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# Modeling impacts of sea-level rise, oil price, and management strategy on the costs of sustaining Mississippi delta marshes with hydraulic dredging

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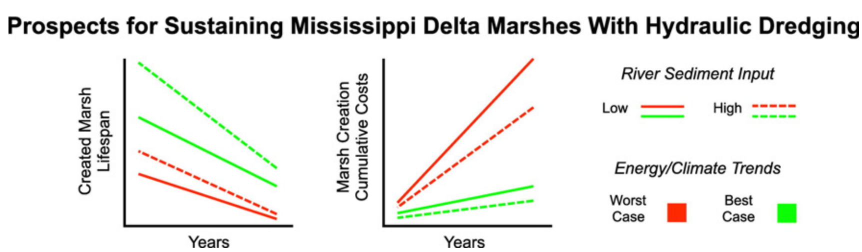
## HIGHLIGHTS

- Hydraulic dredging can be used to create new coastal marsh.
- Oil price has a significant effect on the costs of hydraulic dredging.
- We modeled energy and climate impacts on marsh creation costs.
- Costs increase significantly due to increasing dredging price and frequency.
- Marshes receiving sediment from river diversions are cheaper to sustain.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Over 25% of Mississippi River delta plain (MRDP) wetlands were lost over the past century. There is currently a major effort to restore the MRDP focused on a 50-year time horizon, a period during which the energy system and climate will change dramatically. We used a calibrated MRDP marsh elevation model to assess the costs of hydraulic dredging to sustain wetlands from 2016 to 2066 and 2016 to 2100 under a range of scenarios for sea level rise, energy price, and management regimes. We developed a subroutine to simulate dredging costs based on the price of crude oil and a project efficiency factor. Crude oil prices were projected using forecasts from global energy models. The costs to sustain marsh between 2016 and 2100 changed from $128,000/ha in the no change scenario to ~$1,010,000/ha in the worst-case scenario for sea level rise and energy price, an ~8-fold increase. Increasing suspended sediment concentrations, which is possible using managed river diversions, raised created marsh lifespan and decreased long term dredging costs. Created marsh lifespan changed nonlinearly with dredging fill elevation and suspended sediment level. Cost effectiveness of marsh creation and nourishment can be optimized by adjusting dredging fill elevation to the local sediment regime. Regardless of management scenario, sustaining the MRDP with hydraulic dredging suffered declining returns on investment due to the convergence of energy and climate trends. Marsh creation will likely become unaffordable in the mid to late 21st century, especially if river sediment diversions are not constructed before 2030. We recommend that environmental managers take into consideration coupled energy and climate scenarios for long-term risk assessments and adjust restoration goals accordingly.



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# 1. Introduction

## 1.1. 21st century megatrends and Mississippi delta restoration

About 28% of the wetlands of the Mississippi River Deltaic Plain (MRDP) were lost in the 20th century, due to land subsidence, exclusion of river sediment by dams and levees, and other hydrologic modifications along the coast (Couvillion et al., 2011; Day et al., 2005). Major restoration is needed to sustain the MRDP (CPRA, 2017a). The forces expected to impact coastal areas during the 21st century include accelerating sea-level rise (SLR), changes in river discharge, increase in the frequency of extreme weather events (including drought, intense precipitation, and tropical cyclones), and the cost and availability of energy (Balaguru et al., 2016; Day et al., 2016a; IPCC, 2013; Prein et al., 2017; Tao et al., 2014; Tessler et al., 2015; Sobel et al., 2016). $CO_2$ levels are now tracking the highest IPCC scenarios (Friedlingstein et al., 2014; Strauss et al., 2015) and 1–2 m of SLR is projected during the 21st century (DeConto and Pollard, 2016; Horton et al., 2014; IPCC, 2013). World fossil fuel production is projected to peak by mid-century or possibly sooner (Mohr et al., 2015). The net energy ratio, an indicator of energy quality, is declining for fossil fuel production, with negative implications for societal well-being (Hall et al., 2014; Lambert et al., 2014; Tripathi and Brandt, 2017). In coming decades, the transition from cheap, high net energy yielding fossil fuels to expensive, low net energy yielding fuels will increase the cost of energy, unless there is revolutionary new technology or dramatic reduction in demand (Heun and de Wit, 2012; EIA, 2015). This will affect petroleum prices (McGlade, 2014), upon which maritime activities and delta restoration are heavily reliant (Bray et al., 1997).

