Journal of Coastal Research	SI	67	51–59	Coconut Creek, Florida	Summer 2013

A Computer Model to Forecast Wetland Vegetation Changes Resulting from Restoration and Protection in Coastal Louisiana

Jenneke M. Visser[†], **Scott M. Duke-Sylvester**[‡], **Jacoby Carter**[§], **and Whitney P. Broussard III**[††]

[†]University of Louisiana at Lafayette
School of Geosciences
P.O. Box 44650
Lafayette, LA 70504, U.S.A.
jvisser@louisiana.edu

[‡]University of Louisiana at Lafayette
Department of Biology
P.O. Box 42451
Lafayette, LA 70504, U.S.A.

[§]USGS National Wetlands Research Center
700 Cajundome Boulevard
Lafayette, LA 70506, U.S.A.

[††]University of Louisiana at Lafayette
Institute for Coastal Ecology and Engineering
P.O. Box 43688
Lafayette, LA 70504, U.S.A.

ABSTRACT

Visser, J.M.; Duke-Sylvester, S.M.; Carter, J., and Broussard, W.P., III, 2013. A computer model to forecast wetland vegetation changes resulting from restoration and protection in coastal Louisiana. *In*: Peyronnin, N. and Reed, D. (eds.), *Louisiana's 2012 Coastal Master Plan Technical Analysis*, Journal of Coastal Research, Special Issue No. 67, 51–59. Coconut Creek (Florida), ISSN 0749-0208.

The coastal wetlands of Louisiana are a unique ecosystem that supports a diversity of wildlife as well as a diverse community of commercial interests of both local and national importance. The state of Louisiana has established a 5-year cycle of scientific investigation to provide up-to-date information to guide future legislation and regulation aimed at preserving this critical ecosystem. Here we report on a model that projects changes in plant community distribution and composition in response to environmental conditions. This model is linked to a suite of other models and requires input from those that simulate the hydrology and morphology of coastal Louisiana. Collectively, these models are used to assess how alternative management plans may affect the wetland ecosystem through explicit spatial modeling of the physical and biological processes affected by proposed modifications to the ecosystem. We have also taken the opportunity to advance the state-of-the-art in wetland plant community modeling by using a model that is more species-based in its description of plant communities instead of one based on aggregated community types such as brackish marsh and saline marsh. The resulting model provides an increased level of ecological detail about how wetland communities are expected to respond. In addition, the output from this model provides critical inputs for estimating the effects of management on higher trophic level species though a more complete description of the shifts in habitat.

ADDITIONAL INDEX WORDS: *Plant community modeling*, *wetlands*, *submerged aquatic vegetation*, *species composition*, *wetland community*, *habitat modeling*, *Coastwide Reference Monitoring System (CRMS)*.

INTRODUCTION

Plant communities play a central role in shaping wetland ecosystems. Both the species and plant growth forms define habitat conditions for a diverse collection of arthropods, birds, reptiles, fish, mammals, and a host of other organisms. The plant species that comprise a wetland also shape hydrology and edaphic conditions through processes such as evapotranspiration and frictional resistance to water flow, thus affecting sedimentation and erosion rates. For these reasons, vegetation models are an integral part of ecosystem modeling projects (Davis and Ogden, 1994; DeAngelis, 1998). We developed a vegetation model (LAVegMod) that is an integral part of a suite of models developed for the 2012 Louisiana Coastal Master Plan (LCMP).

The LCMP is the result of actions taken by the Louisiana legislature after the severe hurricanes (Katrina and Rita) in 2005 that combined coastal protection and restoration under one authority. This Coastal Protection and Restoration Authority was charged with coming up with a comprehensive approach to Louisiana's coastal problems, which is adaptively managed and updated every five years. The 2007 LCMP laid the groundwork by identifying the major objectives for the plan as well as identifying all restoration and protection projects that have been proposed. The basis for the LCMP is a

DOI: 10.2112/SI_67_4 received 5 November 2012; accepted in revision 15 February 2013; corrected proofs received 6 May 2013.

systematic evaluation of all these projects using a suite of modeling tools (see Peyronnin *et al*., 2013). LAVegMod is the vegetation model that was developed to work in concert with these other models.

The purpose of LAVegMod is twofold. First, it is designed to provide a landscape-scale assessment of potential changes in the response of Louisiana coastal plant communities to natural and anthropogenic perturbations that may occur in coming decades. Second, it is a tool to assess the potential for management and restoration projects aimed to preserve and enhance wetlands for their ecological values as well as a natural resource for sustainable commercial use.

The linked models used for the LCMP predict change in the conditions of the Louisiana coastal system under two future conditions: a future without action (no additional restoration and risk-reduction projects) and a future with action, which would result from project implementation. The evaluation process was implemented under three different scenarios that reflect environmental uncertainties in specifying the overall ecosystem driving factors into the next 50 years and that could affect coastal planning. These factors included sea-level rise (27 or 45 cm over 50 years), subsidence (spatially variable), hurricane frequency (one category three or higher every 19 or 18 years), hurricane intensity (1.1 or 1.2 times the historic intensities), Mississippi River discharge (annual mean 14,413 or 15,121 m^3 s^{-1}), rainfall, evapotranspiration, Mississippi River nutrient concentration, and marsh collapse threshold (see Peyronnin *et al*., 2013). The moderate scenario used the lower range of the values. The less optimistic scenario used the higher range of the values. The third scenario was the same as the moderate scenario except it used the higher sea-level rise value.

Based on the results from the individual project evaluations, the LCMP was formulated (Groves and Sharon, 2013). Finally, the combined projects were evaluated with the linked models as the future with the LCMP.

MODEL DESCRIPTION

The system that LAVegMod represents is the emergent wetland vegetation and submerged aquatic vegetation (SAV) in the Louisiana coastal zone (Table 1). The emergent wetlands of coastal Louisiana traditionally have been classified into five habitat types (Chabreck, 1972): swamp, fresh marsh, intermediate marsh, brackish marsh, and saline marsh. Each of these marsh habitat types represents multiple vegetation types. We identified 19 common emergent vegetation types (Table 1) based on our familiarity with coastal Louisiana and the literature (O'Neill, 1949; Penfound and Hathaway, 1938; Visser *et al.,* 1998, 1999, 2000, 2002). SAV in coastal Louisiana consists of a variety of native and introduced species (Merino, Carter, and Merino, 2009).

