Feedback Of Coastal Marshes To Climate Change: Long-Term Phenological Shifts

Y Mo
moyu@terpmail.umd.edu

M S. Kearney

R. Eugene Turner
euturne@lsu.edu

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INTRODUCTION

Coastal marsh carbon is an important component of the global carbon budget (Duarte, Losada, Hendriks, Mazarrasa, & Marbà, 2013). Coastal marshes have high primary production, efficiently trap suspended organic carbon when flooded, and undergo slow carbon decomposition rates under anaerobic conditions (McLeod et al., 2011; Nellemann & Corcoran, 2009). The amount of carbon stored per unit area in stable coastal marshes can be far greater than that of forests, and the carbon stored may remain for millennia, as compared to decades or centuries in forests (Nellemann & Corcoran, 2009). The marshes and their carbon stocks, however, are susceptible to the direct and indirect effects of climate change (Hinson et al., 2017; Nahlik & Fennessy, 2009).
Depending on the marshes’ vegetation composition, the current ambient conditions, and other environmental factors such as nutrients, the marsh plant growth, and the resulting primary production can be stimulated or hindered by temperature warming, sea-level rise, and elevated atmospheric CO₂ concentration (Charles & Dukes, 2009; Erickson, Megonigal, Peresta, & Drake, 2007; Langley & Megonigal, 2010; Langley, Mozdzer, Shepard, Hagerty, & Megonigal, 2013; Morris, Sundareshwar, Nietch, Kjerfve, & Cahoon, 2002). The decomposition of marsh substrates and hence the carbon sequestration rate can be promoted or inhibited by saltwater intrusion and global warming, varying among different marsh systems and being controlled by concurrent stressors (Craft, 2007; Wu, Huang, Biber, & Bethel, 2017). Given the complex and dynamic outcomes of the various factors, it is hard to predict how coastal marshes will respond to the simultaneous climatic stresses at a landscape scale. Yet, this is a key piece of information needed in order to assess ecosystem sustainability and to predict future changes.

Here, we study the multi-decadal phenology of four distinct coastal marsh systems to gain insights into their ability to uptake carbon in relation to climate change at a broad scale (Walther et al., 2002). We use the longest continuous satellite-based record of the Earth’s ecosystems, the Landsat Climatic Data Records (CDRs) and an advanced modeling technique, the nonlinear mixed model, to reconstruct the phenology between 1984 and 2014 for the different coastal marsh systems in Louisiana, USA, one of world’s largest coastal marsh habitats that share the same climatic stressors as many other coastal ecosystems around the world. We speculate that climate change (i.e., temperature, sea-level, and atmospheric CO₂ concentrations) has influenced the phenology of the marshes at the ecosystem level and that the influence is a function of whether the marshes are tidal freshwater, intermediate, brackish, or saline systems. We also hypothesize that the climatic influences will continue, if not increase, under future climate scenarios.

2 | METHODS

2.1 | Study area

The study area is in four major basins in Louisiana, USA, at the northern Gulf of Mexico: the Barataria, Breton Sound, Pontchartrain, and Terrebonne basins (Figure 1). The marshes are classified into freshwater, intermediate, brackish, and saline systems based on vegetation association and salinity (Gosselink, 1984). Freshwater marshes occupy habitats with a salinity <0.5 ppt and are dominated by Panicum hemitomon, Sagittaria falcata, and Eleocharis sp. Intermediate marshes occupy habitats with salinity from 0.5 to 5 ppt and are dominated by Spartina patens and Phragmites australis. Brackish marshes are characterized by salinities ranging from 5 to 18 ppt, and the dominant species are Spartina patens and Distichlis spicata. Saline marshes occur where salinity is >18 ppt, and the dominant species are Spartina alterniflora, Distichlis spicata, and Juncus roemerianus. The percentage of C4 plants increases with higher salinities, whereas the species richness and diversity decrease. The boundaries of the different marshes are obtained from the United States Geological Survey (USGS) vegetative survey for Louisiana coastal marshes (Chabreck & Linscombe, 1988, 1997; Linscombe & Chabreck, 2001; Sasser, Visser, Mouton, Linscombe, & Hartley, 2008, 2014).

2.2 | Marsh phenology modeling

We use the longest continuous satellite record of the Earth’s ecosystems, the Landsat CDRs from 1984 to 2014, to create the phenological records of the marshes (Table A1). The data are collected by three Landsat series satellites: (a) the Landsat 5 equipped with the Thematic Mapper (TM) that launched in 1984 and decommissioned in 2011; (b) the Landsat 7 equipped with the Enhanced Thematic Mapper Plus (ETM+) that launched in 1999; and (c) the Landsat 8
equipped with the Operational Land Imager (OLI) that launched in 2013. All three sensors have a 30-m spatial resolution and a 16-day temporal revisit cycle. The study area locates within the Landsat scenes of Path 22 Row 40 and Path 22 Row 39. There are 359 relatively cloudless images (mosaics of the two Landsat scenes) used for the phenology modeling.

