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Marsh Collapse Thresholds for Coastal Louisiana Estimated Using Elevation and Vegetation Index Data

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ABSTRACT

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Forecasting marsh collapse in coastal Louisiana as a result of changes in sea-level rise, subsidence, and accretion deficits necessitates an understanding of thresholds beyond which inundation stress impedes marsh survival. The variability in thresholds at which different marsh types cease to occur (*i.e.*, marsh collapse) is not well understood. We utilized remotely sensed imagery, field data, and elevation data to help gain insight into the relationships between vegetation health and inundation. A Normalized Difference Vegetation Index (NDVI) dataset was calculated using remotely sensed data at peak biomass (August) and used as a proxy for vegetation health and productivity. Statistics were calculated for NDVI values by marsh type for intermediate, brackish, and saline marsh in coastal Louisiana. Marsh-type specific NDVI values of 1.5 and 2 standard deviations below the mean were used as upper and lower limits to identify conditions indicative of collapse. As marshes seldom occur beyond these values, they are believed to represent a range within which marsh collapse is likely to occur. Inundation depth was selected as the primary candidate for evaluation of marsh collapse thresholds. Elevation relative to mean water level (MWL) was calculated by subtracting MWL from an elevation dataset compiled from multiple data types including light detection and ranging (lidar) and bathymetry. A polynomial cubic regression was used to examine a random subset of pixels to determine the relationship between elevation (relative to MWL) and NDVI. The marsh collapse uncertainty range values were found by locating the intercept of the regression line with the 1.5 and 2 standard deviations below the mean NDVI value for each marsh type. Results indicate marsh collapse uncertainty ranges of 30.7–35.8 cm below MWL for intermediate marsh, 20–25.6 cm below MWL for brackish marsh, and 16.9–23.5 cm below MWL for saline marsh. These values are thought to represent the ranges of inundation depths within which marsh collapse is probable.

ADDITIONAL INDEX WORDS: *Marsh collapse, inundation depth, Louisiana, wetland change.*

INTRODUCTION

Coastal Louisiana wetlands make up the seventh largest delta on Earth, contain about 37% of the estuarine herbaceous marshes in the conterminous United States, and support the largest commercial fishery in the lower 48 states (Coleman, Huh, and Braud, 2008; NOAA, 2006a, 2010). Louisiana currently experiences more wetland loss than all other states in the contiguous United States combined, with an average rate of wetland loss of 42.9 km^2 per year (Couvillion *et al.*, 2011). This wetland loss can be attributed to a suite of natural and anthropogenic factors, but many researchers consider high rates of relative sea-level rise (RSLR), which accounts for eustatic sea-level rise and subsidence, and an insufficient sediment supply to be two of the most important factors (Bjerstedt, 2011; Boesch *et al.*, 1994; Kuhn and Mendelssohn, 1999). These two factors combined can change the position of a marsh in the tidal frame, which may result in increased depth, duration, and frequency of flooding.

Recent investigations have found that coastal Louisiana experiences higher rates of RSLR than anywhere else on the North American continent (NOAA, 2006b; Penland and Ramsey, 1990). RSLR rates at the locations of long-term gages at Grand Isle and Eugene Island (Figure 1) have been calculated to be 9.24 mm/yr (1947–2006) and 9.65 mm/yr (1932–1974), respectively (NOS, 2009). These rates far exceed the average RSLR trend from all long-term gages along the Gulf of Mexico coastal zone (3.67 mm/yr) and the continental average (1.54 mm/yr) (NOS, 2009).

To compensate for RSLR, marshes must maintain elevation through accretion of mineral sediment and organic matter. Anthropogenic controls (*e.g.*, dams, levees, channels, and impoundments) have altered hydrology and sediment distribution, contributing to insufficient accretion rates to offset RSLR (Bryant and Chabreck, 1998; Hatton, DeLaune, and Patrick, 1983; Reed, 1995). These alterations of the landscape

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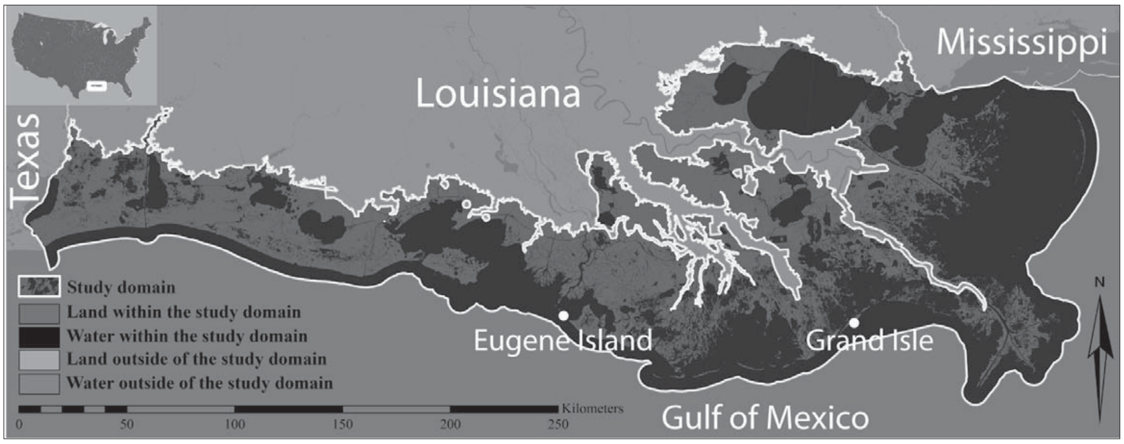

