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SETBACKS AND SURPRISES

Net land gain or loss for two Mississippi River diversions: Caernarvon and Davis Pond

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Coastal wetland restoration can be complex and expensive, so knowing long-term consequences makes it important to inform decisions about if, when, and where to conduct restoration. We determined temporal changes in land gain and loss in receiving basins and adjacent reference areas for two diversions of the Mississippi River in south Louisiana (Davis Pond and Caernarvon initiated in 1991 and 2002, respectively). Water from both diversions went into receiving basins with vegetated areas as did the adjoining reference areas. The results from two different types of satellite imagery analyses demonstrate a net land loss after diversions began. The results were confirmed for the Caernarvon diversion using a before–after/control–impact analysis of independently collected data over a larger area of the estuary. These results are consistent with an analysis of land gain and loss after a natural levee break on the Mississippi River in 1973. The positive influences of adding new sediments were apparently counter-balanced by other factors, and consistent with the conclusion from other studies indicating that increased nutrient supply and flooding are, by themselves, negative influences on marsh health. Modeling the ecosystem effects of diversions can be calibrated and tested using landscape-scale analyses like this to understand the chronic and delayed effects, including the unintended consequences. Basing the legitimacy of river diversion on ecosystem modeling will be premature without successfully reproducing empirical results like these in ecosystem models.

Key words: land loss and gain, restoration, river diversions, wetlands

Implications for Practice

- The net land loss after the Mississippi River was diverted through three diversions suggests that the rationale to build them was inadequate.
- Ecosystem models should reproduce landscape changes at these diversion locations before building new diversions, in order to train new models and reduce predictive errors.
- The inclusion and evaluation of meaningful monitoring at a landscape scale, not just small-scale experimentation, should be included in an adaptive management scheme to fully assess future restoration conditions.
- Both flooding and increased nutrient availability are threats to coastal marsh survival on coastal plains.

Introduction

The availability of dredges, pumps, conveyance pipes and channels, etc., makes it possible to move large amounts of sediments and water over great distances or to restrict water movements with an extensive system of levees. Conspicuous large coastal projects include the levee construction and hydraulic management of Roman land reclamations (Rippon 2000) and Dutch polders (Danner et al. 2005), and levee de-constructions involved in coastal retreat in England (Boorman & Hazelden 2017). Today's projects are framed in the uncertain world of sea level rise, storms, and hydrologic anomalies, and also with the consequences of biological factors—the levees may fail from burrowing animals, soil subsidence lowers marsh elevation, plant communities change, and tidal restrictions and sea level rise have consequences for soil and plants (Silliman et al. 2009; Roman 2017; Turner et al. 2018*b*). Ecosystem models can be a heuristic device to explore and predict the consequences of these known and unrealized conditions. Model uncertainty is reduced by populating them with field data.

A large and modern restoration project on the Louisiana coast is where about 25% of the 1.95 million hectare coastal wetlands existing in the 1930s are now open water (Couvillion et al. 2016). The primary driving force causing land loss over the entire deltaic plain was the dredging of 16,853 km of canals and waterways for oil and gas recovery whose temporal rise and fall across the coast, and spatial distribution within,

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is coincidental with land loss rates (Turner & McClenachan 2018). Over 200 years, the rise and fall of the size of the wetlands in the subsection of deltaic plain known as the "birdfoot" delta, located at the terminal end of the Mississippi River, was driven by proportional changes in sediment supply as soils were eroded during colonization and then reduced with soil conservation and sediment trapping behind dams (Meade & Moody 2010; Tweel & Turner 2012; Turner 2017). In order to address these landscape changes Louisiana developed a restoration plan called the Louisiana Comprehensive Master Plan for a Sustainable Coast (Master Plan; CPRA 2017). The Master Plan includes $5.1 billion (US) for river diversions to move water and sediments from the Mississippi River into adjacent wetlands with the intention of maintaining and expanding them. However, the century-long nutrient enrichment of the diverted water may increase the decomposition rates of the accumulated organics, reduce root strength, and minimize roots and rhizome biomass as the pressure for nutrient foraging is eased (Swarzenski et al. 2008; Kearney et al. 2011; Turner 2011; Deegan et al. 2012; Hollis & Turner 2019). There is also uncertainty about the consequences of wetland freshening (Howes et al. 2010), a declining sediment load of the river (Mize et al. 2018), social costs (Caffry et al. 2014), the physiological consequences of flooding from the diverted water, increased storm frequency, and sea level rise (Hansen et al. 2016; Morris et al. 2016; Turner et al. 2018*b*).