Our model is spatially explicit and simulates changes in plant-community composition over time in response to changes in abiotic environmental conditions. The spatial domain for our model includes all of the coastal wetlands of Louisiana, defined as all wetland vegetation that occurs seaward of the 3 m land elevation contour. Space is divided into a regular grid of 500 $\times$ 500 m cells. Within each cell, the model tracks the fraction of the area occupied by different types of plants or plant groups. Changes in the composition of each cell are computed at a yearly time interval and are the result of plant senescence and establishment that result from dynamic changes in the abiotic environment.

The environmental dynamics that drive plant community change in our model come from the ecohydrology (Meselhe *et al*., 2013) and the morphology model (Couvillion *et al*., 2013) developed as part of the larger State Master Plan Modeling effort (Peyronnin *et al*., 2013). The ecohydrology model provides us with spatially explicit estimates of water depth (daily) and salinity (monthly) over the entire model study area. The morphology model simulates the processes that govern soil erosion and land building along the Louisiana coastline and provides inputs describing the amount of land that is available to support plants as well as areas where land has been lost and emergent plant persistence is no longer possible. The morphology model also provides spatial data for the entire Louisiana coastline, but our model only obtains information from that model at 25-year intervals. Part of the reason for less frequent inputs from the morphology model is that the cumulative changes that occur on a shorter time scale do not have a significant effect on plant dynamics. The reduced frequency is also a result of computation difficulties involved in linking the vegetation model and the morphology model.

Each plant species responds to changes in environmental conditions individualistically (Gleason, 1926), and our goal in designing the LAVegMod was to include as much of this reality as is supported by available data and the existing literature. In previous approaches (Reyes *et al*., 2000; Twilley *et al*., 2008), the habitats (swamp, fresh marsh, intermediate marsh, brackish marsh, and saline marsh) represent either an aggregation of multiple plant species (*e.g*. swamp) or are largely descriptive of a particular environmental condition (*e.g*. saline marsh). One difficulty with this approach is that the classes become little more than a simple categorization of environmental conditions into specific ranges. Another drawback is that the plant species assigned to a habitat type do not all respond at the same rate and might not necessarily remain in association with each other under future environmental conditions. This can be problematic if a particular plant placed in a broad category plays an important role in creating habitat for species in higher trophic levels. For example, mangroves (*Avicennia germinans*) are an important breeding habitat for Brown Pelican (*Pelecanus occidentalis*) and support different estuarine fishes than oyster grass (*Spartina alterniflora*), yet both are classified as salt marsh habitats. Such a broad category will not reflect a change in the distribution of a component species that might be of concern for the sustainability of a species at higher trophic levels.

We have moved toward a more complete representation of coastal plant communities by including 20 categories of plants that are largely characterized by the ecology of a particular species instead of a category based upon environmental conditions (Table 1). Fourteen of our classes are defined in terms of individual species that are dominant (comprising more than 50% of the biomass) species in the coastal wetlands of Louisiana (Table 1). The remaining five (brackish mixture, scrub-shrub, thin mat, and swamp forest and SAV) are

Table 1. *Emergent wetland vegetation types and environmental parameters associated with dominant vegetation used in LAVegMod.*

Habitat Type	Vegetation Type	Abbreviation	Characteristic Species[a]	Salinity[b]	Water-level Variability[c] (m)	2007 Occurence[d] (%)
Saline	Mangrove	MANGR	*Avicennia germinans* (L.) L.	26.1 (18.7–27.1)	0.20 (0.16–0.22)	0.3
Saline	Oyster grass	OYST	*Spartina alterniflora* Loisel.	15.5 (6.1–21.9)	0.20 (0.12–0.26)	16.7
Saline	Salt grass	SALT	*Distichlis spicata* (L.) Greene	11.8 (4.7–15.2)	0.16 (0.10–0.20)	2.2
Saline	Needle rush	NEEDL	*Juncus roemerianus* Scheele	9.6 (3.1–17.8)	0.20 (0.12–0.25)	1.9
Brackish	Brackish mixture	BRACK	Mixture of *Spartina patens* (Ait.) Muhl., *Distichlis spicata* (L.) Greene, *Spartina alterniflora* Loisel.	7.3 (1.1–20.6)	0.17 (0.07–0.25)	7
Brackish	Paspalum	PASP	*Paspalum vaginatum* Sw.	6.1 (2.2–13.4)	0.13 (0.08–0.27)	2.5
Brackish	Wire grass	WIRE	*Spartina patens* (Ait.) Muhl.	5.7 (1.6–11.4)	0.16 (0.07–0.24)	34.5
Intermediate	Scrub-shrub	SCRUB	Mixture of *Iva frutescens* L., *Baccharis halimifolia* L.	3.9 (0.8–11.2)	0.19 (0.11–0.28)	1
Intermediate	Bullwhip	WHIP	*Schoenoplectus californicus* (C.A. Mey.) Palla	3.3 (0.2–7.6)	0.18 (0.09–0.25)	1.6
Intermediate	Roseau cane	ROSEAU	*Phragmites australis* (Cav.) Trin. ex Steud.	1.4 (0.5–5.9)	0.18 (0.13–0.22)	4.4
Intermediate	Bulltongue	BULL	*Sagittaria lancifolia* L.	1.1 (0.2–3.8))	0.19 (0.09–0.29)	8.8
Fresh	Cattail	CAT	*Typha domingensis* Pers	0.9 (0.3–5.5)	0.16 (0.05–0.25)	5.6
Fresh	Saw grass	SAWG	*Cladium mariscus* (L.) Pohl	0.8 (0.3–5.4)	0.22 (0.11–0.27)	1.2
Fresh	Cut grass	CUTGR	*Zizaniopsis miliacea* (Michx.) Doell & Aschers.	0.5 (0.2–2.1)	0.20 (0.13–0.31)	0.6
Fresh	Maiden cane	MAID	*Panicum hemitomon* J.A. Schultes	0.4 (0.2–5.0)	0.22 (0.09–0.29)	7
Fresh	Delta splay	SPLAY	Mixture of *Sagittaria latifolia* Willd. *Schoenoplectus deltarum* (Schuyler) Sojak, *Colocasia esculenta* (L.) Schott	0.4 (0.2–1.6)	0.20 (0.13–0.28)	0.8
Fresh	Thinmat	THIN	Mixture of *Eleocharis baldwinii* (Torr.) Chapm., *Hydrocotyle ranunculoides* L. f. *Bidens laevis* (L.) B.S.P.	0.3 (0.2–4.6)	0.22 (0.11–0.31)	2.4
Fresh	Wax myrtle	WAXM	*Morella cerifera* (L.) Small	0.3 (0.2–1.7)	0.22 (0.08–0.29)	1.6
Water	Submerged aquatic vegetation	SAV	Primarily *Ruppia maritima* L., or *Myriophyllum spicatum* L.	NA	NA	NA
Swamp	Swamp forest	SWAMP	*Taxodium distichum* (L.) L.C. Rich. and *Nyssa aquatica* L.	0.5 (0.3–4.7)	0.19 (0.09–0.3)	NA