The Normalized Difference Vegetation Index (NDVI) values are calculated as a proxy for the marshes’ aboveground biomass ($R^2 = 0.7$; Mo, Kearney, Riter, Zhao, & Tilley, 2018), and the NDVI-based phenological records of the marshes are modeled using an advanced modeling technique, the nonlinear mixed model (Mo, Momen, & Kearney, 2015). This method is developed by Mo et al. (2015) to provide a rigorous statistical analysis for phenological curves of different vegetation that are represented by nonlinear functions with repeated-measure variables. Phenological measurements (i.e., the NDVI) made on the same observational units (i.e., marsh systems) over time are treated as repeated measurements. The phenological records of the different marsh systems are fitted into three nonlinear models, the Gaussian, the stepwise Gaussian, and the stepwise logistic functions. The goodness-of-fit of the models is assessed via the Efron’s pseudo $R^2$ and the Akaike Information Criterion (AIC), the Akaike Information Criterion Correction (AICC), and the Bayesian Information Criterion (BIC). The pseudo $R^2$, a statistic similar to $R^2$ in the linear regression, indicates the percent variance explained by the nonlinear models (Hardin, Hilbe, & Hilbe, 2007). The pseudo $R^2$ ranges from $\sim$ to 1. A pseudo $R^2$ closer to 1 indicates more variability in the data is explained. The AIC, AICC, and BIC indices evaluate models based on the principle of parsimony, that is, a model explains more variation in the data with fewer variables is considered a better fit (Boye, Vernier, Nielsen, & Schmiegelow, 2002; Richards, 2005).

Key phenological parameters, that is, peak NDVI, peak NDVI day, and growing season length (bracketing days that had NDVI $>90\%$ of peak NDVI) for each marsh system in each year are estimated from the best-fit model. The phenology modeling only considered existing marshes, that is, it is corrected for the marsh area changes over the 30 years.

2.3 | Marsh area estimation

The areas of the freshwater, intermediate, brackish, and saline marshes are estimated using cloud-free Landsat 5 TM and Landsat 8 OLI data. The marshes type boundaries are determined using the USGS vegetation survey for Louisiana coastal marshes done in 1988, 1997, 2001, 2007, and 2013 (Chabreck & Linscombe, 1988, 1997; Linscombe & Chabreck, 2001; Sasser et al., 2008, 2014). The marshland within the boundaries is estimated using the C version of the Function Mask (CFMask) that comes with the Landsat CDRs (Zhu & Woodcock, 2012). There are 2, 6, 5, 4, and 1 mosaic images used for 1988, 1997, 2001, 2007, and 2013, respectively, for a total of 18 images (Table A2). The overall accuracy of using the CFMask for estimating the marshland area is $0.89 \pm 0.04$ (verified using the USGS Digital Orthoephoto Quadrangle, DOQ; Table A3).

2.4 | Climatic and environmental data

We acquire records of the atmospheric CO$_2$, air temperature, Oceanic Niño Index (ONI), sea-level, and salinity of the study area from stations of different US Federal and State agencies. The annual mean sea-level data are from the National Oceanic and Atmospheric Administration (NOAA) station # 8761724 Grand Isle, Louisiana, USA (Tides and Currents). The annual mean sea-level are calculated from the monthly means. The atmospheric CO$_2$ records are from the NOAA Carbon Cycle Cooperative Global Air Network Niwot Ridge station, Colorado, USA (Earth System Research Laboratory). The National Weather Service (NWS) #12916 New Orleans Airport station, Louisiana, USA, is the source for the precipitation and temperature data (Climatological Data Publications). The ONI records are obtained from the NWS Climate Prediction Center (Cold & Warm Episodes by Season). The Louisiana Department of Wildlife and Fisheries station #317/USGS station #07380251 St. Mary’s Point, Barataria Bay, Louisiana, USA, provides the salinity data (National Water Information System), and the annual means are calculated from the daily measurements. The correlations between the marsh phenology and marsh area with the climatic and environmental factors are analyzed using the pairwise Pearson's correlation analysis.

2.5 | Phenology prediction

Linear models describing the correlations between the marsh phenology and the climatic variables are built on the historical data and used to predict the marsh phenology in the future (until 2050). The future sea-level and air temperature in the study area are estimated using linear models based on the sea-level data from the NOAA Grand Isle station, and the air temperature data from the NWS New Orleans Airport station, both dating back to the 1940s (Figure A1a, b). The slope of the sea-level increase is 9 mm/year ($p < 0.01$), which is in consistence with the literature (González & Törnqvist, 2011; Jankowski, Törnqvist, & Fernandes, 2017). The temperature increases at a speed of 0.016°C/year ($p < 0.01$), falling within the lower ranges of projections from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4, 2007). The ranges of possible future atmospheric CO$_2$ concentrations are obtained from the IPCC AR4 (Data Distribution Centre). The future atmospheric CO$_2$ concentrations are from two carbon cycle models (i.e., the Bern model, or BERN, and the Integrated Science Assessment Model, or ISAM) and under different emission scenarios (i.e., A1B, A1T, A1F, A2, B1, B2, A1p, A2p, B1p, B2p, IS92a, and IS92a/SAR; Figure A1c).

