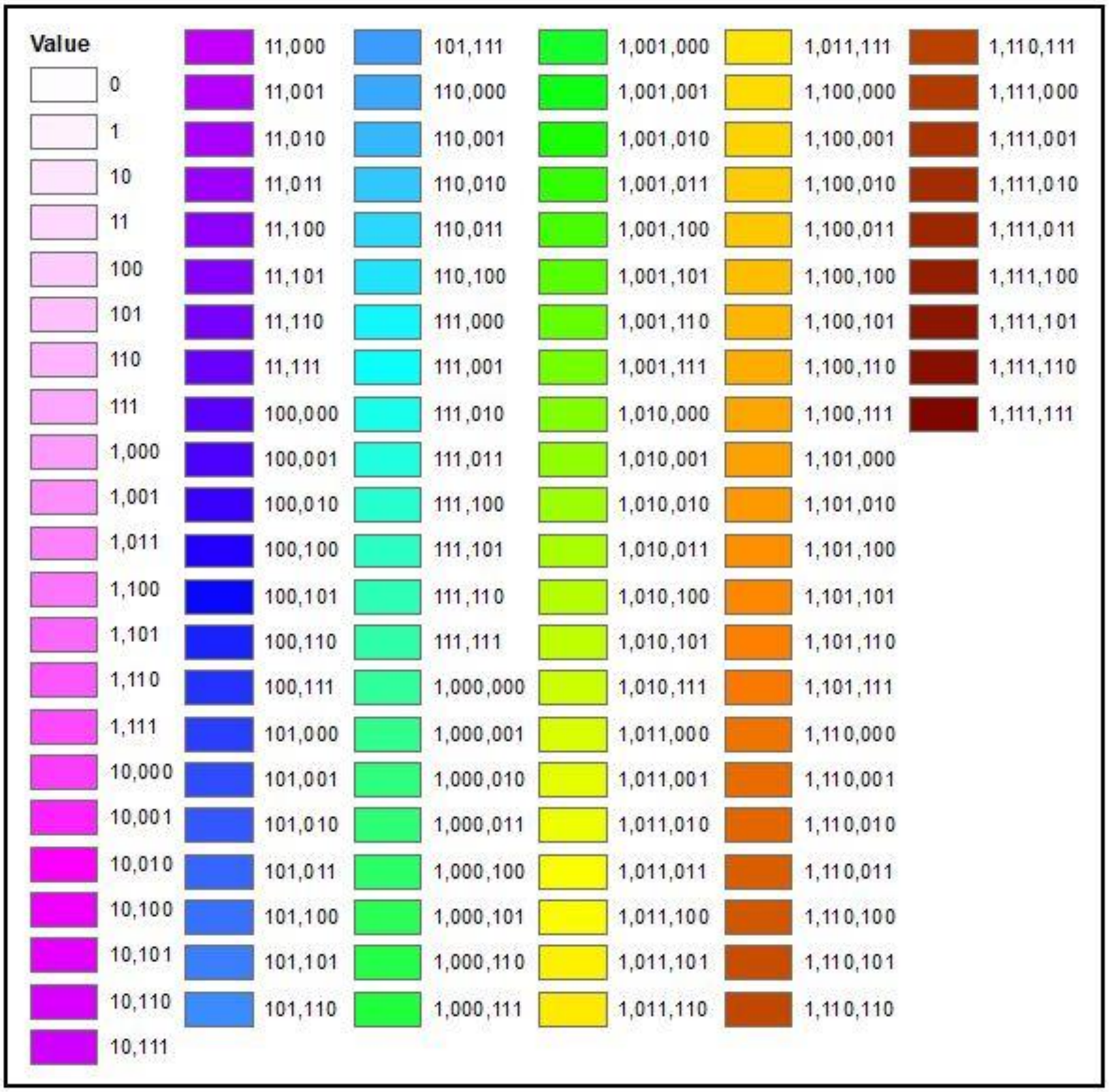

Figure 33 – Symbolizing I35 TWR presence with unique values. A value of 1 in each order of magnitude corresponds to the year TWR was present at that location, i.e., 1 = 2013, 10 = 2014, 100 = 2015, 1,000 = 2016, 10,000 = 2017, 100,000 = 2018, 1,000,000 = 2019. For example, when interpreting the values, a '1' implies TWR was only present at that site in 2013, whereas a value of '1011' would have been present for the years 2013, 2014 and 2016.