[a] Dominant species unless no clear dominant can be identified.
[b] Median of annual salinity (2007–2009) observed at Coastwide Reference Monitoring Stations. Range from the 5th to the 95th percentile is provided in parentheses.
[c] Median of annual water level standard deviations (2007–2009) observed at Coastwide Reference Monitoring Stations. Range from the 5th to the 95th percentile is provided in parentheses.
[d] Percentage of Louisiana coastal zone marsh stations that were classified as the vegetation type based on vegetation cover data collected by Sasser *et al*. (2008).

aggregates that represent important community types within Louisiana wetlands. These types represent a compromise similar to the one that lead to defining the traditional five classes. Nonetheless, they are still an advance over the traditional approach, as they refine the five traditional classes and represent ecologically important communities that are stable and persistent elements of Louisiana's wetlands.

LAVegMod is a niche-based modeling approach for plant species that characterizes species by the range and combination of environmental conditions that allow them to become established and to continue to persist (Figure 1). A list of the model parameters is provided in Table 2. Within the model, two distinct approaches are taken to represent species niches and plant species dynamics. For 19 of the 20 vegetation type's species, we use a two-dimensional niche defined in terms of the range of tolerable salinity and water-level variability (WLV) conditions. Dynamics emerge within a cell as environmental conditions in the cell move out of the niche of one species, indicating a loss in cover within the cell, and into the niche of another species, resulting in the establishment and/or expansion of the other species. For SAV, we developed a linear regression model that relates the area covered by SAV to water temperature, water depth, and salinity. For this model, dynamics emerging as year-to-year changes in the environmental conditions result in changes in the area covered by SAV predicted by the linear model. The different approach used to model SAV and the other habitat types reflects the availability of a smaller data set for SAV in which SAV-cover and environmental parameters were repeatedly measured at an established system of study sites.

The results from the two approaches are merged using data from the morphology model (Couvillion *et al*., 2013). The morphology model produces spatial data at the same 500×500 m resolution used by our model and gives the fraction of each cell that is occupied by land (E_{land}) and open water ($E_{\mathrm{open\ water}}$), where $E_{\mathrm{land}} + E_{\mathrm{open\ water}} = 1$. The SAV model computes the fraction of open-water area that is covered by SAV (C'_{SAV}). The total fraction of the 500×500 m cell occupied by SAV is $C_{\mathrm{SAV}} = C'_{\mathrm{SAV}} \times E_{\mathrm{open\ water}}$. If $C_{\mathrm{SAV}} < E_{\mathrm{open\ water}}$, LAVegMod records the balance of open water without SAV in $C_{\mathrm{open\ water}} = E_{\mathrm{open\ water}} - C_{\mathrm{SAV}}$. The cover of the 19 emergent vegetation types are constrained so that their sum is always less than or equal to E_{land}, with bare land filling the land not occupied by emergent vegetation. We assume that the emergent types can only be