The high wetland loss rates in the MRDP are projected to continue with an additional loss of over 5000 km$^2$ by 2050 (Blum and Roberts, 2009; CPRA, 2017a). The Louisiana Coastal Master Plan (LACMP), developed by the Louisiana Coastal Protection and Restoration Authority (CPRA), is a 50-year, $50 billion effort to restore and protect the MRDP's coastal ecosystems and economy (CPRA, 2012a, 2017a). CPRA projects that 2017 LACMP restoration projects will build and/or sustain ~2000 km$^2$ of wetlands that would otherwise be lost (CPRA, 2017a). The two main restoration strategies for land building in the LACMP are marsh creation (MC) and nourishment via hydraulically dredged sediments and river sediment diversions (henceforth referred to as "diversions") (CPRA, 2017a). Marsh "creation" refers to filling an open water area with a mean depth of 30 cm or greater. Marsh "nourishment" refers to filling area with patches of deteriorating marsh with a mean depth between 0 and 30 cm. In terms of land building, MC is an energy-intensive approach with immediate impacts, while diversions, once constructed, are a lower energy approach with recurring positive impacts over time (Day et al., 2016a, 2016b). Here, we investigate the influence of energy costs, SLR, river sediment input, and construction specifications on the costs and sustainability of marsh creation and nourishment using hydraulic dredging.

## 1.2. Environmental controls on coastal marsh sustainability

Coastal marsh elevation is a function of relative SLR (RSLR), tidal range, total suspended sediment concentration (TSS), and marsh productivity (Fagherazzi et al., 2012; Morris et al., 2002; Mudd et al., 2009). RSLR is the sum of eustatic SLR and isostatic movement of the earth's crust. Deltas subside naturally due to consolidation of Holocene sediment (Meckel et al., 2006). Compared to most coastal regions, the MRDP has high RSLR and low tidal range, therefore high sediment input and productivity are needed to sustain marsh elevation (Fig. 1). Much early focus on MRDP restoration has been on deposition of coarse grain sediment (sand) for delta building. At least 75% of the sediment carried by the Mississippi river are fine sediments (Allison et al., 2012; Allison and Meselhe, 2010), but the majority of silt and clay is not deposited immediately within a newly forming delta (Roberts et al., 2015). Rather, fine sediments are deposited in nearby bays and wetlands, or are exported to the coastal ocean. Riverine sediments deposited in bays are re-suspended during storms and some of these sediments are advected onto coastal marshes (Perez et al., 2000). This process has been identified as a key driver sustaining MRDP coastal wetlands, where there is a steady supply of river sediment (Day et al., 2011; Roberts et al., 2015; Twilley et al., 2016). In this paper, we model the influence of increased TSS from river throughput on sustaining coastal marshes (Fig. 1). The analysis is based on data from natural analogs in the MRDP, including new delta lobe development (DeLaune et al., 2016; Roberts et al., 2015; Twilley et al., 2016) and crevasses (Day et al., 2012, 2016a, 2016c).

## 1.3. The costs and energy intensity of sustaining coastal areas

Coastal restoration is costly and energy intensive (Table 1, Clark et al., 2015; Moerschbaecher and Day, 2014; Tessler et al., 2015). $17.8 billion dollars is allocated for MC projects in the LACMP, while $5.1 billion dollars is allocated for diversion projects (Table 1). To deliver sediment, MC requires large machinery such as "cutter-suction" dredges, bulldozers, booster pumps, generator barges and more (Clark et al., 2015; CPRA, 2017a; Day et al., 2005 Murphy, 2012). Diversions vary in their complexity, but in most cases building a diversion is a major construction project, where concrete, steel, and heavy machinery, are required (Kenney et al., 2013).

The price of energy, oil in particular, influences the costs of restoration (and other) activities directly through changes in fuel prices (which closely follow the price of crude oil) and indirectly by influencing other input commodity prices, such as steel and concrete (Ji and Fan, 2012; World Bank, 2015). Dredges, like most heavy construction equipment, are almost exclusively powered by diesel fuel and costs of operation are sensitive to diesel price (Hollinberger, 2010; Murphy, 2012). Proposed dredging for the 2012 LACMP is estimated to require between 0.71 and 5.2 L of diesel fuel per cubic meter of sediment, depending on pumping distance (Clark et al., 2015). The mean real price of dredging in the U.S. increased 72% between 2000 and 2010 (Cohen et al., 2011), coinciding with a 150% increase in the real price of crude oil (EIA, 2015). Fluctuations in oil prices are linked to economic expansions and recessions, which affect material prices as well (Hamilton, 2012; Murphy and Hall, 2011).

Highly developed deltaic coasts that rely on energy-intensive management are at high risk for non-sustainable outcomes with climate change in a high energy price future (Day et al., 2016a; Tessler et al., 2015). But even without consideration of energy there are significant financial constraints on coastal management in Louisiana. Only about $26 billion dollars have been secured for the LACMP, roughly half of the total cost (CPRA, 2016a). The actual cost to restore and protect Louisiana's coastline, after including omissions from the LACMP, such as maintenance of existing flood control structures, is estimated to exceed $91 billion (Barnes et al., 2015). This amount could rise significantly with increasing energy costs. Our focus on quantifying the influence of energy costs on hydraulic dredging (for marsh creation) makes this study important for the MRDP, and developed coastal areas worldwide.

