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Lavaca River Delta Marsh Assessment
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Final Report

by
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List of Abbreviations

Abbreviation	Definition
CL BBASC	Colorado-Lavaca Basin and Bay Area Stakeholder Committee
DEM	Digital Elevation Model
EROS	Earth Resources Observation and Science
GEE	Google Earth Engine
GIS	Geographic Information Systems
GLMM	Generalized Linear Mixed Model
GPS	Geographic Positioning System
Ha	Hectare
LiDAR	Light Detection and Ranging
MSAVI	Modified Soil-Adjusted Vegetation Index
NAD 83	North American Datum of 1983
NAIP	National Agricultural Imagery Program
NAVD88	North American Vertical Datum of 1988
NDVI	Normalized Difference Vegetation Index
NIR	Near-Infrared
NOAA	National Oceanic and Atmospheric Administration
NTDE	National Tidal Datum Epoch
NWI	National Wetland Inventory
P	Probability that the observed result could have occurred under a null hypothesis
rSLR	relative Sea Level Rise
TDWR	Texas Department of Water Resources
TNRIS	Texas Natural Resources Information System
TWDB	Texas Water Development Board
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
UTMSI	University of Texas Marine Science Institute
VARI	Visible Atmospherically Resistant Index

Executive Summary

We assessed the percent cover and species composition of the emergent vascular vegetation in the Lavaca River Delta (hereafter referred to as Lavaca Delta) to characterize the extent and distribution of marsh habitat. This work was initiated, in part, to evaluate the effects of alterations in freshwater inflows to the Lavaca Delta marsh habitats. Digital imagery acquired in 2020 was used to map the current (2021) extent of marsh vegetation. The trained classification model was applied to historical aerial imagery from 2010 to 2018. Geostatistical analyses using GIS software allowed a change analysis of landscape and vegetation over the 10-year period. In addition, we were able to determine the correlation between variations freshwater inflows and marsh vegetation species composition and areal extent. Our results reveal that the vegetative composition of the Lavaca Delta has undergone system-wide changes that are significantly related to freshwater inflows over the past decade. Some major highlights of our study:

1. The Lavaca Delta is a relatively low salinity system, however, from 2008 to 2020, the watershed experienced hydrologic extremes including multiple years of extreme drought and record flooding caused by Hurricane Harvey in 2017.
2. Our classification results are moderately accurate, as reflected by an average overall accuracy of 49.6% and an average Kappa Index value of 0.412. These results were based on 496 field-based observations split into training (75%) and testing (25%) data sets.
3. We did not observe distinct zonation in vegetative communities in the Lavaca Delta. Stands of marsh plants are very patchy and heterogeneous.
4. High biodiversity and variation over time precluded the formation of dominant vegetation assemblages. Some of the most common species found are *Juncus roemerianus* (6.5-9.9%), *Distichlis spicata* (2.9-9.2%), *Spartina alterniflora* (2.1-14.5%), and *Scirpus maritimus* (0.4-10.6%). Water constitutes around 30-37% of the Lavaca Delta. Bare, unvegetated areas represent from 10-20% of the Delta.
5. The vegetative community composition and areal extent of marsh changed significantly with changes in freshwater inflows, as revealed by a generalized linear mixed modeling approach.
6. Vegetated habitat responses to changes in freshwater inflows occur within seasonal to annual time frames, as revealed by the significance of interactions at the 3-month time step but not 12-month time step.
7. Challenges in mapping the Lavaca Delta marsh vegetation include high spatial variability in vegetation stands, high biodiversity, and limitations in accessibility to field sampling sites. Despite these challenges, this classification effort represents the first species-level mapping in the Lavaca Delta. With additional targeted field sampling, classification accuracy will improve and will allow for more confidence in the vegetation change analysis. Due to the sensitivity and responsiveness of the vegetated habitats, imagery acquisition should occur more frequently to capture short-term changes in vegetation in response to inflows.

Introduction

Background

The Lavaca River Delta (28° 43' N, 96° 35' W) is a tidal marsh system centrally located along the Texas Gulf Coast. The Lavaca Delta is a component of the larger Colorado-Lavaca Estuary which includes two major bays, Lavaca and Matagorda, and several smaller bays (Fig. 1). The climate is warm temperate and subtropical, characterized by mild summers and winters with rainy periods in the early spring and early fall and year-round southeasterly winds (Lockwood, Andrews & Newman, Inc., 1967). Mean precipitation is about 105 cm yr^{-1} (PRISM). However, Lavaca Bay is susceptible to extended dry hydrologic periods. From 2008 to 2012, average annual precipitation was 80 cm yr^{-1}, and average total inflow was 906,000 acre-ft yr^{-1} (PRISM, 2022; TWDB). Conversely, precipitation from 2013 to 2020, a period marked by intense storms such as Hurricane Harvey, averaged about 104 cm yr^{-1}, and total inflow averaged 1,225,700 acre-ft yr^{-1} (PRISM, 2022; TWDB). Mean salinity in Lavaca Bay falls around 15 (Longley, 1994; Montagna et al., 2020), and average tidal amplitude is 25 cm with a diurnal tidal regime (NOAA Tidal Gage # 8773259, NTDE 1983-2001). Upstream, the watershed is composed of 6,010 km^2 of coastal plain lands dominated by agricultural and ranching activities. Lake Texana (the only major reservoir) and the Navidad River join the Lavaca near Lolita, TX (TDWR, 1980). Additionally, the Lavaca River has the smallest absolute annual sediment load on the Texas coast, at 133 million kg yr^{-1} (Longley, 1994; TDWR, 1980; Coonrod, 1998).

A wide variety of marsh vegetation is present in the Lavaca Delta. Common species include: *Scirpus maritimus*, *Juncus roemerianus*, *Spartina spartinae*, *Spartina alterniflora*, *Batis maritima*, *Distichlis spicata*, *Borrichia frutescens*, and *Aster tenuifolius*. Additional species present in portions of the marsh are: *Limonium nashii*, *Spartina patens, Salicornia virginica, Phragmites australis*, *Monanthochloe littoralis*, *Lycium carolinianum, Typha angustifolia*, and *Iva frutescens*. The vegetative community is more diverse than typical salt marshes due to reduced salt stress from heightened freshwater influence and lessened tidal inundation (TDWR, 1980). Historical marsh salinities in the Lavaca Estuary range from 0.1 to 25 in the lower delta and from 0 to 10 in the upper delta (Zimmerman et al., 1990). The Lavaca Delta margin has not changed significantly with only about 39 hectares of new marsh has formed due to progradation of the delta since the mid-1850s (Longley, 1994). Areal extents of vegetation are most directly related to the estuarine water budget, regulated by climate and freshwater input. Annual net productivity in these marshes is around 1300 g m^{-2} yr^{-1}, with 68% of production occurring during spring and summer (TDWR, 1980).

Significance of Freshwater Inflows to Estuarine Wetlands

Freshwater inflow affects estuaries at all levels. Inflows play a functional role in diluting seawater, transporting materials, moderating water temperatures, reducing salt stress on estuarine organisms, modifying biogeochemical cycling and other chemical reactions, and aiding in the distribution of organisms in the water column (Longley, 1994). Because so many crucial estuarine processes depend on freshwater inflows, the reduction of flow, due to drought, impoundment, or diversion, can have extreme impacts. Increased salinity and saltwater intrusion, diminished nutrient and organic matter supply, higher risk of erosion, and deterioration of fisheries and wetland habitats are all caused by reduced freshwater inflows (Allen et al.; Longley, 1994).

Deltaic marsh vegetation requires a specific range of salinities for establishment, growth, and reproduction. Annual plant species, located at the colonizing margin and lower marsh areas, are replaced by germination and establishment of seeds each spring when salinity is sufficiently reduced by secular (semi-annual) tidal flushing (< 20; Alexander & Dunton, 2002; Woodell, 1985). Seedling growth is also facilitated by extended immersions in normal seawater, increasing spring temperatures, longer day lengths, and increased sun angles. Freshwater inflows in spring also promote the reduction of salinity levels (< 10; Longley, 1994; Zimmerman et al., 1990). In contrast, perennial species are not as sensitive to fluctuations in salinity. Many marsh species can grow in both saline and non-saline soils. However, at lower salinities (< 10), obligate halophytes lose their competitive advantage with more aggressive fast-growing non-salt tolerant species (Longley, 1994; Forbes & Dunton, 2006).

Vegetation is dependent on rainfall for the replenishment of saline groundwater with freshwater to decrease water table depth and salinity (Allen et al.; Boorman, 2019). In deltaic marshes, the upstream distance of salinity influence on marsh vegetation is a function of the dilution of tidal seawater with freshwater runoff. Since Lavaca Bay is microtidal, the intertidal zone influenced by regular seawater inundation is restricted (Kearney & Turner, 2016; Humphreys et al., 2021). However, with rising sea level, the area inundated with seawater is increasing, which will subject the existing brackish water marsh vegetation to greater salinity stress. Further upstream in tidal freshwater marshes, lower salinities (< 5) and broad expanses of low elevation landscapes contribute to the high diversity and abundance of vascular plants (TDWR, 1980; Zimmerman et al., 1990).

Sea level rise is a growing threat to coastal regions globally, and marshes are no exception. As relative sea level rise (rSLR) increases to an approximate rate of 4-6 mm yr^{-1} on the Texas coastline, microtidal marshes are at high risk of being converted to open water (Paine et al., 2012; Kearney & Turner, 2016). The high rate of rSLR on the Texas coast (regional subsidence, due to local groundwater pumping, is occurring at 0.5-1.2 cm yr^{-1}) has the potential to exacerbate marsh elevation loss (White & Calnan, 1990). Coastal regions are prone to high development for industrial, residential, and recreational purposes. Marshes in the Lavaca Estuary are most altered by agriculture, cattle-ranching, and oil production (Longwood, Andrews & Newman, Inc., 1967). These activities result in alterations to the natural hydrologic regimes through the construction of artificial levees, canals, and reservoirs which cause reductions in fluvial sediment loads. In 1980, the Lake Texana reservoir was completed, diverting water and sediment from the Navidad River. Some estimate the trapping efficiency of Lake Texana is close to 95% (White & Calnan, 1990). Sediment load to downstream wetlands may be reduced by as much as 32% compared to pre-Lake Texana levels (White & Calnan, 1990; Longley, 1994), potentially causing deltaic marshes in the Lavaca River valley to fall behind sea level rise and promoting extensive submergence. Vegetated wetlands in the Lavaca River valley decreased by 153 ha from 1930 to 1958 and by 430 ha from 1958 to 1979 (White & Calnan, 1990). Reduced freshwater inflow from damming may also slow the velocity of water at the delta, leading to a reversal of flow and saltwater intrusion into wetlands. An increase in soil salinity due to saltwater intrusion will allow colonization by salt marsh vegetation or upland semi-terrestrial species (TDWR, 1980). The overall expected consequence of the combination of sea level rise, subsidence, and hydrologic regime alterations is an increased frequency of exposure of naturally brackish marshes to higher salinities, which can have significant consequences on marsh vegetation diversity, productivity, and community composition (Kearney & Turner, 2016; Humphreys et al., 2021).

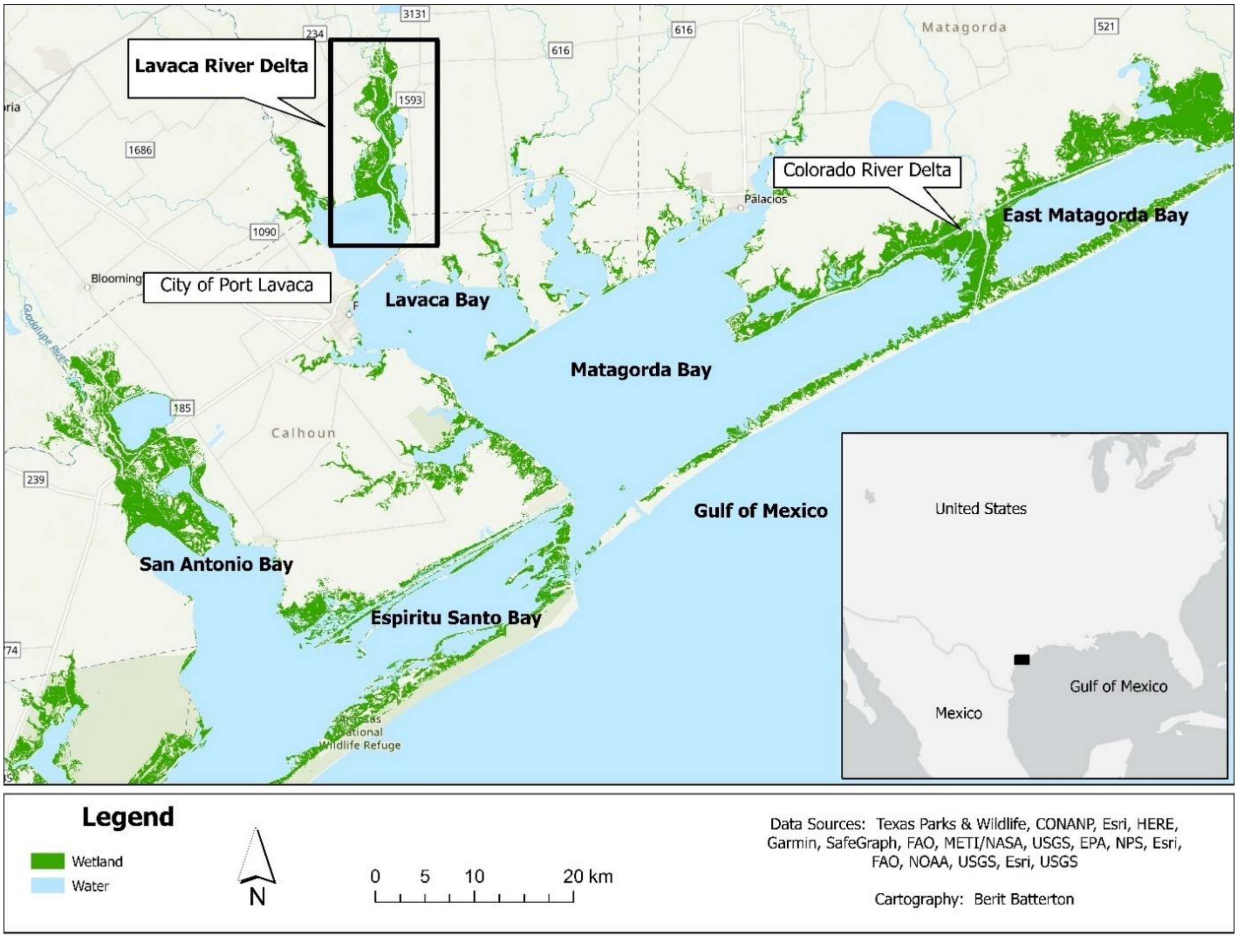

Figure 1. Location of the Lavaca River Delta with respect to surrounding bay systems along the Texas Coastal Bend.

Project Justification

The Texas Water Development Board supports implementation of adaptive management work plans that were developed through the stakeholder-driven Senate Bill 3 environmental flows process (80th Texas Legislature, 2007). In 2019, the Colorado-Lavaca Basin and Bay Area Stakeholder Committee recommended funding a priority work plan study to inform adaptive management of freshwater inflows to the Lavaca River Delta and Lavaca Bay. The University of Texas Marine Science Institute (UTMSI) was contracted to examine changes in marsh habitats in the Lavaca Delta in response to variations in freshwater inflow levels.

Current freshwater inflow standards for Lavaca Bay were developed through the application of methodology used to create freshwater inflow recommendations for the eastern Matagorda Bay and from the Colorado River (Montagna et al., 2020). Presently, there is limited data available for the Lavaca Delta for validation of the inflow recommendations and standards. Data and conclusions from this study are intended to provide key information to help inform an evaluation of whether the current flow standards for Lavaca Bay are appropriate for supporting healthy marsh habitats.

Vegetation Mapping

The two primary challenges associated with mapping vegetation in the Lavaca Delta are (1) vegetation occurs in patches that can vary in size; and (2) the patches of vegetation are often mixed with several species. These challenges require the use of remotely sensed data that has a high spatial resolution. A more detailed literature review of the application of high resolution, multispectral aerial imagery for vegetation mapping is presented in Dunton et al. (2019).

The major objective of this study was to characterize the extent and distribution of marsh habitat in the Lavaca Delta to understand the relationships between marsh habitats and changes in freshwater inflow. Specific goals are listed below:

1. Characterize the distribution of wetland habitats based on the National Wetland Inventory categories
2. Identify marsh habitats affected by changes in inflow patterns
3. Identify significant decadal trends in marsh habitats

To accomplish this objective, we used a combination of remote sensing and geospatial analysis. This project quantified the change in marsh vegetation community composition and areal extent from 2010 to 2020 in response to changes in freshwater inflow. These biennial data provide information that contributes to a broader understanding of the potential roles of freshwater inflows.

Methods

The 2021 Study Area

PI Dunton and Lead Scientist Batterton worked together to identify the target area for analysis. The target area was selected after completing several aerial and ground reconnaissance trips to demarcate the boundaries of the delta marshes and exclude surrounding uplands. The resulting area as shown by the thick outline forms the boundary of subsequent analyses performed for this project (Fig. 2).

Ground Data Sampling

We used a random clustered sampling approach to select ground control points (Dunton et al., 2019). Thirty-two random points were distributed throughout the defined study area and 16 random points were generated within 200 meters of these, producing 512 sampling locations. Challenges with accessibility only permitted us to visit a total of 234 points in 21 clusters (Fig. 2). The Lavaca Delta marsh has an extensive tidal creek network with narrow and steep creek banks, very shallow water (< 30 cm), and large ponds that restrict navigation by boat. Densely forested, and sometimes fenced, upland regions along the river banks prevented access to some interior marsh zones, and gas pipeline infrastructure blocked access to several points (Fig. 2).

At each accessible sample point, we visually assessed vegetative cover with a 0.25 m^2 quadrat. Digital photographs and field notes were taken to document ground conditions in the vicinity of each point (see Appendix for field data). Ground truth surveys began on 1 July 2021 and were completed 16 November 2021 (Table 1). Over 60% of the sites were visited during an 8-week period from July through August 2021. All photos were made with a Garmin GPS camera (Model GPSMAP 64csx) and georeferenced with an associated latitude and longitude.

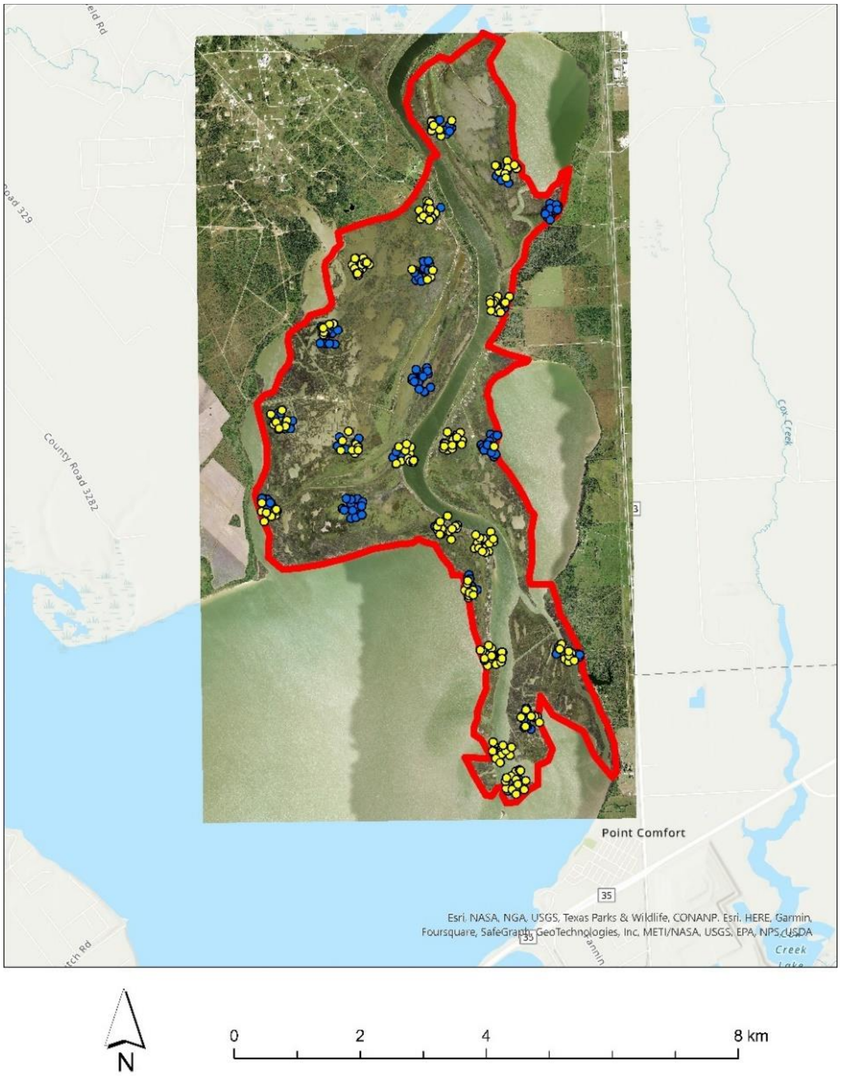

Figure 2. Project study area (red boundary) containing sites visited (yellow dots) and inaccessible sites (blue dots), with the complete imagery dataset as a backdrop.

The procedure for creating sampling clusters is as follows:

1. Use the **Create Random Points** tool with the following parameters:
   a. Constraining Feature Class: Study Boundary
   b. Number of Points: 32
   c. Minimum Allowed Distance: 1 km
2. Use the **Buffer** tool to create a circle of 200 m radius around your random points
   a. Input Features: Random Points
   b. Distance: 200 m
3. Use the **Create Random Points** tool again to place 16 random points within the buffer zone

   a. Constraining Feature Class: Buffer
   b. Number of Points: 16

Image Acquisition

We collected imagery from the National Agricultural Imagery Program (NAIP). NAIP data consists of digital aerial imagery acquired biennially during the agricultural growing season at a resolution of 0.6 to 1-meter ground sample distance in UTM Zone 14 North Coordinate System (NAD83 horizontal datum) with a horizontal accuracy that matches within 6 meters of ground control points. The imagery products were delivered as 4 digital ortho quarter quad tiles (3.75 min x 3.75 min) in uncompressed GeoTIFF format. Cloud cover is no more than 10% in any given image. Image bands represent red, green, blue, and near-infrared (NIR) wavelengths (USGS NAIP). We conducted minimal post-processing of NAIP images for the years 2010, 2014, 2016, 2018, and 2020.

Images from 2012 were not suitable for analysis. Parts of the image were oversaturated in the red band, while other parts of the image were almost completely saturated in all bands (Fig. 3). For example, a pixel representing green marsh vegetation in a normal image (2016) had band values of 131, 147, and 112, for the red, green, and blue bands, respectively. In the 2012 image (Fig. 3), the same pixel had band values of 123, 105, and 107, indicating that the pixel is red instead of green. In addition, due to sun glint, water appears bright white, which means all bands were equally saturated (214, 218, 217).

We contacted the staff at the USGS Earth Resources and Observation Science (EROS) Center with regards to this image, however they were unable to find a solution. Because the issues span most of the marsh in the image, attempting an analysis would be unproductive. The image analysis procedure, described in detail below, incorporates both raw band values and several indices derived from these values, and thus, results of this procedure would be highly inaccurate. The lack of suitable imagery for 2012 is a major hindrance to the overall examination of changes in marsh habitats in the Lavaca Delta in response to variations in freshwater inflow levels, as this year marks the end of an extended dry period that began locally in 2008.

Esri, NASA, NGA, USGS, Texas Parks & Wildlife, CONANP, Esri, HERE, Garmin, Foursquare, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, USDA

Figure 3. 2012 NAIP image that was unsuitable for analysis.

Field Work

Visits to the marsh provide valuable geotagged photographs and percent cover evaluations (Tables 1 & 3; see Appendix for field data and photographs). This information was used as training data and accuracy assessment data, where training data is used to train the image classifier and accuracy assessment data is used to evaluate the accuracy of the resulting classification. While several additional species were found in the Lavaca Delta marsh in small quantities, the following ground cover categories were used in training and testing data:

- *BM* *Batis maritima*
- *DS* *Distichlis spicata*
- *ML* *Monanthochloe littoralis*
- *SA* *Spartina alterniflora*

• *SS*	*Spartina spartinae*
• *SP*	*Spartina patens*
• *SV*	*Salicornia virginica*
• *SM*	*Scirpus maritimus*
• *JR*	*Juncus roemerianus*
• *AT*	*Aster tenuifolius*
• *BF*	*Borrichia frutescens*
• *PA*	*Phragmites australis*
• *BC*	*Cyanobacterial mat*
• *BD*	*Dry bare*
• *BW*	*Wet bare (mud)*
• *BE*	*Beach*
• *U*	*Upland vegetation*
• *F*	*Forested vegetation*
• *R*	*Road*

Table 1. Ground truthing field work summary, from 1 July 2021 – 16 November 2021.

	Point Type			
# Field Days	# Points	Water	Unvegetated	Vegetated (includes ALL species found)
14	234	115	17	102

Elevation data were not collected during this study. Without a Real-Time Kinematic (RTK) GPS device, elevation measurements must be taken using a stadia rod. This method relies on stationary reference points, such as the river shoreline, and is limited by the visual range of the observers. The Lavaca Delta system is not suitable for this method due to the presence of tall (up to 4 m high) and steep (up to 90 degrees) river banks that block the view of the shoreline and interior marsh sites that can be up to 250 m away from the river.

Water quality data were collected in May 2021 and August 2022. Seven points, located along the riverine salinity gradient from upstream (~12 km) to the mouth of Lavaca Bay, were sampled in each period (Fig. 4). Porewater salinity was also sampled haphazardly throughout the marsh in each period. Precipitation in April and May 2021 totaled 63.7 cm, while precipitation in July and August 2022, thus far, totals 2.61 cm (PRISM). These two sampling periods reflect above- and below-average freshwater input, respectively, and thus may represent high and low flow conditions. Average riverine salinity in 2021 was ~4.5 (Table 2), with an average porewater salinity of ~9. In 2022, average riverine salinity was ~28 (Table 2) and average porewater salinity was ~37. Additionally, water level and temperature were collected continuously (measurements taken every 30 minutes) from 23 September 2021 to 3 May 2022 (data not analyzed).

Esri, NASA, NGA, USGS, FEMA, Texas Parks & Wildlife, CONANP, Esri, HERE, Garmin, Foursquare, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, USDA

Figure 4. Project study area (red boundary) containing water quality sampling sites visited (green drops), with the complete imagery dataset as a backdrop.

Table 2. Water quality sampling summary, from 11 May 2021 – 16 August 2022.

Date	Site	Salinity
5/11/21	LVR1	1.31
	LVR2	2.8
	LVR3	3.9
	LVR4	4.48
	LVR5	4.78
	LVR6	10
	LVR7	4.2
8/16/22	LVR1	24.21
	LVR2	25.38
	LVR3	26.86
	LVR4	27.77
	LVR5	30.47
	LVR6	30.51
	LVR7	30.71

Training Data

We collected 262 photos made with the Garmin GPS camera and selected examples of pure stands of major marsh plant species, water, and bare substrate types (Table 3). Representative points were added to the training data set (Fig. 5).

Table 3. Additional ground truthing training data based on field photos, from 1 July 2021 – 16 November 2021.

	Point Type		
# Photos	Water	Unvegetated	Vegetated (includes ALL species found)
262	4	52	206

Figure 5. Project study area (red boundary) containing photo-derived training data (green dots), with the complete imagery dataset as a backdrop.

Creating the Mosaic

Using ArcGIS Pro, we created a mosaic of the analysis area. To prepare the images and create the mosaic:

1. Build pyramids and calculate statistics for each raster in the pop-up window after adding data.
2. Set 0 as NoData using the **Set Raster Properties** tool.
3. Create the mosaic using the **Mosaic to New Raster** tool and setting these properties.
   a. Coordinate System: NAD_1983_UTM_Zone_14N
   b. Product Definition: None
   c. Number of Bands: 4
   d. Pixel Type: 16-bit unsigned
4. Add the new raster to the open map by clicking **Add Data** and navigating to the raster file.