Figure 1. Map of the study area in coastal Louisiana.

often result in increased depth, duration, and/or frequency of flooding experienced in wetland areas, leading to extended submergence of vegetation and decreases in plant productivity.

Louisiana's coastal wetlands represent a salinity gradient that generally transitions from freshwater runoff-dominated inland areas to saline areas near the coast. Coastal wetlands consequently support a variety of vegetation types suited to each of these salinity zones, including forested wetlands, fresh marsh, intermediate marsh, brackish marsh, and saline marsh (Chabreck and Linscombe, 2001; Sasser *et al.*, 2008; Visser *et al.*, 1998, 2000). These communities generally exist at different elevations relative to mean water level (MWL), and exhibit varying tolerances to the increasing depth, duration, and frequency of flooding. An understanding of the differences in flooding tolerance among these various vegetation types is vital to ensure the accuracy and utility of landscape modeling projections under various RSLR scenarios. Plant species common in coastal Louisiana marshes such as *Spartina alterniflora* and *Spartina patens* are adapted to flooding but can still be stressed by excessive inundation (Chalmers, 1982; Delaune, Baumann, and Gosselink, 1983; Mendelssohn, McKee, and Patrick, 1981). Excessive flooding is known to inhibit growth and can eventually cause mortality in *S. patens* and *S. alterniflora* (Mendelssohn and McKee, 1988). Increased flooding and salinity has been shown to lead to decreased underground biomass and eventually mortality in *S. lancifolia* (Howard and Mendelssohn, 1995; Webb and Mendelssohn, 1996). The likelihood for RSLR to continue or even accelerate in the near future emphasizes the need for an understanding of potential landscape change resulting from RSLR.

Projections of coastal landscape change often require an ability to estimate wetland change under variable RSLR scenarios. The elevation of a wetland relative to MWL is considered to be one of the most important factors influencing the productivity, stability, and resilience of coastal wetlands (Fragoso and Spencer, 2008; Morris *et al.*, 2002; Stagg and Mendelssohn, 2011). Wetlands at lower elevations relative to the typical variation in water level are often subject to increases in the depth, duration, and frequency of flooding, which can inhibit vegetative productivity, reduce a wetland's resiliency to disturbance, and eventually cause vegetation mortality (Mendelssohn and Morris, 2000; Morris, 1995).

Important uncertainties exist concerning the conditions under which marsh converts to open water as a result of factors related to RSLR. Much of the available information on the relationships between vegetation productivity and inundation are derived from greenhouse studies and is limited to particular species such as *S. alterniflora*, but the response of other vegetation types to changes in inundation patterns are less well understood. Data regarding marsh collapse across a variety of vegetation types is often limited as field investigations of each vegetation type would require substantial time and resource allocation, and can be logistically complex. In contrast, remotely sensed data is usually inexpensive, spatially expansive, and can be analyzed through automated processes. While field data is limited in quantity and spatial extent, a great deal of remotely sensed data exists that could prove helpful in determining inundation thresholds beyond which various marsh types cease to occur.

One of the benefits of remotely sensed data is that the population of samples is much larger than that of field data. While in traditional field-based studies, the sample size may not be large enough to address variability across a given marsh type, that is seldom the case with remotely sensed data. Using remotely sensed data, the number of samples can reach hundreds of thousands, or even millions, as each pixel is a data point. A disadvantage of remotely sensed data is that multiple environmental factors may affect its quality and accuracy, but in situations where field data is not available or insufficient, remotely sensed data can provide a reasonable alternative.

The methodology presented here describes a relatively simple means of analyzing patterns pertaining to wetland productivity and inundation in three marsh types common in coastal Louisiana: intermediate, brackish, and saline marsh. Fresh marsh has been omitted from this analysis as marsh collapse in fresh marsh is thought to be more sensitive to increases in salinity than flooding depth or frequency (Willis and Hester, 2004). This analysis has been conducted using data sources that are readily available in many regions, and as such, this method could be easily transferred to other wetland types and regions. This approach may further an understanding of wetland response to inundation, and the potential landscape changes which may occur as a result of those responses.

STUDY AREA

The Louisiana Coastal Area (LCA) encompasses an area of about 37,780 km^2 (Figure 1), consisting of a mosaic of wetland plains, deltaic lobes, and open water. Landscapes are dynamic in this region due to episodic events and environmental variability, but in 2010 land comprised approximately 14,667 km^2 of the coastal zone (Couvillion *et al.*, 2011). Wetland loss is an all too frequently observed phenomena in the region, with a net wetland loss of approximately 4,877 km^2 between 1932 and 2010 (Couvillion *et al.*, 2011).