## 1.4. Objectives & hypotheses

The objective of this study is to simulate the cost of hydraulic dredging to sustain coastal marshes of the MRDP with and without elevated TSS from a river diversion for a range of trajectories in future SLR and oil prices. We pursued the following sub-objectives: (1) Analyze the statistical relationship between oil prices and the cost of dredging using data from projects completed in the MRDP. (2) Model the costs of coastal restoration into the future as a function of oil prices and sea-level rise (SLR). (3) Investigate the sensitivity of the cost effectiveness of MC efforts to changes in TSS concentration, and the fill elevation of MC projects ($E_{fill}$).

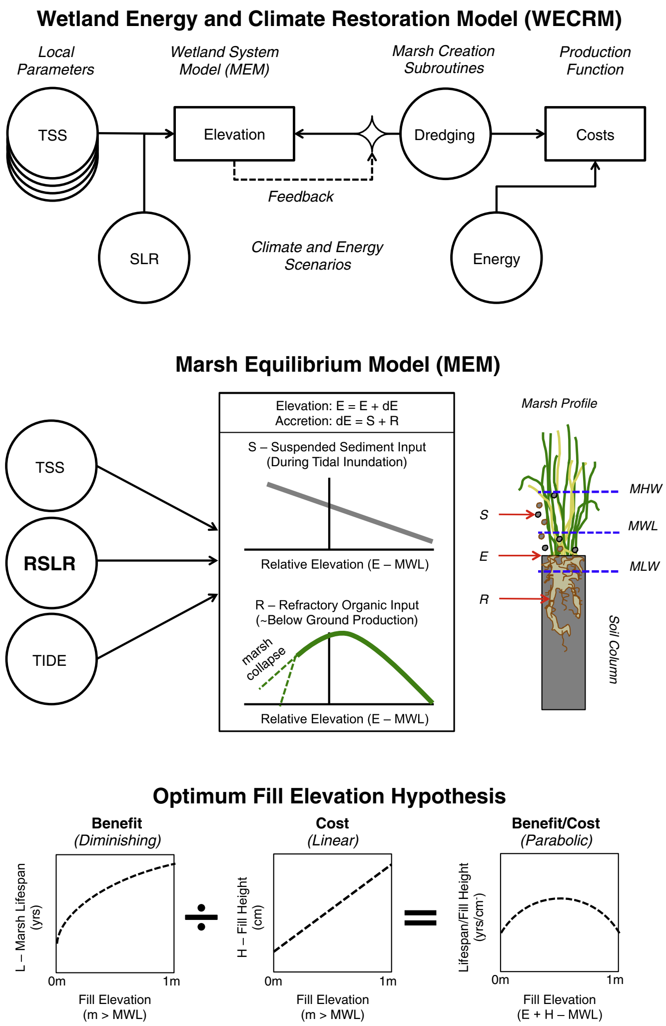


**Fig. 1.** Conceptual diagrams of the Wetland Energy and Climate Restoration Model (WECRM, top), the Marsh Equilibrium Model (MEM, center), and the optimum fill elevation hypothesis for marsh creation (bottom). TSS – total suspended sediments, MC – marsh creation (hydraulic dredging), Energy – oil prices, SLR – sea-level rise, RSLR – relative sea-level rise (SLR plus subsidence), MHW – mean high water, MLW – mean low water, MWL – mean water level, E – elevation, S – sediment input, R – root/rhizome input.

We hypothesized that: (H1) The unit cost of dredging for MRDP restoration is positively correlated with the price of oil. (H2) Marshes with higher TSS concentrations due to riverine input will incur lower restoration costs and be more sustainable over time than areas isolated from river influence. (H3) (a) There are diminishing marginal returns on restored marsh lifespan per unit increase of the dredging fill height (Fig. 1). This is due to predicted acceleration of SLR (DeConto and Pollard, 2016), and feedbacks that occur with increasing elevation such as: decreasing plant productivity and mineral sediment input, as well as increasing oxidation. These feedbacks are stronger in microtidal regions such as the MRDP (Kirwan and Guntenspergen, 2010). (b) Costs, however, increase linearly with fill elevation. (c) Therefore, in terms of dredging effectiveness – created marsh lifespan divided by cost of MC or amount of fill – an optimal dredging fill height exists at some elevation above mean water level but <1 m (Fig. 1).