Two ecosystem models explore the complexity of these interrelated factors whose physical forcings (e.g. salinity, water depth, and sediment deposition) are supported by field measurements made at a landscape scale and in laboratory studies. The Mid-Breton diversion (east bank of the Mississippi River) and Mid-Barataria (west bank of the Mississippi River) diversion are proposed to be built below New Orleans and were modeled by Brown et al. (2019) using a discharge of 141.6 and 1,416 m^{-3}/second, respectively (Brown et al. 2019; table 6.3). The Brown et al. (2019) and Baustian et al. (2018) models predict net land gain near the diversion outlets as a result of sand accumulation, and loss further way as a result of plant inundation and minimal sediment accumulation. Predictive results from the two models diverge when they predict the inundation effects on wetlands (Brown et al. 2019). Wetland vegetative growth is exclusively a function of local water depth in the Brown et al. (2019) model which says that "[s]ignificant uncertainty exists with respect to the response of the existing wetland vegetation to diversion-induced inundation." (abstract). The Baustian et al. (2018) model is dependent on an "expert assessment" for 9 of 14 validations for model components (http://coastal.la.gov/wp-content/uploads/2017/04/Attachment-C3-1&uscore;FINAL&uscore;02.22.2017.pdf; Table 3), implying that these are partly subjective conclusions that will be less definitive than the equations calculating hydrologic flow and sediment transport. Neither model includes a quantified consideration of the 30% decline in root strength (Hollis & Turner 2019) or soil strength (Turner 2011) after small increases in nutrient availability, which Baustian et al. (2018, p 415) suggest is a concern. The interactive effect of hurricanes and diversions is not included, and land gain or loss in wetland soils beyond the initial outfall area are not used to calibrate either model. The Brown et al. (2019) model validates the area of delta formation in the outfall area of the Caernarvon diversion, but not in the far-field. The changes in the West Bay diversion (birdfoot delta) that are used to validate their model are for an area that has open water areas overlying mineral soils, and the model uses sediment deposition, not land area, as the metric. The far-field inundation of wetlands, therefore, is not significant in the West Bay diversion, unlike for the two proposed diversions located northward and halfway to New Orleans (Brown et al. 2019). These latter two diversions go into shallower water with wetlands.

We agree, therefore, with a recent qualitative assessment of possible ecosystem responses to diversions by Elsey-Quirk et al. (2019): "Many of these interactions cannot be fully assessed through small-scale experimentation and thus, diversions will also serve as an important model through which to further test hypotheses and inform future management." Land–water changes occurring from existing man-made river diversions can inform coastal management plans. The quantified results can populate restoration models and be used to develop adaptive management strategies, to exploit more favorable outcomes, and to minimize or avoid undesirable outcomes.

Here we measure the relative changes in land gain and loss for two diversions to test the hypothesis that river diversions stimulate land building. A specific objective is to determine the land-building consequences of the two diversions of the Mississippi River that have been operating since 2002 (Davis Pond) and 1992 (Caernarvon). Simply put, did land loss rates increase, stabilize, or decline after diversions become operational? We address this question using: (1) two different remotely sensed imagery analyses (Data 1 and Data 2) of the percent land in the diversion flow path and adjacent reference areas that are specific to each diversion and (2) a BACI (before–after control–impact) analysis of independently developed data for one diversion. We examine differences in the percent land area before and after the diversion became operational using the average percent land for the intervals, and the relative slopes of the percent land versus year. The results, regardless of whether there is a land loss or gain, can populate models with on-the-ground data, reduce the uncertainty in model predictions, and be used to inform policy.

Methods

Experimental Design

Two river diversions were examined: Davis Pond and Caernarvon. The Davis Pond diversion is between Baton Rouge and New Orleans (190.5 km above the birdfoot delta), and Caernarvon is 24 km downstream from New Orleans (131 km above the birdfoot delta; Fig. 1). We identified pixels as either land or water within files overlaid on all geographic information system maps. The areas designated as receiving basins had levees on the east and west sides and open water to the south. Swamp and developed areas were excluded. The definition of what is a receiving basin is partly subjective, in that diversion water flows beyond it and into the entire estuary. In this sense, the