3 | RESULTS

3.1 | Marsh phenological changes

The NDVI-derived phenological records of the freshwater, intermediate, brackish, and saline marsh systems from 1984 to 2014 are well-described by our models (pseudo-$R^2$ 0.86 ± 0.11; Table 1).
Exceptions are years when not enough relatively cloudless images were collected, and thus the phenological parameters of the respective marsh units in those years cannot be estimated: that is, all marshes in 1990, 1991, 1997, 2001, 2002, and 2012 and the saline marshes in 1994 and 1998. The phenology of the different marsh systems varies. The freshwater marshes had the highest annual peak NDVI (around 0.7), followed by the intermediate, brackish, and saline marshes (around 0.6, 0.5, and 0.4, respectively; Figure 2a). The NDVI of the freshwater, intermediate, and brackish marshes peaked between July and August, while the NDVI of the saline marshes peaked between July and October (Figure 2b). The length of the growing seasons of the freshwater, intermediate, brackish, and saline marshes varied between 2 and 8 months among different marsh systems and years (Figure 2c).

The local sea-level, temperature, and CO₂ all rose from 1984 to 2014 (p < 0.05) (Figure A1). The phenology of the different systems varied in response to the climate conditions (Table A4). The peak NDVI values of all four marsh systems did not significantly change over time. The peak NDVI day of the saline marshes showed no significant changes over time but correlated with air temperature (r = 0.5, p < 0.05). The length of the growing seasons of the intermediate and brackish marshes significantly increased (by 36.4 and 38.0%, respectively; p < 0.05 in both cases), and positively correlated with variations in the atmospheric CO₂ (r = 0.4 and p < 0.05 in both cases).

3.2 Marsh area changes

The total marsh area in 2013 was about 80% of the total marsh area in 1988, and 16% of the marshes in 1988 turned into water by 2013 (Figure 3). In 1988, the freshwater, intermediate, brackish, and saline marshes composed 28%, 10%, 33%, and 29% of the marshes in the study area, respectively, and 35%, 13%, 26%, 26% in 2013. The areas of the freshwater and intermediate marshes were quite stable, and their increased percentage was mostly a result of the decrease of the total marsh area. The marsh loss mainly occurred in the brackish and saline marshes, contributing to most of the 16% change of marsh-to-water from 1988 to 2013. The decrease of the brackish and saline marshes’ areas were significant over time (p < 0.05 in both cases; Figure 2d). The area of the brackish marshes decreased for 52.9% (from 2,326 km² in 1988 to 1,541 km² in 2013), and the area of the saline marshes decreased for 17.9% (from 2,080 to 1,631 km²). The area of the brackish marshes was negatively correlated with sea-level, CO₂ concentration, and temperature, and positively with precipitation (r = −0.8, −0.7, −0.9, and 0.7, respectively; p < 0.05 in all cases; Table A4); the area of the saline marshes was negatively correlated with sea-level rise rates and CO₂ concentration (r = −0.5 and −0.6, respectively; p < 0.05 in both cases; Table A4).

The area changes of the different marsh systems from 1988 to 2013 varied spatially (Figure 1). There was an expansion of brackish marshes into intermediate marshes and saline marshes in the Terrebonne Basin and a replacement of intermediate marshes with saline marshes in the Barataria Basin. Brackish marshes expanded into intermediate and freshwater marshes in the Breton Sound Basin.

3.3 Future marsh phenology

In Section 3.1, we find that the peak NDVI day of the saline marshes was significantly correlated with air temperature and that the length of the growing seasons of the intermediate and brackish marshes was significantly correlated with atmospheric CO₂ (p < 0.05 in all cases). Based on these correlations, we use the phenological and environmental data from 1984 to 2014 to build models to predict the marshes’ future phenology. The model for predicting the brackish marsh growing season length (day) is −171.0538 + 0.8606 × CO₂. The model for predicting the intermediate marsh growing season length (day) is −139.3226 + 0.7169 × CO₂. The model for predicting the saline marsh peak NDVI day (day of year) is −376.507 + 29.365 × Temperature.