5. Generating seamlines was not necessary as the images did not overlap.
6. Right-click the mosaic raster in the Table of Contents and click **Export Data**. Set 0 as NoData, set **TIFF** as the format with no compression, and click **Save**.
7. Use the **Clip Raster** tool to clip the exported mosaic to the study boundary.
8. No color balancing was applied to the mosaic.

Use of Ancillary Data

Dunton et al. (2019) appended the following bands to the imagery to provide additional information for the classifier to utilize:

- Elevation
- MSAVI (Modified Soil-Adjusted Vegetation Index)
- Texture (standard deviation of MSAVI)
- Distance from tidal creeks and significant water bodies

For this project, we included that ancillary information plus rasters representing NDVI (Normalized Difference Vegetation Index) and VARI (Visible Atmospherically Resistant Index). Freshwater inflow data will not be included as ancillary data for the classification process because it will not aid the classifier in predicting spatial distribution of marsh vegetation.

Forest-based classification algorithms, such as those used in this study, work best when the various analysis rasters have the same range of pixel values. Therefore, the general procedure we used is to align all bands to the same grid, convert to the same numerical type (e.g., integer), and scale values to match the range of pixels in the imagery.

Elevation

Elevation is a key driver of marsh vegetation zonation as it directly influences the range of abiotic conditions in the marsh landscape (i.e., inundation frequency and salinity; Pennings & Callaway, 1992). Thus, by combining our field-based training data with landscape-level elevation data, the classifier can better predict where certain species of vegetation may exist.

This project utilizes a floating-point 1-meter DEM derived from LiDAR taken in winter 2018 (USGS one meter x73y318 & x73y318 TX South B6 2018; acquired from the USGS Earth Explorer). The DEM did not have any gaps and was continuous over the entire study area.

The DEM was processed in ArcGIS Pro for Desktop using geoprocessing tools. To process the DEM:

1. Convert the DEM to an integer raster.
    a. Run the **Times** tool to multiply the DEM by 10,000.
    b. Convert the result to integer with the **Int** tool.
2. Use the **Resample** tool on the DEM to match the imagery grid (only applicable for 2018 and 2020)
    a. Input raster: Int DEM
    b. Cell Size: 0.6 x 0.6 m
    c. Resampling Technique: Bilinear

   d. Environments:
      i. Snap Raster: NAIP Imagery Mosaic
3. Run the **Clip Raster** tool to clip the resampled DEM to the Study Boundary
4. Rescale the DEM using **Plus** and **Divide** to match the imagery band value range (0-255).
5. Export the result as a **TIFF** file (Fig. 6).

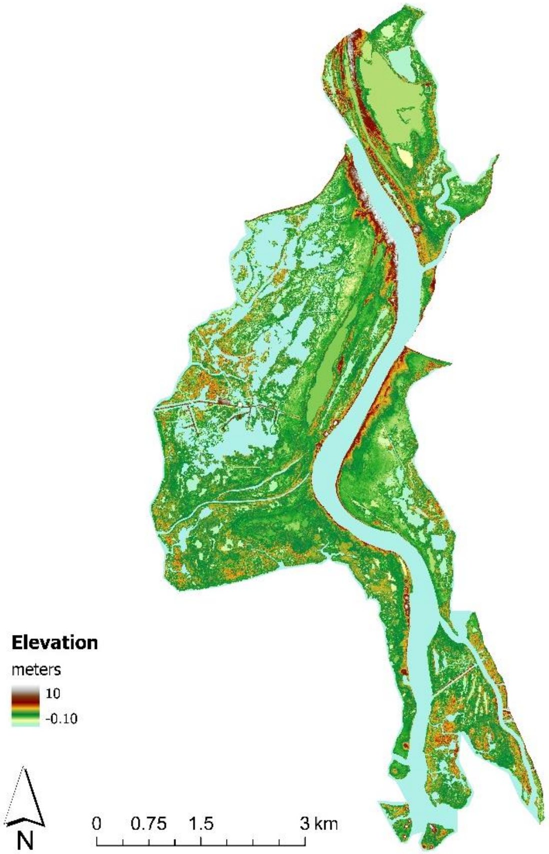

Figure 6. Example DEM layer (2018).

Modified Soil-Adjusted Vegetation Index (MSAVI), Normalized Difference Vegetation Index (NDVI), and Visible Atmospherically Resistant Index (VARI)

The Modified Soil Adjusted Vegetation Index (MSAVI; Qi et al., 1994, Fig. 7a) and Normalized Difference Vegetation Index (NDVI; Weier & Herring, 2000; Fig. 7b) are derived from Red and Near-Infrared imagery bands. These indices provide a measure of vegetation color, which can be used to distinguish between species and/or patches of marsh vegetation (Rouse et al., 1973). MSAVI was calculated in ArcGIS Pro using the predefined **Band Arithmetic** tool in the Raster Functions, and NDVI was calculated using the NDVI function. The Visible Atmospherically Resistant Index (VARI; Fig. 7c) is derived from the red, green, and blue imagery bands. This index also measures vegetation color, but it is less impacted by atmospheric light scattering (Gitelson et al., 2002). VARI was also calculated using the predefined **Band Arithmetic** tool. Index rasters were rescaled using the **Times** tool, then converted to integer using the **Int** tool.

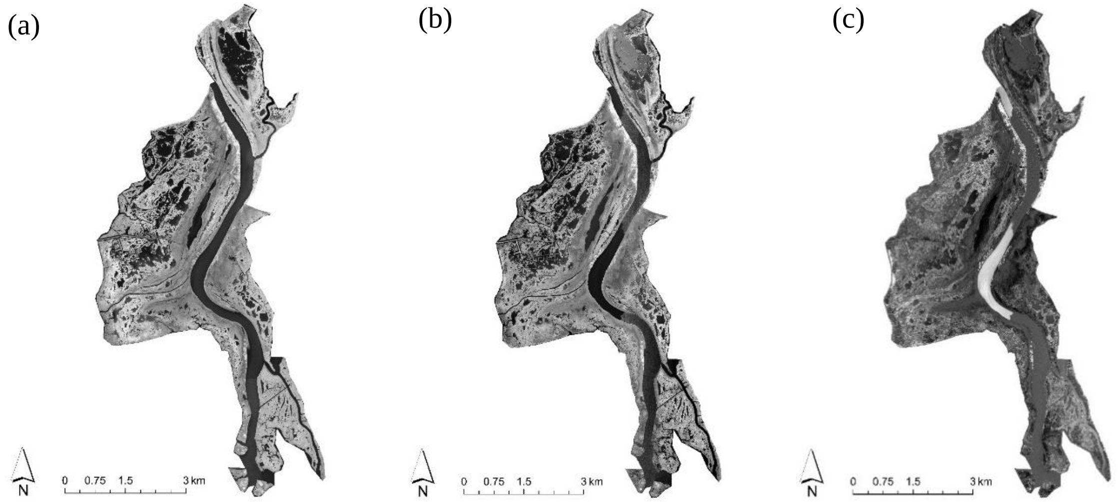

Figure 7. Example (a) MSAVI, (b) NDVI, and (c) VARI layers (2014).

Texture

Texture provides an estimate of vegetation patch boundaries and size. By looking at the texture of the marsh landscape, we can distinguish the canopy structure of patches and land/water interfaces, further improving the classifier's ability to predict the spatial distribution of vegetation and other cover types (i.e., bare ground, water, forest, etc). Texture is derived from MSAVI by a 3-by-3 moving window from which standard deviation is calculated using the **Statistics** tool in the Raster Functions tool in ArcGIS. The resulting raster was rescaled using the **Times** tool, then converted to integer using the **Int** tool (Fig. 8).

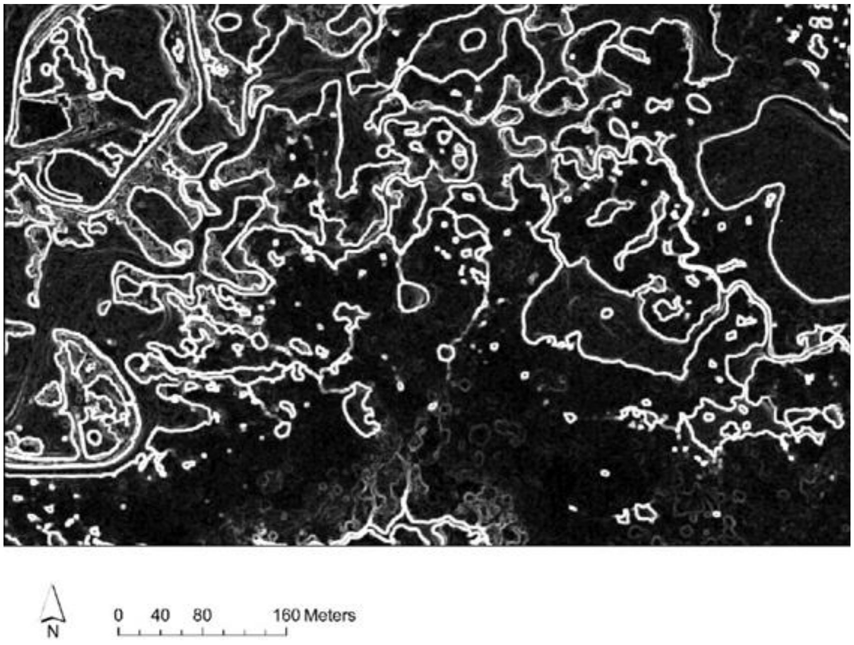

Figure 8. Example texture layer (2014).

Distance from Water

Like elevation, distance from water provides information about the abiotic factors, inundation and salinity, experienced by the marsh vegetation (Stachelek & Dunton, 2012; Tang et al., 2022). Using a subset of training data that included only water and non-water as categories, we ran a random forest classification to produce a classified raster of water. The procedure for performing the classification is described in more detail later in this document.

With a classified water raster, the procedure to compute distance from water is:

1. Use the **Set Null** tool to set non-water pixels to NoData.
2. Use the **Euclidean Distance** tool to compute distance from water.
3. Use the **Times** tool to rescale the raster to comparable values from the imagery.
4. Use the **Int** to convert the result to integer (Fig. 9).

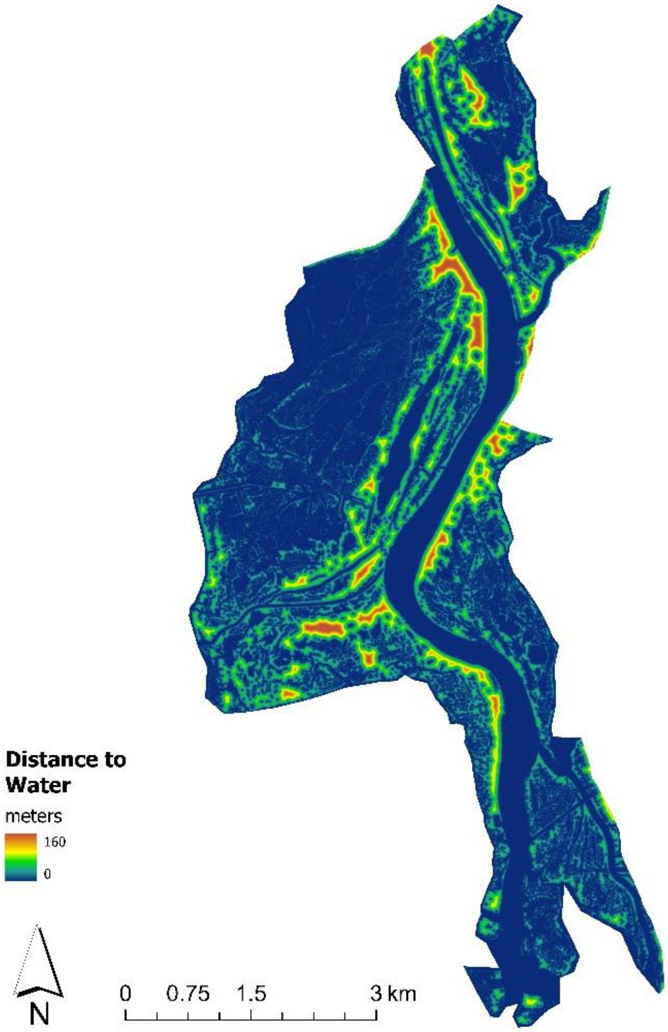

Figure 9. Example distance to water layer (2014).

Classification and Accuracy Assessment

Previous studies have found that the Forest-Based Classification algorithm has the best performance in classifying marsh vegetation (Rasser, 2009; Dunton et al., 2019). We found that combining scarce, such as *Aster tenuifolius*, and/or difficult to distinguish species, such as *Batis maritima* and *Salicornia virginica*, improved classification results. Because the classification tool we used does not provide a Kappa Index value, we used Google Earth Engine to derive user's accuracy, producer's accuracy, and Kappa. The Sensitivity and Accuracy indices and Variable Importance values were derived from ArcGIS Pro diagnostic outputs. Sensitivity is the percentage of times features with an observed category were correctly predicted for that category. Accuracy considers both how well features with a particular category are predicted and how often other categories are miscategorized for the category of interest. It gives an idea about how frequently a category is identified correctly among the total number of confusions for that category. While sensitivity and producer's accuracy are generally the same index, there were discrepancies between the Google Earth Engine-derived values and the ArcGIS Pro-derived values, and thus all values were kept in the final confusion matrix tables.

Kappa Index is a statistical value that represents the agreement between observed values and the values predicted by the classification model (Landis & Koch, 1977). Kappa Index can answer questions such as: 1) are there differences between the observed and predicted values?, 2) are there greater differences between certain classes in the observed and predicted values?, 3) is the agreement between the observed and predicted values significantly different from chance agreement based on the overall distributions of values?, 4) are there certain patterns of disagreement which may reflect significant imprecision?. Kappa is calculated using the following formula:

$$K = \frac{\pi_0 - \pi_e}{1 - \pi_e},$$

where π_0 is an observational probability of agreement and π_e is a hypothetical expected probability of agreement under an appropriate set of baseline constraints. Mathematically, it represents the extent to which the observational probability of agreement is in excess of the probability of agreement hypothetically expected. These probabilities are calculated based on confusion matrices (contingency tables).

The procedure to produce and assess a classified raster is (Fig. 10):

1. Run the **Forest-based Classification and Regression** tool in **Train only** mode with the following inputs:
    a. Input Training Features: 2021 Training Data
    b. Variable to Predict: Species category
    c. Treat Variable as Categorical: Yes
    d. Explanatory Training Rasters:
        i. 2020 NAIP Mosaic
        ii. 2020 Elevation
        iii. 2020 Distance from Water
        iv. 2020 MSAVI
        v. 2020 NDVI
        vi. 2020 VARI

        vii. 2020 Texture
    e. Compensate for Sparse Categories: Yes
    f. Number of Trees: 100
    g. Maximum Tree Depth: Default
    h. Training Data Excluded for Validation (%): 25
    i. Number of Runs for Validation: 1
2. Run the **Forest-based Classification and Regression** tool in **Predict to raster** mode with the same inputs as the Training step for each corresponding year.
    a. Define a file name and location for the Output Classification Performance Table (Confusion Matrix)
3. Remap classes that performed poorly, as indicated by the Diagnostics output, into the following categories using the **Reclassify** tool:
    a. BF, AT, PA, SP, ML, F to Other (O)
    b. BE, BD, BC, BW, R to Bare (B)
    c. BM and SV to BM + SV
4. Use the **Table to Excel** tool to export the confusion matrices to Excel files for further analysis.
5. Manually reclassify the resulting Excel tables to reflect the updated categories.
6. Input the confusion matrices into Google Earth Engine as arrays and run accuracy statistics functions (see Appendix for code).

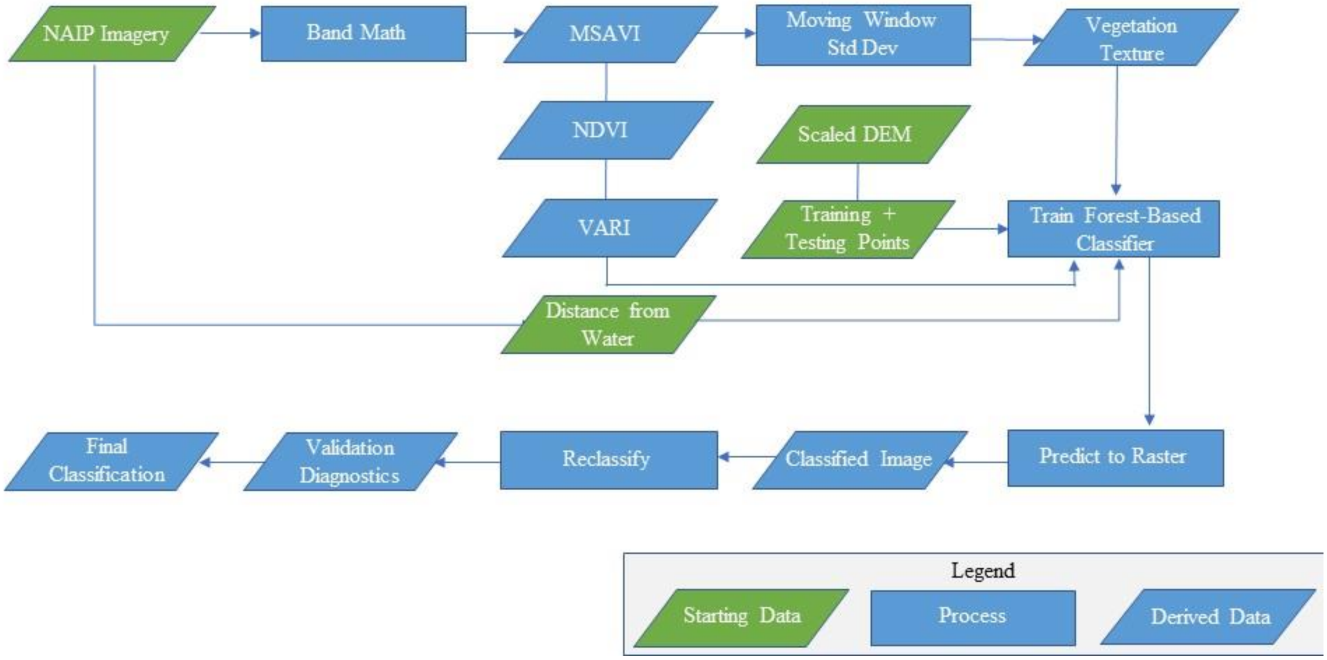

Figure 10. The image classification workflow, with ancillary data incorporated.

National Wetland Inventory (NWI) Mapping

The National Wetland Inventory (NWI) is a database of all wetland habitats across the United States. In the NWI, wetlands are categorized using a universal schema created by Cowardin et al. and the US Fish and Wildlife Service (USFWS) in 1979. This schema classifies wetlands by system (marine, estuarine, etc.), subsystem (subtidal, intertidal, etc.), class (rock bottom, reef, forested wetland, etc.), and subclass (bedrock, coral, broad-leaved evergreen, etc.) with several additional modifiers based on water regime, water chemistry, and soil (Cowardin et al., 1979). A habitat map following the NWI categories was created for the Lavaca Delta using the 2018 classified vegetation map, the 2018 DEM, and tidal data. This study did not gather significant water chemistry or soil data, and therefore these modifiers will not be included in the habitat map. Relevant classification definitions are listed in Table 4.

Table 4. National Wetland Inventory classification schema.

System	E	Estuarine
Subsystem	E2	Intertidal
Class/Subclass	EM1	Emergent persistent
	US	Unconsolidated shore
	FO3	Broad-leaved evergreen forested
	SS3	Broad-leaved evergreen scrub-shrub
Water Regime Modifiers	N	Regularly flooded
	P	Irregularly flooded

Tidal levels with respect to mean sea level (mean high water, mean low water, etc.) were gathered from the NOAA tidal gauge at Port Lavaca (Station #8773259; Gill & Schultz, 2001). Using the NOAA *vdatum* tool (vertical uncertainty = ±0.10), all tidal data were converted to the same vertical datum as the DEM (North American Vertical Datum of 1988 (NAVD88); Parker et al., 2003). These data were used to separate regularly flooded pixels from irregularly flooded pixels. According to USFWS, the division between Regularly Flooded and Irregularly Flooded Water Regimes occurs just above mean tide level on the Gulf Coast (Federal Geographic Data Committee, 2013). We decided to use the mean high water level (0.219 m elevation with respect to NAVD88) to represent this division.

The procedure for mapping marsh habitats according to the NWI (Fig. 11, Fig. 12) is:

1. Reclassify the 2018 14-class map into the following categories using the **Reclassify** tool:
    a. BM, DS, JR, ML, O, SA, SM, SS, SV to E2EM1 (value = 1)
    b. B, R to E2US (value = 2)
    c. F to E2FO3 (value = 3)
    d. U to E2SS3 (value = 4)
    e. W to W (value = 5)
    f. Save this reclassified raster as **NWI**
2. Use the **Raster Calculator** tool to further categorize pixels based on whether they fall above or below mean high water via the following conditional statements:
    a. E2EM1P: Con((“NWI” == 1) & (“DEM” >= 0.219), 1)
    b. E2EM1N: Con((“NWI” == 1) & (“DEM” <= 0.219), 1)
    c. E2USP: Con((“NWI” == 2) & (“DEM” >= 0.219), 1)

d. E2USN: Con((“NWI” == 2) & (“DEM” <= 0.219), 1)
e. E2FO3P: Con((“NWI” == 3) & (“DEM” >= 0.219), 1)
f. E2FO3N: Con((“NWI” == 3) & (“DEM” <= 0.219), 1)
    i. No pixels satisfied these conditions
g. E2SS3P: Con((“NWI” == 4) & (“DEM” >= 0.219), 1)
h. E2SS3N: Con((“NWI” == 4) & (“DEM” <= 0.219), 1)
    i. No pixels satisfied these conditions

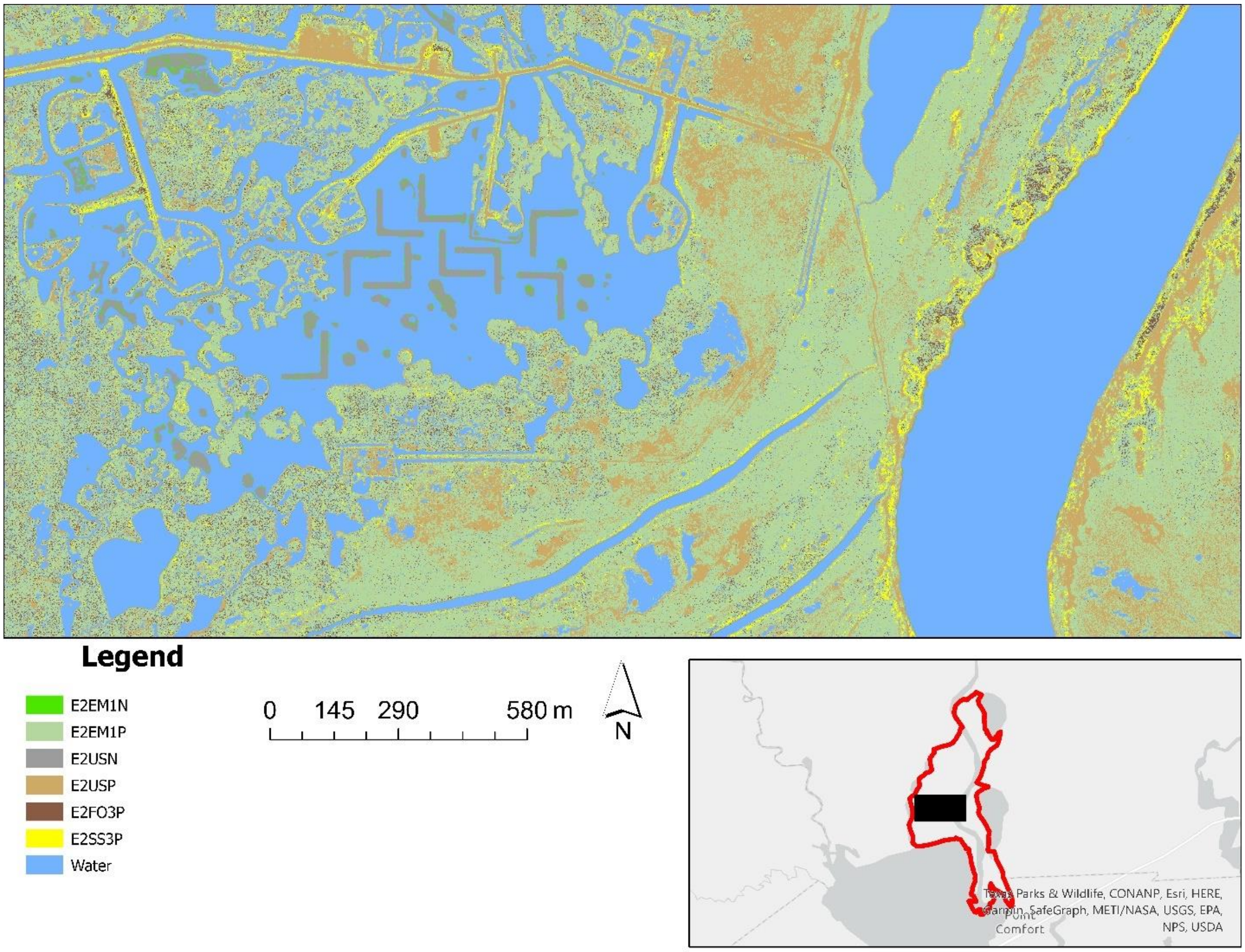

Figure 11. National Wetland Inventory marsh habitat map, at 1:10,000 scale.

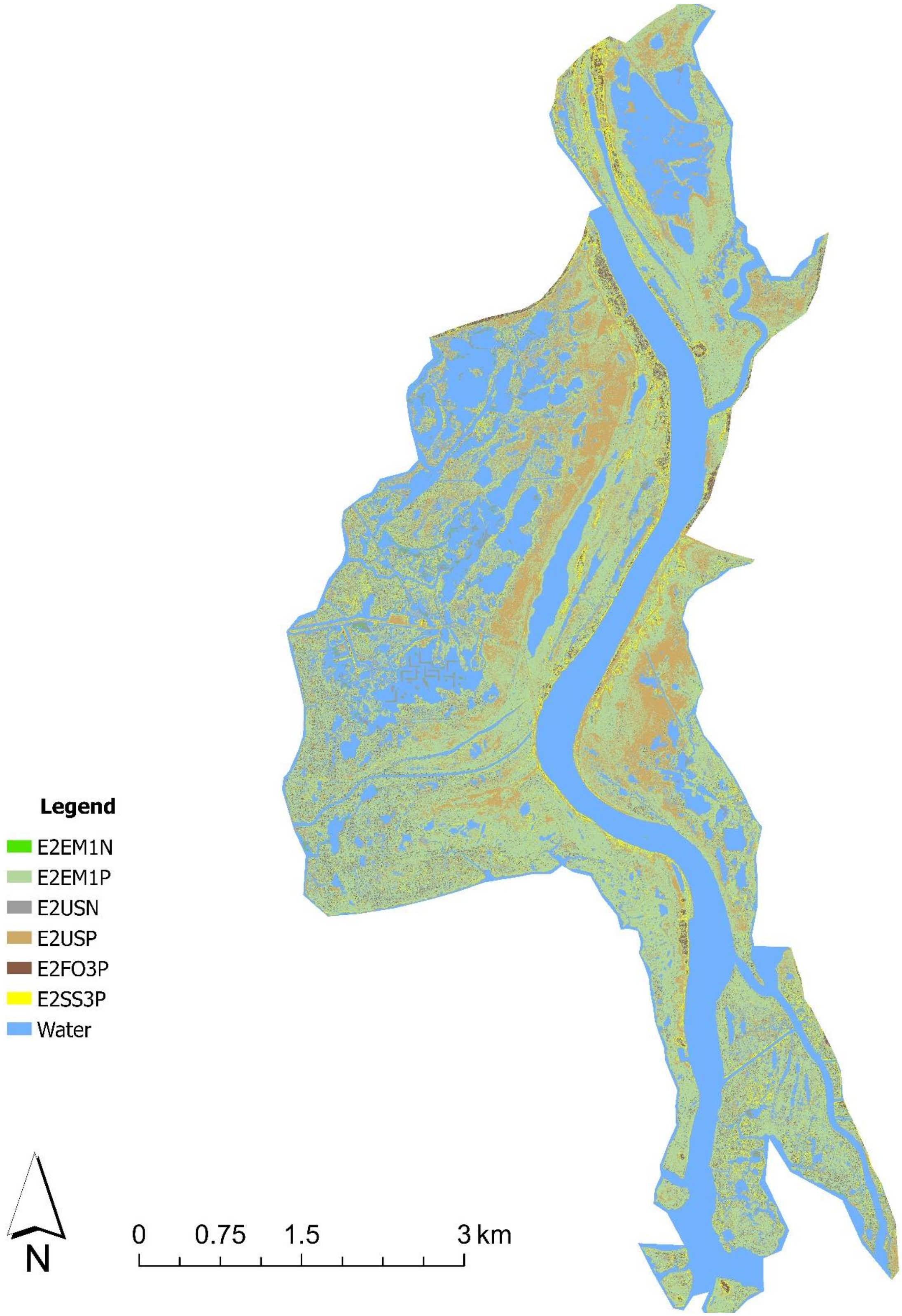

Figure 12. National Wetland Inventory marsh habitat map, at 1:43,500 scale.