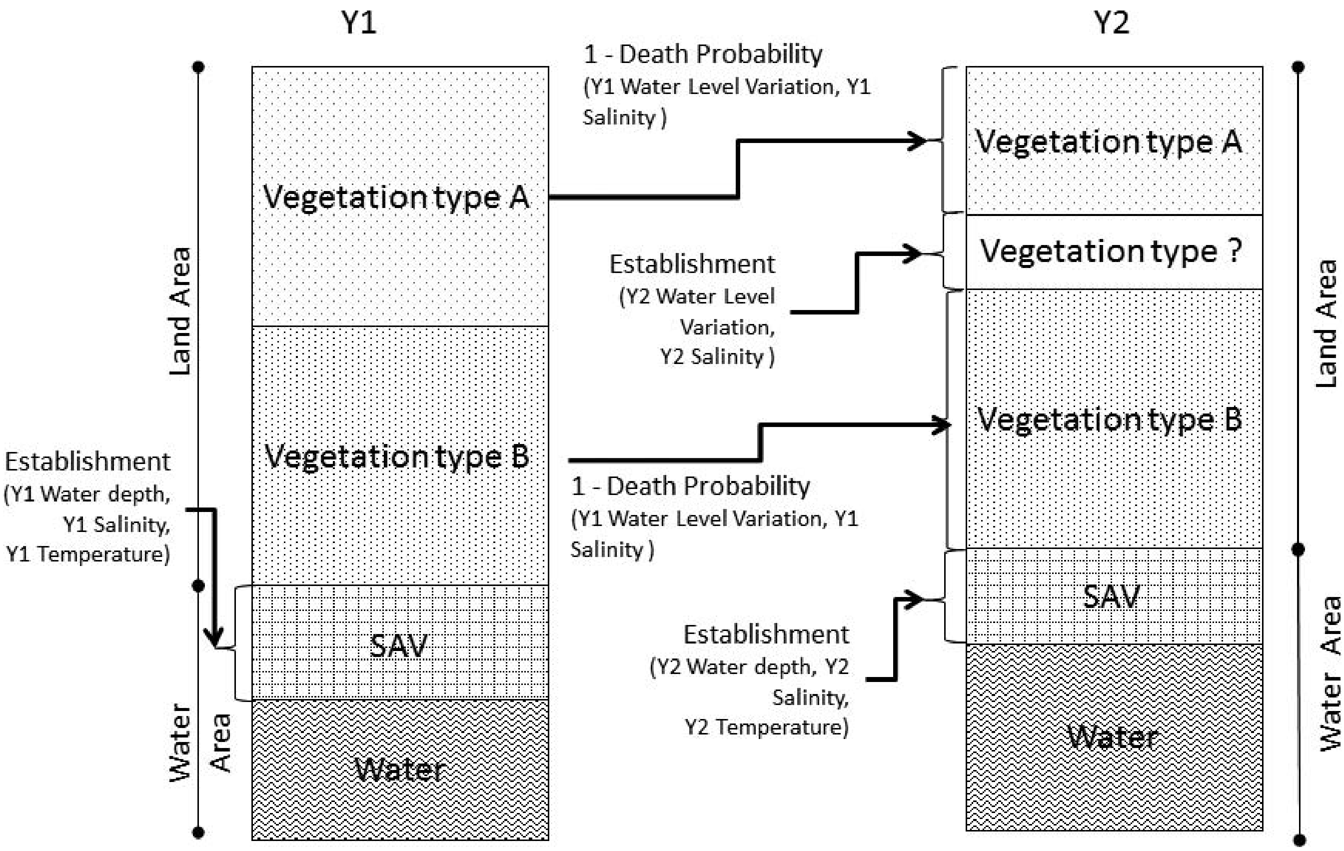

Figure 1. A summary of one time step in one cell of the vegetation model. Y1 is the first year representing either the initial condition or the result from a previous time step. Establishment of SAV in any year is based on average annual water depth of the cell, area of water in the cell, and salinity and temperature in the water of the cell. To forecast emergent vegetation in the next year, the model determines the percentage of a vegetation class present in the cell that dies based on the water-level variability and average salinity in the previous year. Space that becomes available because of the death of the previous year's vegetation can be occupied by a new vegetation class. Establishment of this new vegetation class is determined by the hydrologic conditions.

Table 2. *Listing of model parameters for the emergent vegetation submodel and the SAV submodel.*

Parameter	Description
t	Time
i, j	Emergent vegetation type indices
Environmental inputs	
E_{land}	Fraction of a model cell that is classified as land (above water)
$E_{\text{open water}}$	Fraction of a model cell that is classified as open water
W_t	Average annual water level variation (WLV) at time step t
S_t	Average annual salinity at time step t
T	Mean summer water temperature
S	Mean summer salinity
D	Mean summer water depth
Emergent vegetation response parameters	
$d_i(W_t, S_t)$	Probability of cover lost by vegetation type i under conditions W_t and S_t
$P_i(W_t, S_t)$	Probability that vegetation type i will expand into unoccupied area under conditions W_t and S_t
$C_{i,t}$	Fraction of a model cell covered by vegetation type i at time step t
ΔC_i	Change in cover of vegetation type i from time step t to $t + 1$
C_{SAV}	Fraction of a cell covered by SAV
C'_{SAV}	Fraction of open water ($E_{\text{open water}}$) occupied by SAV

present in the area designated as land by the morphology model. Land in the morphology model included coastal wetlands as well as uplands. Because our model is focused on wetland vegetation, we excluded any areas that were classified as an upland habitat in the baseline condition and assigned them the generic class of NOTMOD, and the area of NOTMOD remained unchanged over the course of the simulation. This treatment assumes that there is no conversion from upland to wetland or vice versa during the 50-year run. All new land created in the morphology model (through marsh creation projects, barrier island projects, and delta formation from river diversions) was assumed to be wetland area available for emergent vegetation establishment.

Emergent Vegetation Submodel

The niche model for the 19 emergent vegetation types has three primary parts: a matrix defining the range of environmental conditions allowing each vegetation type to become established; a second set of 19 matrices defining senescence rates for each vegetation type; and a finite-difference equation that computes the change in the cover of each vegetation type based on the rates of establishment and senescence (Pacala and Tillman, 1994). The matrices used are available in Visser *et al.* (2012). The equation for change in vegetation-type cover within each 500×500 m cell is

$$\Delta C_i = -d_i(W_t, S_t)C_{i,t} + \left[\left(1 - \sum_j C_{j,t}\right) + \sum_j dC_{j,t}\right]P_i(W_t, S_t),$$

where vegetation type is indexed by i and j, and time is t. We have omitted the spatial index in this equation to simplify the notation, and, unless otherwise noted, all terms apply to cells on an individual basis. This equation is used to compute the change in cover from the current time period, t, to the cover in the following year, $t+1$, where $C_{i,t}$ is the cover in the current time period, and ΔC_i is the change in cover over the time interval. The environmental conditions are given by W_t, the annual WLV, and S_t is the mean annual salinity. Both W_t and S_t are computed over the interval from t to $t+1$. The probability of cover lost by vegetation-type i under environmental conditions W_t and S_t is $d_i(W_t, S_t)$, and the decrease in the cover is given by $-d_i(W_t, S_t)C_t$. The probability that vegetation-type i can become established in any unoccupied area is $P_i(W_t, S_t)$. This probability is multiplied by the area that was unoccupied at time t and the area that becomes available over the interval (t, $t + 1$) because of mortality. The computed changes in vegetation type cover (ΔC_i) are then added to the current cover values ($C_{i,t}$) to obtain the change in cover over the time interval from t to $t+1$.

Model Parameterization

The niche for each of the 19 emergent vegetation types is defined by a pair of matrices. One matrix defines the range of conditions under which a vegetation type can become established, while the other defines the rate of mortality under different environmental conditions. At each time step, the model consults the matrices to find the probability of establishment and mortality for each vegetation type under the current environmental conditions. The matrices define these probabilities for specific pairs of conditions, and probabilities are linearly interpolated as needed.

These matrices are based on data from the Coastal Wetland Planning Protection and Restoration Act Coast-wide Reference Monitoring system (CRMS) (http://www.lacoast.gov/crms2). This monitoring system consists of 390 stations randomly distributed throughout the Louisiana coastal zone wetlands. Each CRMS station has a data sonde that records water level and salinity at hourly intervals. In addition, herbaceous vegetation cover is estimated in 10 2×2 m plots that are sampled in the late summer (July–October) of each year. At swamp forest stations, nine herbaceous plots are sampled, and basal area is estimated for three plots. Extensive details on the data collection at each CRMS station are provided in Folse *et al.* (2008). We computed the annual mean salinity and standard deviation of water level relative to average marsh elevation for the years 2007, 2008, and 2009 at each available CRMS location using hourly data records. The standard deviation of water level relative to the marsh surface is a proxy for the volume of water exchanged between the interior marsh and adjacent water bodies, and we call this parameter WLV. Each CRMS location and year was assigned to one of the 19 emergent vegetation types based on its vegetation cover. A few records that did not fit any of our vegetation types were discarded. We then calculated the median, 5th, 25th, 75th, and 95th percentile of mean annual salinity and WLV for each vegetation type. For establishment assignment, a matrix of possible salinity (0 to 30 ppt) and WLV (0–2) was populated with the different vegetation types. The median of the known distribution of the vegetation types was assigned to establishment of that vegetation type. Empty cells (those not representing the median of a species distribution) were proportionally assigned by the relative frequency at which the vegetation type occurred in 2007 around the position of median of its distribution (*e.g.* maidencane occupied approximately 36% of the fresh areas of the coast and was assigned approximately 36% of the matrix below 2 ppt). A separate mortality matrix was created for each vegetation type using the same ranges of salinity and WLV. Mortality of a given vegetation type was assumed to be zero if hydrologic conditions were between the 25th and 75th percentile of the observed niche of the species and increased to 50% from the 25th to the 5th or from the 75th to the 95th percentile, grading to 100% based on the slope of the values.