METHODS

The general approach for this investigation was to compile a variety of field collected and remotely sensed datasets pertaining to vegetation occurrence, type, and productivity, and compare them to datasets pertaining to elevation relative to MWL. The primary dataset utilized to inform vegetation productivity was a Normalized Difference Vegetation Index (NDVI).

NDVI

The Normalized Difference Vegetation Index (NDVI) is a ratio that exploits varying absorption and reflection characteristics of red and near infrared (NIR) wavelengths of light. The general formula for the NDVI is as follows (Equation 1):

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{Red})}{(\mathrm{NIR} + \mathrm{Red})} \qquad (1)$$

NDVI has been shown to be related to a variety of parameters including vegetation productivity, leaf area index, fraction of radiation intercepted, and canopy cover (Filella *et al.*, 2004; Gamon *et al.*, 1995; Pettorelli *et al.*, 2005; Rundquist, 2002). Previous investigations have examined the seasonal patterns in NDVI values by habitat type and have found that in coastal Louisiana NDVI values typically reach a peak in August (Steyer, Couvillion, and Barras, 2013). It is generally accepted that this peak corresponds to peak biomass. Therefore, the month of August was chosen to generate average NDVI values to approximate vegetation productivity for this analysis. Figure 2 shows the resulting dataset, which consists of a composite of NDVI values from multiple sensors (MODIS and Landsat Thematic Mapper (TM)) during the month of August. Average values were calculated from imagery collected by both of these sensors during the months of August for multiple years (2007–2009). Higher NDVI values (shown in bright white) indicate healthy, dense vegetation while lower NDVI values (shown in black) indicate lower vegetation density or vigor.

NDVI values can be very useful in determining thresholds between vegetated and nonvegetated areas. Figure 3 illustrates the drastic difference in NDVI values as one moves along a transect from vegetated marshes (as seen in green) into open water (as seen in red). It is these drastic differences that this investigation sought to exploit to extract information pertaining to the occurrence and productivity of vegetation at a range of inundation depths.

Vegetation Type

To examine patterns of productivity and inundation by vegetation type we used vegetation cover data obtained during a coast-wide vegetation survey in 2007 (Sasser *et al.*, 2008) as training data to classify marsh and shrub communities in the Louisiana coastal zone. During that survey, species composition

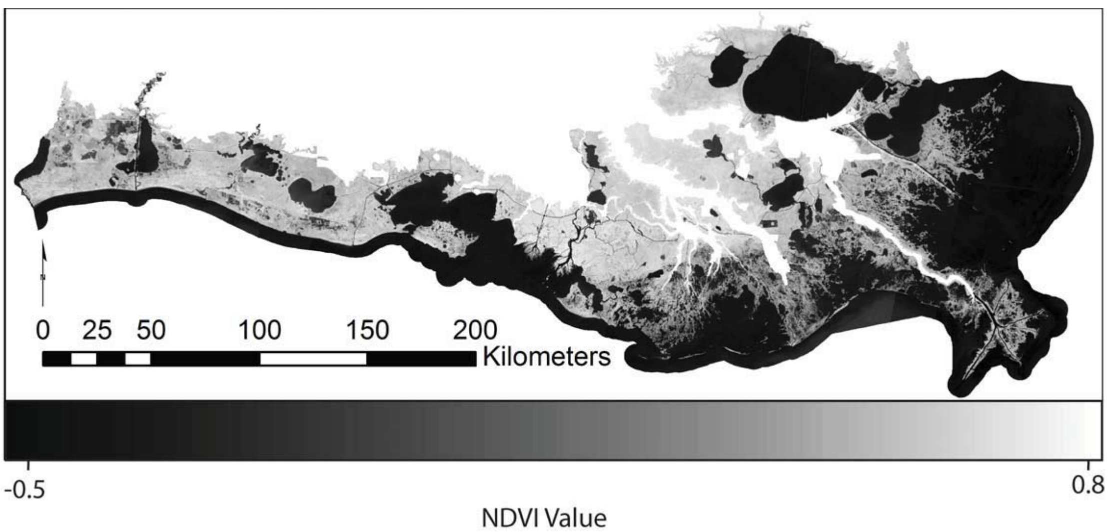

Figure 2. Average peak biomass conditions as estimated by the Normalized Difference Vegetation Index for coastal Louisiana. Higher NDVI values (shown in bright white) indicate healthy, dense vegetation while lower NDVI values (shown in gray) indicate lower vegetation density or vigor, and the lowest values (shown in dark gray/ black) indicate the absence of vegetation. White areas are excluded from the analysis.