Change Analysis, 2010-2020

Classified maps were created to compare the vegetation patterns in 2010, 2014, 2016, 2018, and 2020. These maps represent the marsh community under a range of flow conditions from severe (2009) to dry (2010-2014) to average (2015-2020; USGS Gage # 08164525; TCEQ, 2012). To extract statistically valuable information from the maps, a grid with 0.5 km^2 cell size was overlayed and areal extents of each class within the grid cell boundaries were tabulated and exported.

The procedure for extracting area data from the maps is:

1. Convert the classified raster maps into integer using the **Int** tool.
2. Convert the integer rasters into polygons using the **Raster to Polygon** tool.
    a. Input raster: Integer raster map
    b. Field: Value
    c. Simplify polygons: Yes
    d. Create multipart features: Yes
3. Use the **Generate Tessellation** tool to create a grid with the following inputs:
    a. Extent: Study boundary
    b. Shape Type: Square
    c. Size: 0.5 Square Kilometers
    d. Spatial Reference: NAD 1983 UTM Zone 14N
4. Use the **Tabulate Intersection** tool to extract the areal extents within each grid cell.
    a. Input Zone Features: Tessellation Grid
    b. Zone Fields: GRID_ID
    c. Input Class Features: Polygon map layer
    d. Class Fields: OBJECTID
    e. Sum Fields: Shape_Area
5. Rerun the **Tabulate Intersection** tool for each year by changing the Input Class Feature layer.
6. Export tables to Excel using the **Table to Excel** tool.

All marsh areal extent data was then converted to CSV files and analyzed using R (R Core Team, 2020). To examine the relationships between marsh area and composition and freshwater inflows, we ran two generalized linear mixed models (GLMMs). GLMMS can assess both random and fixed effects, which makes them ideal for accounting for both the fixed effects of inflows and the random effects of time and the grid cell location (Bolker et al., 2009). The first set of models assessed the following habitats: of marsh vegetation, non-marsh vegetation, bare ground, and water. The second set of models assessed marsh vegetation species composition.

Freshwater inflows data were obtained from the Texas Water Development Board Coastal Hydrology data set and spatially filtered to represent only inflows to Lavaca Delta (shapefile of study area provided to TWDB staff; Fig. 13). We ran the GLMMS using three different time steps of inflows data: 3 months, 12 months, and 24 months. For each time step, we identified the specific date of image acquisition for each year (ex. 05/03/2010) and isolated and averaged the corresponding previous months of data. Total freshwater inflows were used for the first set of models, while gaged flow was used for the second set of models (see Appendix for code).

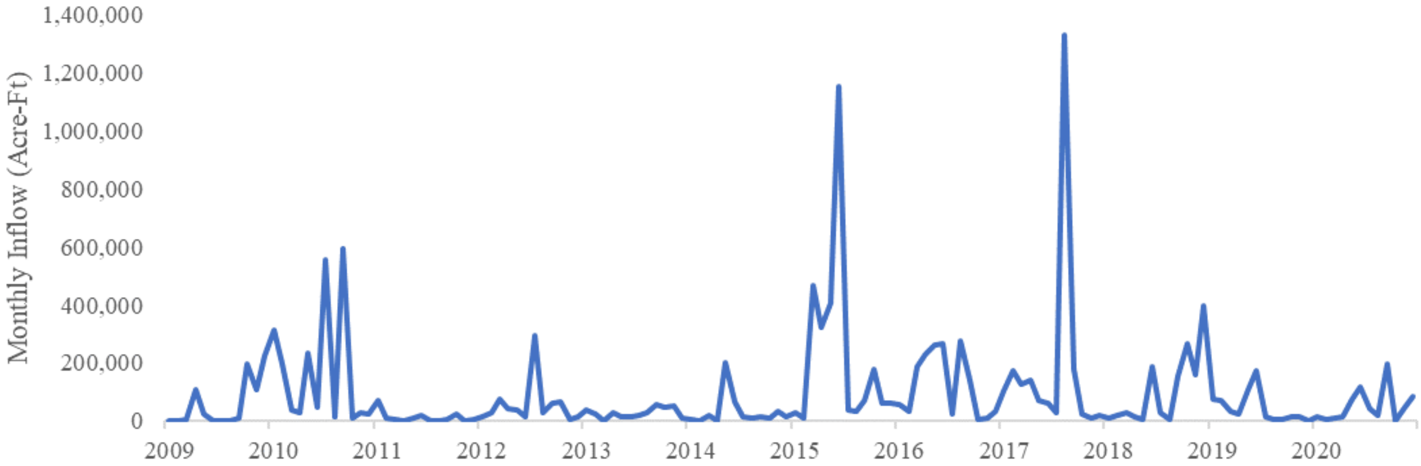

Figure 13. Monthly freshwater inflow (acre-ft) from 2009-2020 in the Lavaca Delta.

Data Archival

We propose to archive datasets from this work with the Texas Natural Resources Information System (TNRIS). We have not yet contacted TNRIS. We plan to archive the following datasets:

- Study area shapefile
- Training data points
- National Wetland Inventory habitat map
- Raw classified results, which include 14 classes
- Reclassified results, which include 9 classes
- Confusion matrices
- Raw field data (vegetation percent cover)

Results and Discussion

Vegetation Classification

The results of this study demonstrate that marshes with considerable freshwater influence are much more difficult to accurately map than typical salt marsh plant communities. Despite utilizing supervised imagery classification integrated with several sources of ancillary data, the average Kappa Index value we obtained was 0.412 (fair to moderate level of agreement; Landis & Koch, 1977; Table 5) and the average overall accuracy was 49.6%. These results are similar to the accuracy values of Rasser (2009) (Kappa Index of 0.41 and overall accuracy of 57%), however, they are considerably lower than results from Dunton et al. (2019). Our results are likely a product of limited accessibility to numerous sampling sites, as previously described, as well as the nature of the marsh itself. The Lavaca Delta marsh has considerably more species present than similar estuarine marshes in Texas. For example, in Dunton et al. (2019), 11 species were sampled in the Rincon Delta marsh. We encountered and/or sampled at least 17 species in this study. The number of species present effectively dilutes the training data, creates sparse categories, and results in an imbalanced training dataset that impacts classification accuracy. In addition, nearly the entire Lavaca Delta marsh is composed of mixed stands of several species including both canopy and understory vegetation. This makes classification more difficult as the spectral profile of each pixel represents a mix of spectral signatures from multiple species. Andrew and Ustin (2008) found that a remote sensing-based classification analysis becomes less successful as site complexity, represented by either species, structural, or landscape diversity, increases.

Table 5. Kappa Statistic categories. Adapted from Landis & Koch (1977).

Kappa Statistic	Strength of Agreement
<0.00	Poor
0.00-0.20	Slight
0.21-0.40	Fair
0.41-0.60	Moderate
0.61-0.80	Substantial
0.81-1.00	Almost Perfect

Integrating ancillary data was a crucial element of the classification process in this study. Model diagnostics reveal that the aerial imagery mosaics were consistently the least important variables in the classification process, while elevation was the most important explanatory variable. Furthermore, NDVI and VARI generally had similar importance to MSAVI, justifying our inclusion of these indices in our classification model (Table 6; see Appendix for additional years).

Our major mapping errors were associated with errors of both omission (user's accuracy) and commission (producer's accuracy) (Table 7; see Appendix for additional years). These were related to the both the inability to spectrally separate species and the unbalanced and limited training data set. Many plant species were underrepresented in the training data, while substrate categories such as water were overrepresented. This explains why the water class performed very well in all classifications, while most plant species did not. User's and producer's accuracies and sensitivity were generally highest for the most well-represented species or classes. Because accuracy all falls within a small range of high values, it does not provide a lot of diagnostic power.

NAIP imagery is taken during the "growing season" when marsh vegetation should be at its highest biomass, and thus vegetation should appear the same in imagery across years. This assumption is the basis for the application of current field data to historical imagery. However, differences in classifications between years may still be an artifact of the image acquisition process. Because we were not able to contract new imagery flights, we were limited to freely available and accessible data. NAIP imagery is the highest resolution, multispectral data available for the study area, but the temporal resolution of NAIP imagery is coarse, and environmental conditions, such as season, water level, tidal stage, and recent weather, are not standardized in the image acquisition process. Therefore, differences in image timing may impact the final classified results. In addition, with images available only every two years, it is difficult to say with certainty whether the variations in community composition reflect natural variability or a true trend.

In conclusion, the integration of high-resolution multispectral aerial imagery and ancillary data such as LiDAR and spectral indices provided a relatively accurate classification of vegetation in the Lavaca Delta. Due to the increasing availability of high-resolution remote sensing data, the methods here provide a foundation upon which to build with the inclusion of additional imagery sources. The methods incorporated in this study are part of a growing body of research that has shown the utility of remote sensing in monitoring coastal and estuarine systems. This study will serve as the basis for future work in the Lavaca Delta marshes.

Table 6. Variable importance for the 2020 classification analysis.

Variable	Percent
Elevation	17
NDVI	15
MSAVI	15
VARI	14
Distance	14
Texture	13
NAIP	12

Table 7. Confusion matrix for the 2020 classification analysis.

Category	BM + SV	B	DS	JR	O	SA	SM	SS	W	Sensitivity	Accuracy	User's accuracy	Kappa
BM + SV	1	4	1	0	1	1	1	0	0	0.25	0.95	0.13	NA
B	0	16	1	0	1	0	0	0	1	0.57	0.94	0.55	NA
DS	4	2	7	0	3	1	0	2	0	0.25	0.88	0.7	NA
JR	0	1	0	3	1	0	1	0	0	0.33	0.97	0.33	NA
O	3	1	1	2	10	0	3	0	0	0.38	0.95	0.4	NA
SA	0	1	0	2	4	2	0	0	2	0	0.88	0.5	NA
SM	0	2	0	2	4	0	2	1	1	0.2	0.86	0.25	NA
SS	0	0	0	0	1	0	1	3	0	0.5	0.93	0.5	NA
W	0	2	0	0	0	0	0	0	28	0.83	0.95	0.88	NA
Producer's accuracy	0.11	0.84	0.37	0.5	0.5	0.18	0.17	0.6	0.93	NA	NA	0.55	NA
Kappa	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.47

Landscape Vegetation Patterns in the Lavaca River Delta

Vegetation patterns were examined using geospatial analysis to gain a better understanding of landscape-scale patterns of vegetation. These landscape patterns were often difficult to interpret due to the diverse vegetative community present in the Lavaca Delta. For example, the river banks, which generally have an elevational gradient of about a meter and a slope of 13 to 90 degrees, are dominated by both bare ground and upland or forested vegetation. The interior marsh is dominated by *Distichlis spicata* with patches of *Scirpus maritimus*, *Spartina alterniflora*, and *Juncus roemerianus* distributed throughout (Fig. 14). This pattern is likely due to the steep slope of the river banks and mild elevational gradient of the interior marsh. We also found that the lower reaches of the Lavaca Delta were more dominated by *J. roemerianus*.

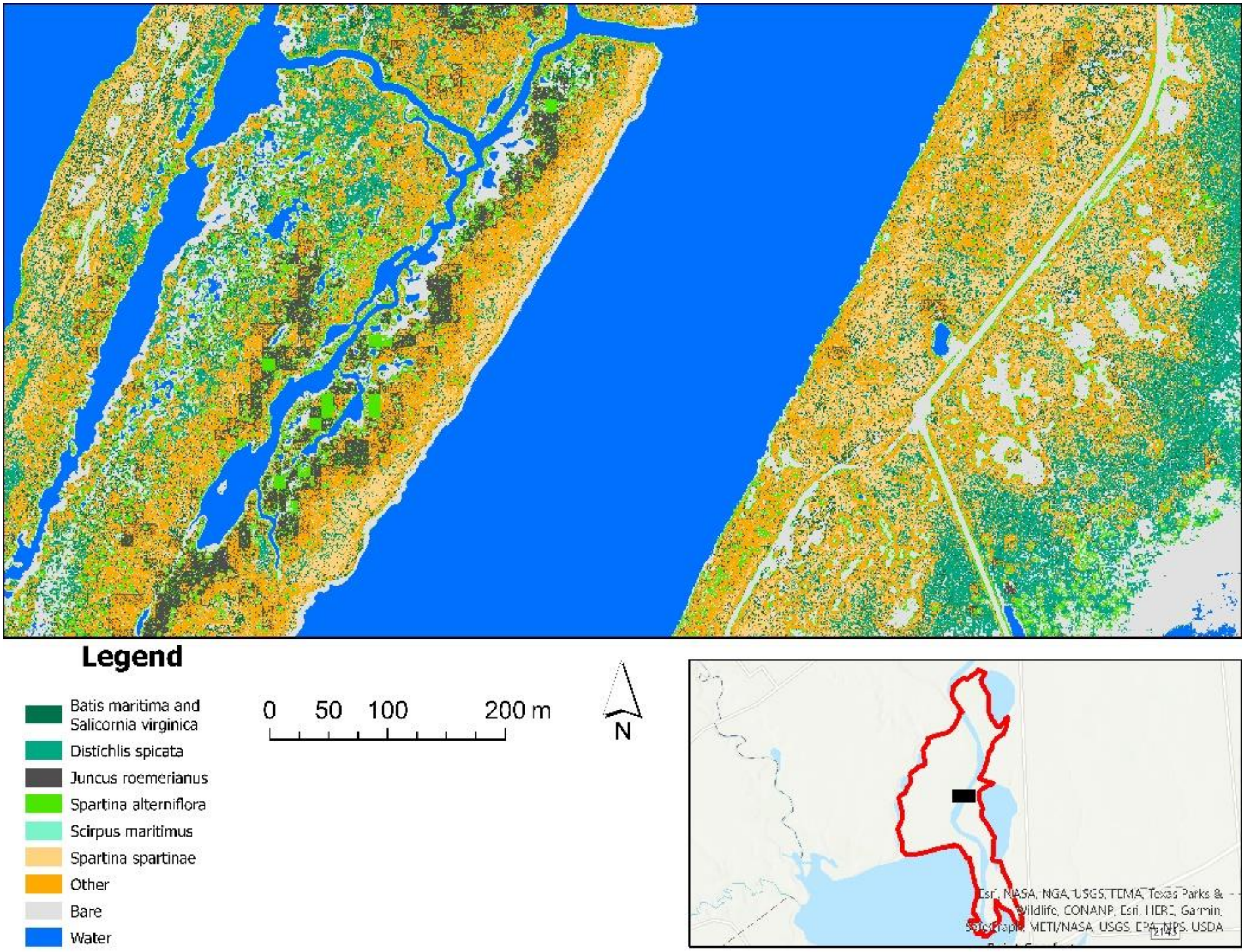

Figure 14. Zonation of vegetation along river banks is dominated by bare ground and upland vegetation.

The general nine-category classification of the Lavaca Delta in 2020 depicts a system that has an extensive tidal creek and pond network (Fig. 15). Open water areas compose nearly 40% of the area, with unvegetated areas composing another 17% of the study area. Other vegetation represented about 15% of the system. There were no dominant marsh vegetation assemblages due to high biodiversity. However, the most widespread species found were *Juncus roemerianus* (~7%), *Distichlis spicata* (~7%), *Spartina alterniflora* (~9%), and *Spartina spartinae* (~4%).

A more detailed 14-category classification shows that the other vegetation is split fairly evenly between forest (~4%), upland (~6%), and minor marsh species (~5%). *Batis maritima* (~2%) *Salicornia virginica* (~3%), and *Scirpus maritimus* (~0.5%) are the least common species found in 2020 (Fig. 16; Table 8). In general, these results match our field observations, except for *S. maritimus*, which seems to be heavily underrepresented in the final classification.

The most conspicuous difference between the marsh community of the Lavaca Delta and other Texas marshes, particularly the Nueces Delta marshes, is the lack of typical zonation patterns. For example, in Dunton et al. (2019), classic low marsh species, such as *Borrichia frutescens*, were found to neighbor the extensive tidal creek network, while *B. maritima*, *S. virginica*, and *S. spartinae* were found at progressively higher elevations. In contrast, the Lavaca Delta marsh is significantly patchier, with the main zonation being between upland or forested habitat and marsh. In addition, in the upper reaches of the delta, small regions of tidal brackish marsh, with species such as *Phragmites australis* and *Typha angustifolia*, were present. This reflects the natural gradient in salinity, decreasing with distance from Lavaca Bay.

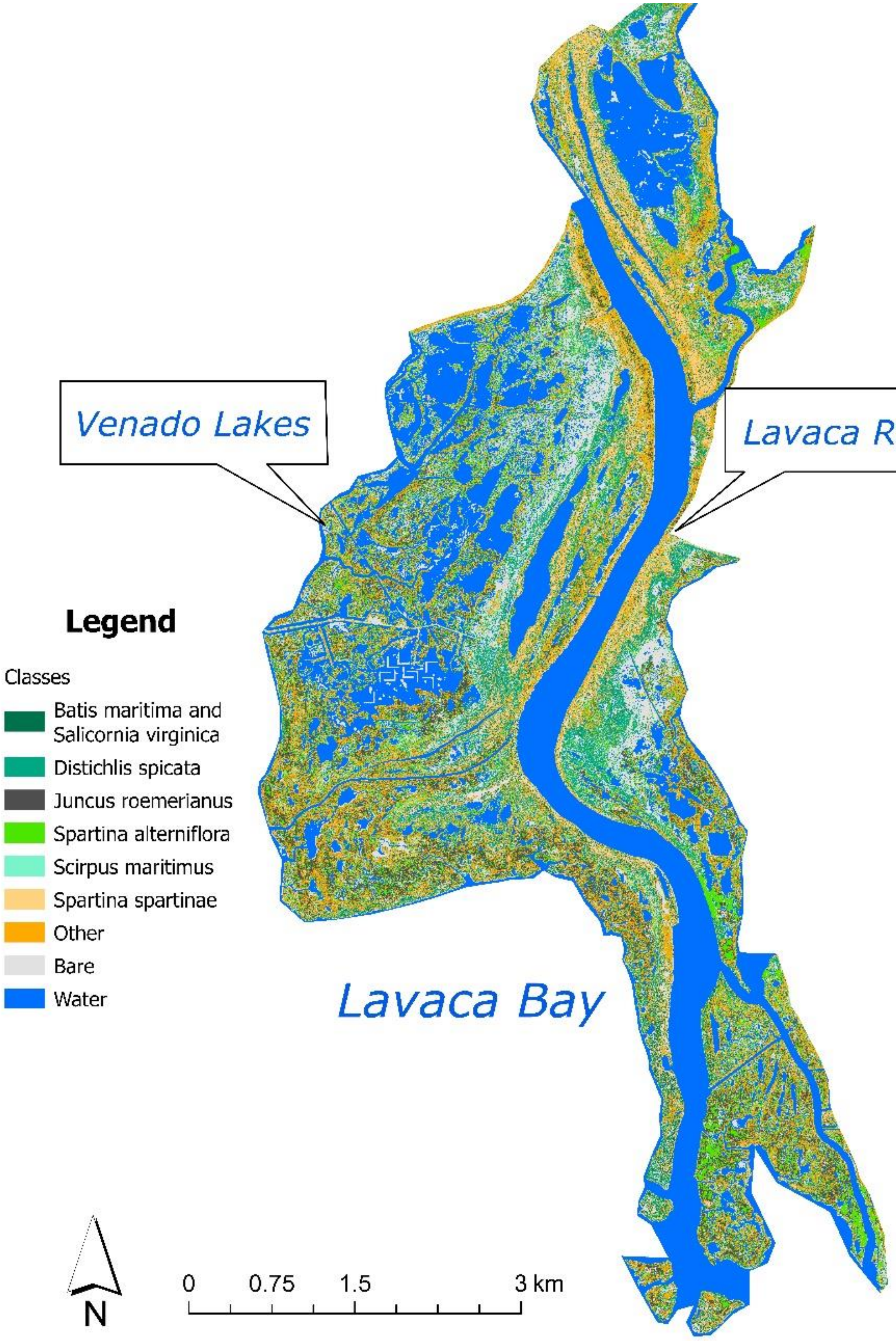

Figure 15. Generalized vegetation classification of the Lavaca Delta from 2020.

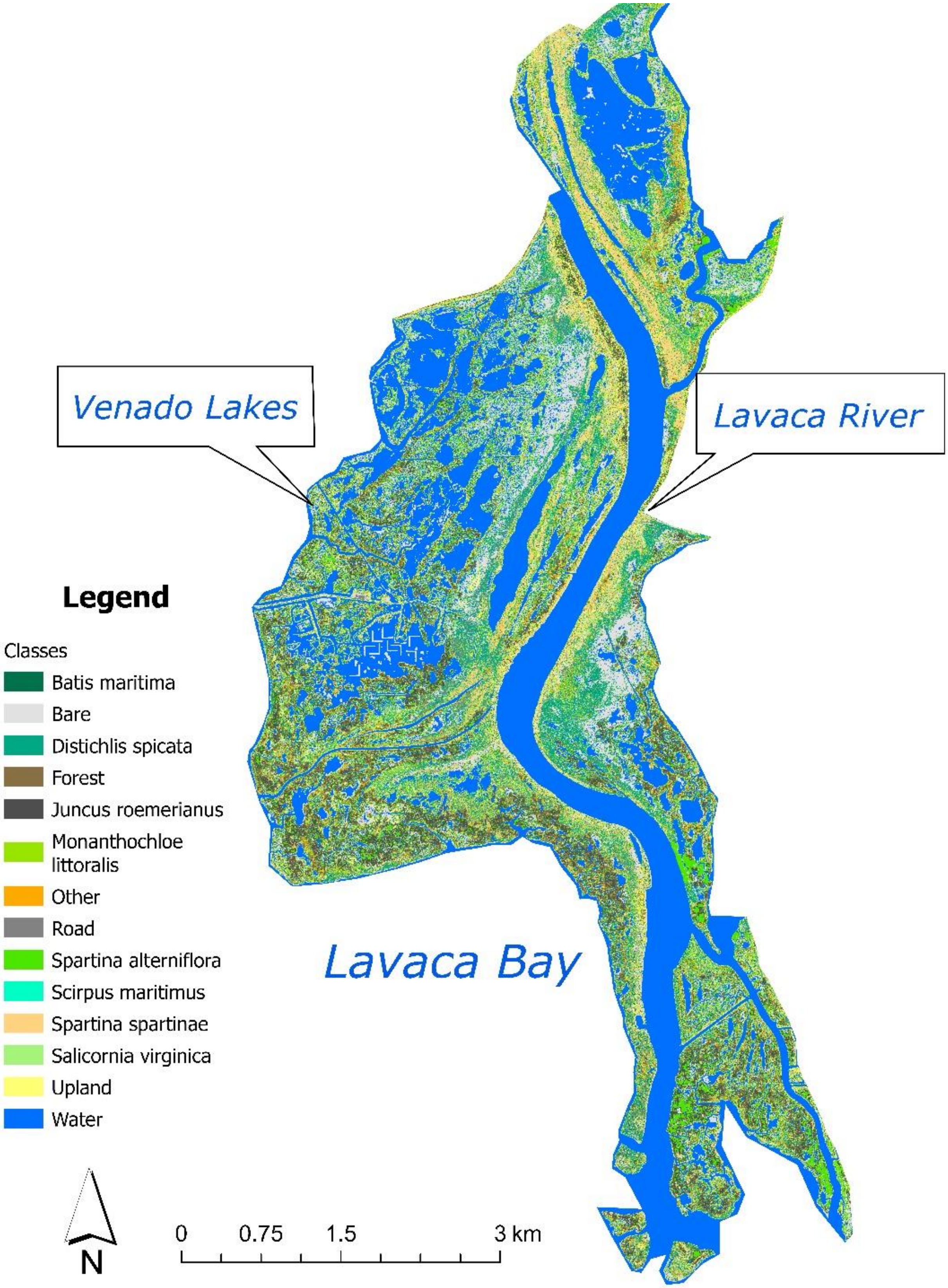

Figure 16. Detailed vegetation classification of the Lavaca Delta from 2020.

Table 8. Composition of the vegetative communities in the Lavaca Delta from 2010-2020.

Cover Class	Area (ha)					Percent of Total Area				
	2010	2014	2016	2018	2020	2010	2014	2016	2018	2020
Batis maritima	154	42	115	172	43	5.4	1.5	4.0	6.2	1.5
Distichlis spicata	125	82	102	255	199	4.3	2.9	3.6	8.7	6.9
Juncus roemerianus	216	283	236	180	199	7.5	9.9	8.2	6.5	6.9
Monanthochloe littoralis	84	65	85	159	68	2.9	2.3	3.0	3.7	2.4
Spartina alterniflora	150	417	67	57	257	5.2	14.5	2.4	2.1	9.0
Scirpus maritimus	305	32	153	126	13	10.6	1.1	5.3	4.5	0.4
Spartina spartinae	64	132	210	68	109	2.2	4.6	7.3	2.4	3.8
Salicornia virginica	50	49	126	48	73	1.7	1.7	4.4	1.7	2.6
Other marsh vegetation	146	95	89	98	55	5.1	3.3	3.1	3.5	1.9
Forested vegetation	39	196	105	155	124	1.4	6.8	3.7	4.6	4.3
Non-forested vegetation	82	207	301	119	182	2.9	7.2	10.5	4.3	6.3
Bare	575	385	301	448	485	20.0	13.4	10.5	16.3	16.9
Water	882	883	979	985	1063	30.7	30.8	34.1	35.5	37.1

Long-Term Vegetation Response to Freshwater Inflows

Previous studies have shown that the emergent plant community is responsive to variations in freshwater inflow and salinity (Alexander & Dunton, 2002; Forbes & Dunton, 2006). Patterns in species composition seen over a decade in the Lavaca River Delta reveal system-wide changes that are significantly related to freshwater inflows. This dataset considers both some of the driest (2010-2012) and wettest periods (2013-2018) in the local Lavaca Bay area (Nielsen-Gammon et al., 2020; Montagna et al., 2020; Fig. 13).

At the habitat scale, we found that marsh vegetation areal extent decreased from 45% to 35%, while water increased from 30 to 37%. Bare ground (10-20%) and non-marsh vegetation (4-14%) experienced opposite and variable patterns throughout the decade (Fig. 17).

Our GLMM modeling effort revealed that these shifts in marsh vegetation, bare ground, and water were statistically significant across all time steps ($p < 0.05$, Fig. 17; Table 9). However, only marsh vegetated areas had significant interactions with total inflows ($p < 0.05$; Table 9). Despite this relationship, it appears that marsh vegetation area may not be directly correlated with inflows, as evidence by the lack of clear pattern in Figure 18. This may suggest an alternate explanation for the decline in marsh area, such as sea level rise or erosion. In addition, the low R^2 value for the habitat models indicates that freshwater inflows are only explaining approximately 10% of the variation in habitat areas, supporting the consideration of alternate explanations. Variation in such a complex marsh habitat mosaic would be near impossible to fully model with a single explanatory variable, such as inflows, so this result is to be expected.