LAVegMod starts from an initial vegetation distribution map. This map was created by the U.S. Geological Survey—National Wetlands Research Center (Coastal Restoration Assessment Branch) (Couvillion *et al.*, *unpublished data*) as follows. A 2010 baseline land-cover dataset for the study area was created with a training data set based on our assignment of the 2007 coast-wide vegetation survey stations (Sasser *et al.,* 2008) to the 18 herbaceous vegetation types (excluding swamp forest, which is not surveyed during the coastwide survey) and GAP analysis maps (http://gapanalysis.usgs.gov/), which include upland and forests. Survey points were categorized as one of the 18 herbaceous vegetation types (Table 1) following methods similar to those described by Visser *et al.* (2002). Forested wetlands were classified into seven categories (following the GAP analysis maps). One of the forested wetland categories is the swamp forest vegetation type used in our model; the other six are bottomland hardwoods. Other land cover, such as water, agricultural land, and human settlement are based on the GAP analysis maps. A change-vector analysis was employed to eliminate any training data points, which appeared to have changed from 2007 to 2010 using remotely sensed imagery from 2007 and 2010. The 2010 imagery was then utilized to conduct a vegetation classification. Nationally recognized classification methodologies, such as those utilized in the U.S. Environmental Protection Agency's National Land Cover Data (NLCD) and the National Oceanic and Atmospheric Administration Coastal Change Analysis Program (C-CAP), were altered slightly to provide increased value yet retain consistency with these programs. All land that did not fall within the 19 wetland vegetation types was combined in the not modeled category (NOTMOD).

SAV Submodel

The goal of the SAV submodel is to predict the annual localized presence of SAV in response to environmental forcing variables. To develop this submodel, we used unpublished data collected from November 1999 through October 2002 from Sabine National Wildlife Refuge. Over the 3-year study, 498 sites were sampled, 234 sites with SAV and 264 without SAV, with salinity ranging from 0 to 39 ppt. Data collected included notation of SAV presence/absence, name of various SAV species (if present), date, time, latitude and longitude, temperature, salinity, conductivity, dissolved oxygen (concentration and percent saturation), water depth, pH, turbidity, and substrate type. Data were analyzed using logistic multiple linear regression (SAS V9.2).

The presence of SAV was seasonal, and seasonal peaks varied somewhat from year to year, similar to results of Merino, Nyman, and Michot (2005). In general, however, there was a large peak in occurrence in spring through summer, followed by a drop in the fall and then by a smaller peak in December. Because LAVegMod predicts the presence of SAV on an annual basis, we focused the analysis on the period with the highest likelihood of SAV occurrence during the summer months. In order to model the annual presence of all SAV in any given location in response to environmental conditions, we used environmental data from no SAV plots during the peak SAV months (April to August) to estimate the annual probability of finding SAV. The SAV equation is based on a logistic regression and is

$$C'_{\mathrm{SAV}} = 1.83 - 3.731 \times 10^{-2} \times T - 7.766 \times 10^{-2} \times S - 2.588 \times 10^{-4} \times D,$$

where C'_{SAV} is the fraction of the area in open water ($E_{\text{open water}}$) covered by SAV, T is the mean summer water temperature, S is the mean summer salinity, and D is the mean summer water depth.

MODEL OUTPUT

Vegetation change was forecasted for 50 years under three different future scenarios (Figure 2). The results indicate that the estuarine gradient is maintained both with and without implementation of the LCMP. As expected, the less optimistic future scenario results in a higher proportion of Louisiana's coastal wetlands in more saline vegetation types compared to the moderate scenario. Our model shows that, without the LCMP, fresh and intermediate habitats remain relatively stable, and they expand with all the diversions that are included in the LCMP (Figure 2). Expansion of saline habitats occurs without implementation of the LCMP, while saline habitats remain relatively stable with the LCMP. As a result, brackish habitats decrease under all circumstances. With the LCMP, the coastal zone becomes fresher with more SAV (Figure 3). This expansion of fresher vegetation is mostly at the expense of brackish vegetation types, although saline marsh area is smaller with the LCMP than without it. It is noteworthy that the effect of the LCMP is fairly similar among the different future scenarios (Figure 3).

Although the model predicts maintenance of the estuarine gradient at a coast-wide scale, it does not mean that specific projects do not have a significant effect on vegetation composition at a more local scale (Figure 4). A 4250 cms, sediment diversion from the Atchafalaya River (modeled as 60% of southward Atchafalaya flow exceeding 1416 cms in the ecohydrology model) into western Terrebonne Parish converts most of the area, which is currently a complex of fresh and intermediate vegetation types to the fresh maidencane vegetation type. In contrast, without this diversion the forecast is that this area converts to brackish marsh in approximately 10 years and that invasion of saline marsh types starts in 2050. Because the results in Figure 4 reflect data from an area that is one box in the ecohydrology model, it illustrates that LaVegMod allows multiple vegetation types to coexist under the same hydrologic regime. This is because there is a persistence of vegetation among years.

DISCUSSION

The greatest model uncertainty stems from using the growing conditions under which the vegetation types are currently found to generate the death and establishment matrices. As more data becomes available (more years in the CRMS database), the conditions under which vegetation composition changes in sites and the conditions under which vegetation composition remains stable can inform future versions of the model. Currently, establishment is open to all vegetation types and not restricted to plant species that are within the vicinity of the cell. More research is needed on how dispersal affects species establishment. Species composition changes at the CRMS sites provide information that was previously unavailable. Other factors, such as the assumed inability of a fresh floating marsh to be replaced by more salt-tolerant species that only occur in attached marshes, can only be incorporated by closely integrating wetland morphology and vegetation models. Currently, neither model accounts for floating marshes.