The changes in the peak NDVI day for saline marshes will continue at the same rate (Figure 4a). The peak NDVI day of the saline marshes moved from July to August during the past 30 years and is projected to be in September in 2050. It should be noted that based on our analysis, the changes of the peak NDVI day of saline marshes were not directly correlated to time, but were correlated to air temperature in the study area which increases over time. The changes in the brackish and intermediate marshes’ growing season length will accelerate under all CO₂ emission scenarios tested (Figure 4b,c). From 1984 to 2014, the length of the growing seasons of the intermediate and brackish marshes increased for around 40 and 50 days, at rates of 1.3 and 1.6 days/year, respectively. Under the A1F1 scenario (a future world of very rapid economic growth with fossil intensive energy sources) with the ISAM, the growing seasons of the intermediate and brackish marshes will lengthen at the highest rates, for around 140 and 175 days in the next 30 years, equals to 4 and 5 days/year, respectively. Under the B1p scenario (a convergent world with the same global population) with the BERN, the length of the growing seasons of the intermediate and brackish marshes will increase at the lowest rates—but still faster than the past 30 years—for around 80 and 90 days in the next 30 years, equals to 2.2 and 2.7 days/year, respectively. It should be noted that these predictions rely solely on air temperature and CO₂ emissions scenarios and do not take nutrient limitations or other limiting factors into account.

4 DISCUSSION

4.1 The marshes’ phenological changes in the last 30 years

The correlations between the growing season length and the atmospheric CO₂ concentration may be the result of the stimulation of elevated CO₂ concentration on photosynthesis in marsh plants (Cherry, McKee, & Grace, 2009; Rasse, Peresta, & Drake, 2005). This is the first study we know of that reports a positive
correlation between atmospheric CO$_2$ concentration and coastal marshes’ growing season length, which reflects a broad pattern of ecosystem change due to a changing climate (Walther et al., 2002). The various responses among marsh systems are likely to reflect the different physiological characteristics of the marsh plants. The intermediate and brackish marshes have a high percentage of C3 plants, whereas saline marshes are mostly C4 plants. Elevated atmospheric CO$_2$ promotes the plant growth of C3 marsh species, for example, Schoenoplectus americanus, Scirpus maritimus, Scirpus olneyi, and Puccinellia maritima, but does not enhance, or even impairs, the plant growth of C4 species, for example, Distichlis spicata, Spartina alterniflora, and Spartina patens (Arp, Drake, Pockman, Curtis, & Whigham, 1993; Cherry et al., 2009; Drake, 2014; Erickson et al., 2007; Rasse et al., 2005). This is because the increased atmospheric CO$_2$ stimulates photosynthesis of C3 plants, but not the photosynthesis of C4 plants that is nearly saturated under ambient conditions as C4 plants concentrate CO$_2$ at the site with their primary CO$_2$-fixing enzyme. Moreover, the elevated CO$_2$ may even inhibit the plant growth of C4 species by reducing their stomatal conductance, transpiration, and ion uptake (Ghannoum, 2009; Rozema et al., 1991). Yet, the freshwater marshes, which have the highest percentage of C3 plants among the different marsh systems, demonstrate no response to higher CO$_2$ levels in our study. One possible explanation is that the high nutrient loading in freshwater marshes—freshwater marshes are closest to the surface runoff—favors species that are unresponsive to elevated atmospheric CO$_2$ (Langley & Megonigal, 2010; Langley et al., 2013).

Global warming has a general effect of promoting plant growth that is manifested in increasing the growing season NDVI and lengthening the active growth season, especially in the middle and high latitudes (Myneni, Keeling, Tucker, Asrar, & Nemani, 1997; Zhou et al., 2001). Although it was reported that warming increased the annual peak biomass of the marshes