Time step seemed to only impact non-marsh vegetated habitats. It appears that these habitats may only approach statistically significant interactions with smaller time steps. Consequently, in the gaged flow models, non-marsh vegetation does reach a significant interaction with inflow at the 3-month time step (Table 9).

Based on the general consistency of significance in vegetated habitats across all three time steps, it appears that time step does not have a substantial impact on the overall conclusion that marsh vegetation is significantly impacted by changes in freshwater inflows. The comparison of significance across time steps does reveal, however, that there may be variations in the sensitivity or responsiveness to freshwater inflows in different habitats or species.

The overall marsh vegetation community composition changed in expected ways between the dry and wet periods reflected in this study. Dry years were dominated by bare ground, *S. maritimus*, and *J. roemerianus*. Conversely, wet years had increased cover of water, forest, upland, and, most importantly, *S. alterniflora*, which is considered to be an indicator of freshwater inflow condition, as it prefers fairly low porewater salinities of around 25 (Fig. 19; Stachelek & Dunton, 2013).

At the species level, modeling reveals that all marsh species shifted significantly over the study period ($p < 0.05$; Fig. 20; Table 10). In particular, *S. alterniflora* and *S. maritimus* displayed the greatest range in extent over time (12% and 10%, respectively). All species demonstrated significant interactions with both total freshwater inflows and gaged flows ($p < 0.05$) at each time step. Model fit, as indicated by the R^2 values, is low in these species models (~0.11-0.12), but again, that is to be expected given the level of complexity in the marsh community.

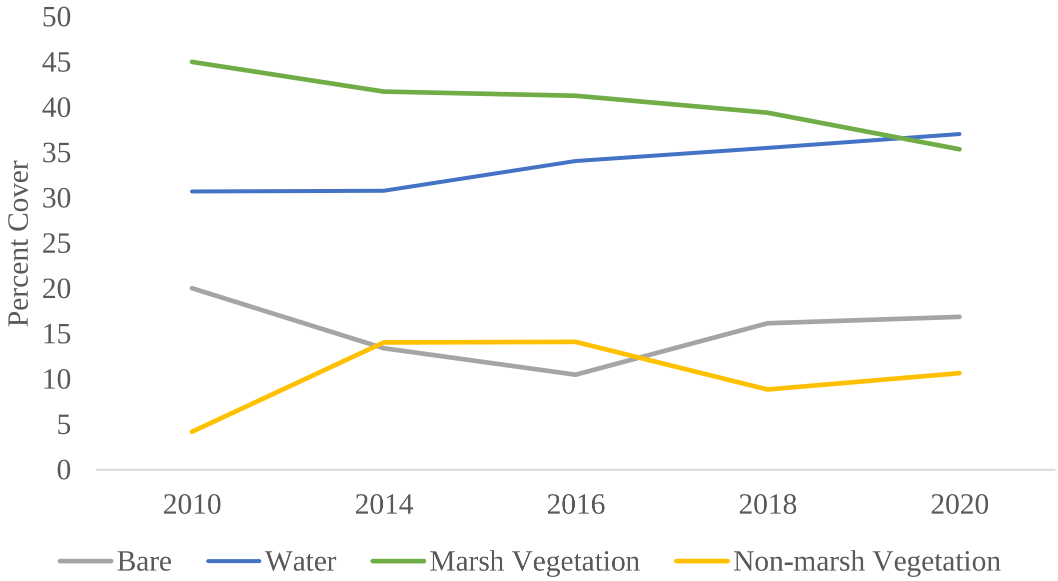

Figure 17. Percent cover of habitats in the Lavaca Delta from 2010-2020.

Table 9. P-values for habitat GLMMs across three time steps for freshwater inflows: 3 months, 12 months, and 24 months.

	3 months	12 months	24 months		3 months	12 months	24 months
Bare	< 2e-16	< 2e-16	< 2e-16	Bare	< 2e-16	< 2e-16	< 2e-16
Marsh veg	< 2e-16	< 2e-16	< 2e-16	Marsh veg	< 2e-16	< 2e-16	< 2e-16
Non marsh veg	0.1927	0.752	0.593	Non marsh veg	3.11e-06	0.0735	0.330
Water	< 2e-16	< 2e-16	< 2e-16	Water	< 2e-16	< 2e-16	< 2e-16
Bare x fresh	0.3320	0.382	0.234	Bare x gaged	0.627	0.5187	0.239
Marsh x fresh	1.88e-11	4.58e-10	2.88e-13	Marsh x gaged	5.28-07	2.37-08	8.45e-13
Non marsh x fresh	0.0981	0.607	0.638	Non marsh x gaged	1.05e-08	0.1050	0.323
Water x fresh	0.2633	0.379	0.157	Water x gaged	0.847	0.7757	0.129
R^2	0.103	0.102	0.104	R^2	0.104	0.102	0.103

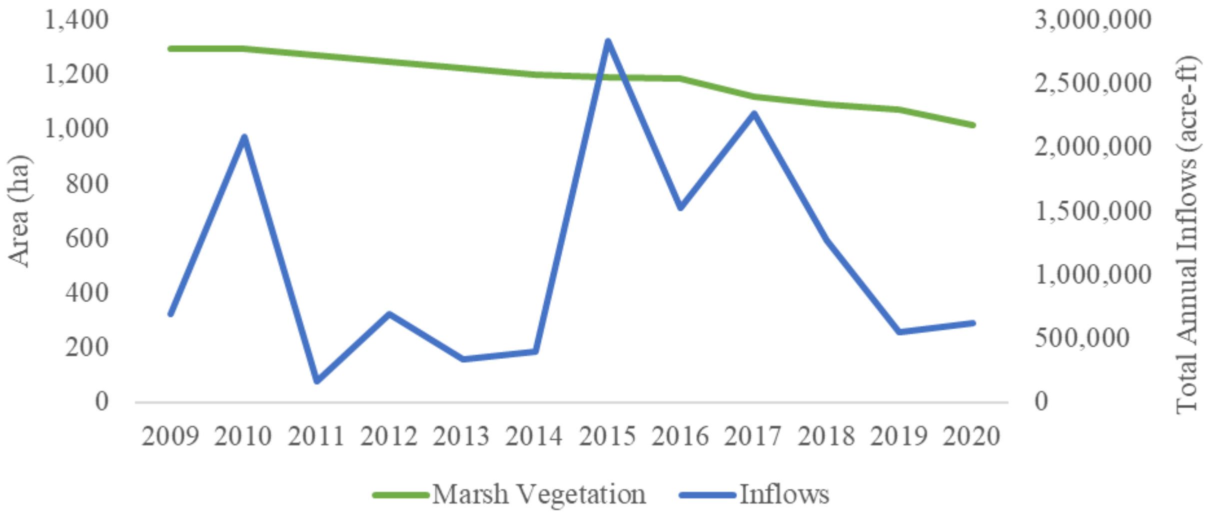

Figure 18. Marsh vegetated habitat area and total annual inflows from 2009 to 2020.

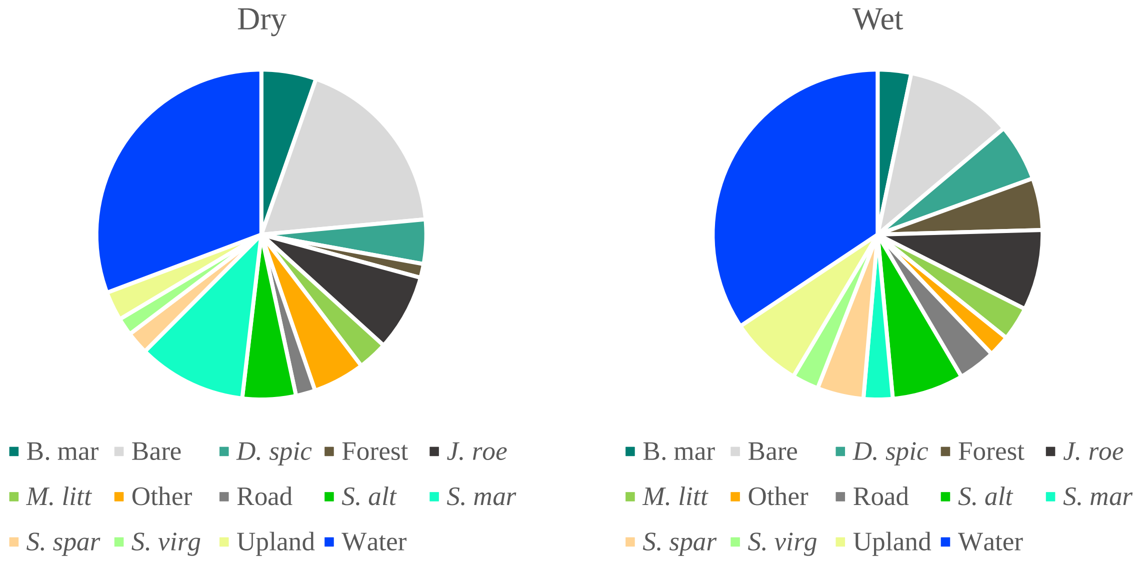

Figure 19. Marsh vegetation community composition between dry (2008-2012) and wet periods (2013-2020).

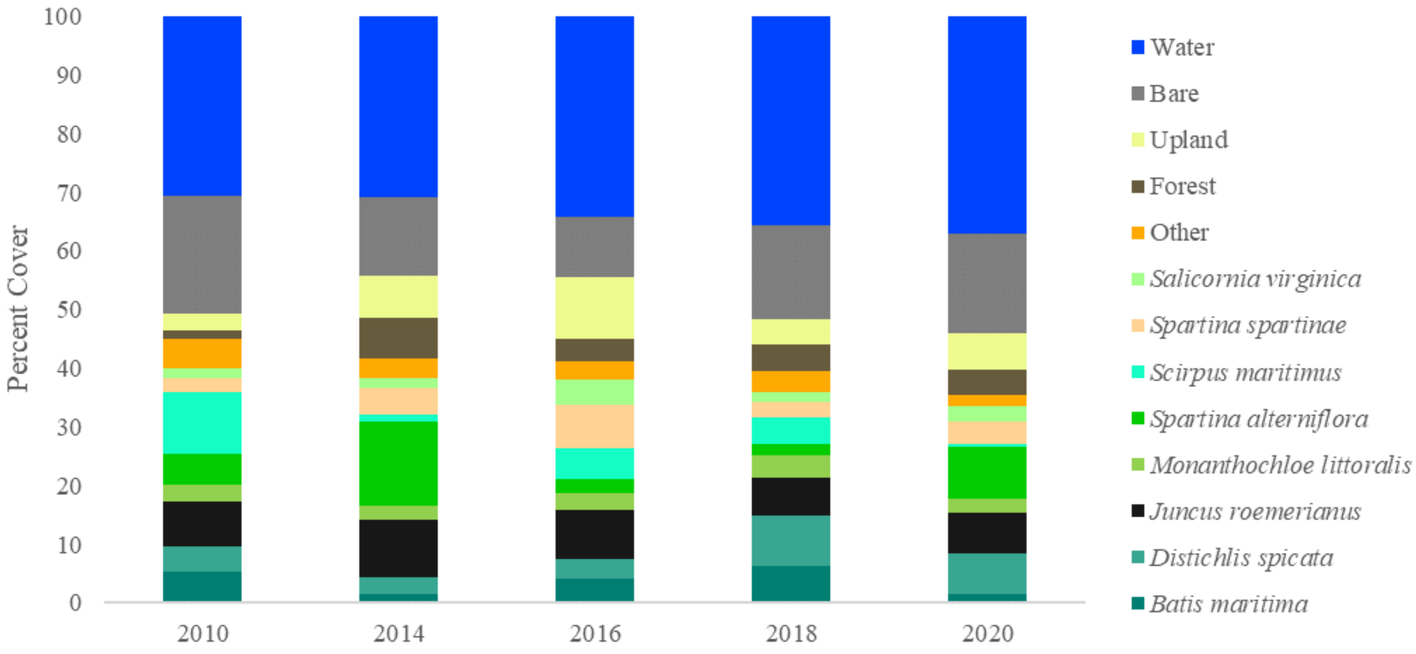

Figure 20. Percent cover of emergent plants and other habitats in the Lavaca Delta from 2010-2020.

Table 10. P-values for species GLMMs across three time steps for freshwater inflows: 3 months, 12 months, and 24 months.

	3 months	12 months	24 months		3 months	12 months	24 months
BM	< 2e-16	< 2e-16	< 2e-16	BM	2.19e-07	< 2e-16	< 2e-16
DS	2.83e-14	< 2e-16	< 2e-16	DS	1.24e-12	< 2e-16	< 2e-16
JR	< 2e-16	< 2e-16	< 2e-16	JR	< 2e-16	< 2e-16	< 2e-16
ML	0.001136	0.000381	0.000558	ML	7.11e-05	0.000303	0.00373
O	3.07e-09	0.000111	3.12e-08	O	0.000183	0.005569	1.17e-07
SV	0.000695	0.075571	0.261951	SV	1.24e-05	0.021161	0.87161
SM	8.46e-10	3.64e-16	1.16e-13	SM	2.71e-13	< 2e-16	2.92e-12
SA	< 2e-16	< 2e-16	< 2e-16	SA	< 2e-16	< 2e-16	< 2e-16
SS	5.03e-11	0.570628	0.000928	SS	1.30e-15	0.649878	0.04328
BM x fresh	1.04e-15	4.17e-09	1.39e-13	BM x gaged	0.001820	3.98e-08	1.36e-12
DS x fresh	1.57e-09	1.39e-14	1.68e-14	DS x gaged	5.06e-08	1.21e-14	1.77e-13
JR x fresh	< 2e-16	1.89e-13	< 2e-16	JR x gaged	< 2e-16	3.57e-11	< 2e-16
ML x fresh	2.88e-06	5.94e-07	1.55e-06	ML x gaged	1.04e-08	1.63e-08	1.11e-05
O x fresh	1.03e-11	9.44e-06	3.59e-10	O x gaged	9.98e-06	0.000626	5.87e-10
SV x fresh	2.95e-16	0.034466	9.47e-08	SV x gaged	< 2e-16	0.013942	1.17e-05
SM x fresh	1.14e-06	3.37e-13	1.89e-10	SM x gaged	3.68e-10	2.47e-16	4.48e-09
SA x fresh	< 2e-16	< 2e-16	< 2e-16	SA x gaged	< 2e-16	< 2e-16	< 2e-16
SS x fresh	< 2e-16	0.000390	4.66e-11	SS x gaged	< 2e-16	2.01e-05	2.92e-08
R^2	0.127	0.113	0.128	R^2	0.112	0.107	0.124

Recommendations for Future Analyses

Future analyses in the Lavaca Delta should focus on improving confidence in the vegetation classification analysis and establishing a more direct, empirical relationship between marsh vegetation and freshwater inflows. A targeted field sampling effort, avoiding inaccessible areas and selecting representative vegetation patches, will maximize the quality and quantity of training data. In turn, classification accuracy and confidence in the vegetation analysis will improve. Through our modeling efforts, we found that vegetated habitats show sensitivity to freshwater inflows on seasonal to annual timeframes. This justifies the need for additional imagery that is acquired at least annually to capture short-term changes in vegetation.

Moreover, additional soil porewater salinity data should also be collected for each vegetation type to facilitate a direct assessment of the ecological impact of changes in freshwater inflows. Porewater salinity reflects the salinity of flooding waters, such as tides or riverine flow, as well as evaporation, making it a great indicator of overall hydrologic conditions. By monitoring porewater salinity for each marsh species, we can examine the direct relationships between inflows and the local environmental conditions that marsh vegetation is exposed to. This species-level relationship can be used, in conjunction with established marsh vegetation salinity requirements, to identify freshwater inflow levels needed to maintain marsh habitats and evaluate the adjustment of environmental flow standards.

Additional possible considerations include access to an airboat to help with sampling site accessibility, a drone to perform quick ground truthing and accuracy assessment, a PhenoCam to determine flooding frequency in various portions of the marsh, and an RTK GPS device to gather precise elevation measurements without the need for benchmarks or reference points.

Concluding Statements

The biennial assessments of area occupied by water, bare ground, and vegetation are critical to understanding how the Lavaca Delta is responding to regional climate, sea level rise, and freshwater inflow events. Emergent marsh vegetation is particularly sensitive to climatic conditions and serves as an indicator of long-term changes in the hydrological regime. The patterns apparent in the imagery are also reflective of salinity, which is a product of droughts and/or reduced freshwater inflow events. Our results suggest that if droughts become longer and more frequent, as is predicted in Texas, marsh vegetation community composition shifts are likely to occur (Rasser, 2009). Drought conditions, as evidenced in this study, may also decrease the overall extent of emergent salt marsh plants in the Lavaca Delta. Under these conditions, typical marsh zonation patterns dissolve and large areas of bare ground are created (Alexander & Dunton, 2002). Conversely, when freshwater inflows are restored, vegetation follows a predictable pattern of displacement and/or re-establishment (Forbes & Dunton, 2006; Dunton et al., 2019). However, these typical salt marsh zonation and successional patterns in response to periodic drought are not as clear in marshes with greater freshwater influence, such as in the Lavaca Delta. While our analyses reveal quantifiable shifts in vegetated habitats and communities, it is critical to continue to study these complex interactions at varying temporal scales to determine how both short-term and long-term shifts in freshwater inflows might impact ecosystem change or loss.

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Appendix

Contents

Appendix 1. Raw vegetation cover field data.

Appendix 2. Digital photographs of representative cover types.

Appendix 3. Code to produce confusion matrices and accuracy metrics for classifications.

Appendix 4. Statistical modeling code.

Appendix 5. GLMM results.

Appendix 6. Vegetation classification maps, classification variable importance tables, and confusion matrices for the period 2010 to 2018.

Appendix 1. Raw vegetation cover field data

Site	UTM East	UTM North	BM	BF	DS	ML	SV	SS	SP	SA	PA	JR	SM	AT	LN	LC	W	D	B	O	U
17	734647.21	3184415.99															100				
18	734734.06	3184271.91															100				
19	734638.03	3184441.19															100				
20	734821.68	3184376.32															100				
21	734728.31	3184337.19															100				
22	734755.41	3184442.14															100				
23	734668.25	3184168.54															100				
24	734849.52	3184339.25															100				
25	734781.19	3184373.80															100				
26	734578.90	3184334.73															100				
27	734684.72	3184223.19															100				
28	734617.68	3184277.94															100				
29	734649.67	3184201.95															100				
30	734809.12	3184373.24															100				
31	734661.52	3184198.37															100				
32	734621.78	3184440.46															100				
49	737831.24	3178282.36															100				
50	737898.92	3178046.32															100				
52	737994.84	3178138.61															100				
54	737804.74	3178208.81															100				
55	737790.24	3178230.37								75			15	10							
56	737883.22	3178043.96															100				
57	737946.74	3177996.88		5									40					55			
60	737956.39	3178092.82	10	15								60		15							
61	737951.98	3178165.20															100				
62	738038.36	3178018.07															100				
63	737838.81	3178280.13															100				
64	737807.99	3178203.90															100				
65	736777.41	3179915.93															100				
66	736599.64	3179791.46	25		15	60															
67	736505.61	3179865.73			90		10														
68	736631.79	3179821.05					35												65		
69	736697.68	3179766.05															100				
70	736474.00	3179815.69					80			20											
71	736732.79	3180076.67															100				
72	736523.14	3179909.09			80		20														

Site	UTM East	UTM North	BM	BF	DS	ML	SV	SS	SP	SA	PA	JR	SM	AT	LN	LC	W	D	B	O	U
73	736609.15	3179972.92															100				
74	736643.83	3179750.44																	100		
75	736555.83	3179983.86																	100		
76	736543.32	3179818.60			60		40														
77	736494.98	3180031.27			40	60															
78	736597.79	3179768.31	42.5			42.5	10								5						
79	736709.72	3179893.27								25							75				
80	736772.60	3179965.13															100				
81	736005.28	3181490.50			85		15														
82	736022.40	3181482.31			90		5							5							
83	736289.68	3181523.46			25													20	55		
84	736299.02	3181529.95			5													20	75		
85	736153.08	3181547.44			10														90		
86	736248.00	3181630.70			30														70		
87	736285.84	3181469.33			15													42.5	42.5		
88	736061.87	3181379.21			95		5														
89	736061.78	3181667.12						100													
90	736135.43	3181402.27			10														90		
91	736211.03	3181620.88			20			80													
92	736267.53	3181655.73			20													5	75		
93	736209.62	3181581.57			50														50		
94	735992.11	3181405.97			100																
95	736007.23	3181443.40			100																
96	736138.50	3181457.94																20	80		
97	736845.10	3176528.17															100				
98	736857.07	3176587.02															100				
99	736998.60	3176524.54															100				
100	736755.88	3176671.95															100				
101	736863.48	3176538.82															100				
102	736890.68	3176669.74															100				
103	736745.15	3176554.82															100				
104	736872.20	3176664.19															100				
105	736745.11	3176604.03															100				
106	736723.69	3176595.31															100				
107	736935.50	3176601.98															100				
108	737024.88	3176651.14										100									
109	736771.96	3176478.21															100				

Site	UTM East	UTM North	BM	BF	DS	ML	SV	SS	SP	SA	PA	JR	SM	AT	LN	LC	W	D	B	O	U
110	736734.70	3176738.46															100				
111	736889.52	3176685.10															100				
112	736844.54	3176411.60															100				
113	737063.98	3176014.52	65				20								5				10		
114	737093.45	3176272.05															100				
115	736933.26	3176000.91															100				
116	737221.40	3175976.94										80	20								
117	737155.80	3176130.33	30										10				30	30			
118	736923.03	3176113.97															100				
119	737028.79	3175983.07	10		80		10														
120	737012.68	3176194.77															100				
121	736960.89	3175958.96			10								10	10			35		35		
122	737246.75	3176121.44															100				
123	737147.54	3176292.31															100				
124	737092.68	3176139.92																			100
125	737166.11	3176280.34															100				
126	737119.76	3176065.17																			100
127	736939.77	3176169.24															100				
128	737090.54	3175907.73		5	75		15						5								
129	736204.44	3180188.80															100				
130	735892.25	3180114.09			40								60								
131	736067.48	3180094.27	50		15											5		30			
132	735850.41	3180173.22								20			20					35	25		
133	736194.30	3180142.24																	100		
134	735913.66	3180233.85			20		5	15					10	50							
135	736051.28	3180337.06															100				
136	735963.99	3180077.84	5							25			20	50							
137	736172.50	3180170.18	15		25											2			58		
138	735937.81	3180043.30								75							25				
139	736104.60	3179961.72								65				25				10			
140	736121.27	3180128.81	20			75	5														
141	735956.37	3180133.67	2		63		35														
142	735923.35	3180045.28											60	40							
143	735885.16	3180166.84					2						63	35							
144	735932.37	3180246.37	25					65						5				5			
145	735864.05	3186454.79										50					50				
146	735882.59	3186527.62		30					20									5	45		

Site	UTM East	UTM North	BM	BF	DS	ML	SV	SS	SP	SA	PA	JR	SM	AT	LN	LC	W	D	B	O	U
148	736009.78	3186367.88															100				
151	735893.18	3186532.10		20				80													
152	735991.34	3186460.98															100				
153	735989.87	3186468.48															100				
154	735868.77	3186612.28			100																
157	736182.83	3186611.74															100				
159	735863.51	3186596.73		5				95													
160	735892.73	3186537.85						100													
161	736684.89	3178140.36	70				5									10		15			
162	736725.55	3178227.74	20		10	50															
163	736795.00	3177973.42	20		20		5											55			
164	736582.33	3178193.14	60	10														25	5		
165	736871.15	3178155.70															100				
166	736901.30	3178162.01															100				
167	736874.48	3178005.53															100				
168	736744.05	3178110.34	25	5		25	25							10	10						
169	736660.42	3177954.26	10							50								20	20		
170	736610.69	3178038.58															100				
171	736888.82	3178163.78															100				
172	736611.24	3178067.46								20		10	50						20		
173	736680.31	3178270.87															100				
174	736727.17	3178108.19	85				5							5				5			
175	736890.69	3178063.67															100				
176	736546.96	3178201.75															100				
198	735823.94	3184129.00								10			30				60				
201	735770.45	3184091.19															100				
202	735527.88	3184256.48															100				
207	735855.80	3184237.11			80									20							
209	736881.57	3183812.66															100				
211	736870.17	3183565.76															100				
212	737076.72	3183799.89							100												
213	736840.03	3183736.70															100				
214	737068.52	3183808.04			20			80													
216	736888.62	3183616.96															100				
217	736802.04	3183677.28															100				
218	736987.57	3183690.50											60						40		
219	736810.28	3183709.69															100				

Site	UTM East	UTM North	BM	BF	DS	ML	SV	SS	SP	SA	PA	JR	SM	AT	LN	LC	W	D	B	O	U
220	736929.08	3183558.56		10				50											40		
221	736762.47	3183761.96															100				
222	736765.45	3183711.71															100				
223	736775.72	3183585.62															100				
224	737003.94	3183715.38							90				10								
225	733303.91	3181819.98															100				
227	733260.93	3181981.64															100				
228	733438.52	3182044.29								10				80					10		
234	733386.28	3181738.50															100				
235	733342.09	3181851.83															100				
237	733418.59	3181992.56						30						30			40				
238	733514.85	3181877.89																			100
239	733492.97	3181785.26		10						50				40							
240	733390.17	3181754.61		50										50							
241	734109.53	3183231.47								60			40								
242	734270.53	3183406.71															100				
244	734208.60	3183398.63															100				
247	734148.33	3183213.81					10			40							25	25			
248	734116.32	3183273.23										60	40								
255	734105.05	3183340.05															100				
256	734135.18	3183247.41					5			47.5			47.5								
257	735888.83	3185115.94			75		25														
258	735651.35	3185190.39																	100		
260	735779.21	3185333.36			90		10														
261	735670.38	3185053.75															100				
262	735803.82	3185075.59																	100		
263	735718.83	3185100.16															100				
264	735808.22	3185308.54			60		40														
265	735910.03	3185148.04			10												80	10			
266	735850.60	3185073.66			50												40	10			
267	735779.93	3185218.08			70		30														
268	735796.90	3185277.22			45		45							10							
269	735814.45	3185035.48																	100		
270	735818.69	3185177.91															100				
271	735788.29	3185275.36			50		50														
272	735828.38	3185211.01			65		15												20		
273	736885.95	3185724.91		10									45					45			

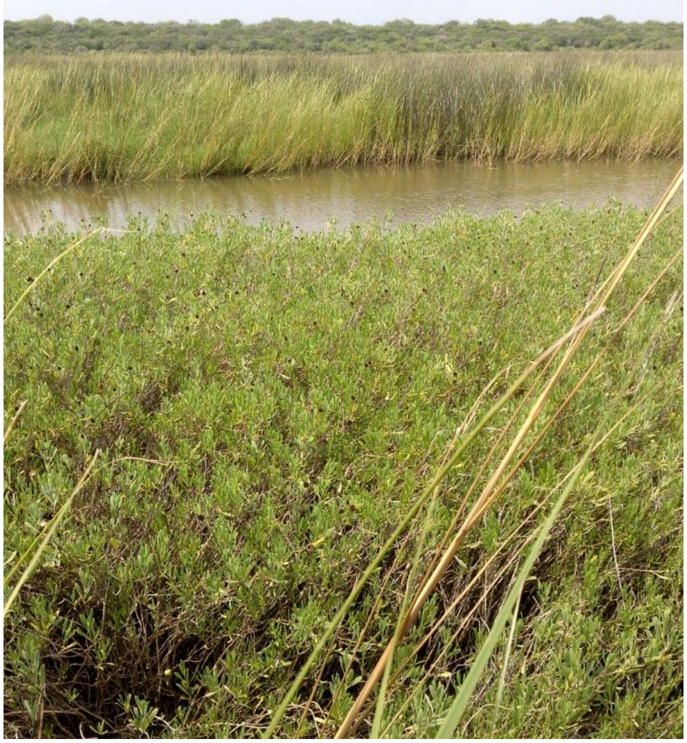
Site	UTM East	UTM North	BM	BF	DS	ML	SV	SS	SP	SA	PA	JR	SM	AT	LN	LC	W	D	B	O	U
274	737050.54	3185793.70							50				30					20			
275	736927.03	3185792.75			5								10	15				70			
276	737213.46	3185845.52			5							95									
277	737058.75	3185964.74			85								10					5			
279	736960.81	3185655.87		25									35	5				35			
280	736899.23	3185880.23											15					85			
281	736892.71	3185881.66			5								10					85			
282	737067.87	3185844.40			90								10								
283	737020.48	3185757.86											40					60			
284	736870.65	3185891.92			10								15					75			
285	737206.51	3185839.43			5				70				25								
286	737077.13	3185902.58			40								40					20			
287	737172.10	3185895.62															100				
288	737038.31	3185692.41										100									
289	735459.27	3181336.89															100				
290	735334.87	3181314.42		30	5			30										10	15		
291	735479.89	3181435.15															100				
292	735321.56	3181214.03					40												60		
293	735239.25	3181170.84		5	10								50					35			
294	735528.20	3181229.33															100				
295	735390.81	3181380.95															100				
296	735432.63	3181253.41															100				
297	735410.32	3181484.82								40									60		
298	735463.93	3181204.95															100				
299	735512.82	3181197.72															100				
300	735286.18	3181442.65			65		15	10										10			
301	735193.00	3181274.17			40		25	10										25			
302	735244.13	3181175.82	5	10									80					5			
304	735521.29	3181222.10															100				
353	737259.70	3177243.75										90		10							
354	737250.97	3176981.54								50			10	40							
357	737286.48	3177215.36								15		40		15			30				
358	737189.90	3177140.53										100									
359	737439.01	3177133.66															100				
361	737182.29	3177125.86		25														75			
363	737381.34	3177127.18															100				
364	737401.35	3177139.57										100									

Site	UTM East	UTM North	BM	BF	DS	ML	SV	SS	SP	SA	PA	JR	SM	AT	LN	LC	W	D	B	O	U
365	737225.97	3177090.99								50				50							
366	737280.16	3176979.93								50				50							
367	737472.70	3177043.62															100				
368	737344.19	3177139.21								100											
369	736347.86	3179134.22											50	15			35				
371	736445.50	3179153.40								20				10				70			
372	736505.65	3179159.67								33			33	34							
376	736312.18	3179156.38															100				
377	736367.20	3179033.83															100				
378	736351.78	3179259.78								5			95								
379	736377.62	3179065.22								60			5				35				
380	736382.83	3179113.08															100				
381	736359.81	3179304.40								10				90							
382	736445.60	3179078.18								60							40				
417	734347.38	3181604.77								45				30		25					
418	734603.81	3181488.56					25			25								50			
421	734492.74	3181695.46															100				
422	734584.07	3181392.58								90				10							
423	734364.60	3181395.54								60			10	30							
424	734638.44	3181455.61		25			25			25				5				20			
425	734590.02	3181345.07								80				20							
426	734642.83	3181438.76															100				
427	734442.49	3181413.76								50				50							
428	734544.53	3181395.48															100				
429	734642.35	3181395.42								100											
430	734315.51	3181462.93								40			30	30							
432	734393.45	3181546.00															100				
450	733138.33	3180277.31															100				
453	733100.55	3180601.17								50			50								
454	733323.92	3180379.30	5	5						70							20				
457	733096.11	3180437.01	30											70							
459	733343.49	3180443.13															100				
460	733332.65	3180468.03	20											50				30			
461	733102.68	3180573.87											100								
462	733251.13	3180360.61															100				
464	733173.44	3180419.05		30									70								
500	736800.38	3181430.44															100				

Appendix 2. Digital photographs of representative cover types.