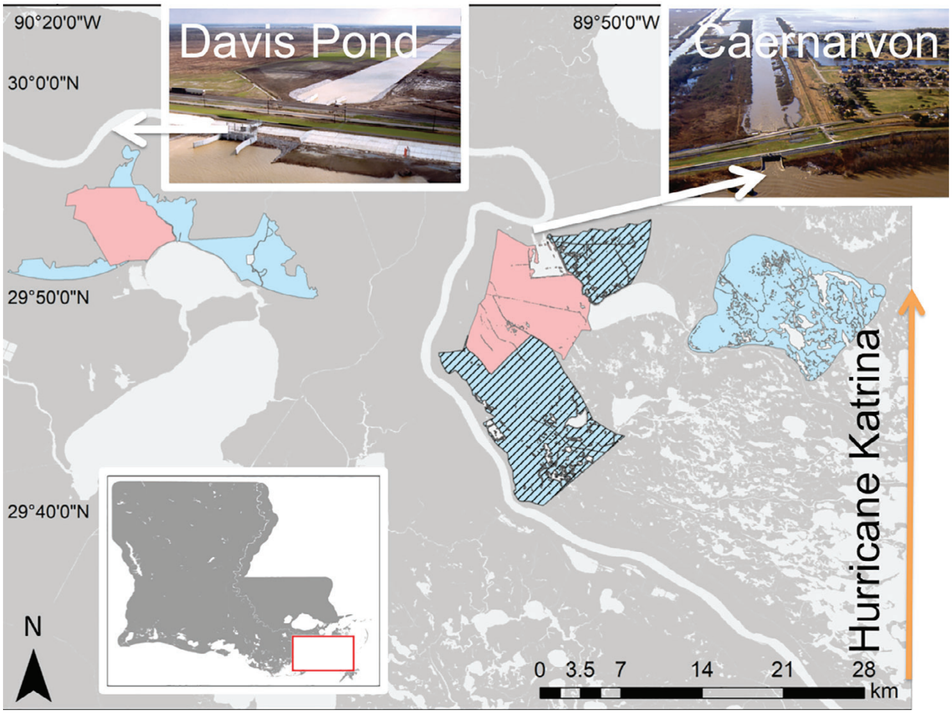

Figure 1. The location and relative position of the two river diversions bringing Mississippi River water into the adjacent wetlands. The area in the immediate flow path of the diverted water (pink) is hydrologically separated on either side by reference sites (blue) (principally levees). The Caernarvon diversion is adjacent to a reference area (location a) that is striped blue; the reference area to the east (location b) is bordered by a road that limits west-to-east flow of the diverted water, although there is some cross-linkage at Reggio, LA. The orange vertical line is the path of hurricane Katrina in 2005.

entire estuary is the receiving basin. We used the receiving basin defined by the project in State of Louisiana–defined restoration boundaries. The receiving basins are separated from the reference area by a natural or constructed levee. The Caernarvon diversion flow path closest to the diversion outfall (location a) continues far beyond the diversion discharge point. The reference areas are, therefore, partially isolated from the water flowing through the diversion's downstream path, but some water enters into reference areas at the downstream end of the diversion outfall area (Fig. 1). A second reference area outside of the hydrologic unit (location b) is located to the east that is adjacent to the Caernarvon diversion area and receives some minor amounts of diversion water through an opening in the levee at Regio, LA, on the eastern edge of the estuarine watershed. This area is the same reference area defined by Kearney et al. (2011) in their study of land loss in the area.

The land area for each diversion and reference area is shown in Table 1, along with the first year operating date, design capacity, and anticipated land area to be benefitted as determined before the diversion opened. The Davis Pond and Caernarvon diversions are the largest two sites in terms of discharge capacity and anticipated influence. The oldest diversion is Caernarvon, located on the east side of the descending bank below New Orleans. The maximum flow capacity there is 227 m^{-3}/second, and it began operations after 1991. Caernarvon was projected to benefit or create 396 km^2 of wetlands by delivering sediments and freshwater (USCOE 2004). The largest diversion is Davis Pond, which began operation in 2002, has a design capacity of 396 m^{-3}/second, and was projected to benefit or enhance at least 3,278 km^2 wetlands (USCOE 2004).

We examined state and dederal records to estimate the average discharge for each diversion. The diversion daily discharge did not usually reach the design capacity. The Caernarvon diversion from January 2000 to August 2018 had an average discharge of 41.8 m^{-3}/second; the Davis Pond diversion from January 2002 to August 2018 had an average discharge of 46.1 m^{-3}/second. Graphs of the daily discharge at each diversion are shown in Fig. S1.

Satellite Imagery

The land loss in each area was determined using two remote sensing imagery analyses that estimated the percent land in multiple years beginning in 1985. The data sets were developed using Landsat satellites equipped with different multispectral sensors. The Landsat 5, equipped with Thematic Mapper, was launched in 1984 and decommissioned in 2011; Landsat 7 was launched in 1999 and equipped with Enhanced Thematic Mapper Plus; Landsat 8 was launched in 2013 and equipped with an Operational Land Imager. These sensors have a spatial resolution of 30 m and a temporal revisit cycle of 16 days. The results from using the two data sets are classified herein as either land or water, but not wetland, because some pixels may be roads or structures, even though overwhelmingly composed of emergent wetland.

Table 1. The diversion starting date (year), maximum flow capacity (m^{-3}/second), study area size (km^2), and anticipated land gain or preservation in agency documents.

Area	Year First Opened	Capacity (m^{-3}/second)	Average Flow (m^{-3}/second)	Study Area Land (km^2)	Study Area Water (km^2)	Size Project Area (km^2)	Projected Area Benefitted (km^2)	Projected Area Preserved (km^2)	Source
Davis Pond Diversion	2002	306	46.1	39	1.0	3,278 (sum benefited and preserved)	3,144	134	USCOE (2004)
Reference				56	0.4				
Caernarvon Diversion	1991	227	41.8	62	10.4	396	332	65	USCOE (1998)
Reference				77	26				

The first data set (Data 1) was primarily developed to measure seasonal changes in wetland greenness (revealing phenological changes; Mo et al. 2019). We used 91 cloud-free Landsat Climatic Data Records (CDRs) images (mosaics of Scenes of Path 22 Row 40 and Path 22 Row 39) collected from 1985 to 2014 to estimate the wetland area (range: 1–4 images/year). The Landsat CDRs were pre-processed using the Landsat Ecosystem Disturbance Adaptive Processing System atmosphere correction tool by Schmidt et al. (2013). Further processing of the data was performed using ENVI 4.8 (ITT Exelis, Tyson Corners, Fairfax, VA, U.S.A.). The wetland area was estimated using the C version of the Function Mask (CFMask) with the Landsat CDRs. The overall accuracy of the CFMask to estimate the wetland area is $0.89 \pm 0.04\%$ (verified with the USGS Digital Orthophoto Quadrangle) (Mo et al. 2019).