| Year | Best-fit model | AIC | AICCC | BIC | Pseudo R$^2$ (Freshwater) | Pseudo R$^2$ (Intermediate) | Pseudo R$^2$ (Brackish) | Pseudo R$^2$ (Saline) |
|------|---------------|-----|-------|-----|---------------------------|---------------------------|------------------------|---------------------|
| 1984 | G             | -322.7 | -317.0 | -311.3 | 0.97                     | 0.99                      | 0.91                   | 0.57                |
| 1985 | G             | -264.7 | -258.2 | -253.3 | 0.96                     | 0.97                      | 0.90                   | 0.57                |
| 1986 | SG            | -241.5 | -231.0 | -227.3 | 0.94                     | 0.89                      | 0.89                   | 0.91                |
| 1987 | G             | -360.1 | -356.2 | -348.7 | 0.97                     | 0.95                      | 0.93                   | 0.85                |
| 1988 | G             | -428.4 | -423.8 | -417.1 | 0.94                     | 0.94                      | 0.83                   | 0.61                |
| 1989 | G             | -224.5 | -217.2 | -213.2 | 0.90                     | 0.93                      | 0.83                   | 0.81                |
| 1990 | G             | -373.3 | -367.9 | -362.0 | 0.92                     | 0.93                      | 0.93                   | 0.92                |
| 1991 | G             | -397.3 | -393.3 | -384.9 | 0.90                     | 0.93                      | 0.95                   | 0.88                |
| 1992 | G             | -358.7 | -354.1 | -346.3 | 0.87                     | 0.88                      | 0.82                   | -                  |
| 1993 | G             | -459.2 | -455.7 | -446.8 | 0.95                     | 0.96                      | 0.93                   | 0.80                |
| 1994 | G             | -346.3 | -342.7 | -333.9 | 0.89                     | 0.89                      | 0.87                   | 0.71                |
| 1995 | G             | -498.3 | -494.6 | -485.9 | 0.98                     | 0.96                      | 0.94                   | -                  |
| 1996 | G             | -918.2 | -916.4 | -905.9 | 0.94                     | 0.89                      | 0.87                   | 0.89                |
| 1997 | G             | -934.7 | -932.9 | -922.3 | 0.91                     | 0.84                      | 0.63                   | 0.58                |
| 1998 | G             | -794.3 | -792.0 | -781.9 | 0.86                     | 0.91                      | 0.86                   | 0.80                |
| 1999 | G             | -534.6 | -531.5 | -522.3 | 0.89                     | 0.94                      | 0.91                   | 0.77                |
| 2000 | G             | -1173  | -1170  | -1157 | 0.94                     | 0.92                      | 0.91                   | 0.83                |
| 2001 | G             | -790.0 | -788.1 | -777.7 | 0.92                     | 0.95                      | 0.90                   | 0.86                |
| 2002 | G             | -654.3 | -651.7 | -642.0 | 0.85                     | 0.82                      | 0.75                   | 0.56                |
| 2003 | G             | -881.0 | -879.1 | -868.6 | 0.92                     | 0.81                      | 0.74                   | 0.51                |
| 2004 | G             | -861.8 | -859.9 | -849.4 | 0.94                     | 0.91                      | 0.85                   | 0.78                |
| 2005 | G             | -670.8 | -668.8 | -658.5 | 0.94                     | 0.92                      | 0.89                   | 0.93                |
| 2006 | G             | -1102  | -1101  | -1090 | 0.88                     | 0.76                      | 0.66                   | 0.58                |
| 2007 | G             | -510.5 | -507.5 | -498.2 | 0.99                     | 0.99                      | 0.96                   | 0.87                |
| 2008 | G             | -981.4 | -979.8 | -969.1 | 0.91                     | 0.89                      | 0.84                   | 0.66                |

TABLE 1 The pseudo R$^2$, the Akaike Information Criterion (AIC), the Akaike Information Criterion Correction (AICC), and the Bayesian Information Criterion (BIC) of the best-fit phenological model (i.e., the Gaussian, G; the stepwise Gaussian, SG; or the stepwise logistic, SL, function) of the freshwater, intermediate, brackish, and saline marshes from 1984 to 2014 (Exceptions are years when not enough cloudless images were collected, including all marshes in 1990, 1991, 1997, 2001, 2002, and 2012 and saline marshes in 1994 and 1998. The phenological parameters of the respective marsh units in the years cannot be estimated and are not shown in the table).
in Massachusetts, USA (Charles & Dukes, 2009), this study did not find a similar effect of temperature on the peak NDVI nor on the growing season length of the marshes in Louisiana. This result might be expected because the ambient temperatures in Louisiana (at latitudes around 30ºN) are already close to the optimum conditions for the marsh growth.

Indeed, the linear models used in this study are highly simplified. These models do not consider other environmental factors, such as water temperature and nutrient availability, which can vary substantially with in situ conditions, or the nonlinear effects and the interactions among the different factors. For instance, the enhancement of CO₂ uptake by C3 plants may be eventually slowed down by photosynthetic downregulation, nutrient limitations, or increased disturbance from sea-level rise, thus the CO₂ fertilization on the marshes will not continue over long time frames as decades (Erickson et al., 2007; Langley et al., 2013). In addition, the marshes may suffer from other stresses such as pests, herbivores, and pathogens that can also be intensified by a warmer climate (Van der Putten, Macel, & Visser, 2010). Nevertheless, this study provides a "baseline" scenario for future marsh phenology with unconstrained sole impacts from temperature or CO₂, as well as observational inputs for more advanced modeling studies.