Batis maritima

Spartina alterniflora



Borrichia frutescens

Juncus roemerianus

Scirpus maritimus

Distichlis spicata

Typha angustifolia

Phragmites australis

Spartina spartinae

Spartina patens

Upland

Forest

Sandy bare ground with *Salicornia virginica* patches

Dry cyanobacterial mat

Wet mud/cyanobacterial mat

Beach with *Spartina alterniflora* and forested/upland banks

Appendix 3. Code to produce confusion matrices and accuracy metrics for classifications.

```
// Construct a confusion matrix from an array (rows are actual values,
// columns are predicted values).
var cm_2020 = ee.Array([[1,3,0,0,0,0,0,0,0],
[0,9,0,0,0,0,0,1,0],
[2,1,2,0,0,0,0,3,0],
[0,1,0,0,1,1,0,0,0],
[2,1,0,0,3,0,0,3,0],
[1,2,0,0,1,0,0,0,1],
[0,0,1,1,1,1,0,0,1],
[0,0,0,1,0,0,0,1,0],
[0,0,0,0,0,1,0,0,11]]);

var cm_2018 = ee.Array([[3,0,1,0,0,0,0,0,0],
[2,5,2,0,0,0,0,1,0],
[1,1,5,0,1,0,0,3,0],
[0,0,0,2,1,0,0,0,0],
[1,0,0,0,5,0,2,1,0],
[1,1,0,0,3,0,0,0,1],
[0,0,1,0,2,0,2,0,0],
[0,0,0,0,2,0,0,0,0],
[0,1,0,0,0,0,0,0,11]]);

var cm_2016 = ee.Array([[1,4,1,0,1,1,1,0,0],
[0,16,1,0,1,0,0,0,1],
[4,2,7,0,3,1,0,2,0],
[0,1,0,3,1,0,1,0,0],
[3,1,1,2,10,0,3,0,0],
[0,1,0,2,4,2,0,0,2],
[0,2,0,2,4,0,2,1,1],
[0,0,0,0,1,0,1,3,0],
[0,2,0,0,0,0,0,0,28]]);

var cm_2014 = ee.Array([[1,1,1,0,0,1,0,0,0],
[2,5,0,0,1,1,0,1,0],
[0,4,3,0,1,0,0,0,0],
[0,0,0,0,1,1,0,0,1],
[0,1,0,1,5,1,0,1,0],
[0,2,0,2,0,1,0,0,0],
[1,0,0,0,1,2,1,0,0],
[0,0,1,0,1,0,0,0,0],
[0,1,0,0,0,1,0,0,10]]);

var cm_2010 = ee.Array([[1,1,2,0,0,0,0,0,0],
[0,6,0,0,2,0,0,2,0],
[1,1,4,0,1,1,0,0,0],
[0,1,0,2,0,0,0,0,0],
[1,2,2,0,1,0,3,0,0],
[1,1,1,0,0,1,1,0,0],
```

```
[2,0,0,2,1,0,0,0,0],
[0,1,0,0,1,0,0,0,0],
[0,3,0,0,0,0,1,0,8]]);

var confusionMatrix20 = ee.ConfusionMatrix(cm_2020);
print("Constructed confusion matrix 20", confusionMatrix20);
var confusionMatrix18 = ee.ConfusionMatrix(cm_2018);
print("Constructed confusion matrix 18", confusionMatrix18);
var confusionMatrix16 = ee.ConfusionMatrix(cm_2016);
print("Constructed confusion matrix 16", confusionMatrix16);
var confusionMatrix14 = ee.ConfusionMatrix(cm_2014);
print("Constructed confusion matrix 14", confusionMatrix14);
var confusionMatrix10 = ee.ConfusionMatrix(cm_2010);
print("Constructed confusion matrix 10", confusionMatrix10);

// Calculate overall accuracy.
print("Overall accuracy 20", confusionMatrix20.accuracy());
print("Overall accuracy 18", confusionMatrix18.accuracy());
print("Overall accuracy 16", confusionMatrix16.accuracy());
print("Overall accuracy 14", confusionMatrix14.accuracy());
print("Overall accuracy 10", confusionMatrix10.accuracy());

// Calculate user's accuracy, or specificity and the
// complement of commission error (1 − commission error).
print("Consumer's accuracy 20", confusionMatrix20.consumersAccuracy());
print("Consumer's accuracy 18", confusionMatrix18.consumersAccuracy());
print("Consumer's accuracy 16", confusionMatrix16.consumersAccuracy());
print("Consumer's accuracy 14", confusionMatrix14.consumersAccuracy());
print("Consumer's accuracy 10", confusionMatrix10.consumersAccuracy());

// Calculate producer's accuracy, also known as sensitivity and the
// complement of omission error (1 − omission error).
print("Producer's accuracy 20", confusionMatrix20.producersAccuracy());
print("Producer's accuracy 18", confusionMatrix18.producersAccuracy());
print("Producer's accuracy 16", confusionMatrix16.producersAccuracy());
print("Producer's accuracy 14", confusionMatrix14.producersAccuracy());
print("Producer's accuracy 10", confusionMatrix10.producersAccuracy());

// Calculate kappa statistic.
print('Kappa statistic 20', confusionMatrix20.kappa());
print('Kappa statistic 18', confusionMatrix18.kappa());
print('Kappa statistic 16', confusionMatrix16.kappa());
print('Kappa statistic 14', confusionMatrix14.kappa());
print('Kappa statistic 10', confusionMatrix10.kappa());
```

Appendix 4. Statistical modeling code.

~~~
```{r setup, include=FALSE}
library(tidyverse)
library(here)
library(lme4) #for GLMM
library(lmerTest) #p-values from GLMM
library(mgcv)
library(vegan)
library(viridis)
library(RColorBrewer)
library(anytime)
library(lubridate)
```

```{r Reading in data}
X2010_grid <- read_csv(here("species_grid/2010_grid_1.csv"))
X2014_grid <- read_csv(here("species_grid/2014_grid_1.csv"))
X2016_grid <- read_csv(here("species_grid/2016_grid_1.csv"))
X2018_grid <- read_csv(here("species_grid/2018_grid_1.csv"))
X2020_grid <- read_csv(here("species_grid/2020_grid_1.csv"))
```



```{r Cleaning and merging data}
X2010_grid$GRID_ID <- paste0(X2010_grid$GRID_ID,"_2010")
X2014_grid$GRID_ID <- paste0(X2014_grid$GRID_ID,"_2014")
X2016_grid$GRID_ID <- paste0(X2016_grid$GRID_ID,"_2016")
X2018_grid$GRID_ID <- paste0(X2018_grid$GRID_ID,"_2018")
X2020_grid$GRID_ID <- paste0(X2020_grid$GRID_ID,"_2020")

combined<-rbind(X2010_grid,X2014_grid,X2016_grid,X2018_grid,X2020_grid)
rm(X2010_grid,X2014_grid,X2016_grid,X2018_grid,X2020_grid)
```

```{r Cleaning data in long form}
cat_names <- tibble(species=c("1", "2", "3", "4", "5", "6", "7", "8", "9", "10", "11", "12", "13", "14", "15", "16", "17"), category=c("Batis maritima", "Bare", "Bare", "Bare", "Bare", "Distichlis spicata", "Forest", "Juncus roemerianus", "Monanthochloe littoralis", "Other vegetation", "Road", "Spartina alterniflora", "Scirpus maritimus", "Spartina spartinae", "Salicornia virginica", "Upland", "Water"), category_broad=c("Marsh vegetation", "Bare", "Bare", "Bare", "Bare", "Marsh vegetation", "Non-marsh vegetation", "Marsh vegetation", "Marsh vegetation", "Marsh vegetation", "Bare", "Marsh vegetation", "Marsh vegetation", "Marsh vegetation", "Marsh vegetation", "Non-marsh vegetation", "Water"))

long_dat <- combined %>%
  separate(col=GRID_ID, into=c("grid_id", "year"), sep = "_") %>%
  rename(species=Id, area=AREA) %>%
  mutate(species=as.character(species)) %>%
~~~

```
  left_join(cat_names) %>%
  select(-species) %>%
  group_by(grid_id, year, category, category_broad) %>%
  #adding values for bare
  summarise(area_m2=sum(area)) %>%
  mutate(year=as.double(year))

biannual_inflow_data <- read.csv("~/Lavaca Map/Inflow Data/biannual_inflow_data.csv")
names(biannual_inflow_data)[1] <- "year"
long_dat <- merge(long_dat,biannual_inflow_data,by="year")

lavaca_inflow <- read.csv("~/Lavaca Map/Inflow Data/fresh_inflow_monthly_2009-
        2020_LavacaBay.csv")
lavaca_inflow$year.month<-anytime(lavaca_inflow$year.month)

## Pulling different time steps of inflows
img_date <-
        c(anytime("05/03/2010"),anytime("05/04/2014"),anytime("10/09/2016"),anytime("12/01/2018"),any
        time("11/06/2020"))

month_before_analysis<-data.frame(matrix(nrow =  10, ncol = 4))
names(month_before_analysis) <- c("year","anal_type","M_gage","M_fresh")
w <- 1

for(q in 1:length(img_date)){

month_3<-lavaca_inflow[c(which(difftime(img_date[q],lavaca_inflow$year.month,units="days") <= 92
        & difftime(img_date[q],lavaca_inflow$year.month,units="days") >= 0)),]

month_12<-lavaca_inflow[c(which(difftime(img_date[q],lavaca_inflow$year.month,units="days") <=
        366 & difftime(img_date[q],lavaca_inflow$year.month,units="days") >= 0)),]

month_before_analysis[w,1]<-year(img_date[q])
month_before_analysis[w+1,1]<-year(img_date[q])

month_before_analysis[w,2]<-"3"
month_before_analysis[w+1,2]<-"12"

month_before_analysis[w,3]<-mean(month_3$gaged)
month_before_analysis[w+1,3]<-mean(month_12$gaged)

month_before_analysis[w,4]<-mean(month_3$fresh_in)
month_before_analysis[w+1,4]<-mean(month_12$fresh_in)

w <- w +2

}

three_month_before_analysis <- month_before_analysis[c(1,3,5,7,9),]
twelve_month_before_analysis <- month_before_analysis[c(2,4,6,8,10),]
```

~~~
long_dat <- merge(long_dat,three_month_before_analysis,by="year")
long_dat <- merge(long_dat,twelve_month_before_analysis,by="year")

```
~~~

lmerTest extracts p-values using Satterthwaite degrees of freedom method
R2m is the marginal R2 value, the proportion of the variance explained by fixed effects alone (so category and year)
R2c is the conditional R2, the proportion of the variance explained by fixed effects and random effects (so, including grid_id)

~~~
```{r GLMMs Inflows Original 2 Year Time Step}
#model 1: habitats
glmm_1 <- lmerTest::lmer(log(area_m2) ~  category_broad*M_fresh.x + (1|year/grid_id), data=long_dat)
glmm_1_summary <- summary(glmm_1)
glmm_1_summary

capture.output(glmm_1_summary, file = "GLMM1_2year.doc")

#visualizing the residuals
as.tibble(glmm_1_summary$residuals) %>% rowid_to_column() %>%
  ggplot(aes(x=rowid, y=value))+
  geom_point(alpha=0.05)

#r2 for model 1
MuMIn::r.squaredGLMM(glmm_1)


#model 2: species
marsh_dat <- long_dat %>% filter(category_broad=="Marsh vegetation")

glmm_2 <- lmerTest::lmer(log(area_m2) ~ category*M_fresh.x + (1|year/grid_id), data=marsh_dat) #running model
glmm_2_summary <- summary(glmm_3) #extracting summary
glmm_2_summary

capture.output(glmm_2_summary, file = "GLMM2_2year.doc")

#r2 for model 2
MuMIn::r.squaredGLMM(glmm_2)

#visualizing residuals
as.tibble(glmm_2_summary$residuals) %>% #extracting residuals
  rowid_to_column() %>% #converting row id to a column
  ggplot(aes(x=rowid, y=value))+
  geom_point(alpha=0.05) #alpha=0.05 changes opacity to 5%
```

```{r GLMM Inflows Discharge Only 2 Year}
#model 3: habitats
glmm_3 <- lmerTest::lmer(log(area_m2) ~  category_broad*M_gage.x + (1|year/grid_id), data=long_dat)
~~~

~~~
glmm_3_summary <- summary(glmm_3)
glmm_3_summary

capture.output(glmm_3_summary, file = "GLMM3_2year_discharge.doc")

#visualizing the residuals
as.tibble(glmm_3_summary$residuals) %>% rowid_to_column() %>%
  ggplot(aes(x=rowid, y=value))+
  geom_point(alpha=0.05)

#r2 for model 3
MuMIn::r.squaredGLMM(glmm_3)


#model 4: species

glmm_4 <- lmerTest::lmer(log(area_m2) ~ category*M_gage.x + (1|year/grid_id), data=marsh_dat)
        #running model
glmm_4_summary <- summary(glmm_4) #extracting summary
glmm_4_summary

capture.output(glmm_4_summary, file = "GLMM4_2year_discharge.doc")

#r2 for model 4
MuMIn::r.squaredGLMM(glmm_4)

#visualizing residuals
as.tibble(glmm_4_summary$residuals) %>% #extracting residuals
  rowid_to_column() %>% #converting row id to a column
  ggplot(aes(x=rowid, y=value))+
  geom_point(alpha=0.05) #alpha=0.05 changes opacity to 5%

```


```{r GLMM Total Inflows 3 Months}
#model 5: habitats
glmm_5 <- lmerTest::lmer(log(area_m2) ~  category_broad*M_fresh.y + (1|year/grid_id), data=long_dat)
glmm_5_summary <- summary(glmm_5)
glmm_5_summary

capture.output(glmm_5_summary, file = "GLMM5_3months.doc")

#visualizing the residuals
as.tibble(glmm_5_summary$residuals) %>% rowid_to_column() %>%
  ggplot(aes(x=rowid, y=value))+
  geom_point(alpha=0.05)

#r2 for model 5
MuMIn::r.squaredGLMM(glmm_5)
~~~

~~~
#model 6: species

glmm_6 <- lmerTest::lmer(log(area_m2) ~ category*M_fresh.y + (1|year/grid_id), data=marsh_dat)
        #running model
glmm_6_summary <- summary(glmm_6) #extracting summary
glmm_6_summary

capture.output(glmm_6_summary, file = "GLMM6_3months.doc")

#r2 for model 6
MuMIn::r.squaredGLMM(glmm_6)

#visualizing residuals
as.tibble(glmm_6_summary$residuals) %>% #extracting residuals
  rowid_to_column() %>% #converting row id to a column
  ggplot(aes(x=rowid, y=value))+
  geom_point(alpha=0.05) #alpha=0.05 changes opacity to 5%

```


```{r GLMM Total Inflows 12 Months}
#model 7: habitats
glmm_7 <- lmerTest::lmer(log(area_m2) ~  category_broad*M_fresh + (1|year/grid_id), data=long_dat)
glmm_7_summary <- summary(glmm_7)
glmm_7_summary

#visualizing the residuals
as.tibble(glmm_7_summary$residuals) %>% rowid_to_column() %>%
  ggplot(aes(x=rowid, y=value))+
  geom_point(alpha=0.05)

#r2 for model 7
MuMIn::r.squaredGLMM(glmm_7)

capture.output(glmm_7_summary, file = "GLMM7_12months.doc")

#model 8: species

glmm_8 <- lmerTest::lmer(log(area_m2) ~ category*M_fresh + (1|year/grid_id), data=marsh_dat)
        #running model
glmm_8_summary <- summary(glmm_8) #extracting summary
glmm_8_summary

capture.output(glmm_8_summary, file = "GLMM8_12months.doc")

#r2 for model 8
MuMIn::r.squaredGLMM(glmm_8)

#visualizing residuals
as.tibble(glmm_8_summary$residuals) %>% #extracting residuals
  rowid_to_column() %>% #converting row id to a column
~~~

```
  ggplot(aes(x=rowid, y=value))+
  geom_point(alpha=0.05) #alpha=0.05 changes opacity to 5%
```

```{r GLMM Inflows 3 Months Discharge Only}
#model 9: habitats
glmm_9 <- lmerTest::lmer(log(area_m2) ~  category_broad*M_gage.y + (1|year/grid_id), data=long_dat)
glmm_9_summary <- summary(glmm_9)
glmm_9_summary

#visualizing the residuals
as.tibble(glmm_9_summary$residuals) %>% rowid_to_column() %>%
  ggplot(aes(x=rowid, y=value))+
  geom_point(alpha=0.05)

#r2 for model 9
MuMIn::r.squaredGLMM(glmm_9)

capture.output(glmm_9_summary, file = "GLMM9_3months_discharge.doc")

#model 10: species

glmm_10 <- lmerTest::lmer(log(area_m2) ~ category*M_gage.y + (1|year/grid_id), data=marsh_dat)
        #running model
glmm_10_summary <- summary(glmm_10) #extracting summary
glmm_10_summary

#r2 for model 10
MuMIn::r.squaredGLMM(glmm_10)

capture.output(glmm_10_summary, file = "GLMM10_3months_discharge.doc")

#visualizing residuals
as.tibble(glmm_10_summary$residuals) %>% #extracting residuals
  rowid_to_column() %>% #converting row id to a column
  ggplot(aes(x=rowid, y=value))+
  geom_point(alpha=0.05) #alpha=0.05 changes opacity to 5%
```

```{r GLMM Inflows 12 Months Discharge Only}
#model 11: habitats
glmm_11 <- lmerTest::lmer(log(area_m2) ~  category_broad*M_gage + (1|year/grid_id), data=long_dat)
glmm_11_summary <- summary(glmm_11)
glmm_11_summary

capture.output(glmm_11_summary, file = "GLMM11_12months_discharge.doc")

#visualizing the residuals
as.tibble(glmm_11_summary$residuals) %>% rowid_to_column() %>%
  ggplot(aes(x=rowid, y=value))+
  geom_point(alpha=0.05)
```

~~~
#r2 for model 11
MuMIn::r.squaredGLMM(glmm_11)


#model 12: species

glmm_12 <- lmerTest::lmer(log(area_m2) ~ category*M_gage + (1|year/grid_id), data=marsh_dat)
        #running model
glmm_12_summary <- summary(glmm_12) #extracting summary
glmm_12_summary

capture.output(glmm_12_summary, file = "GLMM12_12months_discharge.doc")

#r2 for model 12
MuMIn::r.squaredGLMM(glmm_12)

#visualizing residuals
as.tibble(glmm_12_summary$residuals) %>% #extracting residuals
  rowid_to_column() %>% #converting row id to a column
  ggplot(aes(x=rowid, y=value))+
  geom_point(alpha=0.05) #alpha=0.05 changes opacity to 5%
```
~~~

Appendix 5. GLMM results.

Model 1

```
Linear mixed model fit by REML. t-tests use Satterthwaite's method
['lmerModLmerTest']
Formula: log(area_m2) ~ category_broad * M_fresh.x + (1 | year/grid_id)
   Data: long_dat

REML criterion at convergence: 20093

Scaled residuals:
    Min      1Q  Median      3Q     Max 
-6.0193 -0.5827  0.0441  0.6088  4.1620 

Random effects:
 Groups       Name        Variance Std.Dev.
 grid_id:year (Intercept) 2.014    1.419   
 year         (Intercept) 0.000    0.000   
 Residual                 1.261    1.123   
Number of obs: 6062, groups:  grid_id:year, 440; year, 5

Fixed effects:
                                               Estimate Std. Error
df t value
(Intercept)                                   9.186e+00  1.619e-01
6.494e+02  56.738
category_broadMarsh vegetation               -9.445e-01  8.784e-02
5.587e+03 -10.752
category_broadNon-marsh vegetation           -5.993e-02  1.122e-01
5.588e+03  -0.534
category_broadWater                           1.744e+00  1.376e-01
5.610e+03  12.671
M_fresh.x                                    -1.612e-06  1.354e-06
6.501e+02  -1.190
category_broadMarsh vegetation:M_fresh.x      5.381e-06  7.354e-07
5.587e+03   7.318
category_broadNon-marsh vegetation:M_fresh.x  4.413e-07  9.391e-07
5.588e+03   0.470
category_broadWater:M_fresh.x                 1.630e-06  1.151e-06
5.610e+03   1.415
                                             Pr(>|t|)    
(Intercept)                                   < 2e-16 ***
category_broadMarsh vegetation                < 2e-16 ***
category_broadNon-marsh vegetation              0.593    
category_broadWater                           < 2e-16 ***
M_fresh.x                                       0.234    
category_broadMarsh vegetation:M_fresh.x     2.88e-13 ***
category_broadNon-marsh vegetation:M_fresh.x    0.638    
category_broadWater:M_fresh.x                   0.157    
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Model 2

```
Linear mixed model fit by REML. t-tests use Satterthwaite's method
['lmerModLmerTest']
Formula: log(area_m2) ~ category * M_fresh.x + (1 | year/grid_id)
   Data: marsh_dat

REML criterion at convergence: 11908.7

Scaled residuals: 
    Min      1Q  Median      3Q     Max 
-5.3107 -0.5812 -0.0003  0.5791  3.4169 

Random effects:
 Groups       Name        Variance Std.Dev.
 grid_id:year (Intercept) 2.0296   1.4246  
 year         (Intercept) 0.0000   0.0000  
 Residual                 0.8223   0.9068  
Number of obs: 3895, groups:  grid_id:year, 435; year, 5

Fixed effects:
                                             Estimate Std. Error
df t value
(Intercept)                                 7.492e+00  1.686e-01
7.557e+02  44.431
categoryDistichlis spicata                  1.163e+00  1.284e-01
3.432e+03   9.063
categoryJuncus roemerianus                  2.061e+00  1.282e-01
3.433e+03  16.077
categoryMonanthochloe littoralis            4.434e-01  1.284e-01
3.432e+03   3.454
categoryOther vegetation                    7.111e-01  1.282e-01
3.433e+03   5.547
categorySalicornia virginica                1.438e-01  1.282e-01
3.433e+03   1.122
categoryScirpus maritimus                  -9.564e-01  1.283e-01
3.432e+03  -7.452
categorySpartina alterniflora               3.042e+00  1.282e-01
3.433e+03  23.728
categorySpartina spartinae                  4.253e-01  1.283e-01
3.433e+03   3.314
M_fresh.x                                   1.063e-05  1.411e-06
7.568e+02   7.536
categoryDistichlis spicata:M_fresh.x       -8.278e-06  1.074e-06
3.432e+03  -7.707
categoryJuncus roemerianus:M_fresh.x       -1.105e-05  1.073e-06
3.434e+03 -10.296
categoryMonanthochloe littoralis:M_fresh.x -5.170e-06  1.074e-06
3.432e+03  -4.813
categoryOther vegetation:M_fresh.x         -6.751e-06  1.073e-06
3.433e+03  -6.289
categorySalicornia virginica:M_fresh.x     -5.742e-06  1.074e-06
3.433e+03  -5.348
```

```
categoryScirpus maritimus:M_fresh.x         6.864e-06  1.074e-06
3.432e+03   6.390
categorySpartina alterniflora:M_fresh.x    -2.420e-05  1.074e-06
3.433e+03 -22.539
categorySpartina spartinae:M_fresh.x       -7.090e-06  1.074e-06
3.433e+03  -6.603
                                           Pr(>|t|)
(Intercept)                                 < 2e-16 ***
categoryDistichlis spicata                  < 2e-16 ***
categoryJuncus roemerianus                  < 2e-16 ***
categoryMonanthochloe littoralis           0.000558 ***
categoryOther vegetation                   3.12e-08 ***
categorySalicornia virginica               0.261951
categoryScirpus maritimus                  1.16e-13 ***
categorySpartina alterniflora               < 2e-16 ***
categorySpartina spartinae                 0.000928 ***
M_fresh.x                                  1.39e-13 ***
categoryDistichlis spicata:M_fresh.x       1.68e-14 ***
categoryJuncus roemerianus:M_fresh.x        < 2e-16 ***
categoryMonanthochloe littoralis:M_fresh.x 1.55e-06 ***
categoryOther vegetation:M_fresh.x         3.59e-10 ***
categorySalicornia virginica:M_fresh.x     9.47e-08 ***
categoryScirpus maritimus:M_fresh.x        1.89e-10 ***
categorySpartina alterniflora:M_fresh.x     < 2e-16 ***
categorySpartina spartinae:M_fresh.x       4.66e-11 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
fit warnings:
Some predictor variables are on very different scales: consider rescaling
optimizer (nloptwrap) convergence code: 0 (OK)
boundary (singular) fit: see help('isSingular')
```

Model 3