## 2. Methods

### 2.1. The Wetland Energy and Climate Restoration Model

The Wetland Energy and Climate Restoration Model (WECRM), is a FORTRAN 95 program that we developed to simulate the costs of restoring MRDP coastal marshes under future trajectories of sea-level rise and energy prices (Fig. 1). WECRM uses a 1-D ecogeomorphic wetland model to simulate elevation as a function of sea-level rise and local forcings. Elevation relative to mean water level ($E_{RWL}$) is a feedback to subroutines that determine when to initiate dredging for marsh creation. For example, when a marsh reaches a certain threshold in $E_{RWL}$, a specified amount of dredged sediment is added to the marsh. The year of dredging determines the unit cost of that sediment addition based on the projected oil price.

The Marsh Equilibrium Model (MEM) (Morris et al., 2002, 2012) and the Integrated Wetland Ecosystem Model (IWEM) (Rybczyk et al., 1998; Rybczyk and Cahoon, 2002) were adapted to simulate the soil accretionary dynamics observed in both natural and created marsh habitats of the MRDP (see Appendix-C). A series of forcing scenarios for SLR and oil prices were developed using the full range of values reported in the scientific literature and incorporated into the model (see Appendices-A and -C). To investigate H1, we developed a model for dredging price as a function of oil price based on data from dredging projects in the Louisiana Coastal Zone (see Appendix-B). To investigate H2, we simulated elevation of a prototype MC project that was sustained periodically with re-nourishment starting in 2016 for the full range of SLR and energy forcing scenarios, with TSS levels of 20, 40, 80, and 160 mg/L. To investigate H3, we simulated a series of single marsh creation efforts implemented in 2016 with fill elevations ranging from 2 to 200 cm, increasing at 2 cm increments, for each sea level scenario and with TSS levels of 20, 40 80, and 160 mg/L. Details follow.

### 2.2. Wetland modeling

WECRM's wetland system model simulates water level, marsh productivity and sediment deposition and resulting elevation dynamics

**Table 1**
2017 Louisiana Coastal Master Plan funding allocation by project type.
Source: CPRA (2017a).

| Class | Project type | Funding ($ billions) | Percent of funds | Prime mover |
|---|---|---|---|---|
| Restoration | (Total) | 25.8 | 51% | N/A |
| | Barrier island | 1.5 | 3% | Hydraulic dredge, bulldozer |
| | Hydrologic | 0.4 | 1% | Pump or gravity[a] |
| | Marsh creation | 17.8 | 35% | Hydraulic dredge, bulldozer |
| | Ridges | 0.1 | 0% | Excavator, dragline or bucket dredge |
| | Sediment diversion | 5.1 | 10% | Gravity[a] |
| | Shoreline protection | 0.9 | 2% | Barge, crane or N/A[b] |
| Risk reduction | (Total) | 25 | 49% | N/A |
| | Structural (levees) | 19 | 37% | Excavator, dragline or bucket dredge |
| | Nonstructural | 6 | 12% | Various |
| Total | | 50.8 | 100% | N/A |

[a] Various machinery is required to build the control structures; after which the displacement of water or sediment is controlled by gravity (and pumps in some cases for hydrological restoration).
[b] Oyster reefs have various methods of creation; Rock armor shorelines and jetties require barges and cranes.

on a weekly time step. Primary productivity, organic matter and mineral sediment equations were adapted from the MEM (Morris et al., 2002, 2012), which has been extensively calibrated/validated along the Atlantic and Pacific Coasts (Alizad et al., 2016; Byrd et al., 2016; Davis et al., 2017; Morris et al., 2002; Schile et al., 2014). State equations for biomass and organic sediment were adapted from the IWEM (Rybczyk et al., 1998; Rybczyk and Cahoon, 2002). We calibrated WECRM to Louisiana brackish/saline tidal marshes based on accretion and water level data from sites in the Coastwide Reference Monitoring System (CRMS, LA Coast, 2016). Documentation is provided in Appendix-C.

Using the MEM, sediment deposition was modeled as a function of the maximum inundation depth, the mean TSS (mg/L) of the adjacent water body, and above-ground biomass (g d.w. $m^{-2}$). We parameterized TSS concentrations based on published data from Terrebonne Bay, Fourleague Bay, and the Wax Lake and Atchafalaya Delta areas. Mean TSS for sites with river influence range from 60 to 120 mg/L, while areas without river influence range from 20 to 40 mg/L (Day et al., 2011; Murray et al., 1993; Perez et al., 2000; Wang et al., 1994; Wang, 1997). Mean concentrations in the Mississippi River and deltaic throughput sites can be as high as 200 mg/L (Allison et al., 2012; Allison et al., 2014), with annual mineral deposition exceeding 15,000 g $m^{-2}$ $yr^{-1}$ (see Appendix-C, Table C2).