The second data set (Data 2) is from 1985 to 2015 and is described by Couvillion et al. (2016) and located at: https://www.sciencebase.gov/catalog/item/5a67a8cde4b06e28e9c57150. These authors classified pixels into land and water categories using a modified Normalized Difference Water Index (NDWI) that uses the near-infrared wavelengths (1.55–1.75 μm) to reduce signal noise from land, vegetation, and soil (Xu 2006). A supervised and unsupervised classification was then used to correct for areas incorrectly classified by using only the NDWI. These steps were manually recoded by expert analysis (Couvillion et al. 2017). The resulting data set was further classified to record only the changes occurring between two successive dating intervals in sequence (persistent changes). Data 2 is used by state and federal programs to monitor land loss trends for the whole coast and changes within specific restoration project areas (Couvillion et al. 2017).

The two data sets define different kinds of land loss rates. Data 1 is from 1985 to 2014 and Data 2 is from 1985 to 2015. Data 2 includes relatively less floating vegetation classified as land than do land estimates using Data 1 because seasonal and annual changes in floating vegetation within 1 pixel are not measured as land loss unless they are also observed in the next aerial image. This methodological difference results in a more conservative estimate of the percent land for Data 2 compared to Data 1, and reduces variance from year to year.

The land area in the two diversion areas was converted to the percent of land in 1985 as a common starting point, which was normalized (= 100%). The data were sub-divided into periods for before and after each of the diversions were first opened. The opening date is shown as a dotted vertical line in figures. The Caernarvon data collected after the diversion was opened werefurther divided into periods before and after hurricane Katrina passed directly over the reference site.

Coastwide Reference Monitoring System Data

A third data set measuring land in the Caernarvon diversion area is from the Coastwide Reference Monitoring System (CRMS) administered by Louisiana's Coastal Protection and Restoration Authority. This data set includes measurements of plant cover in geographically fixed 1 km^2 sites using satellite data (Louisiana Department of Natural Resources 2018). There are 14 sites within the Caernarvon flow path and 18 outside of the flow path located to the east, north, and west. We compiled the mean ± 1 SEM (standard error of the mean) of the percent plant cover values for the 65 times that measurements were made for each quadrat from 1985 to 2016, and allocated the values for inside and outside of the flow path. The time periods were for: (1) before the diversion was operational in 1991; (2) after operation began, but before hurricane Katrina; and (3) after hurricane Katrina ($n = 8$, 16, and 11 years, respectively). The data for CRMS stations within the Caernarvon diversion flow path of Breton Sound were also sub-divided into the seven northern and the seven southern stations.

Statistical Analysis

Linear regressions of the percent land versus year were calculated for each time interval for the two river diversions using a $p < 0.05$ as the threshold to determine the significance. We used Prism software to test if there were significant slopes (% per year) within each interval, and then tested for a difference in slope within each area for before and after the diversion was opened. The comparison calculates a p value derived from an analysis of covariance (two-tailed) testing the null hypothesis that the slopes are identical (i.e. the lines are parallel). The before and after slopes for reference and diversion areas were then compared to each other ($p < 0.05$) to test for differences in slope. The intervals for the "after" comparison using the Caernarvon data ended when hurricane Katrina occurred in 2005.

The absolute rates of land loss (% per year) in reference and diversion areas before the diversion opened could be different from each other for a variety of reasons unrelated to a diversion operating. We used the relative changes in slopes to determine if there were effects after the diversion opening; we asked, therefore, if the changes (before−after) were higher or lower in the diversion flow path than in the reference site.

The land area data for the CRMS station had multiple stations sampled at the same time over many years from both reference and diversion areas. These data were used to perform a BACI analysis (Underwood 1994) using the General Linear Models (GLMs) procedure in SAS/STAT software (Version 9.4 TS level 1M2) of the SAS System for Windows (SAS Institute, Cary, NC, U.S.A.). The BACI model was originally formulated to test if an impact occurred; however, it is now mainly used to test if a change occurred (Smith 2002). The "Before" and "After" classes are based upon the timing of the event being studied (diversion or hurricane). The "Control stations" were the CRMS stations outside of the diversion flow path and the "Impact" stations were the CRMS stations within the diversion flow path.

The BACI model looked at the interaction of the "Before−After" and the "Control−Impact" statistical tests. In using the model, the data are divided into "Before" and "After" and "Control" and "Impact" classes. The basic model is:

$$\text{Response Variable} = \text{BA} + \text{YEAR(BA)} + \text{CI STATION(CI)} + \text{BA}^{*}\text{CI} + \text{YEAR}^{*}\text{BA}^{*}\text{STATION(CI)},$$

where BA denotes Before/After class, YEAR denotes measurement over time, CI denotes Control/Impact class, "*" denotes an interaction term, and parentheses indicate nesting. In the BACI analysis the main effects are not of interest, only the interaction. In order to show an impact, the BA*CI interaction term must be significant (McDonald et al. 2000).

It is possible to have a difference between the Control and Impact stations (the CI term in the model would be significant) without an actual impact due to the event if the difference between stations is always present. Similarly, it is possible to have a difference between the Before and After samples (the BA term in the model would be significant) without an actual impact due to the event if all stations had the same response (i.e. all of the stations increased by the same amount after the event). A significant BA*CI term indicates that the Impact stations are responding differently than the Control stations to the event.