```
Linear mixed model fit by REML. t-tests use Satterthwaite's method
['lmerModLmerTest']
Formula: log(area_m2) ~ category_broad * M_gage.x + (1 | year/grid_id)
   Data: long_dat

REML criterion at convergence: 20099.7

Scaled residuals: 
    Min      1Q  Median      3Q     Max 
-6.0267 -0.5830  0.0449  0.6112  4.1485 

Random effects:
 Groups       Name        Variance Std.Dev.
 grid_id:year (Intercept) 2.013    1.419   
 year         (Intercept) 0.000    0.000   
 Residual                 1.263    1.124   
Number of obs: 6062, groups:  grid_id:year, 440; year, 5

Fixed effects:
```

```
                                                  Estimate Std. Error
df t value
(Intercept)                                      9.165e+00  1.474e-01
6.500e+02  62.174
category_broadMarsh vegetation                  -8.682e-01  8.005e-02
5.587e+03 -10.846
category_broadNon-marsh vegetation              -9.962e-02  1.023e-01
5.588e+03  -0.974
category_broadWater                              1.753e+00  1.254e-01
5.610e+03  13.976
M_gage.x                                        -2.591e-06  2.196e-06
6.507e+02  -1.180
category_broadMarsh vegetation:M_gage.x          8.559e-06  1.194e-06
5.587e+03   7.170
category_broadNon-marsh vegetation:M_gage.x  1.508e-06  1.524e-06
5.588e+03   0.989
category_broadWater:M_gage.x                     2.840e-06  1.869e-06
5.610e+03   1.519
                                                Pr(>|t|)
(Intercept)                                      < 2e-16 ***
category_broadMarsh vegetation                   < 2e-16 ***
category_broadNon-marsh vegetation                 0.330
category_broadWater                              < 2e-16 ***
M_gage.x                                           0.239
category_broadMarsh vegetation:M_gage.x         8.45e-13 ***
category_broadNon-marsh vegetation:M_gage.x        0.323
category_broadWater:M_gage.x                       0.129
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:
            (Intr) ctg_Mv ct_N-v ctgr_W M_gg.x c_Mv:M c_N-v:
ctgry_brdMv -0.445
ctgry_brN-v -0.348  0.641
ctgry_brdWt -0.288  0.522  0.409
M_gage.x    -0.849  0.378  0.296  0.244
ctgr_Mv:M_.  0.378 -0.849 -0.544 -0.444 -0.445
ctg_N-v:M_.  0.296 -0.545 -0.849 -0.347 -0.349  0.641
ctgry_W:M_.  0.244 -0.444 -0.347 -0.849 -0.288  0.523  0.409
fit warnings:
Some predictor variables are on very different scales: consider rescaling
optimizer (nloptwrap) convergence code: 0 (OK)
boundary (singular) fit: see help('isSingular')
```

Model 4

```
Linear mixed model fit by REML. t-tests use Satterthwaite's method
['lmerModLmerTest']
Formula: log(area_m2) ~ category * M_gage.x + (1 | year/grid_id)
   Data: marsh_dat

REML criterion at convergence: 11951.5
```

```
Scaled residuals:
    Min      1Q  Median      3Q     Max
-5.2989 -0.5783  0.0043  0.5788  3.4211

Random effects:
 Groups       Name        Variance Std.Dev.
 grid_id:year (Intercept) 2.0293   1.4245
 year         (Intercept) 0.0000   0.0000
 Residual                 0.8346   0.9136
Number of obs: 3895, groups:  grid_id:year, 435; year, 5

Fixed effects:
                                             Estimate Std. Error         df
t value
(Intercept)                                 7.665e+00  1.538e-01  7.609e+02
49.821
categoryDistichlis spicata                  1.035e+00  1.177e-01  3.432e+03
8.793
categoryJuncus roemerianus                  1.883e+00  1.176e-01  3.433e+03
16.020
categoryMonanthochloe littoralis            3.417e-01  1.177e-01  3.432e+03
2.902
categoryOther vegetation                    6.243e-01  1.176e-01  3.433e+03
5.310
categorySalicornia virginica               -1.901e-02  1.176e-01  3.433e+03
-0.162
categoryScirpus maritimus                  -8.249e-01  1.177e-01  3.432e+03
-7.007
categorySpartina alterniflora               2.698e+00  1.176e-01  3.433e+03
22.948
categorySpartina spartinae                  2.380e-01  1.177e-01  3.432e+03
2.022
M_gage.x                                    1.653e-05  2.292e-06  7.621e+02
7.209
categoryDistichlis spicata:M_gage.x        -1.298e-05  1.755e-06  3.432e+03
-7.395
categoryJuncus roemerianus:M_gage.x        -1.720e-05  1.752e-06  3.434e+03
-9.816
categoryMonanthochloe littoralis:M_gage.x -7.724e-06  1.755e-06  3.432e+03
-4.401
categoryOther vegetation:M_gage.x          -1.089e-05  1.754e-06  3.432e+03
-6.212
categorySalicornia virginica:M_gage.x      -7.699e-06  1.754e-06  3.432e+03
-4.389
categoryScirpus maritimus:M_gage.x          1.032e-05  1.755e-06  3.432e+03
5.881
categorySpartina alterniflora:M_gage.x     -3.848e-05  1.754e-06  3.432e+03
-21.936
categorySpartina spartinae:M_gage.x        -9.751e-06  1.754e-06  3.433e+03
-5.559
                                           Pr(>|t|)
(Intercept)                                 < 2e-16 ***
categoryDistichlis spicata                  < 2e-16 ***
categoryJuncus roemerianus                  < 2e-16 ***
```

```
categoryMonanthochloe littoralis           0.00373 **
categoryOther vegetation                  1.17e-07 ***
categorySalicornia virginica               0.87161
categoryScirpus maritimus                 2.92e-12 ***
categorySpartina alterniflora              < 2e-16 ***
categorySpartina spartinae                 0.04328 *
M_gage.x                                  1.36e-12 ***
categoryDistichlis spicata:M_gage.x       1.77e-13 ***
categoryJuncus roemerianus:M_gage.x        < 2e-16 ***
categoryMonanthochloe littoralis:M_gage.x 1.11e-05 ***
categoryOther vegetation:M_gage.x         5.87e-10 ***
categorySalicornia virginica:M_gage.x     1.17e-05 ***
categoryScirpus maritimus:M_gage.x        4.48e-09 ***
categorySpartina alterniflora:M_gage.x     < 2e-16 ***
categorySpartina spartinae:M_gage.x       2.92e-08 ***
```

Model 5

```
Linear mixed model fit by REML. t-tests use Satterthwaite's method
['lmerModLmerTest']
Formula: log(area_m2) ~ category_broad * M_fresh.y + (1 | year/grid_id)
   Data: long_dat

REML criterion at convergence: 20074.2

Scaled residuals: 
    Min      1Q  Median      3Q     Max 
-6.0079 -0.5772  0.0462  0.6049  4.2117 

Random effects:
 Groups       Name        Variance Std.Dev.
 grid_id:year (Intercept) 2.021    1.422   
 year         (Intercept) 0.000    0.000   
 Residual                 1.256    1.121   
Number of obs: 6062, groups:  grid_id:year, 440; year, 5

Fixed effects:
                                               Estimate Std. Error
df t value
(Intercept)                                   9.148e+00  1.555e-01
6.486e+02  58.816
category_broadMarsh vegetation               -8.713e-01  8.420e-02
5.587e+03 -10.348
category_broadNon-marsh vegetation            1.401e-01  1.076e-01
5.589e+03   1.303
category_broadWater                           1.787e+00  1.319e-01
5.610e+03  13.552
M_fresh.y                                    -1.156e-06  1.191e-06
6.490e+02  -0.971
category_broadMarsh vegetation:M_fresh.y      4.339e-06  6.448e-07
5.588e+03   6.729
```

```
category_broadNon-marsh vegetation:M_fresh.y -1.362e-06  8.235e-07
5.589e+03  -1.654
category_broadWater:M_fresh.y                 1.129e-06  1.009e-06
5.610e+03   1.119
                                             Pr(>|t|)
(Intercept)                                   < 2e-16 ***
category_broadMarsh vegetation                < 2e-16 ***
category_broadNon-marsh vegetation             0.1927
category_broadWater                           < 2e-16 ***
M_fresh.y                                      0.3320
category_broadMarsh vegetation:M_fresh.y     1.88e-11 ***
category_broadNon-marsh vegetation:M_fresh.y   0.0981 .
category_broadWater:M_fresh.y                  0.2633
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:
            (Intr) ctg_Mv ct_N-v ctgr_W M_frs. c_Mv:M c_N-v:
ctgry_brdMv -0.444
ctgry_brN-v -0.348  0.641
ctgry_brdWt -0.287  0.523  0.409
M_fresh.y   -0.865  0.384  0.301  0.248
ctgr_Mv:M_.  0.384 -0.866 -0.555 -0.452 -0.444
ctg_N-v:M_.  0.301 -0.555 -0.865 -0.354 -0.348  0.642
ctgry_W:M_.  0.248 -0.453 -0.354 -0.865 -0.287  0.523  0.409
fit warnings:
Some predictor variables are on very different scales: consider rescaling
optimizer (nloptwrap) convergence code: 0 (OK)
boundary (singular) fit: see help('isSingular')
```

Model 6

```
Linear mixed model fit by REML. t-tests use Satterthwaite's method
['lmerModLmerTest']
Formula: log(area_m2) ~ category * M_fresh.y + (1 | year/grid_id)
   Data: marsh_dat

REML criterion at convergence: 11912.8

Scaled residuals:
    Min      1Q  Median      3Q     Max
-5.2518 -0.5566  0.0182  0.5941  3.1614

Random effects:
 Groups       Name        Variance Std.Dev.
 grid_id:year (Intercept) 2.0420   1.4290
 year         (Intercept) 0.0000   0.0000
 Residual                 0.8221   0.9067
Number of obs: 3895, groups:  grid_id:year, 435; year, 5

Fixed effects:
                                             Estimate Std. Error
df t value
```

```
(Intercept)                                 7.455e+00  1.622e-01
7.545e+02  45.965
categoryDistichlis spicata                  9.413e-01  1.232e-01
3.432e+03   7.639
categoryJuncus roemerianus                  2.215e+00  1.230e-01
3.433e+03  18.000
categoryMonanthochloe littoralis            4.014e-01  1.232e-01
3.432e+03   3.257
categoryOther vegetation                    7.312e-01  1.230e-01
3.433e+03   5.943
categorySalicornia virginica                4.177e-01  1.230e-01
3.433e+03   3.395
categoryScirpus maritimus                  -7.583e-01  1.232e-01
3.432e+03  -6.153
categorySpartina alterniflora               2.930e+00  1.230e-01
3.433e+03  23.810
categorySpartina spartinae                  8.124e-01  1.232e-01
3.432e+03   6.591
M_fresh.y                                   1.018e-05  1.242e-06
7.553e+02   8.198
categoryDistichlis spicata:M_fresh.y       -5.710e-06  9.434e-07
3.433e+03  -6.053
categoryJuncus roemerianus:M_fresh.y       -1.159e-05  9.421e-07
3.433e+03 -12.308
categoryMonanthochloe littoralis:M_fresh.y -4.422e-06  9.434e-07
3.433e+03  -4.687
categoryOther vegetation:M_fresh.y         -6.431e-06  9.422e-07
3.433e+03  -6.826
categorySalicornia virginica:M_fresh.y     -7.747e-06  9.429e-07
3.433e+03  -8.216
categoryScirpus maritimus:M_fresh.y         4.598e-06  9.433e-07
3.433e+03   4.874
categorySpartina alterniflora:M_fresh.y    -2.143e-05  9.428e-07
3.433e+03 -22.734
categorySpartina spartinae:M_fresh.y       -9.993e-06  9.438e-07
3.433e+03 -10.588
                                           Pr(>|t|)
(Intercept)                                 < 2e-16 ***
categoryDistichlis spicata                 2.83e-14 ***
categoryJuncus roemerianus                  < 2e-16 ***
categoryMonanthochloe littoralis           0.001136 **
categoryOther vegetation                   3.07e-09 ***
categorySalicornia virginica               0.000695 ***
categoryScirpus maritimus                  8.46e-10 ***
categorySpartina alterniflora               < 2e-16 ***
categorySpartina spartinae                 5.03e-11 ***
M_fresh.y                                  1.04e-15 ***
categoryDistichlis spicata:M_fresh.y       1.57e-09 ***
categoryJuncus roemerianus:M_fresh.y        < 2e-16 ***
categoryMonanthochloe littoralis:M_fresh.y 2.88e-06 ***
categoryOther vegetation:M_fresh.y         1.03e-11 ***
categorySalicornia virginica:M_fresh.y     2.95e-16 ***
categoryScirpus maritimus:M_fresh.y        1.14e-06 ***
categorySpartina alterniflora:M_fresh.y     < 2e-16 ***
```

```
categorySpartina spartinae:M_fresh.y        < 2e-16 ***
```

Model 7

```
Linear mixed model fit by REML. t-tests use Satterthwaite's method
['lmerModLmerTest']
Formula: log(area_m2) ~ category_broad * M_fresh + (1 | year/grid_id)
   Data: long_dat

REML criterion at convergence: 20101.8

Scaled residuals: 
    Min      1Q  Median      3Q     Max 
-5.9886 -0.5818  0.0423  0.6160  4.1432 

Random effects:
 Groups       Name        Variance Std.Dev.
 grid_id:year (Intercept) 2.016    1.420   
 year         (Intercept) 0.000    0.000   
 Residual                 1.263    1.124   
Number of obs: 6062, groups:  grid_id:year, 440; year, 5

Fixed effects:
                                             Estimate Std. Error
df t value
(Intercept)                                 9.135e+00  1.555e-01
6.501e+02  58.745
category_broadMarsh vegetation             -8.371e-01  8.443e-02
5.587e+03  -9.915
category_broadNon-marsh vegetation          3.406e-02  1.078e-01
5.588e+03   0.316
category_broadWater                         1.814e+00  1.322e-01
5.610e+03  13.716
M_fresh                                    -1.553e-06  1.777e-06
6.505e+02  -0.874
category_broadMarsh vegetation:M_fresh      6.028e-06  9.654e-07
5.587e+03   6.244
category_broadNon-marsh vegetation:M_fresh -6.342e-07  1.233e-06
5.588e+03  -0.515
category_broadWater:M_fresh                 1.330e-06  1.511e-06
5.610e+03   0.880
                                           Pr(>|t|)    
(Intercept)                                 < 2e-16 ***
category_broadMarsh vegetation              < 2e-16 ***
category_broadNon-marsh vegetation            0.752    
category_broadWater                         < 2e-16 ***
M_fresh                                       0.382    
category_broadMarsh vegetation:M_fresh     4.58e-10 ***
category_broadNon-marsh vegetation:M_fresh    0.607    
category_broadWater:M_fresh                   0.379    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

```
Correlation of Fixed Effects:
            (Intr) ctg_Mv ct_N-v ctgr_W M_frsh c_Mv:M c_N-v:
ctgry_brdMv -0.445
ctgry_brN-v -0.349  0.641
ctgry_brdWt -0.288  0.523  0.409
M_fresh     -0.865  0.385  0.302  0.249
ctgry_Mv:M_  0.385 -0.865 -0.555 -0.452 -0.445
ctgr_N-v:M_  0.302 -0.555 -0.865 -0.354 -0.349  0.641
ctgry_bW:M_  0.249 -0.453 -0.354 -0.865 -0.288  0.523  0.409
fit warnings:
Some predictor variables are on very different scales: consider rescaling
optimizer (nloptwrap) convergence code: 0 (OK)
boundary (singular) fit: see help('isSingular')
```

Model 8

```
Linear mixed model fit by REML. t-tests use Satterthwaite's method
['lmerModLmerTest']
Formula: log(area_m2) ~ category * M_fresh + (1 | year/grid_id)
   Data: marsh_dat

REML criterion at convergence: 12106.3

Scaled residuals:
    Min      1Q  Median      3Q     Max
-5.1630 -0.5823  0.0219  0.6027  3.6045

Random effects:
 Groups       Name        Variance Std.Dev.
 grid_id:year (Intercept) 2.0236   1.4225
 year         (Intercept) 0.0000   0.0000
 Residual                 0.8721   0.9338
Number of obs: 3895, groups:  grid_id:year, 435; year, 5

Fixed effects:
                                           Estimate Std. Error         df
t value
(Intercept)                               7.768e+00  1.631e-01  7.780e+02
47.621
categoryDistichlis spicata                1.145e+00  1.269e-01  3.432e+03
9.023
categoryJuncus roemerianus                1.713e+00  1.267e-01  3.433e+03
13.518
categoryMonanthochloe littoralis          4.513e-01  1.269e-01  3.432e+03
3.556
categoryOther vegetation                  4.904e-01  1.268e-01  3.432e+03
3.869
categorySalicornia virginica             -2.254e-01  1.268e-01  3.432e+03
-1.778
categoryScirpus maritimus                -1.039e+00  1.269e-01  3.432e+03
-8.190
categorySpartina alterniflora             2.454e+00  1.268e-01  3.432e+03
19.357
```

```
categorySpartina spartinae                 7.197e-02  1.269e-01  3.432e+03
0.567
M_fresh                                    1.108e-05  1.864e-06  7.791e+02
5.945
categoryDistichlis spicata:M_fresh        -1.122e-05  1.451e-06  3.432e+03
-7.731
categoryJuncus roemerianus:M_fresh        -1.070e-05  1.449e-06  3.434e+03
-7.386
categoryMonanthochloe littoralis:M_fresh -7.260e-06  1.451e-06  3.432e+03
-5.002
categoryOther vegetation:M_fresh          -6.434e-06  1.450e-06  3.432e+03
-4.436
categorySalicornia virginica:M_fresh      -3.068e-06  1.450e-06  3.432e+03
-2.115
categoryScirpus maritimus:M_fresh          1.060e-05  1.451e-06  3.432e+03
7.307
categorySpartina alterniflora:M_fresh     -2.571e-05  1.450e-06  3.432e+03
-17.729
categorySpartina spartinae:M_fresh        -5.147e-06  1.450e-06  3.433e+03
-3.550
                                         Pr(>|t|)    
(Intercept)                               < 2e-16 ***
categoryDistichlis spicata                < 2e-16 ***
categoryJuncus roemerianus                < 2e-16 ***
categoryMonanthochloe littoralis         0.000381 ***
categoryOther vegetation                 0.000111 ***
categorySalicornia virginica             0.075571 .  
categoryScirpus maritimus                3.64e-16 ***
categorySpartina alterniflora             < 2e-16 ***
categorySpartina spartinae               0.570628    
M_fresh                                  4.17e-09 ***
categoryDistichlis spicata:M_fresh       1.39e-14 ***
categoryJuncus roemerianus:M_fresh       1.89e-13 ***
categoryMonanthochloe littoralis:M_fresh 5.94e-07 ***
categoryOther vegetation:M_fresh         9.44e-06 ***
categorySalicornia virginica:M_fresh     0.034466 *  
categoryScirpus maritimus:M_fresh        3.37e-13 ***
categorySpartina alterniflora:M_fresh     < 2e-16 ***
categorySpartina spartinae:M_fresh       0.000390 ***
```

Model 9

```
Linear mixed model fit by REML. t-tests use Satterthwaite's method
['lmerModLmerTest']
Formula: log(area_m2) ~ category_broad * M_gage.y + (1 | year/grid_id)
   Data: long_dat

REML criterion at convergence: 20015.7

Scaled residuals: 
    Min      1Q  Median      3Q     Max 
-5.9536 -0.5666  0.0619  0.6003  4.2308 
```

```
Random effects:
 Groups       Name        Variance Std.Dev.
 grid_id:year (Intercept) 2.034    1.426   
 year         (Intercept) 0.000    0.000   
 Residual                 1.244    1.115   
Number of obs: 6062, groups:  grid_id:year, 440; year, 5

Fixed effects:
                                               Estimate Std. Error
df t value
(Intercept)                                   9.076e+00  1.438e-01
6.448e+02  63.129
category_broadMarsh vegetation               -7.072e-01  7.735e-02
5.588e+03  -9.142
category_broadNon-marsh vegetation            4.613e-01  9.881e-02
5.589e+03   4.668
category_broadWater                           1.934e+00  1.211e-01
5.610e+03  15.966
M_gage.y                                     -1.207e-06  2.484e-06
6.447e+02  -0.486
category_broadMarsh vegetation:M_gage.y       6.712e-06  1.337e-06
5.588e+03   5.022
category_broadNon-marsh vegetation:M_gage.y -9.789e-06  1.708e-06
5.588e+03  -5.731
category_broadWater:M_gage.y                 -4.027e-07  2.093e-06
5.610e+03  -0.192
                                            Pr(>|t|)    
(Intercept)                                  < 2e-16 ***
category_broadMarsh vegetation               < 2e-16 ***
category_broadNon-marsh vegetation          3.11e-06 ***
category_broadWater                          < 2e-16 ***
M_gage.y                                       0.627    
category_broadMarsh vegetation:M_gage.y     5.28e-07 ***
category_broadNon-marsh vegetation:M_gage.y 1.05e-08 ***
category_broadWater:M_gage.y                   0.847    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Correlation of Fixed Effects:
            (Intr) ctg_Mv ct_N-v ctgr_W M_gg.y c_Mv:M c_N-v:
ctgry_brdMv -0.441                                          
ctgry_brN-v -0.346  0.641                                   
ctgry_brdWt -0.285  0.523  0.409                            
M_gage.y    -0.840  0.370  0.290  0.239                     
ctgr_Mv:M_.  0.370 -0.840 -0.539 -0.439 -0.441              
ctg_N-v:M_.  0.290 -0.538 -0.840 -0.343 -0.345  0.641       
ctgry_W:M_.  0.239 -0.439 -0.344 -0.840 -0.285  0.523  0.409
fit warnings:
Some predictor variables are on very different scales: consider rescaling
optimizer (nloptwrap) convergence code: 0 (OK)
boundary (singular) fit: see help('isSingular')
```

Model 10

```
Linear mixed model fit by REML. t-tests use Satterthwaite's method
['lmerModLmerTest']
Formula: log(area_m2) ~ category * M_gage.y + (1 | year/grid_id)
   Data: marsh_dat

REML criterion at convergence: 12061.7

Scaled residuals: 
    Min      1Q  Median      3Q     Max 
-5.1644 -0.5587  0.0271  0.5939  3.7087 

Random effects:
 Groups       Name        Variance Std.Dev.
 grid_id:year (Intercept) 2.0407   1.4285  
 year         (Intercept) 0.0103   0.1015  
 Residual                 0.8613   0.9281  
Number of obs: 3895, groups:  grid_id:year, 435; year, 5

Fixed effects:
                                            Estimate Std. Error         df
t value
(Intercept)                                7.694e+00  1.724e-01  4.723e+00
44.631
categoryDistichlis spicata                 8.303e-01  1.165e-01  3.432e+03
7.128
categoryJuncus roemerianus                 1.928e+00  1.163e-01  3.433e+03
16.579
categoryMonanthochloe littoralis           4.633e-01  1.165e-01  3.432e+03
3.977
categoryOther vegetation                   4.356e-01  1.163e-01  3.433e+03
3.746
categorySalicornia virginica               5.091e-01  1.163e-01  3.433e+03
4.377
categoryScirpus maritimus                 -8.545e-01  1.165e-01  3.432e+03
-7.337
categorySpartina alterniflora              2.149e+00  1.163e-01  3.433e+03
18.477
categorySpartina spartinae                 9.354e-01  1.164e-01  3.432e+03
8.033
M_gage.y                                   1.877e-05  2.980e-06  4.726e+00
6.299
categoryDistichlis spicata:M_gage.y       -1.100e-05  2.014e-06  3.432e+03
-5.462
categoryJuncus roemerianus:M_gage.y       -2.108e-05  2.010e-06  3.433e+03
-10.487
categoryMonanthochloe littoralis:M_gage.y -1.156e-05  2.014e-06  3.432e+03
-5.738
categoryOther vegetation:M_gage.y         -8.894e-06  2.010e-06  3.433e+03
-4.424
categorySalicornia virginica:M_gage.y     -1.992e-05  2.013e-06  3.432e+03
-9.899
```

```
categoryScirpus maritimus:M_gage.y         1.265e-05  2.012e-06  3.432e+03
6.286
categorySpartina alterniflora:M_gage.y    -3.375e-05  2.011e-06  3.433e+03
-16.782
categorySpartina spartinae:M_gage.y       -2.577e-05  2.013e-06  3.432e+03
-12.800
                                          Pr(>|t|)
(Intercept)                               2.19e-07 ***
categoryDistichlis spicata                1.24e-12 ***
categoryJuncus roemerianus                 < 2e-16 ***
categoryMonanthochloe littoralis          7.11e-05 ***
categoryOther vegetation                  0.000183 ***
categorySalicornia virginica              1.24e-05 ***
categoryScirpus maritimus                 2.71e-13 ***
categorySpartina alterniflora              < 2e-16 ***
categorySpartina spartinae                1.30e-15 ***
M_gage.y                                  0.001820 **
categoryDistichlis spicata:M_gage.y       5.06e-08 ***
categoryJuncus roemerianus:M_gage.y        < 2e-16 ***
categoryMonanthochloe littoralis:M_gage.y 1.04e-08 ***
categoryOther vegetation:M_gage.y         9.98e-06 ***
categorySalicornia virginica:M_gage.y      < 2e-16 ***
categoryScirpus maritimus:M_gage.y        3.68e-10 ***
categorySpartina alterniflora:M_gage.y     < 2e-16 ***
categorySpartina spartinae:M_gage.y        < 2e-16 ***
```

Model 11

```
Linear mixed model fit by REML. t-tests use Satterthwaite's method
['lmerModLmerTest']
Formula: log(area_m2) ~ category_broad * M_gage + (1 | year/grid_id)
   Data: long_dat

REML criterion at convergence: 20080.2

Scaled residuals:
    Min      1Q  Median      3Q     Max
-5.9531 -0.5777  0.0463  0.6156  4.1579

Random effects:
 Groups       Name        Variance  Std.Dev.
 grid_id:year (Intercept) 2.021e+00 1.422e+00
 year         (Intercept) 1.757e-10 1.326e-05
 Residual                 1.259e+00 1.122e+00
Number of obs: 6062, groups:  grid_id:year, 440; year, 5

Fixed effects:
                                            Estimate Std. Error         df
t value
(Intercept)                                9.085e+00  1.301e-01  6.489e+02
69.802
category_broadMarsh vegetation            -6.965e-01  7.051e-02  5.588e+03
-9.878
```

```
category_broadNon-marsh vegetation        1.612e-01  9.007e-02  5.588e+03
1.790
category_broadWater                       1.889e+00  1.104e-01  5.610e+03
17.109
M_gage                                   -1.721e-06  2.665e-06  6.491e+02
-0.646
category_broadMarsh vegetation:M_gage     8.075e-06  1.445e-06  5.587e+03
5.591
category_broadNon-marsh vegetation:M_gage -4.487e-06  1.845e-06  5.588e+03
-2.432
category_broadWater:M_gage                6.445e-07  2.262e-06  5.610e+03
0.285
                                         Pr(>|t|)
(Intercept)                               < 2e-16 ***
category_broadMarsh vegetation            < 2e-16 ***
category_broadNon-marsh vegetation         0.0735 .
category_broadWater                       < 2e-16 ***
M_gage                                     0.5187
category_broadMarsh vegetation:M_gage    2.37e-08 ***
category_broadNon-marsh vegetation:M_gage  0.0150 *
category_broadWater:M_gage                 0.7757
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Correlation of Fixed Effects:
            (Intr) ctg_Mv ct_N-v ctgr_W M_gage c_Mv:M c_N-v:
ctgry_brdMv -0.444
ctgry_brN-v -0.348  0.641
ctgry_brdWt -0.287  0.523  0.409
M_gage      -0.801  0.356  0.279  0.230
ctgry_Mv:M_  0.355 -0.801 -0.514 -0.419 -0.444
ctgr_N-v:M_  0.279 -0.514 -0.801 -0.328 -0.348  0.641
ctgry_bW:M_  0.230 -0.419 -0.328 -0.801 -0.287  0.523  0.409
fit warnings:
Some predictor variables are on very different scales: consider rescaling
optimizer (nloptwrap) convergence code: 0 (OK)
boundary (singular) fit: see help('isSingular')
```