4.2 The marsh area changes in the last 30 years

Couvillion et al. reported that 25% of Louisiana's coastal marshes that existed in 1932 had been lost by 2010 (Couvillion et al., 2011), and this study shows that 20% of the marshes in 1988 were lost by 2013. These findings document a highly vulnerable ecosystem. Recent studies have found strong correlations between marsh area loss and several climatic variables (Turner, Kearney, & Parkinson, 2017; Turner, Baustian, Swenson, & Spicer, 2006; Kearney & Turner, 2015). In this study, we further the research by separating the area changes of different marsh systems. We find that the areas of the freshwater and intermediate marshes were quite stable; while the area of the brackish and saline marshes decreased significantly and were negatively correlated with sea-level and CO₂ concentration.
Indeed, the area changes of the Louisiana coastal marshes are likely to relate with both climatic and anthropogenic factors, but here we focus on the climatic factors. Sea-level rise may decrease the marsh elevation by reducing their organic accretion (Nyman, Delaune, Roberts, & Patrick, 1993), promoting decomposition of the marsh substrates (Craft, 2007; Weston, Vile, Neubauer, & Velinsky, 2011; Stagg, Schoolmaster, Krauss, Cormier, & Conner, 2017), and increasing erosion (Smith, Cialone, Wamsley, & McAlpin, 2010). Hence, the negative correlation between the marsh area and sea-level can be expected. On the contrary, increased air temperature and CO$_2$ concentration can contribute to the marsh stability against sea-level rise. The elevated air temperature and atmospheric CO$_2$ may promote the marsh plant growth (for both aboveground and belowground) and thus their organic accretion (Langley, McKee, Cahoon, Cherry, & Megonigal, 2009; Ratliff, Braswell, & Marani, 2015). Although the enhancement of plant growth from CO$_2$, as discussed earlier, is mainly for C3 plants, the fertilization of CO$_2$, based on a modeling study, can increase the marsh elevation for a mixed C3 and C4 plant community (by increasing plant production) in similar magnitude to the effect of increasing inorganic sediment input (Ratliff et al., 2015). The maintenance of the marsh elevation can further benefit from the increased belowground biomass: the increased shoot density will enhance the trapping of tidally driven sediment and provide stronger protection against erosion (Temmerman, Moonen, Schoelynck, Govers, & Bouma, 2012; Mudd, D’Alpaos, & Morris, 2010). It should also be noted that the influence of CO$_2$ fertilization on marsh elevation is likely to depend on many other factors such as the inorganic sedimentation rate (Langley & Megonigal, 2010; Langley et al., 2009; Ratliff et al., 2015) and may be offset by the enhanced decomposition resulted from a rising air temperature (Charles & Dukes, 2009; Kirwan & Blum, 2011). The fertilization effects of increased air temperature and atmospheric CO$_2$ allow the coastal marshes to be more resilient against sea-level rise, but this study documents a significant decrease in the brackish and saline marsh systems, where the impact of sea-level is strongest and more likely to overwhelm the fertilization effects of temperature and CO$_2$.

The area changes of the different marsh systems vary spatially. We find an expansion of brackish marshes into intermediate and saline marshes in the Terrebonne Basin, while saline marshes were replaced by intermediate marshes in the Barataria Basin, and brackish marshes were replaced by intermediate and freshwater marshes in the Breton Sound Basin. This study focuses on the temporal changes of the environmental factors over the past decades and only considers the sea-level and salinity information of one station within the study area. Future studies further examine the spatial pattern of the sea-level and salinity changes (Jankowski et al., 2017), the relative relationship between sediment supply and sea-level rise of different locations (Mariotti & Fagherazzi, 2010), and the availability of accommodation space (Schuerch et al., 2018) may provide more insights the spatial patterns of the area changes.

### 4.3 Marshes’ feedback to climate change

Regardless of the causes, the increased length of the marshes’ growing season has a potentially important impact on the global carbon cycles. The extended growing seasons of the intermediate and brackish marshes directly reflect an increase in aboveground primary production (and possibly an increase in the belowground biomass; Langley et al., 2009). On average, roughly 20% of the marshes net primary production results in carbon storage (Duarte & Cebrian, 1996). The increase in aboveground biomass allows for
an increase in photosynthesis and CO2 uptake, providing a negative feedback mechanism to the elevated atmospheric CO2 and climate change. On the other hand, the loss of the brackish and saline marshes impairs the ecosystems’ potential to capture CO2 and the stability of the existing carbon storage, which is quite large in the coastal marsh anaerobic substrates (long-term C accumulation rate at 18-1713 g C m^-2 yr^-1; McLeod et al., 2011; Nahlik & Fennessy, 2016). The stored carbon will be released into the ocean or the atmosphere—which can also be in the form of methane, a more potent greenhouse gas, under the marshes’ anaerobic conditions (Whiting & Chanton, 1993)—providing a positive feedback mechanism to climate change. The Louisiana coastal marshes are representatives of coastal ecosystems around the world experiencing various climatic and anthropogenic stressors (Bianchi & Allison, 2009; Wang et al., 2007). This study documents the climate-driven long-term phenological shifts of the marshes that, in turn, provide a negative feedback mechanism to the changing climate. A stable coastal marsh system will capture and store more carbon under a changing climate, and compensate, to some extent, for anthropogenic carbon emissions. Such mechanisms highlight the marshes’ critical role in climate mitigation and emphasize the importance of the conservation and restoration of coastal ecosystems under the changing climate.

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AUTHORS CONTRIBUTION
Kearney, Mo and Turner conceived and designed the experiments; Kearney and Mo processed and analyzed the data; Kearney, Mo, and Turner wrote the paper.