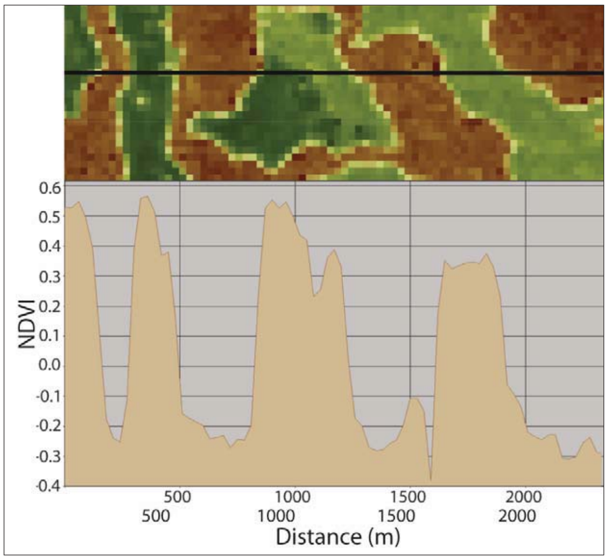

Figure 3. An illustration of NDVI values across a transect (represented by the black line) of marshes and ponds in Breton Sound Basin. (Though the NDVI formula results in a theoretical range from -1 to +1, actual values never reach those extremes. Typically even the most dense and vigorous vegetation observed will have a maximum NDVI value of approximately +0.9, and complete open water can be represented by NDVI values anywhere from a value of +0.2 to a minimum of approximately -0.5. These extremes of NDVI values are typically not observed in herbaceous marsh in coastal Louisiana however. The general maximum values for marshes ranges from approximately +0.6 in saline marshes to +0.7 in fresh marsh).

was recorded at 3,891 marsh and shrub stations throughout coastal Louisiana. These stations were then assigned to vegetation types using common dominants as well as species assemblages known to occur in the area. The vegetation types of interest to this study included intermediate, brackish, and saline herbaceous marsh, and species assemblages were used as training data for a remotely sensed classification of the entire LCA for the 2008 time period. Sampling sites that were observed to have changed spectrally from 2007 to 2008 were excluded from training the 2008 classification. The resulting output provided a complete dataset of vegetation types for all vegetated wetland areas in the LCA.

Once vegetation assemblages were quantified, we then turned our focus to the datasets that would be used to quantify inundation. Inundation frequency and duration can be more difficult to characterize from remotely sensed data since cloud cover and sensor return frequency often do not support the temporal frequency necessary to estimate these parameters. Therefore inundation depth was selected as the primary candidate for use in evaluation of marsh collapse thresholds.

Elevation

An estimation of inundation depth first requires elevation data. The elevation data utilized in this effort consisted of an integrated elevation and bathymetry dataset. Terrestrial elevations were primarily based on light detection and ranging (lidar) data. Lidar is one of the most widely used means of obtaining elevation data in wetland areas because it can provide relatively accurate data over large spatial extents. The lidar data utilized for this investigation consisted of two sources, the first of which was flown on dates ranging from 2000–2003, though the majority of the coastal areas were collected in 2003 (Cunningham, Gisclair, and Craig, 2002), and the second of which was flown in early 2011 (Woolpert, 2011). To facilitate the comparability of the lidar datasets to the 2008 NDVI dataset, vegetation type, and MWL, areas which had undergone a change in land cover type between the date of acquisition and 2008, as determined by Couvillion *et al.* (2011), were excluded from further analysis. Figure 4 details the spatial extent of the lidar datasets, as well as areas excluded from analysis due to a change in land cover type.

The accuracy of elevation data is paramount to the utility of remotely sensed estimates of inundation depth thresholds which

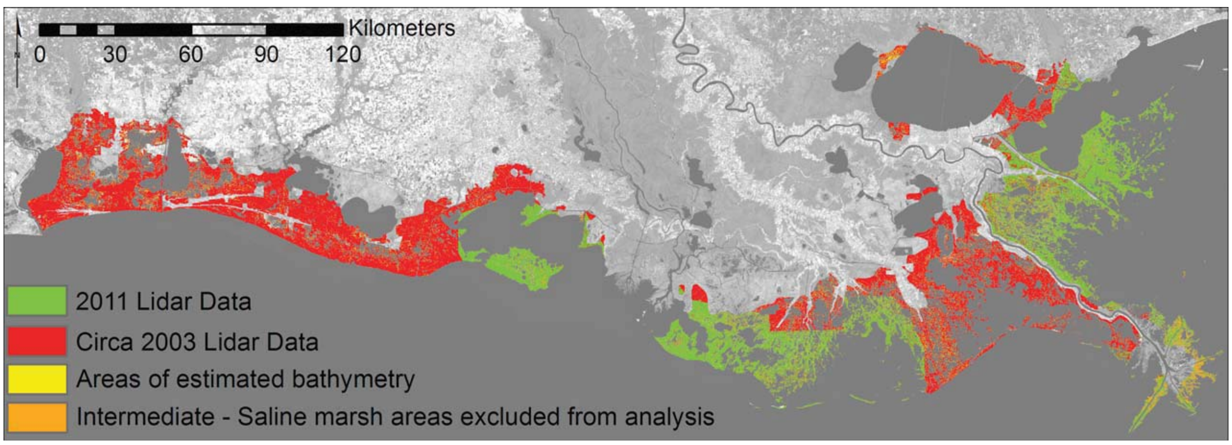

Figure 4. Map detailing coverage of lidar datasets, excluded areas, and areas of estimated bathymetry. Elevation coverage is excluded from forested wetland and fresh marsh areas as marsh collapse thresholds were not examined in these areas. Refer to Cunningham, Gisclair, and Craig, 2002 for more details regarding the date of acquisition of the circa 2003 lidar. More details regarding the 2011 data can be found in Woolpert, 2011.