Model 12

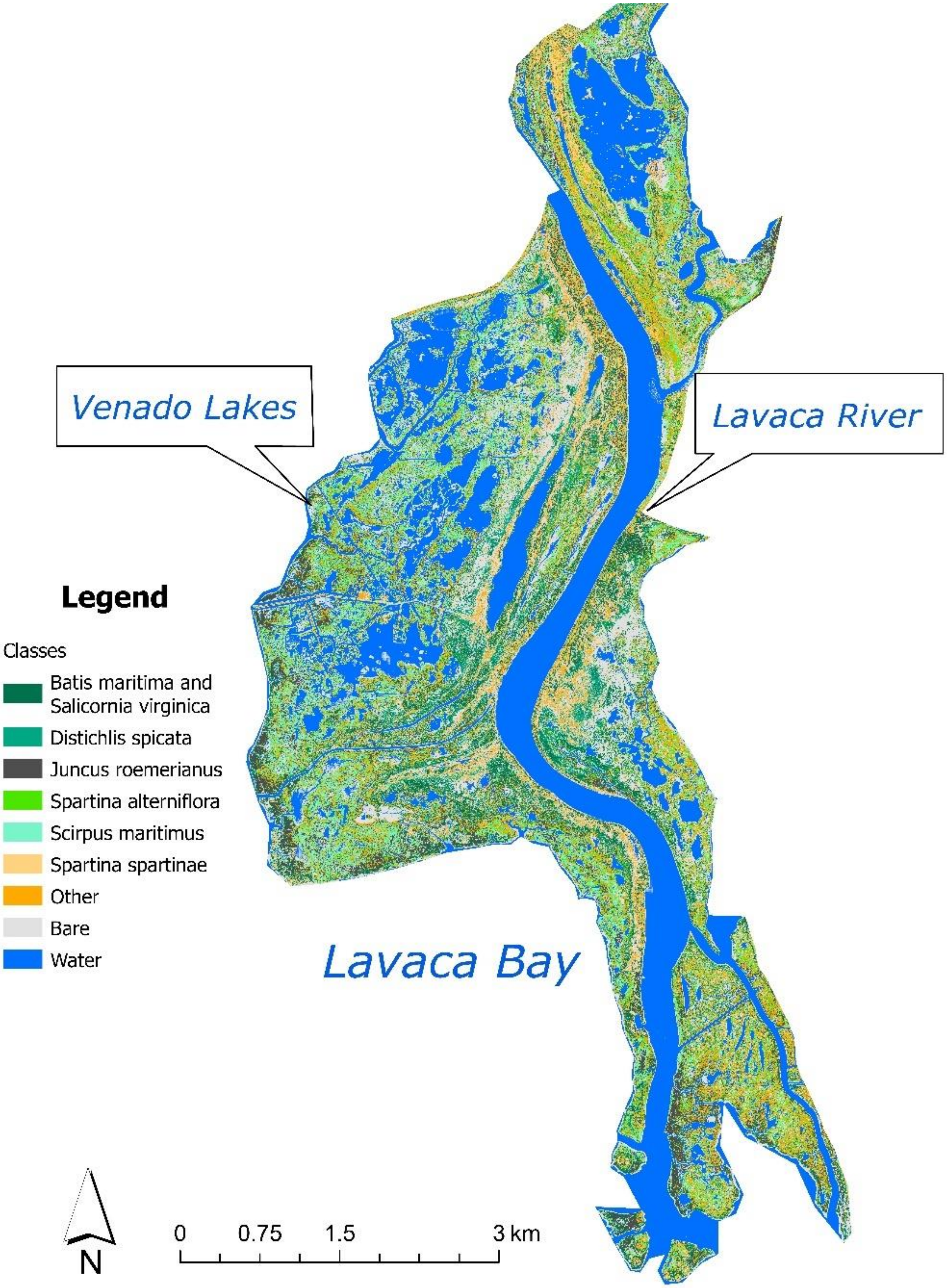
```
Linear mixed model fit by REML. t-tests use Satterthwaite's method
['lmerModLmerTest']
Formula: log(area_m2) ~ category * M_gage + (1 | year/grid_id)
   Data: marsh_dat

REML criterion at convergence: 12162.7

Scaled residuals:
    Min      1Q  Median      3Q     Max
-5.0643 -0.5891  0.0263  0.6059  3.7211

Random effects:
 Groups       Name        Variance  Std.Dev.
```

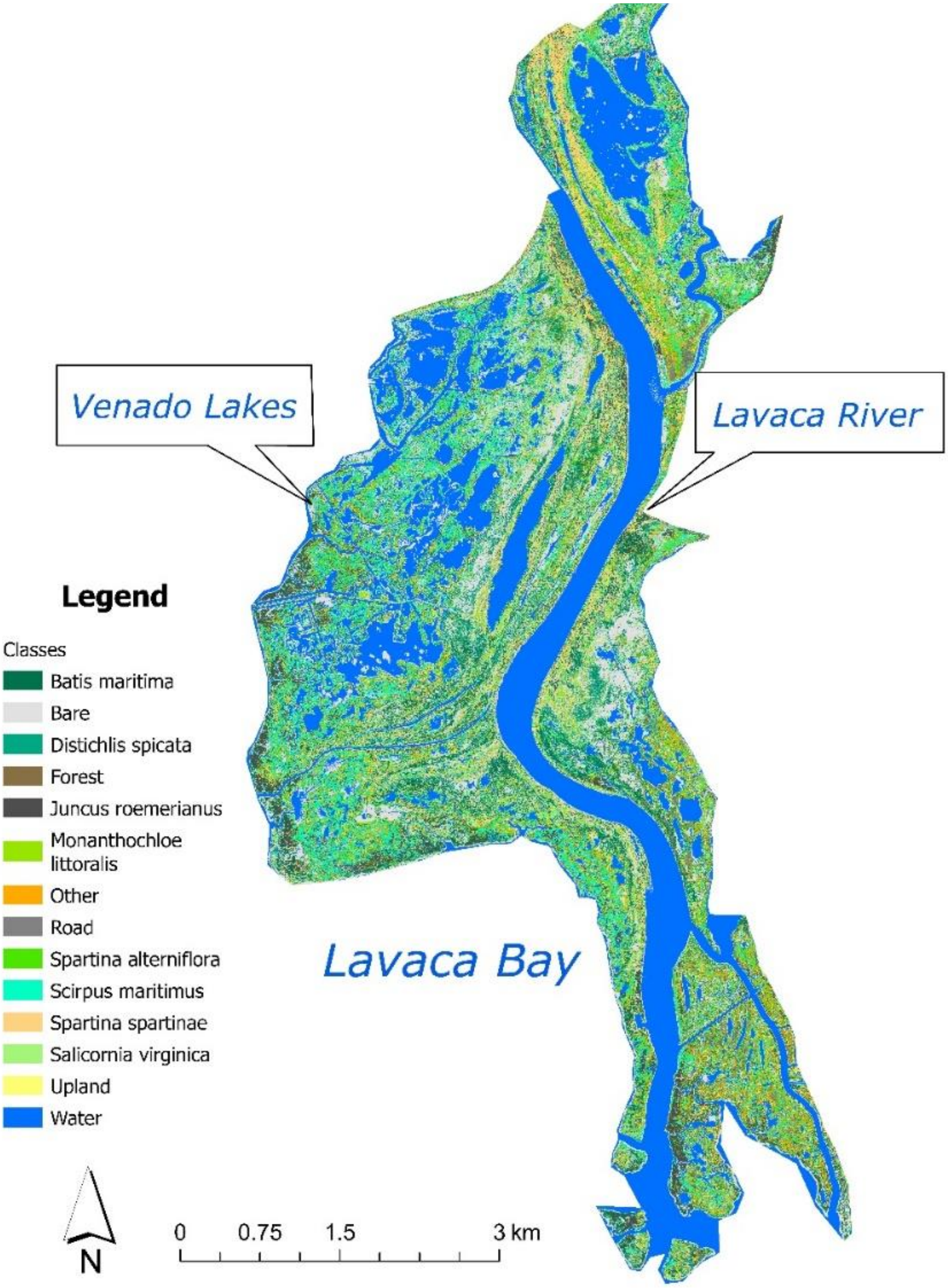
```
 grid_id:year (Intercept) 2.023e+00 1.422185
 year         (Intercept) 8.876e-06 0.002979
 Residual                 8.883e-01 0.942502
Number of obs: 3895, groups:  grid_id:year, 435; year, 5

Fixed effects:
                                          Estimate Std. Error         df t
value
(Intercept)                              7.999e+00  1.368e-01  7.852e+02
58.464
categoryDistichlis spicata               9.605e-01  1.071e-01  3.432e+03
8.967
categoryJuncus roemerianus               1.472e+00  1.070e-01  3.432e+03
13.756
categoryMonanthochloe littoralis         3.874e-01  1.071e-01  3.432e+03
3.616
categoryOther vegetation                 2.968e-01  1.070e-01  3.432e+03
2.774
categorySalicornia virginica            -2.469e-01  1.070e-01  3.432e+03
-2.306
categoryScirpus maritimus               -9.436e-01  1.071e-01  3.432e+03
-8.810
categorySpartina alterniflora            1.830e+00  1.070e-01  3.432e+03
17.097
categorySpartina spartinae               4.864e-02  1.072e-01  3.432e+03
0.454
M_gage                                   1.555e-05  2.803e-06  7.864e+02
5.547
categoryDistichlis spicata:M_gage       -1.702e-05  2.196e-06  3.432e+03
-7.749
categoryJuncus roemerianus:M_gage       -1.456e-05  2.192e-06  3.433e+03
-6.643
categoryMonanthochloe littoralis:M_gage -1.243e-05  2.196e-06  3.432e+03
-5.661
categoryOther vegetation:M_gage         -7.510e-06  2.194e-06  3.432e+03
-3.423
categorySalicornia virginica:M_gage     -5.399e-06  2.195e-06  3.432e+03
-2.460
categoryScirpus maritimus:M_gage         1.808e-05  2.195e-06  3.432e+03
8.238
categorySpartina alterniflora:M_gage    -3.381e-05  2.194e-06  3.432e+03 -
15.410
categorySpartina spartinae:M_gage       -9.367e-06  2.194e-06  3.433e+03
-4.270
                                        Pr(>|t|)    
(Intercept)                              < 2e-16 ***
categoryDistichlis spicata               < 2e-16 ***
categoryJuncus roemerianus               < 2e-16 ***
categoryMonanthochloe littoralis        0.000303 ***
categoryOther vegetation                0.005569 ** 
categorySalicornia virginica            0.021161 *  
categoryScirpus maritimus                < 2e-16 ***
categorySpartina alterniflora            < 2e-16 ***
categorySpartina spartinae              0.649878    
```

```
M_gage                                  3.98e-08 ***
categoryDistichlis spicata:M_gage       1.21e-14 ***
categoryJuncus roemerianus:M_gage       3.57e-11 ***
categoryMonanthochloe littoralis:M_gage 1.63e-08 ***
categoryOther vegetation:M_gage         0.000626 ***
categorySalicornia virginica:M_gage     0.013942 *
categoryScirpus maritimus:M_gage        2.47e-16 ***
categorySpartina alterniflora:M_gage     < 2e-16 ***
categorySpartina spartinae:M_gage       2.01e-05 ***
```

Appendix 6. Vegetation classification maps, classification variable importance tables, and confusion matrices for the period 2010 to 2018.

2010




Venado Lakes
Lavaca River
Legend
Classes
Batis maritima
Bare
Distichlis spicata
Forest
Juncus roemerianus
Monanthochloe littoralis
Other
Road
Spartina alterniflora
Scirpus maritimus
Spartina spartinae
Salicornia virginica
Upland
Water
Lavaca Bay
N
0
0.75
1.5
3 km

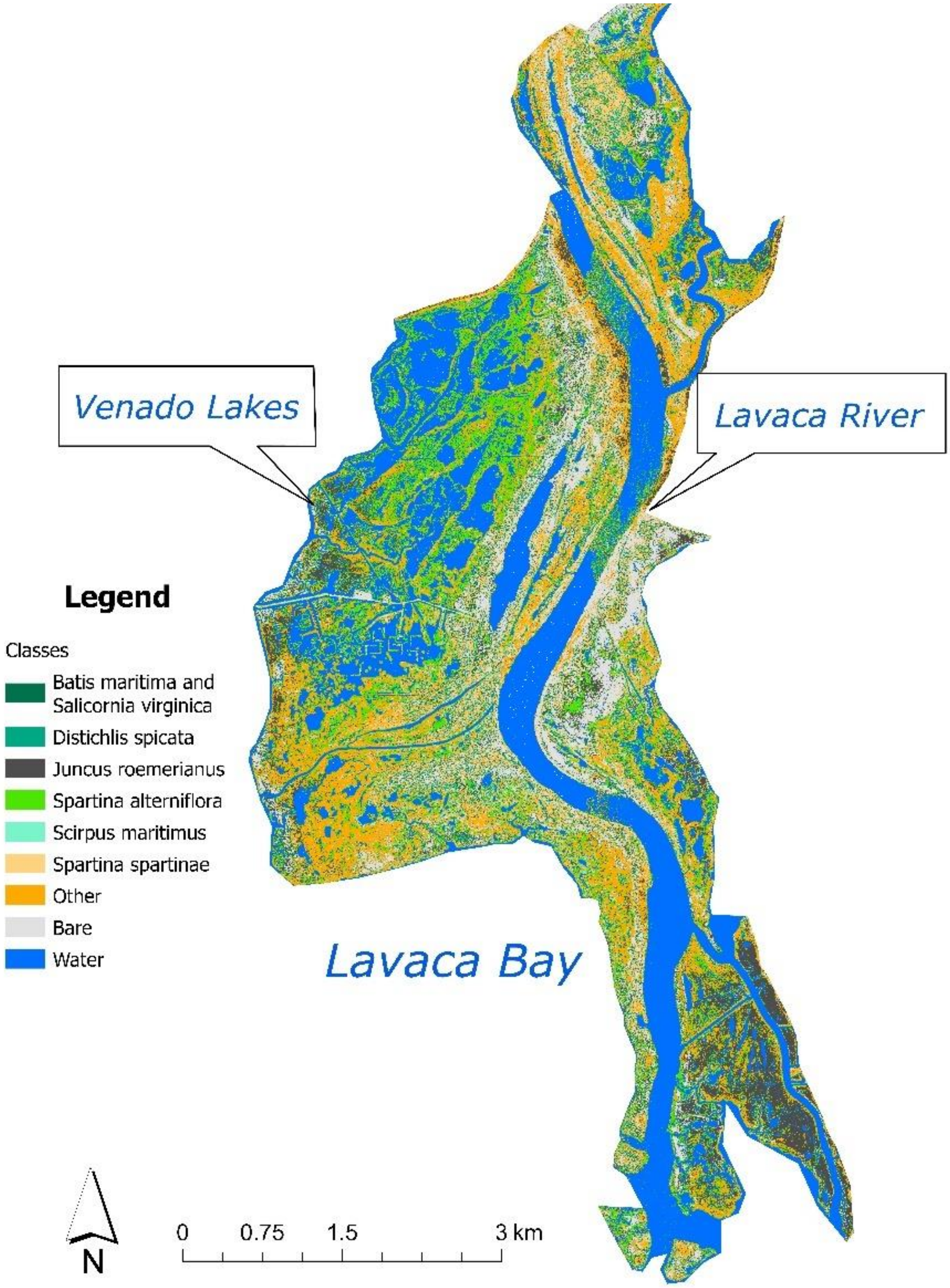
2010 Confusion Matrix

Category	BM+SV	B	DS	JR	O	SA	SM	SS	W	Sensitivity	Accuracy	User's accuracy	Kappa
BM + SV	1	1	2	0	0	0	0	0	0	0.25	0.93	0.17	NA
B	0	6	0	0	2	0	0	2	0	0.3	0.93	0.38	NA
DS	1	1	4	0	1	1	0	0	0	0.5	0.84	0.44	NA
JR	0	1	0	2	0	0	0	0	0	0.67	0.95	0.5	NA
O	1	2	2	0	1	0	3	0	0	0.33	0.94	0.17	NA
SA	1	1	1	0	0	1	1	0	0	0.2	0.91	0.5	NA
SM	2	0	0	2	1	0	0	0	0	0	0.83	0	NA
SS	0	1	0	0	1	0	0	0	0	0	0.93	0	NA
W	0	3	0	0	0	0	1	0	8	0.67	0.93	1	NA
Producer's accuracy	0.25	0.6	0.5	0.67	0.11	0.2	0	0	0.67	NA	NA	0.40	NA
Kappa	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.30

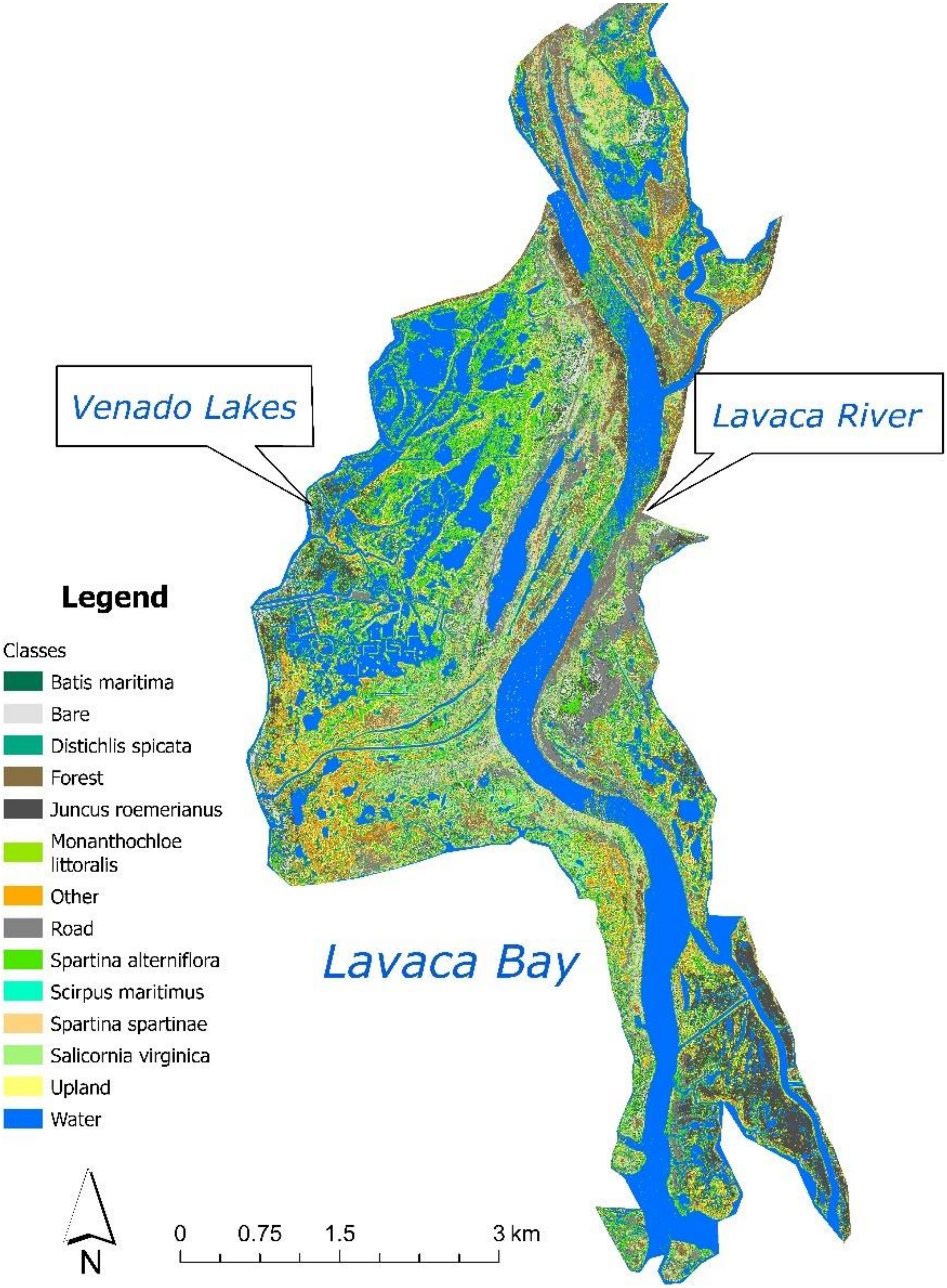
2010 Classification Variable Importance

Variable	Percent
Elevation	17
NDVI	15
MSAVI	15
Distance	14
VARI	14
Texture	13
NAIP	11

2014



Venado Lakes
Lavaca River
Legend
Classes
Batis maritima and Salicornia virginica
Distichlis spicata
Juncus roemerianus
Spartina alterniflora
Scirpus maritimus
Spartina spartinae
Other
Bare
Water
Lavaca Bay
N
0
0.75
1.5
3 km


Venado Lakes
Lavaca River
Lavaca Bay
Legend
Classes
Batis maritima
Bare
Distichlis spicata
Forest
Juncus roemerianus
Monanthochloe littoralis
Other
Road
Spartina alterniflora
Scirpus maritimus
Spartina spartinae
Salicornia virginica
Upland
Water
N
0
0.75
1.5
3 km

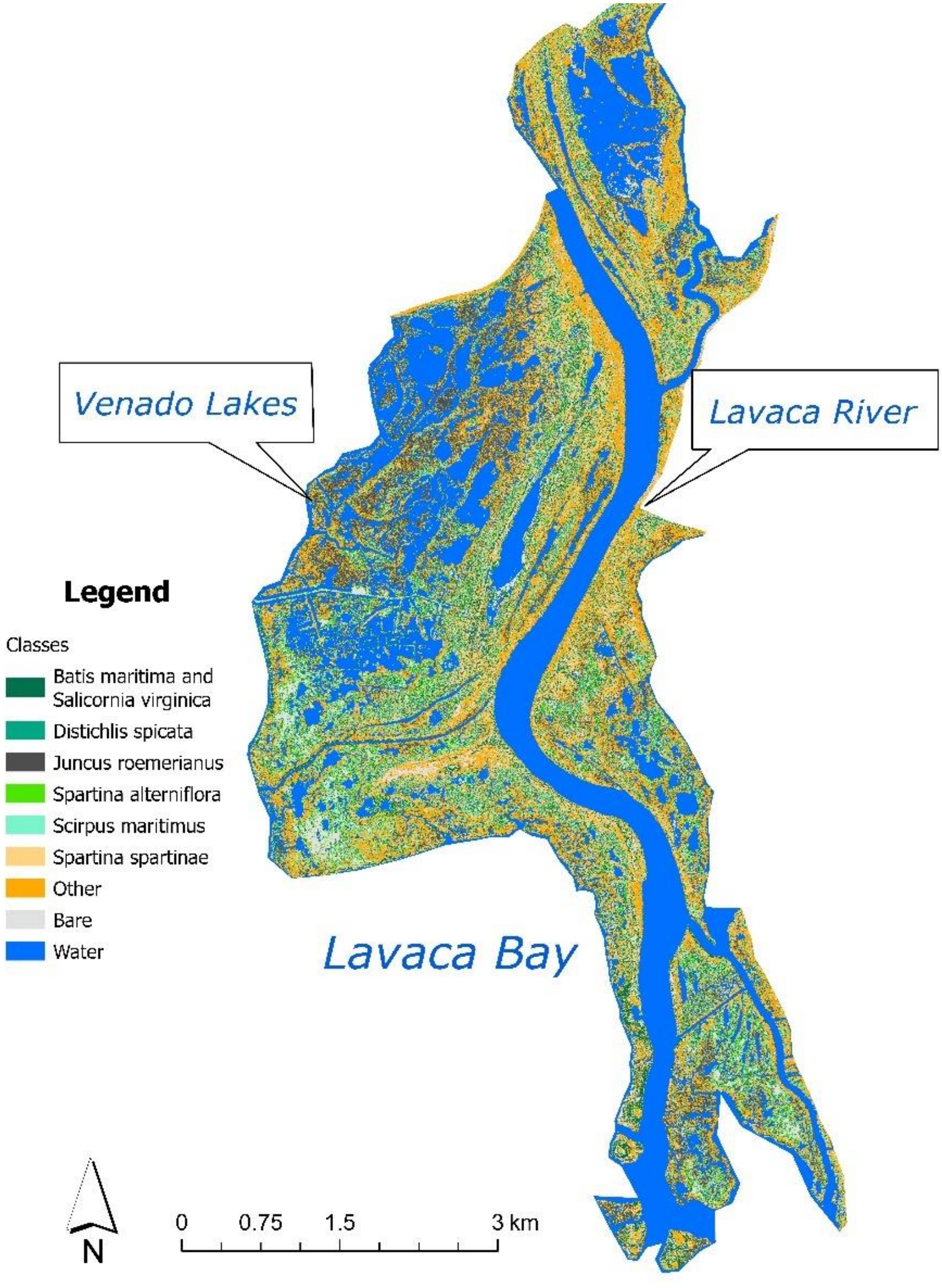
2014 Confusion Matrix

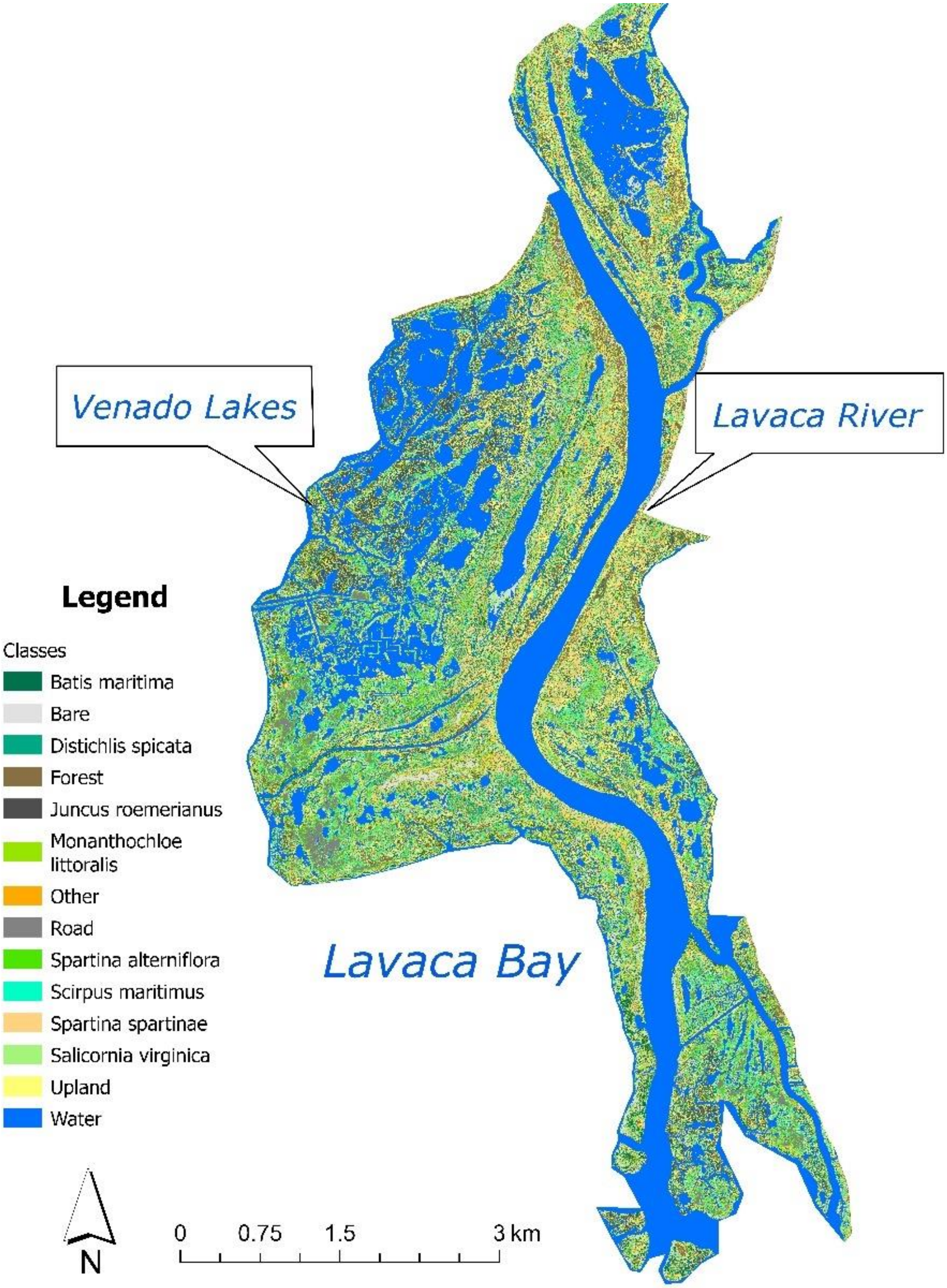
Category	BM+SV	B	DS	JR	O	SA	SM	SS	W	Sensitivity	Accuracy	User’s accuracy	Kappa
BM + SV	1	1	1	0	0	1	0	0	0	0.25	0.95	0.25	NA
B	2	5	0	0	1	1	0	1	0	0.14	0.93	0.36	NA
DS	0	4	3	0	1	0	0	0	0	0.38	0.88	0.6	NA
JR	0	0	0	0	1	1	0	0	1	0	0.9	0	NA
O	0	1	0	1	5	1	0	1	0	0.58	0.94	0.5	NA
SA	0	2	0	2	0	1	0	0	0	0.2	0.81	0.13	NA
SM	1	0	0	0	1	2	1	0	0	0.2	0.93	1	NA
SS	0	0	1	0	1	0	0	0	0	0	0.93	0	NA
W	0	1	0	0	0	1	0	0	10	0.83	0.95	0.91	NA
Producer’s accuracy	0.25	0	0.3	0	0.	0.2	0.2	0	0.8	NA	NA	0.45	NA
Kappa	NA	N	NA	NA	N	NA	NA	NA	NA	NA	NA	NA	0.36