Although there are many factors that affect vegetation change in coastal wetlands, only a few are generally affected by coastal restoration projects and are therefore the focus of LaVegMod. The two factors that are included in this model are water salinity and water-level fluctuation. Grazing is a factor that is affected by management but not included in the current model because of the time constraints in the development

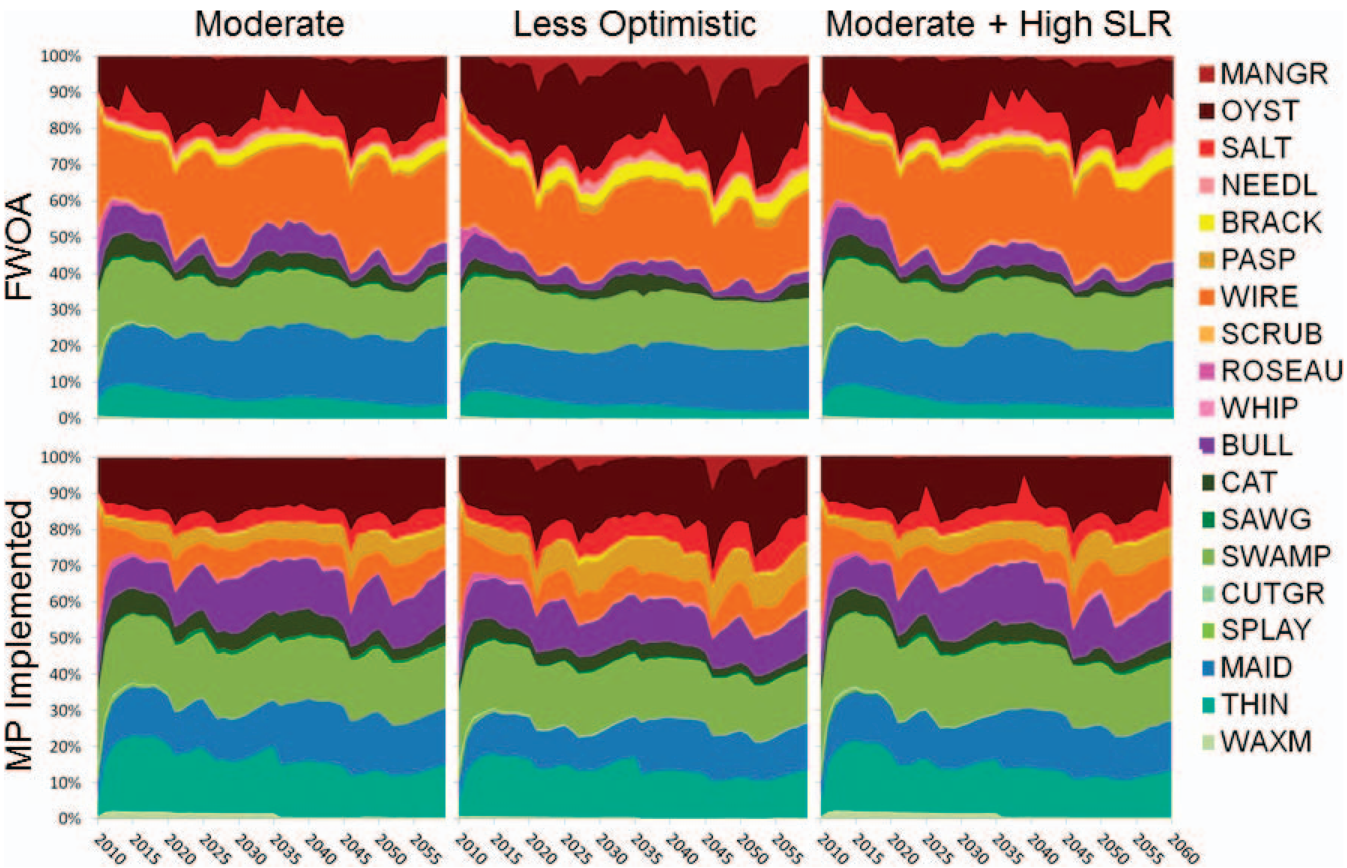

Figure 2. Output from LaVegMod comparing emergent vegetation change in the future without action (FWOA) and with implementation of the LCMP under three different future scenarios coast-wide. Abbreviations for the vegetation types are provided in Table 1.

phase. For example, the Coastwide Nutria Control Program has significantly reduced eat-out areas along the coast (Jordan and Mouton, 2011). Nutrient input and eutrophication are known to affect species composition in wetlands (Childers *et al.,* 2003; McJannet, Keddy, and Pick, 1995); however, we have no available data that can be used to develop a relationship of vegetation change with respect to nutrients in coastal Louisiana. The recent apparent increase cattail marsh might be an early indicator of increased nutrient loading but also could be related to the higher salinity tolerance of *Typha domingensis* relative to the fresh marsh species it is replacing. Fire could affect species composition but is not currently used for marsh restoration, and no database of fire frequency is available for coastal Louisiana.

One of the most interesting results from our model is the "squeeze" of the salinity gradient with the loss of brackish marsh associated with sea-level rise (27 to 45 cm over 50 years). With similar sea-level rates, Craft *et al.* (2009) predicted movement of the salinity gradient landward along the Atlantic coast of the United States. This resulted in an increase in brackish (5–20 ppt) marsh at a low rate of sea-level rise (52 cm over 100 years) and an across-the-board loss of wetlands at the highest rate of sea-level rise (82 cm over 100 years). Louisiana's

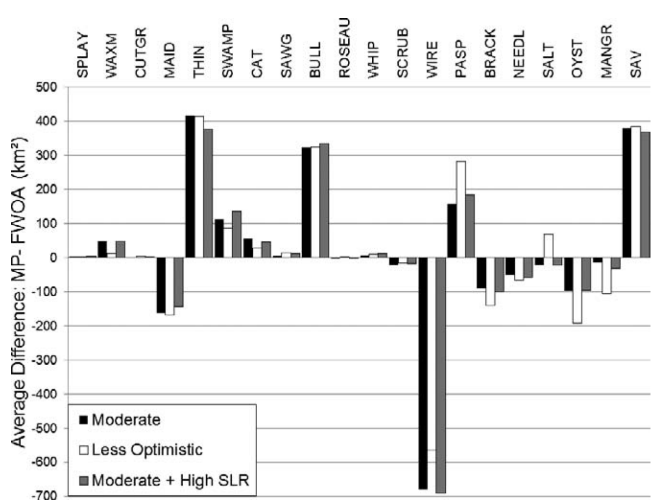

Figure 3. Average difference in vegetation cover is shown between the future without action (FWOA) and with implementation of the LCMP over 50 years. Abbreviations for the vegetation types are provided in Table 1.