Productivity was modeled as a function of percent inundation and weekly mean temperature (e.g. Kirwan and Guntenspergen, 2012; Snedden et al., 2015). Soil volume was modeled using the ideal mixing model, which splits mineral and organic matter into separate volumes with self-packing densities of 1.99 and 0.085 g/$cm^3$ respectively (Morris et al., 2016). Under this assumption, organic matter accumulation is the major driver of marsh elevation change. Refractory organic material in TSS and dredged material was set to 3%, giving a bulk density of 1.18, which is consistent with crevasse splays and newly created marshes (Day et al., 2016c; Edwards & Proffitt, 2003; Mendelssohn and Kuhn, 2003). Maximum above-ground primary productivity was set to 2400 g $m^{-2}$ $yr^{-1}$ and ratio of root/rhizome to shoot productivity was set to 2:1 (Hopkinson et al., 1978; Nyman et al., 1995). It was assumed that below ground biomass was 10% refractory (Hodson et al., 1984; Wilson et al., 1986; Buth and Voesenek, 1987), above-ground biomass was 1% refractory and exported from the marsh at 50% $yr^{-1}$ (Hopkinson et al., 1978; Nyman et al., 1993), and the decomposition rate of labile material was 40% $yr^{-1}$ (Lane et al., 2016) (see Appendix-C). A table of model parameters is given in Appendix-D.

### 2.3. Relative sea level rise

Five eustatic (global) SLR scenarios were used (SLR-1, SLR-2, SLR-3, SLR-4, SLR-5, Fig. 2A, Appendix-C) that cover the range of scientific projections to date. The SLR-1 assumes the rate remains constant at the current 3.5 mm/yr (CUSLRG, 2016). This is near the low end reported by IPCC models. Church et al. (2013) report a minimum value of 0.31 m of sea-level rise by 2100, relative to 1992. SLR-2, 3, 4, and 5 start at 3.5 mm/yr in 2016, and accelerate toward a specified sea-level in 2100 relative to 2016, of 0.57 m, 1.03 m, 1.45 m, and 1.83 m, respectively. SLR-5 is consistent with the highest estimates from semi-empirical models and new findings that indicate greater contributions from polar ice sheets, which suggest up to 2 m of sea-level rise (relative to 1992) by 2100 (DeConto and Pollard, 2016; Pfeffer et al., 2008; Vermeer and Rahmstorf, 2009). A total subsidence rate of 8.7 mm/yr was used based on the median estimate for all CRMS sites made by Jankowski et al. (2017) (see Appendix-C).

### 2.4. Oil prices

We reviewed the energy modeling literature and developed a range of projections for oil prices (Fig. 2B) (EIA, 2015; IEA, 2015; Heun and de Wit, 2012; McGlade, 2014). The Low, Central, and High oil price scenarios are averages of the 0%–33%, 34%–66%, and 67%–100% percentiles of fifteen model outputs from the aforementioned sources (Appendix-A). Oil prices were adjusted to 2010 dollars using the consumer price index, the method used by EIA (2016). The model outputs used in each trajectory go to the year 2035. Forecasts were extrapolated beyond this date to 2100 based on the five-year mean rate of increase from 2030 to 2035 and multiplied this by an annual decay rate of 5% to be conservative (see Appendix-A). A No Change scenario where prices remain constant at $55/bbl was also included (see Appendix-A). Oil prices were significantly higher than during the formulation of the 2012 and 2017 LACMPs in both the High and Central scenario, while the low scenario is not significantly different. In the Central scenario oil prices are above $100/bbl after 2021 and reach $150/bbl by 2050. In the High scenario, oil prices rise to $200/bbl in 2030 and reach $300/bbl by 2040.

### 2.5. Marsh creation costs

We developed a production function – a model for the total output (or cost) of a physical economic activity that transforms energy and material units into final products (e.g. Georgescu-Roegen, 1970, 1972, 1979; Warr and Ayres, 2010) – for a single MC effort using the dredging unit price ($P_D$) and borrow volume (BV) (Eq. (1)). Future $P_D$ was simulated based on the price of crude oil from the scenarios described above (Eq. (2), see Appendix-B).

$$C_{MC} = mf \cdot P_D \cdot BV \quad (1)$$

$C_{MC}$ is the real (CPI adjusted) cost of marsh creation (2010\$/$m^2$); mf is the mark up factor for remaining construction activities, profit and risk; BV is the total borrow volume ($m^3$) for the project (i.e., the total material displaced from the borrow site); $P_D$ is the function from Eq. (2). Dredging costs are 60–70% of total construction costs for MC projects (CPRA, 2012b); accordingly, we set mf to 1.5 (see Appendix-B).