The standard BACI model was run under four scenarios:

BA1: Before = pre-diversion years; After = post-diversion years.

BA2: Before = pre-diversion years; After = post-diversion, but pre-hurricane years.

BA3: Before = post-diversion years, but before the hurricane; After = post-hurricane years.

BA4: Before = pre-diversion years; After = Post-hurricane years.

The mean and standard error ($\mu \pm 1$ SEM) were computed for each year for all seven southern and all seven northern stations used for the BACI model, and a linear regression equation made of all values for each year.

Results

The range in percent land cover (normalized to the 1985 values = 100%) for each of the intervals ranged from 56.3 to 118.0% per year for Data 1 and from 54.4 to 100.0% per year for Data 2. The slopes (% per year) ranged from no changes using Data 1 to −1.07% per year for Data 2. The results for each study area are discussed below in terms of the relative changes in land loss in the reference area and in the diversion flow paths for before and after the diversion opened.

Davis Pond Diversion

The percent land in the reference site at the Davis Pond was equal before and after the diversion opened using Data 1 (mean = 95.9 and 95.4%, respectively) and slightly higher in the diversion site using Data 2 (mean = 99.4 and 98.0%, respectively). The visual appearance of the annual trends demonstrates the higher variability from year to year for Data 1 compared to Data 2 (Fig. 2), which is a consequence of how the two data sets were compiled. Data 2 is a more conservative metric because of the definition of change requires two consecutive interpretations of land conversion to land (or from water to land) for each pixel. There was a significant relationship between year and the percent land for all intervals in the reference and diversion sites using Data 2 ($p < 0.01$), but not Data 1 ($p > 0.05$; Fig. 2A & 2B; Table S1). The slope of the percent land versus year for Data 2 was slightly lower in the reference site compared to after the diversion opening (−0.06 and −0.27% per year, respectively; $F = 27.8$, $p < 0.01$; Table S1), and the slope in the diversion flow path was lower before opening compared to after opening (−0.36 and −1.07% per year, respectively; $F = 48.7$, $p < 0.01$; Table S1). The Data 2 slope in the diversion flow path before the opening, however, was lower (difference = −0.36% per year; $F = 208$, $p < 0.01$; Table S1) than in the reference site (difference = −0.60% per year; $F = 162$, $p < 0.01$; Table S1), so that the relative difference in the reference site compared to the diversion flow path was −0.49% per year after the diversion was opened. We conclude that the percent land loss at Davis Pond remained stable at the reference site, but decreased significantly within the diversion flow path after it was opened at an enhanced loss rate of −0.49% per year.

Caernarvon Diversion

The results from the analysis of the Caernarvon diversion area provides a more complex picture for the first few years after the diversion opened (from 1992 to 2005) compared to after

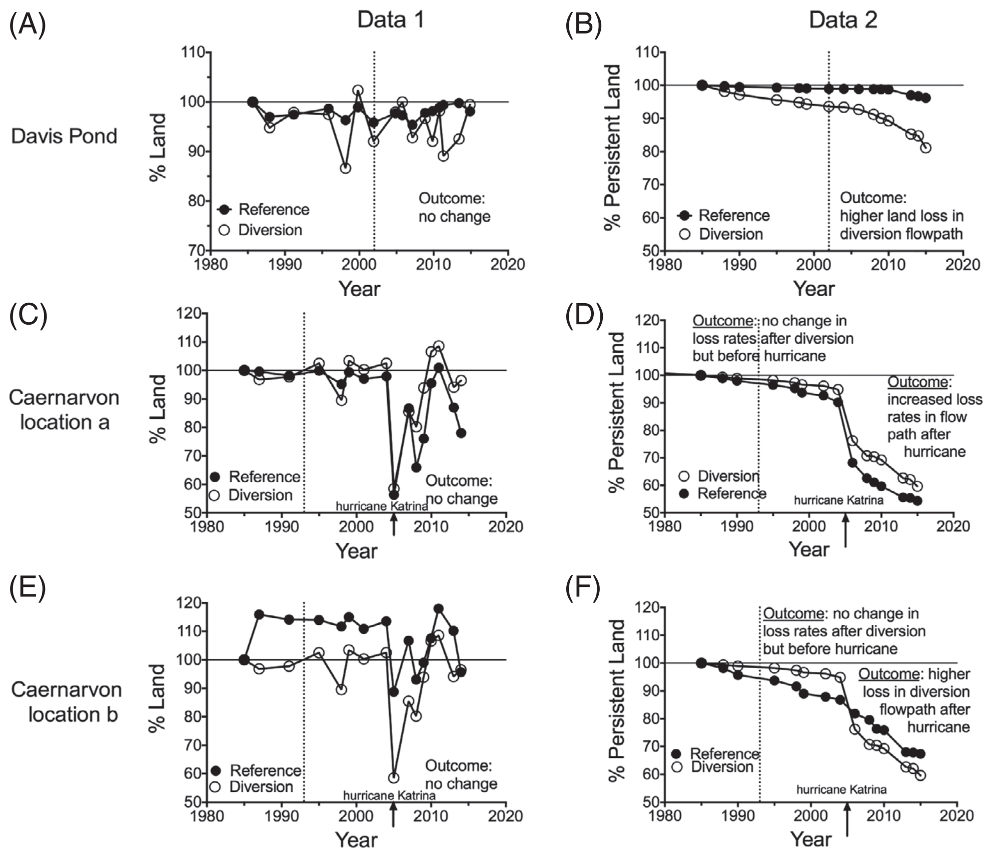

Figure 2. The percent land in the flow path of the diverted water (open circles) and in the reference (filled circles) site for Data 1 and Data 2. The data were normalized to the land area in 1985. The dotted vertical line indicates when the diversion was first opened. (A, B) Davis pond; (C, D) Caernarvon location a; (E, F) Caernarvon location b.