DATA ACCESSIBILITY
Data from this study are publicly available through the Gulf of Mexico Research Initiative Information & Data Cooperative (GRIIDC) at https://data.gulfresearchinitiative.org (https://doi.org/10.7266/n7513w97, 10.7266/N7222RVS, 10.7266/N7X92DB, 10.7266/N71834KW, 10.7266/N7S1JHPM, 10.7266/N7NS0RZW, 10.7266/N7J10178, 10.7266/N7D798HO, 10.7266/N7WH2N25, 10.7266/N78G8HTQ, 10.7266/N74T6GFT, 10.7266/N7125QRV, 10.7266/N7BS6GNT, 10.7266/N7RR1W90, 10.7266/N7WS978Z, 10.7266/N7V98651, 10.7266/N7F4M2T, 10.7266/N7N014MD, 10.7266/N7PN93J0, 10.7266/N7RI4GJ7, 10.7266/N7MS3QTH, 10.7266/N7H1303W, 10.7266/N7CJBBK4, 10.7266/N7C827DM, 10.7266/N77S7KVD, 10.7266/N7GX491R).

ORCID
Yu Mo https://orcid.org/0000-0002-3374-4124

R. Eugene Turner https://orcid.org/0000-0003-0776-7506

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**APPENDIX**

### TABLE A1 Sampling dates of Landsat imagery (mosaics of Landsat scenes Row 22 Path 39 and Row 22 Path 40) used for the marsh phenology modeling

| Year | Day of Year | Satellite | Number of Images |
|------|-------------|-----------|------------------|
| 1984 | 97, 193, 241, 257, 273, 305, 337 | Landsat 5 | 8 |
| 1985 | 19, 83, 99, 211, 243, 323, 339 | Landsat 5 | 7 |
| 1986 | 54, 86, 214, 246, 278, 326 | Landsat 5 | 7 |
| 1987 | 9, 25, 41, 73, 121, 137, 185, 233, 249, 265, 281, 345 | Landsat 5 | 12 |
| 1988 | 28, 44, 76, 124, 140, 172, 252, 284, 300, 316 | Landsat 5 | 10 |
| 1989 | 46, 94, 110, 126, 190, 238, 318, 350 | Landsat 5 | 8 |
| 1992 | 39, 87, 103, 167, 279, 295, 311, 327 | Landsat 5 | 9 |
| 1993 | 25, 73, 105, 137, 153, 201, 217, 233, 249, 265, 361 | Landsat 5 | 11 |
| 1994 | 76, 92, 140, 172, 252, 268, 300, 316, 348 | Landsat 5 | 9 |
| 1995 | 31, 79, 143, 159, 207, 223, 239, 255, 271, 319, 335 | Landsat 5 | 11 |
| 1996 | 18, 82, 98, 130, 146, 162, 178, 194, 210, 306, 338, 354 | Landsat 5 | 12 |
| 1998 | 39, 55, 135, 151, 167, 199, 215, 231, 247, 279, 327 | Landsat 5 | 11 |
| 1999 | 10, 26, 42, 122, 138, 170, 218, 250, 266, 290, 314, 330, 362 | Landsat 5 | 20 |
| 2000 | 210, 226, 258, 274, 298, 306, 322 | Landsat 7 | |
| 2003 | 109, 189, 285, 301, 365 | Landsat 5 | 21 |
| 2004 | 5, 21, 37, 53, 85, 101, 117, 133, 197, 229, 245, 261, 277, 293, 325, 357 | Landsat 5 | 16 |
| 2005 | 5, 21, 69, 117, 149, 197, 245, 261, 277, 293, 349 | Landsat 7 | |
| 2006 | 13, 221, 285, 317, 333, 365 | Landsat 7 | 16 |
| 2007 | 72, 216, 232, 312, 328 | Landsat 5 | 13 |
| 2008 | 16, 80, 128, 192, 224, 240, 272, 304 | Landsat 7 | |
| (Continues) |
### Table A1 (Continued)

| Year | Day of Year | Satellite | Number of Images |
|------|-------------|-----------|------------------|
| 2005 | 42, 106, 122, 138, 154, 170, 202, 234, 250, 282, 298, 314 | Landsat 5 | 24 |
|      | 2, 82, 98, 114, 130, 178, 194, 258, 290, 306, 322, 354 | Landsat 7 |  |
| 2006 | 13, 45, 61, 173, 269, 285, 301, 317 | Landsat 5 | 21 |
|      | 5, 85, 117, 133, 165, 181, 197, 229, 245, 293, 309, 325, 357 | Landsat 7 |  |
| 2007 | 48, 64, 96, 112, 128, 192, 224, 272 | Landsat 5 | 14 |
|      | 8, 88, 120, 232, 312, 344 | Landsat 7 |  |
| 2008 | 83, 99, 115, 147, 163, 179, 195, 227, 243, 275, 307, 323 | Landsat 5 | 20 |
|      | 11, 59, 171, 203, 235, 299, 315, 347 | Landsat 7 |  |
| 2009 | 21, 37, 149, 181, 213, 245, 293, 309 | Landsat 5 | 19 |
|      | 13, 29, 61, 77, 93, 157, 173, 237, 285, 317, 365 | Landsat 7 |  |
| 2010 | 56, 88, 152, 168, 232, 248, 280, 296, 312, 344 | Landsat 5 | 18 |
|      | 48, 64, 144, 160, 176, 256, 288, 336 | Landsat 7 |  |
| 2011 | 43, 75, 91, 107, 155, 171, 187, 219, 235, 251, 267, 299, 315 | Landsat 5 | 22 |
|      | 3, 83, 99, 131, 211, 227, 243, 259, 323 | Landsat 7 |  |
| 2013 | 24, 72, 88, 200, 280, 296, 312 | Landsat 7 | 14 |
|      | 144, 176, 240, 256, 272, 288, 352 | Landsat 8 |  |
| 2014 | 59, 123, 139, 171, 187, 219, 235, 251, 299, 331, 347 | Landsat 7 | 22 |
|      | 19, 99, 115, 211, 227, 243, 275, 291, 307, 323, 339 | Landsat 8 |  |
| Total | | | 359 |