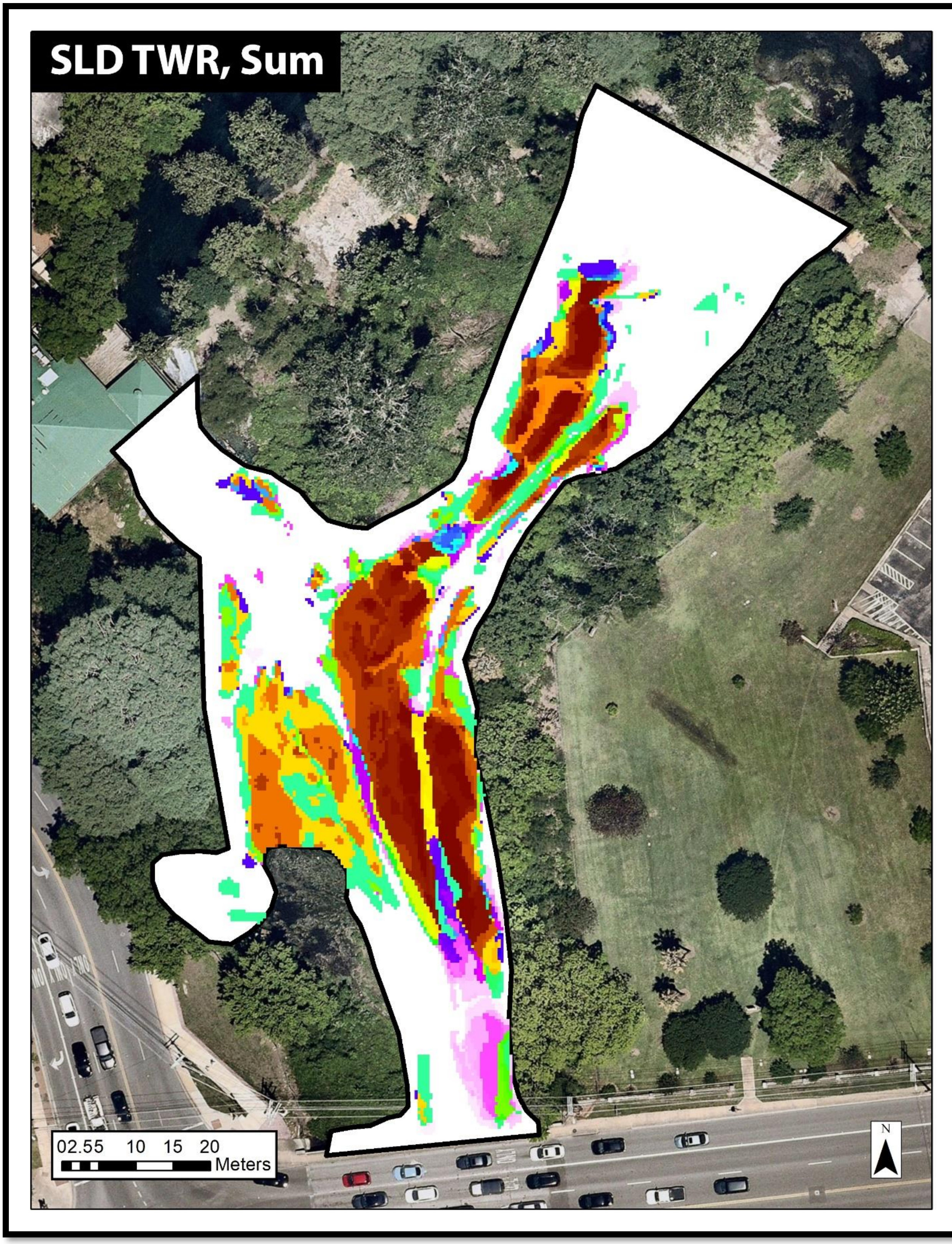

Figure 32 –SLD TWR spread/contraction over time with unique values

IV. Sources of Error and Uncertainty

Measurement of the irregular boundaries of SAV species using GPS devices and generalization into vector-based features is a potential source of error. Stands of vegetation were mapped down to a spatial resolution of 0.5m x 0.5m point, anything less than 0.5m was not mapped due to GPS accuracy. Data collection was done from kayak in a flowing river which could potentially introduce additional error due to the GPS points not being from a consistently stable base. Additional generalization occurs in the conversion of vector data to raster data where raster pixel values are interpolated along polygon edges. Additionally, the data used in this research represents only a snapshot in time for when it was collected and mapped; SAV coverage could vary within each year due to impacts such as flood scouring or recreation that may or may not be captured by the specific timeframe of data collection. The order of magnitude classified raster of TWR spread/contraction over time displayed pixel values which corresponded to all years TWR was present at a given location; however, it was difficult to visualize this data clearly without generalizing. Using unique values for visualization resulted in an image with 119 classes representing all the combinations of years, and this is difficult to display or interpret cohesively (Figures 29, 30). Heatmaps are also an interpolated surface which aren't reflecting the precise location of phenomenon in space but rather a trend in the distribution of data.