hurricane Katrina (2010). The highest average percent land area then was in the reference area for Data 1, location b (110.0%), and ranged from 98.1 to 99.27% in the other five areas. There were no significant slopes (% per year) for any interval using Data 1, or change in them before or after the diversion opened. The percent land in the diversion area using both Data 1 and 2 was slightly higher compared to in the reference area before hurricane Katrina, but was dramatically different afterwards (Fig. 2E & 2F). The percent land using Data 1 did not decrease after the diversion opened but decreased after hurricane Katrina and then recovered (Fig. 2C & 2D). Post-hurricane, however, the percent land in the diversion flow path remained above the percent land in reference location a, but fell below the percent land in the reference area in reference location b. The analysis of Data 2 revealed no significant difference in the loss rates at the reference or diversion locations a and b *after* the diversion opened but before 2010. There were significant losses in all areas after 2010 (Table S1).

Cumulative Changes

A summary of the relative differences between the changing slopes, or not, for Data 2 is shown in Figure 3 for the three comparisons. The relative differences between land loss rates in reference and diversion areas in Davis Pond (Fig. 3A) were increasing before the opening of the diversion; the reference area declined slowly compared to the reference site, and so the slope was decreasing. The decline in percent land increased even faster than in the reference area after the diversion opened because of the increased land loss in the diversion area. The percent land in the Caernarvon area at the reference site compared to in the diversion flow path were not different before or after the diversion opened, but before hurricane Katrina passed over both areas (Fig. 3B & 3C). The percent land area in the reference site was then changing at a slower rate than in the flow path and so the slope is positive. After the hurricane, however, the percent land in the diversion flow path dropped relative to that in the reference area, particularly for location b. It had not recovered by 2015. The data suggest, therefore, that the Caernarvon diversion had no effect on increasing loss rates in the flow path immediately after the diversion opening; after the hurricane, however, the loss rates increased substantially in the diversion flow path in location b, but less so in location a.

BACI Test

The results from the BACI test for the Caernarvon data (Fig. 4; Table S2) demonstrated a significant control−impact interaction

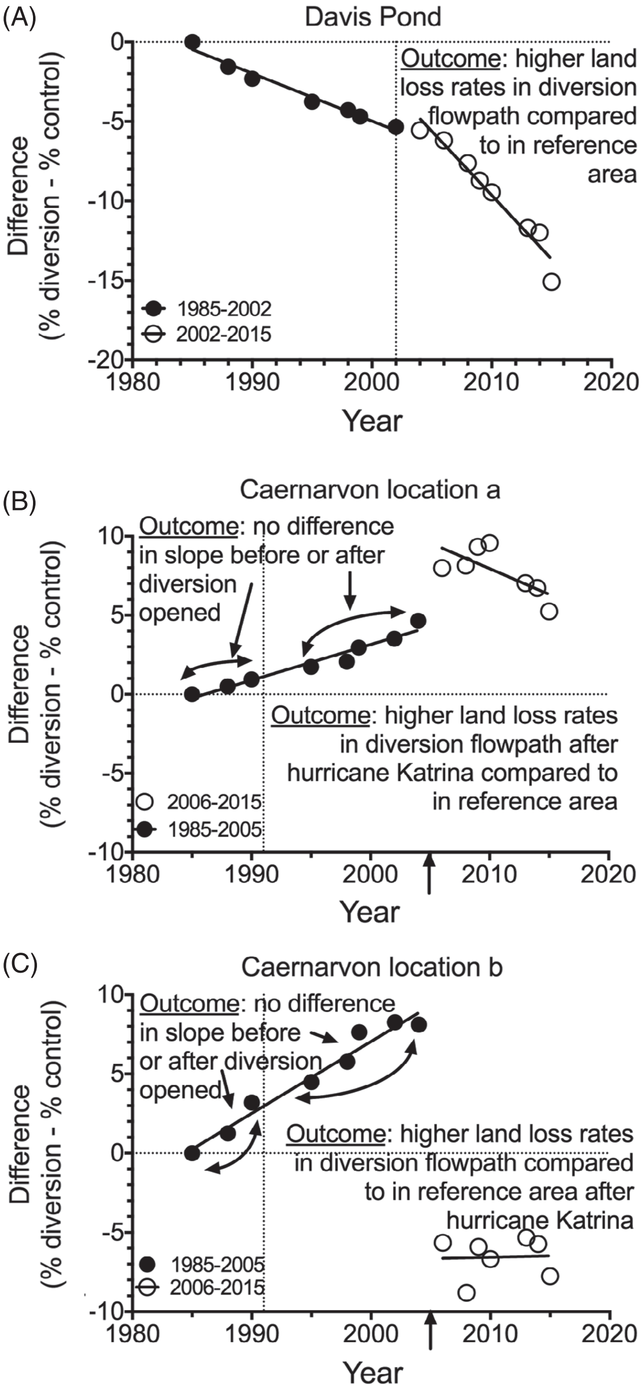

Figure 3. The relative differences between the percent land for the three comparisons using Data 2.