The function for the $P_D$ was developed using data from coastal restoration project completion reports. We compiled a dataset on cutter suction dredging for coastal restoration projects completed in the MRDP (see Appendix-B) and fit a multiple regression model for the real (2010 PPI adjusted, code: BCON, https://www.bls.gov/ppi/) unit price of cutter suction dredging ($P_D$). The "lm" function in R statistical software (R Core Team, 2013, Lumley and Miller, 2009) was used to fit the model given below and in Fig. 2C.

$$P_D = e^{[b_0 + b_1 \cdot \ln(P_{CO}) + b_2 \cdot DR + b_3 \cdot Ek]} \quad (2)$$

$P_D$ is the real unit price of cutter suction dredging (2010\$ $m^{-3}$); $P_{CO}$ is the real (2010 CPI adjusted, https://www.bls.gov/cpi/) mean price of crude oil during the 12 months prior to the contract award; Ek is the efficiency/scaling factor, equal to the log of borrow volume over the log of horsepower capacity of the dredge system (CY/HP); and DR is an integer indicating whether or not dredging is for beach and dune restoration. If sand is being dredged for beach and dune restoration, DR = 1, if dredging is for something else (marsh creation or beneficial navigation dredging), DR = 0; $b_0$-$b_5$ are model generated parameters (Fig. 2C, see Appendix-B).

DR was set to 0 and Ek to 4.9, the mean value across all observations. In addition, the $P_D$ and $C_{MC}$ functions assume the following: the MC project conforms to CPRA specifications (outlined in CPRA, 2012b), the dredge being used is a cutter suction dredge (see Appendix-B), changes in the price of diesel and other commodities used in heavy construction (e.g. steel, equipment and labor) follow fluctuations in crude oil markets (Ji and Fan, 2012; World Bank, 2015), and the dredging contractor modifies the bid price based on recent trends in the price of these input commodities, which are impacted by crude oil. The use of constant 2010 $ in all cost equations implies that reported costs are in real (2010) dollars rather than nominal future dollars. This simplifies comparisons across time, however, since the timing of MC projects is an important

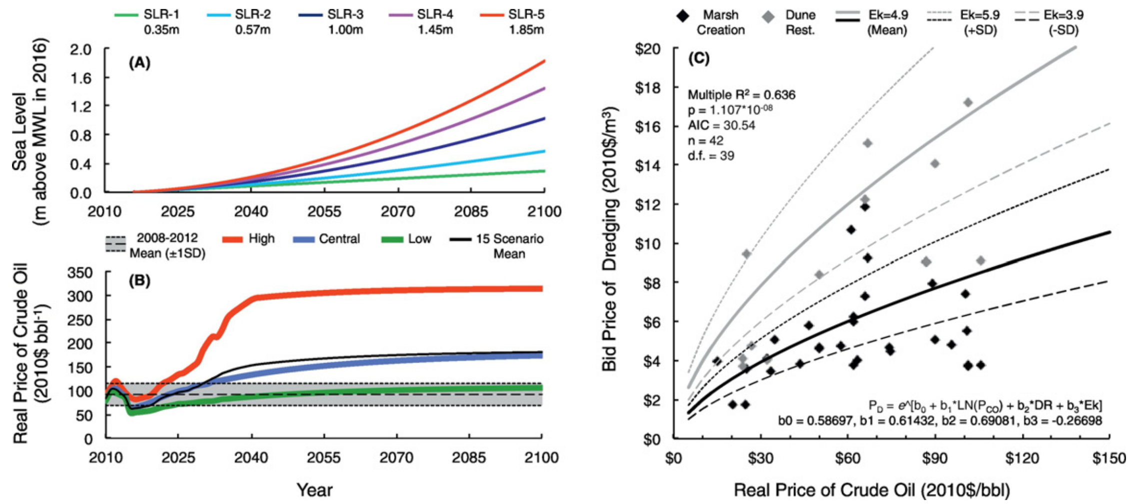

**Fig. 2.** Future scenarios for sea-level (A) and oil price (B), and the relation between oil price and dredging price (C). Oil prices scenarios were averaged from 15 forecasts from various models. Ek is an efficiency factor for dredging, equal to the natural log of borrow volume divided by the natural log of horsepower capacity; DR is binary variable (0/1) indicating if the borrow source is sand for dune restoration. See Methods section for details.

component of the model, it also assumes that real MC unit costs change only with the price of oil rather than economic growth in excess of inflation.