2014 Variable Importance

Variable	Percent
Elevation	17
Distance	17
Texture	14
VARI	13
MSAVI	13
NDVI	13
NAIP	13

2016


Venado Lakes
Lavaca River
Legend
Classes
Batis maritima and Salicornia virginica
Distichlis spicata
Juncus roemerianus
Spartina alterniflora
Scirpus maritimus
Spartina spartinae
Other
Bare
Water
Lavaca Bay
N
0
0.75
1.5
3 km


Venado Lakes
Lavaca River
Lavaca Bay
Legend
Classes
Batis maritima
Bare
Distichlis spicata
Forest
Juncus roemerianus
Monanthochloe littoralis
Other
Road
Spartina alterniflora
Scirpus maritimus
Spartina spartinae
Salicornia virginica
Upland
Water
N
0
0.75
1.5
3 km

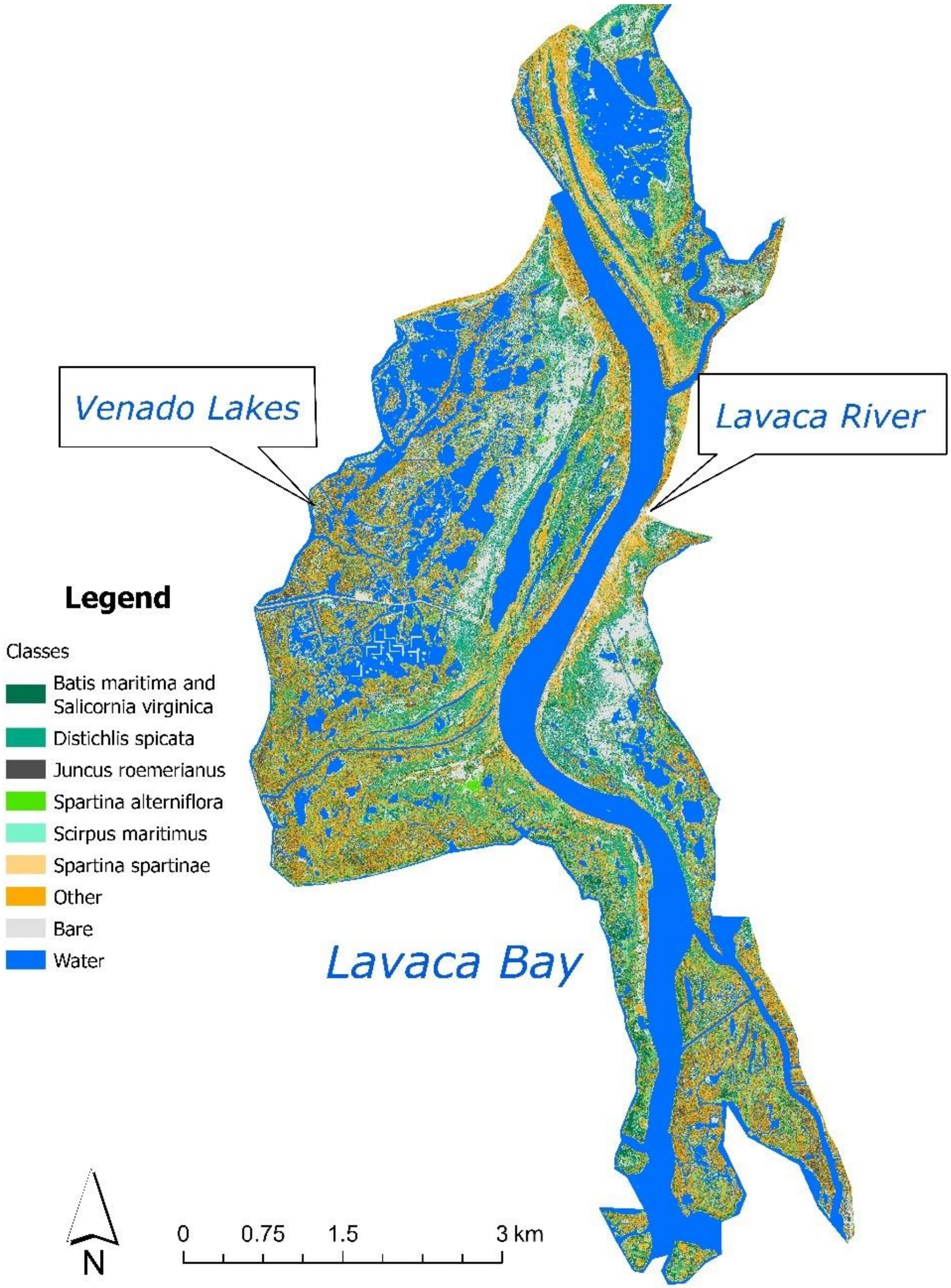
2016 Confusion Matrix

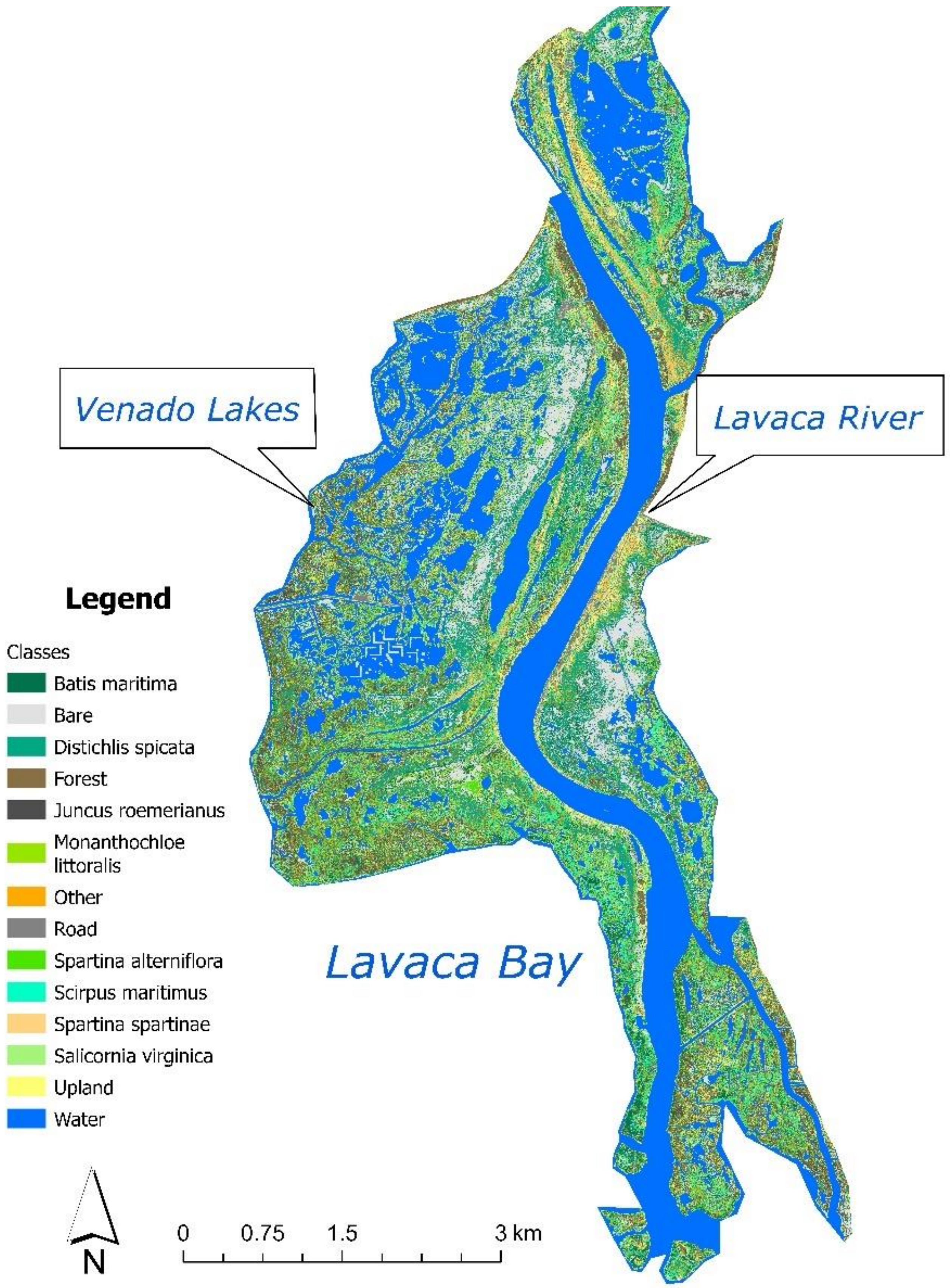
Category	BM + SV	B	DS	JR	O	SA	SM	SS	W	Sensitivity	Accuracy	User's accuracy	Kappa
BM + SV	1	4	1	0	1	1	1	0	0	0.25	0.95	0.13	NA
B	0	16	1	0	1	0	0	0	1	0.57	0.94	0.55	NA
DS	4	2	7	0	3	1	0	2	0	0.25	0.88	0.7	NA
JR	0	1	0	3	1	0	1	0	0	0.33	0.97	0.33	NA
O	3	1	1	2	10	0	3	0	0	0.38	0.95	0.4	NA
SA	0	1	0	2	4	2	0	0	2	0	0.88	0.5	NA
SM	0	2	0	2	4	0	2	1	1	0.2	0.86	0.25	NA
SS	0	0	0	0	1	0	1	3	0	0.5	0.93	0.5	NA
W	0	2	0	0	0	0	0	0	28	0.83	0.95	0.88	NA
Producer's accuracy	0.11	0.84	0.37	0.5	0.5	0.18	0.17	0.6	0.93	NA	NA	0.55	NA
Kappa	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.47

2016 Variable Importance

Variable	Percent
Elevation	17
NDVI	15
MSAVI	15
VARI	14
Distance	14
Texture	13
NAIP	12

2018


Venado Lakes
Lavaca River
Lavaca Bay
Legend
Classes
Batis maritima and Salicornia virginica
Distichlis spicata
Juncus roemerianus
Spartina alterniflora
Scirpus maritimus
Spartina spartinae
Other
Bare
Water
N
0
0.75
1.5
3 km


Venado Lakes
Lavaca River
Legend
Classes
Batis maritima
Bare
Distichlis spicata
Forest
Juncus roemerianus
Monanthochloe littoralis
Other
Road
Spartina alterniflora
Scirpus maritimus
Spartina spartinae
Salicornia virginica
Upland
Water
Lavaca Bay
N
0
0.75
1.5
3 km

2018 Confusion Matrix

Category	BM + SV	B	DS	JR	O	SA	SM	SS	W	Sensitivity	Accuracy	User's accuracy	Kappa
BM + SV	3	0	1	0	0	0	0	0	0	0.75	0.94	0.38	NA
B	2	5	2	0	0	0	0	1	0	0.38	0.96	0.63	NA
DS	1	1	5	0	1	0	0	0	0	0.62	0.88	0.55	NA
JR	0	0	0	2	1	0	0	0	0	0.67	0.98	1	NA
O	1	0	0	0	5	0	2	1	0	0.44	0.94	0.36	NA
SA	1	1	0	0	3	0	0	0	0	NA	NA	NA	NA
SM	0	0	1	0	2	0	2	0	0	0.4	0.91	0.5	NA
SS	0	0	0	0	2	0	0	0	0	0	0.93	0	NA
W	0	1	0	0	0	0	0	0	11	0.92	0.98	0.92	NA
Producer's accuracy	0.75	0.5	0.45	0.67	0.55	0	0.4	0	0.92	NA	NA	0.53	NA
Kappa	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.46

2018 Variable Importance

Variable	Percent
Elevation	18
MSAVI	15
NDVI	15
Distance	14
VARI	14
Texture	13
NAIP	12

TWDB Review Comments

Below is the TWDB review with a response to the review comments following directly below the comments. The response is the italic font.

Lavaca River Delta Marsh Assessment

TWDB Contract #2000012439

DRAFT Comments to Draft Final Report

REQUIRED CHANGES

General Draft Final Report Comments:

1. Please correct the statement on the front cover to the following: "*Pursuant to House Bill 1 as approved by the 86th Texas Legislature, this study report was funded for the purpose of studying environmental flow needs for Texas rivers and estuaries as part of the adaptive management phase of the Senate Bill 3 process for environmental flows established by the 80th Texas Legislature. The views and conclusions expressed herein are those of the author(s) and do not necessarily reflect the views of the Texas Water Development Board.*"

   Done.

2. Please ensure that all acronyms and scientific measurement units are spelled out the first time used.

   Done. This is added after the List of Tables, and the Table of Contents is updated.

3. Consistency with the scope of work:
   a. The scope of work states that field work will focus on marsh habitat verification, (completed), but also collection of elevation data and basic water quality data at key locations. The latter two components do not appear in the report. In the discussion on challenges with field work, please clarify why these variables were not verified.

      Done. Discussion of elevation and water quality data provided in the Field Work section.

   b. The scope of work states that data from field efforts will be included in appendices of the final report. Please ensure that all field data (e.g., digital photographs, quadrat sampling, field notes) are included in the report or as an accompaniment with the transmission of the final report.

Field data and digital photographs are included as Appendices one and two, respectively.

c. The scope of work states that a presentation of final results will be provided to the Colorado-Lavaca Basin and Bay Area Stakeholder Committee and TWDB staff. Please ensure that a presentation of study results is scheduled for the Colorado-Lavaca stakeholders and other interested parties. Please coordinate with TWDB staff who can facilitate a virtual meeting and send notification to stakeholders.

   Presentation of final results occurred on August 25, 2022.

d. As noted in the Scope of Work, a key purpose of the study is to help inform whether adjustments in flow standards for inflows to Lavaca Bay may be appropriate for supporting healthy marsh habitats. Inflow data are characterized as inflows to the Lavaca-Colorado estuary (see, e.g., p. 1, last sentence carrying over to p.2, referencing Longley 1994,[1] and caption for Fig. 11), suggesting the inflow values presented reflect total inflows to the larger estuary system rather than specifically to Lavaca Bay. If that characterization is incorrect, the references should be revised. If the characterization is correct, explanation is needed of why those broader inflow data are appropriate for use in evaluating response of marsh habitat in the Lavaca River delta or presentation of inflow data specific to the Lavaca River is needed.

   Freshwater inflow data has been updated to reflect inflows specifically to the study site (Lavaca Bay/Lavaca Delta). All models using freshwater inflow data have been rerun and results are updated.

Specific Draft Final Report Comments:

1. Table of contents, Introduction: Please substitute "to" for "of" as follows: Significance of Freshwater Inflows ~~of~~ to Estuarine Wetlands.

   Done.

2. Introduction, last sentence, page 1-2: Please clarify if the inflow value stated is for the overall Colorado-Lavaca Estuary, which appears to be true based on Longley (1994), not the Lavaca estuary.

   Done.

3. Introduction, 1st sentence, page 2: please clarify if the salinity data is specific for Lavaca Bay, which appears to be based on Longley (1994), and please add units.

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[1] Longley 1994, at Table 4.1.1 on p. 26 (257,000 X 12= 3.084 maf) and Figure 4.1.5 on p. 27 shows 3 maf as the inflow for the overall estuary system.

Clarified the salinity data. However, salinity is currently recognized as being a unitless ratio.

4. Introduction, 2nd sentence, page 2: Please cite the source of the information for salinity and tides (tide gage and tidal epoch) and please clarify if the information is specific to the Lavaca Delta or more broadly to Lavaca and/or Matagorda Bays.

   Done.

5. Introduction, 2nd paragraph, 2nd sentence, page 3: Please add a citation for relative sea-level rise values.

   Done.

6. Introduction, last paragraph, 7th sentence (referring to consequences of various factors), page 3: please add a citation for the reference to 95% trapping efficiency of the reservoir.

   Done.

7. Project Justification, page 4: Please make the following revisions to the first paragraph: "The Texas Water Development Board supports implementation of adaptive management work plans that were developed through the stakeholder-driven Senate Bill 3 environmental flows process (80th Texas Legislature, 2007). In 2019, the Colorado-Lavaca Basin and Bay Area Stakeholder Committee recommended funding a priority work plan study to inform adaptive management of freshwater inflows to the Lavaca River Delta and Lavaca Bay. The University of Texas Marine Science Institute (UTMSI) was contracted to examine changes in marsh habitats in the Lavaca Delta in response to variations in freshwater inflow levels."

   Done.

8. Ground Data Sampling, page 5:
   1. Vegetative cover was assessed with a 0.25 m^2 quadrat, but the data from this ground sampling effort does not appear to be included in the results. Please ensure the data are included in the final report or as accompaniment with the transmission of the final report.

      Done.

   2. Digital photographs and field notes were taken but these data do not appear to be included in the report. In the report, please include at least one figure showing a digital photograph as an example of representative ground conditions in the Lavaca Delta. Please ensure the photographs and field notes are included in the report or as an accompaniment with the transmission of the final report.

      Done.

9. Field Work, page 7: *Spartina patens* is listed twice in the list of ground cover categories. Please remove one. Please ensure consistent formatting in the list (i.e., italicize all font).

Done.

10. Long-Term Vegetation Response to Freshwater Inflows, page 25: Please add a table showing the statistical results of the GLMM modeling effort to relate marsh area and composition with freshwater inflows, including interactions with inflows for each species.

    Done. Tables included in Long-Term Vegetation Response to Freshwater Inflows section.

11. Concluding statements, pages 26-27: The scope of work states that project investigators will provide recommendations for additional analyses to better inform identification of inflow levels needed to maintain marsh habitats in the Lavaca Delta. While the authors make a recommendation for additional training data and focused imagery analysis to assess marsh habitat, please ensure recommendations for future analyses to identify freshwater inflow levels needed to maintain marsh habitats are included in the discussion.

    Done. Discussion included in Recommendations for Future Analyses and Concluding Statements sections.

Figures and Tables Comments:

1. Figure 5. Please label each plot panel with (a), (b), and (c) as indicated in the figure caption.

   Done.

2. Figure 11: As noted above under general comments, reference in the caption to Lavaca-Colorado estuary inflows requires correction or explanation.

   Freshwater inflow data has been updated/corrected.

SUGGESTED CHANGES

Specific Draft Final Report Comments:

1. Executive Summary, 1st paragraph, 7th sentence: It would be helpful to provide some broader context acknowledging that in the period of record for underlying data used to support this study, the watersheds feeding the Lavaca Delta experienced hydrologic extremes including multiple years of extreme drought, leading up to and during that period, and record flooding caused by Hurricane Harvey.

   Done.

2. Executive Summary, Numbered highlight point 1, page 1: It would be helpful to have some context for the characterization of the stated average overall accuracy for vegetation classification of less than 0% as “moderately accurate.”

   This is discussed in detail in the Vegetation Classification section.

3. Introduction Overall: The sources used to describe meteorology, LAN (1967) and Longley (1994), are based on reviews of data that are nearly 40-50 years old. It would be helpful to have data sources that are more current or more reflective of conditions affecting vegetation during the period being analyzed. Please clarify why more recent data was not used.

   More recent data sources have been added to supplement the older reviews.

4. Introduction, 1st sentence, page 3: suggest substituting “obligate” for “obligative” for clarity.

   Done.

5. Introduction, last paragraph, 4th sentence, page 3: suggest that the term “conduction” be replaced with “construction” to clarify apparent meaning.

   Done.

6. Introduction, last paragraph, 6th sentence (referring to deltaic marsh), page 3: Please consider adding a citation or date on which the conclusion can be based. Alternatively, it might be restated as a description of what might happen.

   Done.

7. Introduction, last paragraph, last sentence (referring to consequences of various factors), page 3: suggest clarifying if this is a statement of expected effect or is based on data or some specific source.

   Done.

8. Project Justification, 2nd paragraph, 1st sentence, page 4: suggest adding a citation for this statement.

   Done.

9. Vegetative mapping, first sentence, page 5: Suggest referring to "...potential role of freshwater inflows" rather than impact of decreasing inflows. Although it might be accurate to say "decreased", up to this point in the report there are no data presented making the point freshwater inflow has decreased or tying a change to a specific decrease in inflow. It may be more accurate to refer to the data as “biennial” rather than “decadal.”

   Done.

10. Methods overall: The report analyzes vegetative changes in response to the sum of the inflows for the two years prior to the year during which the aerial images were taken. However, no discussion is provided of the rationale for looking at two years of inflow data rather than just the single year preceding the images. It would be helpful to have some discussion of the basis for that decision.

    Models have been rerun using various time steps, including the original two year period, the preceding 12 months of inflows, and the preceding 3 months of inflows.

11. Methods, Ground Data Sampling, page 5: Given the significant changes in vegetative extent and species reflected in the data, it would be helpful to have some discussion of the potential role that the time differential between the date of the aerial photography and the collection of field data might have played in causing some of the apparent discrepancy in identifying vegetative type.

    Done. Discussion provided in the Classification and Accuracy Assessment section.

12. Image Acquisition, 2nd sentence, page 6: It would be helpful to have some explanation of why the 2012 images were not suitable for use in analysis. This particular year was the last year of an extended below average hydrologic period that began locally in 2008.

    Done. Discussion in Image Acquisition section.

13. Classification and Accuracy Assessment, 1st paragraph, 3rd sentence, page: please consider explaining how kappa is and how it is calculated. Also consider showing values and their classification.

    Explanation provided in the Classification and Accuracy Assessment section. Kappa values and classification are listed in Table 4 in the Vegetation Classification section.

14. Classification and Accuracy Assessment, 1st full sentence, page 13: Although we may not be understanding the statistical approach taken, it is unclear why freshwater inflow was not considered as a variable of importance. Alternatively, if not considered as a variable of importance, it seems important, consistent with the Scope of Work, to describe in more detail how inflow relates to the variables of importance.

    Done. Discussion provided in the Use of Ancillary Data sections.

15. Change Analysis, 2nd full paragraph, 2nd + 3rd sentences, page 13: The discussion notes that inflows were averaged over a period of two years for the analysis. It would be helpful to include some discussion of the rationale for focusing on full two-year period rather than some other approach such as focusing on the most recent year preceding the aerial photography. See also, comments below, regarding Figure 11.

    See response to comment 10. Discussion of time step results is provided in Long-Term Vegetation Response to Freshwater Inflows section.

16. Change Analysis Overall, page 17: Suggest adding discussion about the different levels of flow (dry, average, wet) matched with historical imagery.

    Done. Discussion included in Change Analysis section.

17. Results, Long-Term Vegetation Response to Freshwater Inflows, page 25:
    a. Consider including a comparative description of the vegetation community between the dry and wet hydrologic periods represented in the study.

       *Done. Figure **.*

b. The authors report that the biennial average of monthly inflows (from the prior and corresponding year) were used to match the temporal resolution of the marsh data. Interestingly, GLMM results show that all marsh species demonstrated significant interactions with inflows at this two-year time-step. Please consider discussing how a different time-step may impact the results and implications with respect to the relationship between freshwater inflow and marsh species.

   See response to comments 10 and 15.

c. Second paragraph, 3rd sentence: suggest adding a figure showing the correlation between inflows and vegetated areas.

   Done. Figure #.

d. Last paragraph, 2nd to last sentence: It would be helpful to show, and discuss, the analysis and results that support this statement. It is not clear how the authors arrived at this interpretation of the data with respect to inflows.

   Done. Paragraph has been edited.

18. Concluding statements, pages 26-27: The Scope of Work states: "Study results from this project are intended to provide key information to help inform an evaluation of whether adjustments to the environmental flow standards for inflows to Lavaca Bay may be appropriate for supporting healthy marsh habitats." It would be helpful to have some discussion of how the analysis in the report can contribute to an evaluation of how the environmental flow standards may be adjusted.

    Done. Discussion in Recommendations for Future Analyses and Concluding Statements sections.

19. Concluding Statements, 1st sentence, page 26: Based on the data discussed, it would appear to be more accurate to refer to "biennial" assessments rather than decadal ones.

    Done.

Figures and Tables Comments:

1. Figure 2. Consider adding additional layers to show sites that were inaccessible but that were originally considered for study.

   Done. A layer is added to Figure 2.

2. Figure 8. In diagram, suggest changing the line between "VAR1" and "Distance from Water" with an arrow indicating the direction of the relationship between the two.

   There is no actual relationship between VARI and Distance from Water, so the arrows in Figure 8 (now Figure 10) have been revised to clarify this.

3. Figure 11. It would be helpful to identify clearly the inflow data being used. If the data provided here are inflows for the entire Lavaca-Colorado Estuary, the potential differences from inflows specific to the Lavaca Delta should be discussed. If the inflow data are specific to the Lavaca estuary and delta, that should be made clear. Common usage of references to the Lavaca-Colorado Estuary includes inflows coming down the Lavaca River watershed, the Colorado watershed, and the coastal watersheds between the two.

   Freshwater inflow data has been updated to reflect inflows specifically to the study site (Lavaca Bay/Lavaca Delta). All models using freshwater inflow data have been rerun and results are updated.

4. Figure 12. Please consider increasing the size of this figure for easier readability of the legend.

   Done.

5. Figure 16. Consider defining the biennium period on the y-axis of the plot (e.g., 2009-2010) or revising the figure caption to indicate that the biennial period includes the preceding year.

   Done. Revised the caption to improve clarity.

6. Table 6. Results indicate considerable variation in the areal coverage and relative percent coverage for most of the species - sometimes changing by 100 or 200% between biennial periods. It seems it would be valuable to attempt to explain why there is that much variability, if the area for a particular species expanded and contracted, or if it showed up in different areas between years, or to suggest potential approaches for doing so.

   Minor discussion has been included in various sections.