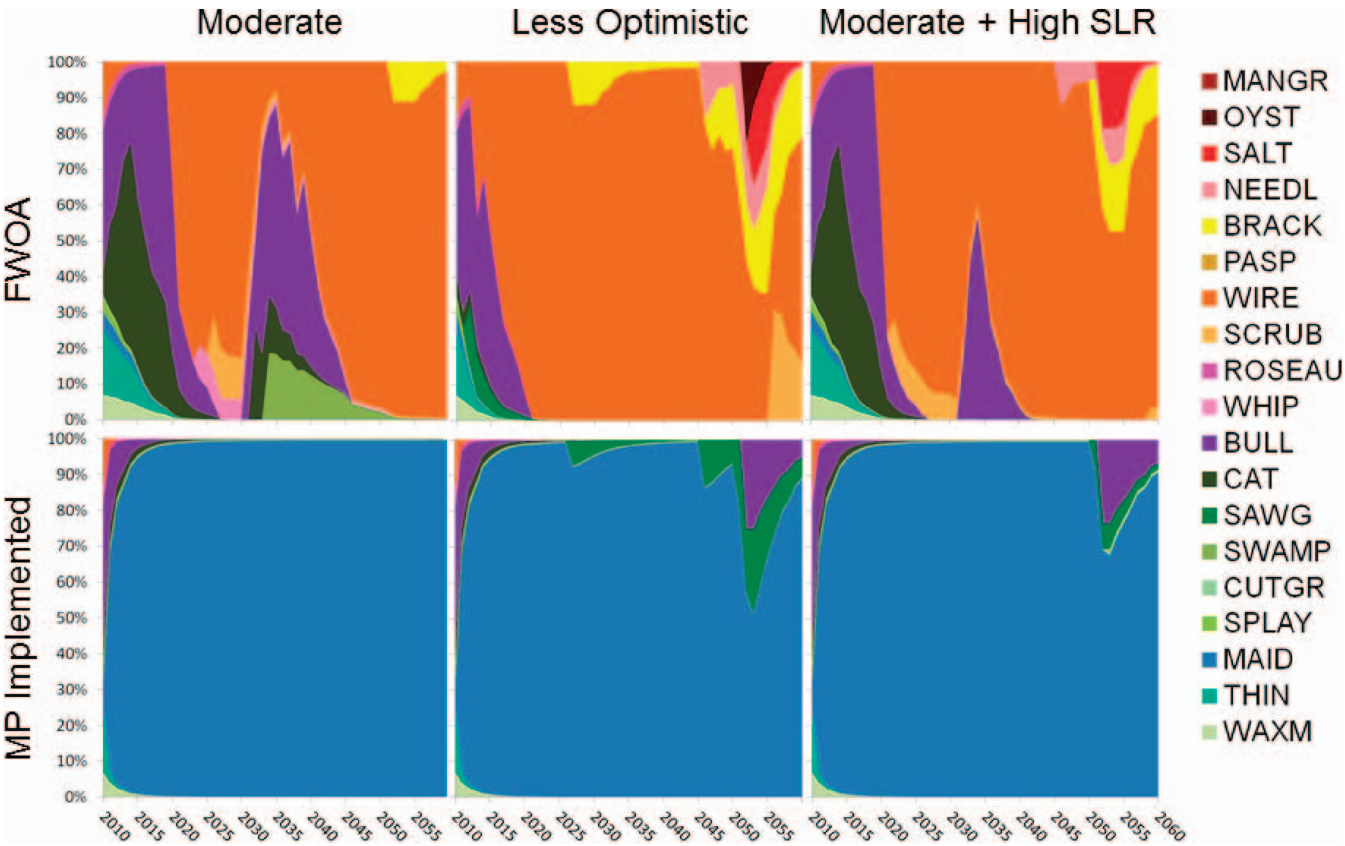

Figure 4. Output from LaVegMod comparing emergent vegetation change in the future without action (FWOA) and with implementation of the LCMP under three different future scenarios in one area in Terrebonne Parish. Abbreviations for the vegetation types are provided in Table 1.

brackish marsh vegetation types span the same salinity range (Table 1); however, Craft *et al*. (2009) report that the brackish marshes in their systems are dominated by *Juncus roemerianus*, while Louisiana brackish systems are dominated by *Spartina patens*. In Louisiana, *J. roemerianus*- and *Distichlis spicata*-dominated marshes have been traditionally classified as saline marshes, but results from our analysis of the CRMS data show that these species occur in the brackish range.

Linscombe and Hartley (2011) showed that, along the Louisiana coast, brackish marsh has been lost between 1978 and 2001, while saline marsh remained stable and fresh and intermediate marshes expanded. One of the largest areas of brackish marsh to intermediate marsh conversion occurred in the Breton Sound basin (Linscombe and Hartley, 2011), an area affected by the Caernarvon Freshwater Diversion. These historical changes in Louisiana's coastal vegetation fit very well with the results from our model.

ACKNOWLEDGMENTS

Funding for this work was provided by the Coastal Protection and Restoration Authority (CPRA) of Louisiana as part of the 2012 LCMP effort. During the development of this model, Dr. Rebecca Howard (USGS), Dr. Ken Krauss (USGS), Dr. Gregg Snedden (USGS), Dr. Greg Steyer (USGS), Dr. Mark Hester (UL Lafayette), and Dr. Charles Sasser (LSU) provided internal review, which greatly improved the model. Brady Couvillion (USGS) created the base map used as the starting point for this model. Dr. Hongqing Wang (USGS) assisted with data transfer and analysis of the CRMS data. Ms. Alison Heppermann assisted with figure preparation. This manuscript was improved by the constructive criticism of two anonymous reviewers.

LITERATURE CITED

Chabreck, R.H., 1972. Vegetation, water, and soil characteristics of the Louisiana coastal region. *Louisiana State University Agricultural Experiment Station Bulletin*, 664, 1–72.

Childers, D.L.; Doren, R.F.; Jones, R.; Noe, G.B.; Rugge, M., and Scinto, L.J., 2003. Decadal change in vegetation and soil phosphorus pattern across the Everglades landscape. *Journal of Environmental Quality*, 32(1), 344–362.

Couvillion, B.R.; Steyer, G.D.; Wang, H.; Beck, H.J., and Rybczyk, J.M., 2013. Forecasting the effects of coastal protection and restoration projects on wetland morphology in coastal Louisiana under multiple environmental uncertainty scenarios. *In:* Peyronnin, N. and Reed, D.J. (eds.), *Louisiana's 2012 Coastal Master Plan Technical Analysis*, Journal of Coastal Research, Special Issue, No. 67, pp. 29–50.

Craft, C.; Clough, J.; Ehman, J.; Joye, S.; Park, R.; Pennings, S.; Guo, H., and Machmuller, M., 2009. Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services. *Frontiers in Ecology and Environment*, 7(2), 73–78.