### 2.6. Marsh creation subroutines

Subroutines to simulate the effects of dredging on marsh elevation were incorporated into the model (Fig. 3). When the marsh reaches a critical $E_{RWL}$ where it is at risk of collapse ($E_{crit}$), MC is triggered and dredged sediments are pumped up to a specified fill elevation ($E_{fill}$), which is the $E_{RWL}$ at initial fill placement. Subsequently, total fill height ($H_{fill}$), mass of dredged sediment per unit area (S), and total borrow volume (BV) are calculated (Eqs. (3)–(5)). The critical elevation ($E_{crit}$) was set to −10 cm, which is a typical average $E_{RWL}$ for a MC project to be considered for marsh nourishment.

$$H_{fill} = E_{fill} - E_{RWL} \tag{3}$$

$H_{fill}$ is fill height (cm) and $E_{fill}$ is the specified fill elevation of marsh creation (cm).

$$S = H_{fill} \cdot BD \tag{4}$$

S is the total mass of dredged material added per unit area (g/cm$^2$), BD is the bulk density of deltaic sediments with 3% organic matter, equal to 1.18 g/cm$^3$ (see Appendix-C, and Morris et al., 2016).

$$BV = Area \cdot (H_{fill}/100) \cdot bf \tag{5}$$

BV is the total borrow volume (m$^3$) (defined in Eq. (1)), Area is the area (m$^2$) of the MC project (set to 1), $H_{fill}$/100 is fill height (m), bf is a loss adjustment factor to account for spillage or pipeline leaks equal to the ratio of the borrow volume to the fill volume for an MC project (set to 1.5, see Appendix-B).

### 2.7. Simulations and metrics

Restoration cost scenarios started in 2016 and ran out to 2066 (50 years) and to 2100 (84 years). Each model run starts in an open bay with a depth of 50 cm that is immediately filled to the $E_{fill}$; the marsh is sustained periodically with dredging throughout the simulation period. We ran sensitivity tests for $E_{fill}$, increasing from 2 to 200 cm at 2 cm increments and ran additional simulations where $E_{fill}$ was held constant and MC completion year and year of TSS increase (analogous to diversion completion year) were delayed from 2016 to 2100 at 1-year increments. For each future scenario and restoration period (e.g. 2016–2100), the total cost ($C_T$) to restore and sustain coastal marsh using dredging was calculated (Eq. (6)).

$$C_T = \sum_{i=1}^{n} [C_{MC,i}] \tag{6}$$

$C_T$ is the total cost to sustain coastal marsh during the restoration period, $C_{MC,i}$ is the cost of marsh creation (from Eq. (1)) for the ith restoration effort, and n is the number of nourishments required to sustain the marsh during the time interval. The Marsh Creation Cost Index (MCCI) is a metric that measures the factor increase in cost of a given scenario relative to the baseline scenario for a given time period (Eq. (7)).

$$MCCI = C_T/C_{TB} \tag{7}$$

$C_{TB}$ is the cost of the baseline scenario, defined as the $C_T$ for the no change energy and SLR scenarios, with initial $E_{RWL}$ of −50 cm relative to mean water level, $E_{fill}$ of 100 cm and TSS of 20 mg/L. The baseline $E_{fill}$ value of 100 cm was based on the maximum fill elevation allowed by CPRA (CPRA, 2012b, see Appendix-B).

Marsh lifespan (L) and dredging effectiveness (DE) were tracked for each sensitivity test. L is measured as the number of years after restoration that $E_{RWL}$ of the restored marsh remains above −10 cm ($E_{crit}$) (Eq. (8)). DE equals marsh lifespan divided by total height added to the bay (Eq. (9)).

$$L = Y_{crit} - Y_{MC} \tag{8}$$

$Y_{MC}$ is the decimal year of dredging for MC; $Y_{crit}$ is the decimal year that $E_{RWL}$ equals $E_{crit}$ (−10 cm)

$$DE = L/H_{fill} \tag{9}$$

$H_{fill}$ is the total fill height of dredging (defined in Eq. (3)).