V. Future Work and Recommendations for GIS-based Data Management

Recommendations for future work involving bio-monitoring data are primarily data standardization and collaboration. Data standardization could be improved in a few ways. The datasets used inconsistent naming scheme for SAV species (e.g., Ludwidgia vs. Ludiwigia repens) which made programmatic data analysis more difficult as additional data cleanup was required. The use of coded domain values which would use a set list of species names would reduce the ambiguity and possibility of human error when inputting species names in further data collection. There also existed variation in the schema of the datasets in the form of different field names representing the same data which similarly made programmatic analysis more cumbersome. Standardization of field names across all the data is recommended to avoid these challenges in the future. The data was also delivered in multiple formats and in several sets; it might be helpful if data deliverables were standardized in a single data format when providing for analysis, such as a single file geodatabase containing all planting, removal, and measured extent data for all years. A final recommendation would be for future work involving EAHCP data to directly collaborate with staff from the EAA to ensure that research aims are cogent and consistent and are in the interest of and to the benefit of the EAA and EAHCP partners and stakeholders.

VI. Conclusion

Total SAV coverage decreased by 37% and 72% in the CP and SLD reaches, respectively (Appendix A, Tables 1, 2, 5, 6). Total SAV coverage increased at the I35 site over the study years by 416% (Appendix A, Tables 3-4). These trends are indications of successful planting and removal efforts as part of the bio-monitoring program. Raster modeling of planting and removal showed concentrated areas across all three sites. Further analysis should be conducted to ascertain what are the implications of these concentrated areas. Heatmap representations of native and invasive diversity over time showed a reduction of invasive diversity and expansion of native diversity over time in the SLD and CP sites and would seem to support vegetation removal efforts. The TWR presence maps helped to visualize how TWR is changing spatially over time and where TWR has been most highly concentrated.

Preserving biodiversity is important to the well-being of an ecosystem and there are opportunities to address and mitigate challenges that occur in spring-fed river ecosystems like the

San Marcos, such as relating groundwater-dependent processes and functions to conservation and management efforts (Boulton 2005). The threats posed to native and endemic species by the introduction of exotic species into aquatic habitats of the San Marcos River—specifically the introduction of invasive non-native SAV species—constitute important challenges in the maintenance of a healthy river ecosystem. One of the most practical approaches to creating sustainable groundwater management programs is ecology-based evaluation of springs ecosystems (Marmonier et al. 2013). The EAHCP has already established successful tracking of biota and habitat conditions (EAA 2012). This research seeks to augment existing conservation and management efforts being conducted by the EAHCP's bio-monitoring program.

Much of the extant data synthesized by the program would benefit from a spatial analysis component. Understanding conditions within these ecosystems requires an understanding of how different components of the ecosystem interact with one another. Spatial analysis can be a useful tool in visualizing the relationship between components and could be used with data outside this research in novel approaches that might facilitate program goals. This research contributes by building on this body of work by mapping and measuring spatial change in SAV over time. Specifically, patterns and trends in spatial distribution and diversity of SAV in three sections of the San Marcos River were investigated during the period of 2013-2019 to explore native and invasive diversity and trends in the areal coverage of SAV species over time. The analyses identify areas where concentrations of removal and planting of non-native and native SAV occur over time. This spatial analysis can be helpful in identifying areas where long-term maintenance efforts have been effective. Quantitatively measuring spatial and temporal changes in SAV and providing visual representation of the patterns and trends is important in informing management decisions involving native vegetation restoration and non-native vegetation management. The EAHCP may benefit from incorporating spatial analysis into their efforts as a criterion for guiding resource allocation or evaluating outcomes. While it is not the intent of this research to directly attribute causation to trends in the data, hopefully the results and analyses will be an additional useful tool in evaluating future vegetation restoration and removal efforts.

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