### Table A2

| Year | Day of Year | Satellite | Total |
|------|-------------|-----------|-------|
| 1988 | 28,44       | Landsat 5 | 2     |
| 1997 | 20, 36, 244, 276, 308, 340 | Landsat 5 | 6 |
| 2001 | 143, 271, 303, 319, 335 | Landsat 5 | 5 |
| 2007 | 48, 64, 96, 224 | Landsat 5 | 4 |
| 2013 | 352         | Landsat 8 | 1     |
| Total |             |           | 18    |

### Table A3

Confusion matrix for assessing the accuracy of using the C version of the Function Mask (CFMask) in the Landsat Climate Data Records (CDRs) for marsh area estimation. The assessment is performed using the Landsat CDRs and the United States Geological Survey (USGS) Digital Orthophoto Quadrangle (DOQ) collected in Barataria Basin at similar times (within two days) in 1998, 1999, and 2005. For each data set, 100 points are generated randomly within the DOQ food print and stratified by land cover classes.

**Data sets:** Landsat CDR 24th Feb 1998 (Path 22 Row 40) and DOQ 23rd Feb 1998 (DI000000001009761)

| Class       | Predicted Land | Predicted water | User |
|-------------|----------------|-----------------|------|
| Actual land | 57             |                 | 1    |
| Actual water| 12             | 31              | 0.72 |
| Producer    | 0.83           |                 | Overall = 0.86 |

**Data sets:** Landsat CDR 10th Jan 1999 (Path 22 Row 40) and DOQ 10th Jan 1999 (DI000000001063570)

| Class       | Predicted Land | Predicted water | User |
|-------------|----------------|-----------------|------|
| Actual land | 48             | 0               | 1    |
| Actual water| 16             | 36              | 0.69 |
| Producer    | 0.75           |                 | Overall = 0.84 |

(Continues)
TABLE A4  Significant correlations (r) between marsh area and phenological changes, and the environmental variables, that is, year, sea-level (SL), atmospheric CO$_2$, temperature (T), precipitation (P), salinity (S), discharge (D), Oceanic Niño Index (ONI) from 1984 to 2014. All the correlations between the variables are tested, but only significant correlations are shown in the table (P < 0.05)

| Year   | SL  | CO$_2$ | T    | P    | S    | ONI |
|--------|-----|--------|------|------|------|-----|
| Marsh area |     |        |      |      |      |     |
| Freshwater |     |        |      |      |      |     |
| Intermediate |   | -0.5   | 0.6  |      |      |     |
| Brackish    |   | -0.8   | -0.8 | -0.7 | -0.9 | 0.7 |
| Saline      |   | -0.6   | -0.5 | -0.6 |      |     |
| Marsh phenology, peak NDVI |     |        |      |      |      |     |
| Freshwater |     |        |      |      |      |     |
| Marsh phenology, peak NDVI day |     |        |      |      |      |     |
| Saline      |   | 0.5    |      |      |      |     |
| Marsh phenology, growing season length |   | 0.4    | 0.4  |      |      |     |

TABLE A3 (Continued)
FIGURE A1  Panel (a) shows the air temperature at the National Weather Service (NWS) #12916 New Orleans Airport station, Louisiana, USA, since 1946 (gray crosses) and its trend (black dash line) and its projection until 2050 (red solid line). Panel (b) shows the sea-level at the National Oceanic and Atmospheric Administration (NOAA) # 8761724 Grand Isle station, Louisiana, USA, since 1947 relative to the most recent National Tidal Datum Epoch (gray crosses) and its trend (black dash line) and projection until 2050 (red solid line). Panel (c) shows the atmospheric CO₂ records from the NOAA Carbon Cycle Cooperative Global Air Network Niwot Ridge Station, Colorado, USA since 1984 (gray crosses) and its trend (black dash line) and projections (rainbow color lines). The future atmospheric CO₂ atmospheric concentrations are obtained from the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4). The projections are from two carbon cycle models (i.e., the Bern model, or BERN, dotted line, and the Integrated Science Assessment Model, or ISAM, dash line) under different emission scenarios (i.e., A1B, A1T, A1FI, A2, B1, B2, A1p, A2p, B1p, B2p, IS92a, IS92a/SAR)