may lead to marsh collapse. Root mean square error (RMSE) is often used to estimate vertical accuracy and is defined as the square root of the average squared differences between lidar values and values from an independent, presumably higher accuracy source. In general, the lower the RMSE, the higher the accuracy of the dataset. The RMSE of the circa 2003 lidar data utilized in this analysis is listed as 15–30 cm, and varied by land cover type (Cunningham, Gisclair, and Craig, 2002). Variable RMSE by land cover type was calculated for this dataset, and in general, the RMSE of wetland areas was better than that of upland, forested and shrub/scrub areas, and were typically observed at the lower end of the published range (Watershed Concepts, 2009). The Woolpert (2011) lidar was preferentially utilized for a majority of the study area (Figure 4) and the RMSE for these data is 7 cm.

Bathymetry consisted of data compiled from various sources, including side-scan sonar, *in situ* soundings, and interpolations in areas with no existing data (NOAA, 1998). The elevation in the transition zone between aquatic and terrestrial environments was estimated using a method of examining the wetting and drying cycles observed in multitemporal imagery and using those patterns as training data to inform a model of elevation. A regression tree classifier was utilized to observe patterns in the wetting and drying cycles of optical imagery at sites of known elevation in order to assign an estimate at sites of unknown elevation, or sites which were inundated at the time of the lidar acquisition. A regression tree classifier was chosen as these models can approximate complex, nonlinear relationships such as the relationships between inundation and elevation. For this effort, Cubist™ software, developed by RuleQuest Research (2012), was utilized to construct the regression trees, which were then used to obtain estimated elevations for sites at which no elevation data was available. Areas in which an estimated elevation value was utilized are shown in Figure 4.

Optical imagery consisted of every cloud-free date of Landsat TM and Enhanced Thematic Mapper (ETM), which was available for the study area from 1984–2007. The exact dates and number of images varies across the study domain. More information regarding cloud-free dates of Landsat imagery is available from the U.S. Geological Survey (2012). Multitemporal imagery was utilized to allow the classifier to detect temporal variation in wetting and drying patterns. The concept at the foundation of this methodology relies upon hydrologic characteristics represented in the optical imagery that are related to elevation.

Mean Water Level (MWL)

The second component necessary to calculate inundation depth is an estimate of water levels. One of the most complete sources for water level data in coastal Louisiana comes from a network of over 390 field monitoring stations, which make up the Coastwide Reference Monitoring System (CRMS) (Steyer *et al.*, 2003; see http://www.lacoast.gov/crms2/Home.aspx). MWLs were calculated from data acquired at over 200 CRMS stations during the 2007–2008 time period. Average MWL was calculated for hydrologically similar polygons covering all of coastal Louisiana. For polygons in which no stations were available, MWL was interpolated using krigging for each polygon. This dataset is shown in Figure 5.

Elevation Relative to MWL

Elevation relative to MWL was calculated by subtracting the MWLs from elevation throughout the coastal Louisiana dataset. The term "Elevation relative to MWL" is utilized as values can be positive, and positive depth measurements are not intuitive. Positive values represent areas that are not flooded at MWL, while negative values represent areas that are flooded at MWL.