Davis, S.M. and Ogden, J.C., 1994. *Everglades: The Ecosystem and Its Restoration*. Boca Raton, Florida: St. Lucie Press, 826p.

DeAngelis, D.L.; Gross, L.J.; Huston, M.A.; Wolff, W.F.; Fleming, D.M.; Comiskey, E.J., and Sylvester, S.M., 1998. Landscape modeling for Everglades ecosystem restoration. *Ecosystems*, 1(1), 64–75.

Folse, T.M.; West, J.L.; Hymel, M.K.; Troutman, J.P.; Sharp, L.A.; Weifenbach, D.; McGinnis, T.; Rodrigue, L.B.; Boshart, W.M.; Richardi, D.C.; Miller, C.M., and Wood, W.B., 2008. *A Standard Operating Procedures Manual for the Coast-wide Reference Monitoring System-Wetlands: Methods for Site Establishment, Data Collection, and Quality Assurance/Quality Control*. Baton Rouge, Louisiana: Louisiana Coastal Protection and Restoration Authority, Office of Coastal Protection and Restoration, 207p.

Gleason, H.A., 1926. The individualistic concept of the plant association. *Bulletin of the Torrey Botanical Club*, 53(1), 7–26.

Groves, D.G. and Sharon, C., 2013. Planning tool to support planning the future of coastal Louisiana. *In:* Peyronnin, N. and Reed, D.J. (eds.), *Louisiana's 2012 Coastal Master Plan Technical Analysis*, Journal of Coastal Research, Special Issue, No. 67, pp. 147–161.

Jordan, J. and Mouton, E., 2011. *Nutria Harvest and Distribution 2010–2011 and A Survey of Nutria Herbivory Damage in Coastal Louisiana in 2011*. Louisiana Department of Wildlife and Fisheries, 47p. http://nutria.com/uploads/1011CNCPfinalreport.pdf.

Linscombe, R.G. and Hartley, S.B., 2011. Analysis of change in marsh types of coastal Louisiana, 1978–2001: U.S. Geological Survey Open-File Report 2010-1282, 52 p. http://pubs.usgs.gov/of/2010/1282/.

McJannet, C.L.; Keddy, P.A., and Pick, F.R., 1995. Nitrogen and phosphorus tissue concentrations in 41 wetland plants: a comparison across habitats and functional groups. *Functional Ecology,* 9(2), 231–238.

Merino, J.H.; Carter, J., and Merino, S.L., 2009. Mesohaline submerged aquatic vegetation survey along the U.S. Gulf of Mexico coast, 2001 and 2002: a salinity gradient approach. *Gulf of Mexico Science*, 27(1), 9–20.

Merino, J.H.; Nyman, J.A., and Michot, T., 2005. Effects of season and marsh management on submerged aquatic vegetation in coastal Louisiana brackish marsh ponds. *Ecological Restoration*, 23(4), 235–243.

Meselhe, E.; McCorquodale, J.A.; Shelden, J.; Dortch, M.; Brown, T.S.; Elkan, P.; Rodrigue, M.; Schindler, J., and Wang, Z., 2013. Ecohydrology component of Louisiana's 2012 Coastal Master Plan: mass-balance compartment model. *In:* Peyronnin, N. and Reed, D.J. (eds.), *Louisiana's 2012 Coastal Master Plan Technical Analysis*, Journal of Coastal Research, Special Issue, No. 67, pp. 16–28.

O'Neill, T., 1949. *The Muskrat in the Louisiana Coastal Marshes*. New Orleans, Louisiana: Louisiana Wildlife and Fisheries Commission, 159p.

Pacala, S. and Tilman, D., 1994. Limiting similarity in mechanistic and spatial models of plant competition in heterogeneous environments. *American Naturalist,* 143(2), 222–257.

Penfound, W.Y. and Hathaway, E.S., 1938. Plant communities in the marshland of southeastern Louisiana. *Ecological Monographs*, 8(1), 1–56.

Peyronnin, N.; Green, M.; Richards, C.P.; Owens, A.; Reed, D.J.; Chamberlain, J.; Groves, D.G.; Rhinehart, K., and Belhadjali, K., 2013. Louisiana's 2012 Coastal Master Plan: overview of a science-based and publicly-informed decision making process. *In:* Peyronnin, N. and Reed, D.J. (eds.), *Louisiana's 2012 Coastal Master Plan Technical Analysis*, Journal of Coastal Research, Special Issue, No. 67, pp. 1–15.

Reyes, E.; White, M.L.; Martin, J.F.; Kemp, G.P.; Day, J.W., and Aravamuthan, V., 2000. Landscape Modeling of coastal habitat change in the Mississippi Delta. *Ecology*, 81(8), 2331–2349.

Sasser, C.E.; Visser, J.M.; Mouton, E., and Linscombe, J., 2008. *Vegetation Types in Coastal Louisiana in 2007*. USGS Open-File Report 2008-1224. http://pubs.usgs.gov/of/2008/1224/.

Twilley, R.R.; Couvillion, B.R.; Hossain, I.; Kaiser, C.; Owens, A.B.; Steyer, G.D., and Visser, J. M., 2008. Evaluating restoration planning in the Mississippi River Deltaic Plain. *American Fisheries Society Symposium*, 64, 29–46.

Visser, J.M.; Sasser, C.E.; Chabreck, R.H., and Linscombe, R.G., 1998. Marsh vegetation types of the Mississippi River Deltaic Plain, USA. *Estuaries*, 21(4B), 818–828.

Visser, J.M.; Sasser, C.E.; Chabreck, R.H., and Linscombe, R.G., 1999. Long-term vegetation change in Louisiana tidal marshes, 1968–92. *Wetlands*, 19(1), 168–175.

Visser, J.M.; Sasser, C.E.; Chabreck, R.H., and Linscombe, R.G., 2000. Marsh vegetation types of the Chenier Plain, USA. *Estuaries*, 23(3), 318–327.

Visser, J.M.; Sasser, C.E.; Chabreck, R.H., and Linscombe, R.G., 2002. The impact of a severe drought on the vegetation of a subtropical estuary. *Estuaries*, 25(6A), 1184–1195.

Visser, J.M.; Duke-Sylvester, D.M.; Broussard, W.P., and Carter, J., 2012. Appendix D-4 Vegetation model technical report. *In:* Coastal Protection and Restoration Authority, *Louisiana's Comprehensive Master Plan for a Sustainable Coast*. http://www.coastalmasterplan.louisiana.gov