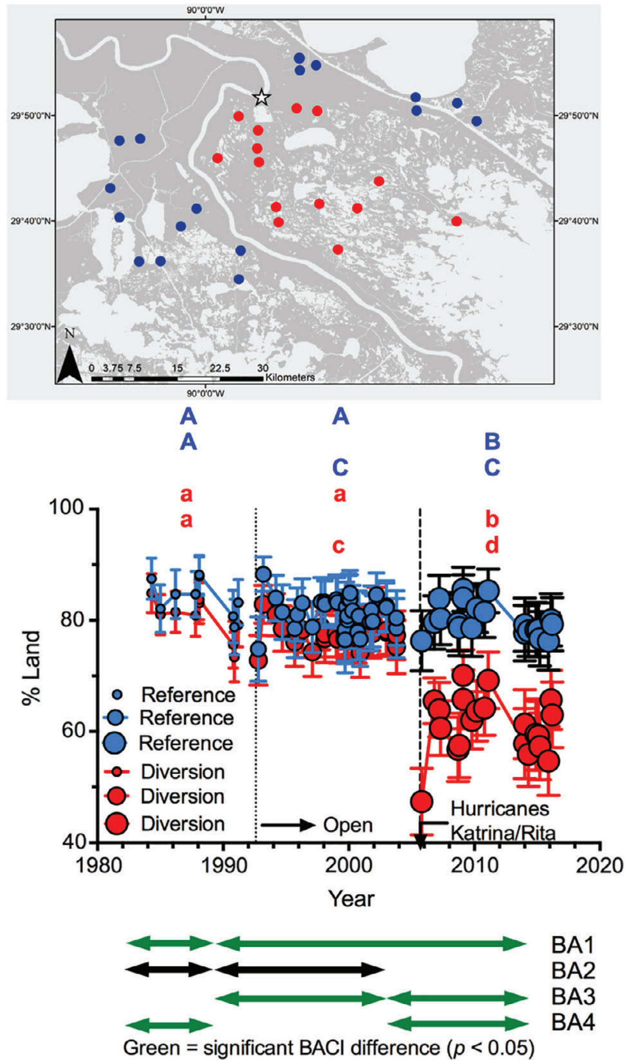

Figure 4. The percent land in the coastal monitoring program (http://lacoast.gov/crms2/) within the Caernarvon diversion flow path (red dots) and outside (blue dots). The mean and SEM is shown. The data are divided into three periods: (1) small circles representing before the diversion was opened; (2) the medium-sized circles after the diversion was opened, but before kurricane Katrina; and (3) the large circles representing after kurricane Katrina. The results from an analysis of variance test of differences between the three periods is indicated by the letters where the uppercase blue letters are for the reference site and the lowercase red letters are in the diversion flow path. The results from the BACI test indicating a significant change in the percent land after the diversion was opened compared to before the opening for all data (BA1) and after hurricane Katrina (BA4) is given. There was no change detected before the diversion opening and in the first few years afterwards (BA2). The percent land after the diversion opened was lower after the hurricane compared to before the hurricane (BA3).

term for intervals BC1, BC3, and BC4, indicating that there was a different response between the control and impact sites. There was no increase in the percent land within the flow path (restoration or rehabilitation) from 2010 to 2016 (Fig. 4). The percent land was the same in the 14 reference sites before the diversion opened compared to afterwards (but before the hurricane) ($p > 0.05$), but lower in the flow path after the hurricane ($p < 0.001$; Fig. 4). The interaction term was not significant for interval BC2 indicating that the control and impact sites had the same rate of change. The average percent land in the seven northern and the seven southern CRMS stations changed coincidentally from 1985 to 2016 (Fig. S2), and the average percent land for the southern stations was a consistent

70% of that in the northern stations ($R^2 = 0.79$; Fig. S2), which confirms that the watershed is an integrated basin in terms of land losses and gains. These results are consistent with the results from the analysis of variance of the aerial imagery for the Caernarvon diversion.

Discussion

Two first-order observations are: (1) there is no evidence of a change in net land gain or conservation within the two sites after the diversion operation began and (2) there is clear evidence of higher land loss rates within a few years after the Davis Pond diversion opened. The Caernarvon diversion had no appreciable land gain, and perhaps a slight land loss in the first few years after it opened, and then considerable losses after hurricane Katrina which were about 25% of the larger area (Kearney et al. 2011). We measured land loss after hurricane Katrina that was about one-third of the wetlands in the flow path, which is a comparable loss to the natural diversion that occurred at Fort St. Philip in 1973 (Suir et al. 2014). There the loss was 58% of the surveyed area and has not been restored after 38 years. The Fort St. Philip diversion was about 12 times larger at maximum flood than the potential discharge size at Caernarvon, and one-third larger than the flow capacity of diversions proposed in the Master Plan. The discharge at Fort St. Philip is not monitored on a regular basis, so further comparisons are not possible with the data presented here.