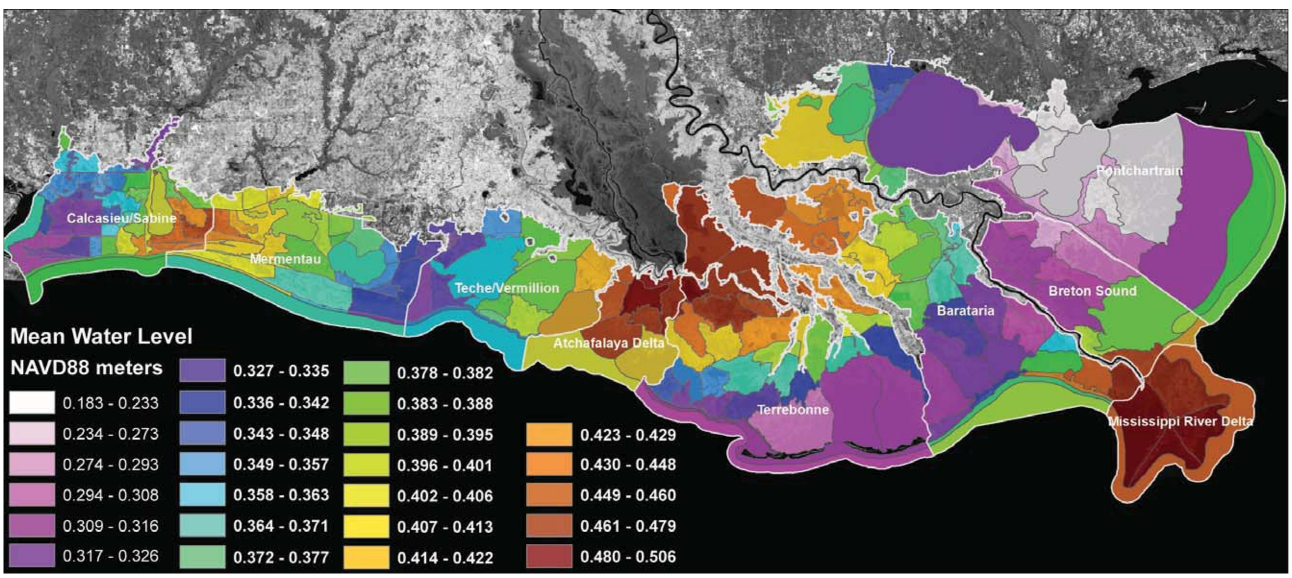

Figure 5. Mean water level (2008) averaged by hydrologically similar areas in coastal Louisiana.

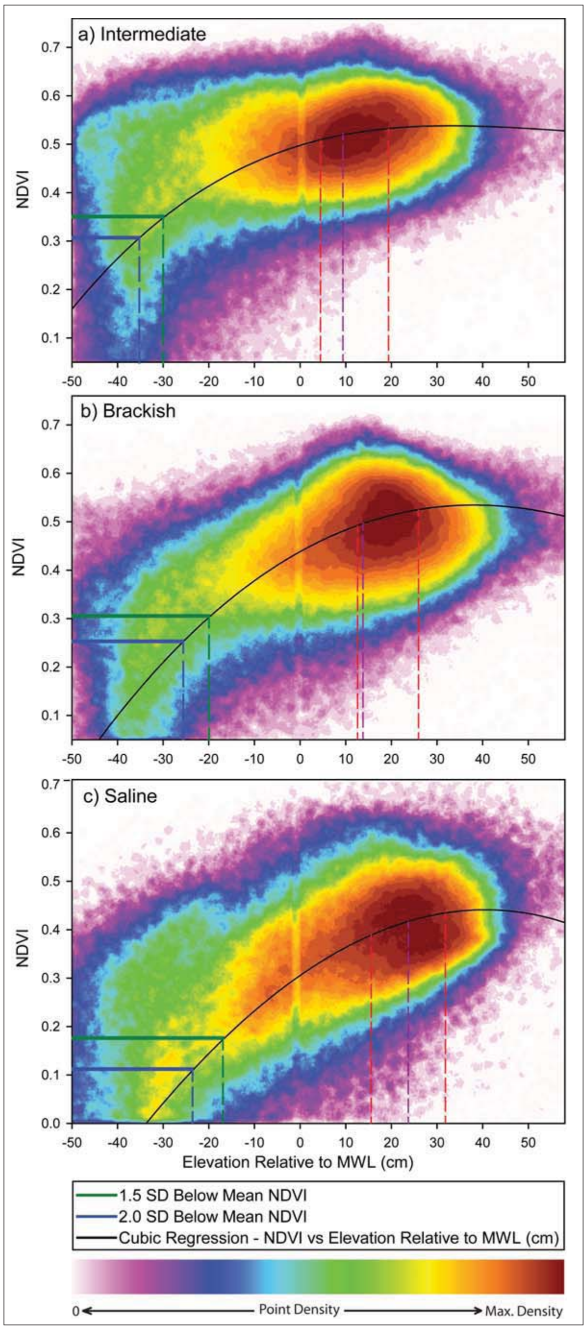

Figure 6. Coastwide plots of peak biomass (August) NDVI values for existing (A) intermediate, (B) brackish, (C) and saline marsh vs. elevation relative to MWL (cm). The black lines represent cubic regressions of NDVI vs. elevation relative to MWL, and are defined by the general formula $f = y0+ax + bx^2 + cx^3$. See Table 1 for regression parameter values. The green and blue lines designate the lower 1.5 and 2.0 standard deviation (SD) of NDVI values (respectively) in each marsh type. The dashed green lines designate the intersection of those values with regard to elevation relative to MWL. Dashed red lines indicate a zone of maximum density of occurrence of each marsh type. The dashed purple lines indicate mean high tide as defined by CRMS field data. See Table 2 for intersection and field data values.