The result of the Brown et al. (2019) modeling analysis of net land change for several diversions was that “none of the scenarios tested have a net land gain, due to the losses of land incurred from inundation of the vegetation.” (p 111) They estimated that these inundation effects are an “overwhelming source of uncertainty” in the model results (p 97), so we think that model improvements might change outcomes to produce different outcomes, including net gains or losses. That uncertainty might be reduced by incorporating the decades-long land loss rates of the diversions studied here. The areas we used as the flow path and reference zones could be enlarged, substituted, or shrunk in order to implement such a training model.

Diverting river water to the adjacent wetlands increases sediment supply, but also affects plant flooding and nutrient availability, but not equally across the landscape. The heavier soil particles (principally sand) introduced with diversions fall out quickly as river currents slow in an open water body, whereas the remaining suspended particles spread out over a larger area and with an eventual capture efficiency on the deltaic plain of roughly 30–70% (Blum & Roberts 2009). The water and its nutrients are distributed horizontally and vertically far beyond where the sand particles accumulate.

The diverted water floods the marsh for longer and more frequent intervals, which is a well-recognized plant stress (Mitsch & Gosselink 2007; Keddy 2011). Further, the nutrient concentrations in the modern Mississippi River are much higher than the organic content of the sediment accumulated centuries ago (Turner et al. 2007; Tweel & Turner 2012). The increased nutrient availability in the receiving basin may cause lower belowground biomass because (1) the accumulated organic matter may decompose faster; (2) the reduced pressure for plants to forage for nutrients leads to a smaller belowground biomass (Darby & Turner 2008; Turner et al. 2018*a*); (3) it results in weakened individual roots as the internal structure of roots adapts to flooding and nutrients (Hollis & Turner 2019); and (4) perennial plants replace annuals to alter the vertical distribution of roots (Howes et al. 2010). These four factors cause a loss in soil strength (Turner 2011). The sediments then become more susceptible to erosion during high water events or from hurricanes (Howes et al. 2010; Kearney et al. 2011). The combined stress of inundation and increased nutrient availability is one explanation for why wetlands converted to open water in the Caernarvon diversion flow path after hurricane Katrina and have not re-vegetated, whereas the reference wetlands are losing land at the same rate as before the diversion opened even though the hurricane passed right over it. Other hurricanes, including hurricane Betsy in 1963, also passed nearby and did not cause this amount of reduction in the percentage of land. From 1956 to 1973, e.g., the percent land in the diversion flow path and at the reference sites decreased by 5% (Couvillion et al. 2017), whereas it declined about 20% after hurricane Katrina.

The two diversions analyzed here are distinctly different from the Atchafalaya Delta located westward in the middle of the coast and sometimes described as a river diversion. The Atchafalaya River carries 30% of the Mississippi River that is sent through a water control structure near St. Francisville, LA, to join with the Red River to create the Atchafalaya River. Unlike the Davis Pond and Caernarvon diversions, the Atchafalaya River discharges into the open water that overlie mineral soils, and not into the shallow water and organic-rich wetland soils of the Caernarvon and Davis Pond diversions (Turner 2017). The far-field effects of nutrients and inundation on vegetation are immaterial there. Further, the Mississippi River main channel below New Orleans traps almost all of the land-building materials (Allison et al. 2012), which means that an upstream diversion of sediments diminishes land building or maintenance downstream, leading to a zero-sum land area change for the whole delta (Turner 2017).

This analytical approach provides data to populate models with empirical data collected at a landscape scale; other areas might also be compared and we recommend doing that using the Data 2, not Data 1, because there is less floating vegetation represented in Data 2. Regardless of the data used, the model results must accurately reflect the empirical results, even if the underlying causes are not understood. The cost, efficacy, and duration of ecological restoration is illuminated, developed, and improved by incorporating the empirically defined field data, especially in a newly developing modeling field like coastal wetland restoration (Zedler 2017). The inclusion and evaluation of meaningful monitoring at a landscape scale should be included in an adaptive management scheme to know if the management action was successful or not (Ralph & Poole 2003; Zedler 2017). Not doing this surely results in a higher scientific uncertainty and reduces public trust. The anticipated benefits of two diversions were not realized, which supports a recommendation to “do no harm.” Implementing the proposed river diversions in the Master Plan appears premature because the modeling is incomplete, and the empirical results from the three nearby diversions are not replicated in model outputs.

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Supporting Information

The following information may be found in the online version of this article:

Figure S1. The daily discharges at the two river diversions.
Figure S2. The annual percent land for the seven northern (*x*) and seven southern stations (*y*) of the diversion flow path shown as red dots.
Table S1. The statistics underlying determinations within intervals (A), the *F* values (B), the loss rates for each interval (C), differences in the rates within between before and after interval (D), relative differences between changes at the reference and diversion sites (E), and interpretations for each interval in all reference and control sites (F–H).
Table S2. Summary of the BACI analysis for the CRMS station land acreage data in the Caernarvon flow path versus the CRMS station land acreage data in the wetlands adjacent to the flow path.

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