Sampling Data Points

Because a total of 9.7 million 30-m pixels (*i.e.*, samples) were collected for the entire coast in the three marsh types of interest, we determined that it was necessary to evaluate only a subset of those pixels. A stratified random sample of 10% of pixels from each marsh type (intermediate, brackish, and saline marshes) was taken. Areas which were observed to have changed land cover categories as a result of Hurricanes Gustav or Ike, which both took place during the study period (2008), were omitted from the random sample. NDVI statistics were summarized for each marsh type for coastal Louisiana. Standard deviations of 1.5 and 2 below the mean NDVI values were calculated. These values were selected as they represent values below which fewer than 6.7% and 2.2% of data occur, respectively, if a normal distribution is assumed. As marshes seldom occur beyond these limits, these values may be a reasonable guide for determining a range within which marsh collapse is probable.

Statistical Analysis

The previously selected random sample of pixels was then examined with respect to depth of inundation and vegetation vigor. Resulting data for NDVI and elevation relative to MWL were graphed in SigmaPlot® (Systat Software, 2012). A polynomial cubic regression was used to fit the data and examine relationships between the two variables. The regression model of the relationship between inundation and NDVI was used to identify the intercepts where marshes cease to occur. The overwhelming number of data points made visual interpretation of patterns within the data difficult to interpret. We therefore calculated a point density which is represented in the graphs of Figure 6.

RESULTS AND DISCUSSION

Marsh collapse uncertainty range values were identified by locating the intercept of the regression line with the 1.5 and 2 standard deviation (SD) lines. These values represent a range of depths in centimeters within which marsh collapse is probable based on the regression model. The plots shown in Figure 6 represent these investigations for intermediate, brackish, and saline marsh.

The range for a potential marsh collapse threshold in an intermediate marsh is identified as occurring at elevations relative to MWL of -30.7 to -35.8 cm. This marsh collapse uncertainty range represents the deepest collapse thresholds for any marsh type examined in this study. Intermediate marsh in coastal Louisiana contains species which tolerate greater inundation depths, such as the codominant *Sagitaria lancifolia*. *S. lancifolia* has been shown to be well adapted to fluctuating water regimes, including flooding conditions of +20 cm (Baldwin, McKee, and Mendelssohn, 1996; Howard and Mendelssohn, 1995; Spaulding and Hester, 2007). Martin and Shaffer (2005) found no significant decrease in aboveground biomass at 30 cm of flooding. There are no studies that document the effects of inundation alone on intermediate marsh collapse; however, increased flooding and salinity have been shown to lead to mortality in short-term field studies using *S. lancifolia* (Howard and Mendelssohn, 1995;

Webb and Mendelssohn, 1996). A study by Martin and Shaffer (2005) found that *S. lancifolia* can tolerate flooding of 30 cm and salinity levels of 6 parts per thousand (ppt) over a three-year period, suggesting that temporal influences and tolerance to long-term flooding and salt stress should be considered in future projections of landscape change.

A shallower range for a potential marsh collapse threshold for brackish marsh was identified as occurring between -20.0 cm and -25.6 cm relative to MWL. Broome, Mendelssohn, and McKee (1995) found that *S. patens*, a common brackish marsh species, exhibited only marginal survival rates at a constant flooding depth of 30 cm. Tobias (2010) found that regression models of *S. patens* live root biomass intersected zero at an average flooding depth of 27 cm, though root biomass was approaching zero at shallower depths of 20–26 cm.

Finally, the shallowest marsh collapse range identified by this analysis occurred in saline marsh at elevations relative to MWL of -16.9 to -23.5 cm. Morris *et al.* (2002) noted that at depths greater than 60 cm below mean high tide (MHT), growth of *S. alterniflora*, a common saline marsh species, was likely limited by anoxic conditions. As MHT in coastal Louisiana for saline marsh averages 23.1 cm above MWL (Table 2), the corresponding marsh collapse uncertainty range relative to MHT would be approximately 40–46.6 cm. While Morris *et al.* (2002) found that salt marshes achieve maximum productivity at a lower elevation relative to MHT than the results of this analysis suggest, he also noted that maximum productivity did not necessarily equate to maximum stability. "Rather, a less productive marsh situated above its optimum elevation should be more stable because it will tolerate a higher RSLR and is less vulnerable to the variability in MSL" (Morris, 2002). McKee and Patrick (1988) noted that growth ranges for *S. alterniflora* at lower latitudes in North America typically fall within the upper portion of the mean tide range (MTR), which is consistent with the findings of this study.

Table 1. *Cubic regressions parameter values of NDVI vs. elevation relative to MWL. Values correspond to the general formula:* $f = y0+ax + bx^2 + cx^3$.

(A) Intermediate Marsh r^2 = 0.348			
	Value	SE	CV%
y0	4.976E-01	2.719E-04	5.463E-02
a	2.843E-03	1.457E-05	5.125E-01
b	-6.067E-05	3.036E-07	5.005E-01
c	3.555E-07	6.888E-09	1.938E+00
(B) Brackish Marsh r^2 = 0.517			
	Value	SE	CV%
y0	4.383E-01	2.908E-04	6.635E-02
a	5.228E-03	1.298E-05	2.482E-01
b	-7.578E-05	3.208E-07	4.233E-01
c	1.266E-07	6.700E-09	5.294E+00
(C) Saline Marsh r^2 = 0.614			
	Value	SE	CV%
y0	3.055E-01	3.780E-04	1.238E-01
a	6.561E-03	1.646E-05	2.509E-01
b	-7.648E-05	3.439E-07	4.497E-01
c	-7.190E-08	7.934E-09	1.103E+01

Table 2. *Marsh collapse uncertainty ranges and zones of maximum density of occurrence. Values given are in centimeters relative to MWL. Also shown is mean high tide (MHT) as determined from CRMS data for 2008.*

	Marsh Collapse Uncertainty Range (cm)		Zone of Maximum Density of Occurence (cm)		MHT (cm) CRMS
Marsh Type	Min	Max	Min	Max	
Intermediate	-35.8	-30.7	4.7	19.0	9.2
Brackish	-25.6	-20.0	12.6	26.8	13.8
Saline	-23.5	-16.9	16.3	31.9	23.1

In all three marsh types, NDVI value rises with increasing elevation relative to MWL up to a limit, beyond which NDVI, and by correlation productivity, either plateaus or begins to decrease. Elevation of a site relative to MWL is known to be an important factor, which affects productivity because it determines flood depth, frequency, and duration, as well as soil salinity (Mendelssohn and Morris, 2000; Morris, 1995). Increasing elevation is known to increase soil drainage (Mendelssohn and Seneca, 1980) and can improve plant productivity. The regression model for intermediate marsh had the lowest r^2 value (0.348; Table 1). This may be due to variability in species composition in intermediate marsh, and the occurrence of species common in the intermediate marsh type at a wide variety of elevations relative to MWL. In contrast, saline marshes usually consist of only a few dominant species, and the range of tolerance of those species is much narrower, leading to the highest r^2 value of 0.614 (Table 1). As brackish marshes are typically represented by species compositions and variability that can be transitional between intermediate and saline, the intermediary r^2 value of 0.517 (Table 1) also seems intuitive.

The point densities in Figure 6 also identify the range of elevations at which each marsh type predominantly occurs. A zone of maximum density of occurrence is designated by the dotted red lines in Figure 6. This zone is thought to represent the optimal conditions for each of these marsh types. The maximum point density of each marsh type occurs at a positive elevation relative to MWL, indicating that the majority of marshes in each type occur at elevations exceeding MWL. Thus, these marshes are intermittently inundated as opposed to permanently inundated, which can lead to low redox potential, reduced dissolved oxygen, and elevated sulfides, which in turn can inhibit growth and eventually lead to mortality (Stagg and Mendelssohn, 2011).

Krone (1985) noted that stable intertidal marshes commonly exist at an elevation that approximates that of the mean high tide. Field data for mean high tide was calculated from CRMS data for 2008 and is represented in Figure 6 by the dashed purple line. For all 3 marsh types, the mean high tide line occurs within the zone of maximum occurrence, suggesting the majority of marshes in coastal Louisiana occur at elevations that approximate mean high tide. These results also suggest marshes at these elevations typically exhibit more spatial contiguity, which generally corresponds to higher NDVI values than fragmented marsh.

Finally, a threshold of occurrence in terms of elevation relative to MWL is evident in all marsh types. At elevations above this threshold relative to MWL, these marshes cease to occur. Elevations above these thresholds may experience a severe drop in soil moisture, low flooding frequency (Brown and Pezeshki, 2007; Naidoo, McKee, and Mendelssohn, 1992; Schrift, Mendelssohn, and Materne, 2008), and wetland vegetation may be out-competed by other vegetation types better suited to drier conditions.

CONCLUSIONS

These results suggest a range of elevations relative to MWL at which marsh communities typically occur and are most productive, a threshold of occurrence beyond which wetland communities generally cease to occur, and a threshold of collapse, below which marsh collapse is probable. Elevations at or exceeding the threshold of occurrence will likely be outcompeted by other nonwetland vegetation types and land use categories. Conversely, marsh communities approaching the marsh collapse threshold uncertainty range are likely unstable and deteriorating marsh communities, which will likely convert to open water.

We predict that the stability of a given marsh community depends on its current elevation relative to MWL, changes in RSLR, and its capacity to adjust its elevation to offset those changes and maintain its position through mineral and organic contributions to accretion. Changes in RSLR often lead to landward migration of coastal wetlands. In coastal Louisiana, landward migration of the marsh is often obstructed by anthropogenic barriers to migration, such as levees. This situation leads to the logical conclusion that future wetland loss is probable if RSLR continues or accelerates at rates that exceed the wetland's capacity to maintain its elevation relative to water levels.

The results of this analysis will enable more accurate projections pertaining to the stability and longevity of these marshes under various relative sea-level rise scenarios. The consequences of wetland losses in the region include continued loss of the ecosystem services that these wetlands provide. This research will facilitate a greater understanding of the risks to these ecosystem services posed by continued RSLR.

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