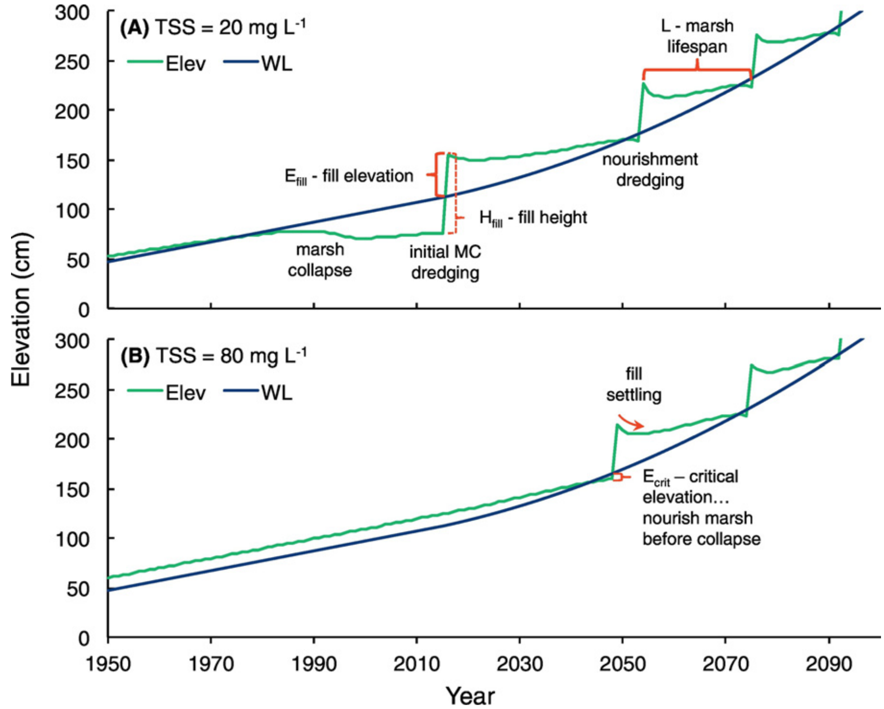


**Fig. 3.** Example WECRM calibration run showing marsh elevation over time with input of dredged materials to sustain marsh for SLR-3 (see Fig. 2A). Results are shown for total suspended sediment (TSS) of 20 mg/L (A) and 80 mg/L (B). Fill elevation ($E_{fill}$) and the critical elevation ($E_{crit}$) at which restoration is triggered are adjustable parameters, set here to 50 cm and −10 cm respectively.

## 3. Results

### 3.1. Oil price impacts on dredging costs

Real dredging price ($P_D$) had a significant positive relation with the real price of crude oil. The $P_D$ model (Eq. (2)) met all assumptions of linear regression and was significant ($p < 0.0001$), explaining 63.6% of the variability in dredging price (Fig. 2C). All independent parameter estimates were significant at a 99% confidence level (see Appendix-B, Table B1). The data were normal with respect to the model residuals (Shapiro-Wilk's test: $p = 0.2271$), and model variance was homoscedastic (Breuch-Pagan test: $p = 0.691$).

### 3.2. Controls on marsh lifespan

Raising TSS had a positive impact on lifespan of created marshes, but its effect diminished with accelerating SLR (Fig. 4A). Changing TSS from 20 to 160 mg/L is the equivalent of going from no river input to the immediate vicinity of a river diversion (see Section 2.2 in Methods section). For a MC project completed in 2016 with an $E_{fill}$ of 100 cm, a TSS increase from 20 to 160 mg/L raised lifespan from 100 years to 131 years in SLR-2 and from 65 years to 72 years in SLR-5, a 10–30% increase. For a MC project completed in 2016 with an $E_{fill}$ of 10 cm, a TSS increase from 20 to 160 mg/L raised lifespan from 37 years to 70 years in SLR-2 and from 27 years to 47 years in SLR-5, a 75–90% increase.

There were diminishing marginal returns on lifespan with increasing $E_{fill}$ (Fig. 4A). The change in lifespan with increasing TSS was greatest at lower fill elevations ($E_{fill}$), where sediment deposition and productivity are higher (Fig. 4A, Fig. 1). This resulted in the emergence of $E_{fill}$ zones where the dredging effectiveness (DE) was highest (Fig. 4B). With increasing TSS, DE maxima tended to become more pronounced and occurred at lower $E_{fill}$ (Fig. 4B). When TSS was lower than 40 mg/L, DE maxima appeared at $E_{fill}$ >30 cm. With TSS at 80 mg/L, DE maxima occurred at $E_{fill}$ of roughly 10 cm. With TSS at 160 mg/L, distinct DE maxima occurred at $E_{fill}$ below 2 cm. This implies that $E_{fill}$ targets near mean water level could be used effectively for MC in areas with high river sediment input.

Created marsh lifespan diminishes over time due to accelerating SLR, regardless of TSS level (Fig. 5A). For an $E_{fill}$ of 50 cm, projects completed in 2020 had a lifespan range from 26 years to over 100 years depending on SLR and TSS. When MC completion year was beyond 2050, lifespan was often below 10 years for SLR-4 and SLR-5, and >20 years only at the highest TSS levels and lowest SLR (Fig. 5A). Delaying the year of TSS increase (analogous to diversion completion year) also reduced the lifespan for MC projects completed in 2016 (Fig. 5B). At an $E_{fill}$ of 50 cm, there was no increase in lifespan with diversion completion year >2080 for all SLR scenarios above no change, because the marsh created in 2016 had already collapsed.

### 3.3. Effects of energy, sea-level rise, and management on costs

The combined effect of SLR and oil prices significantly increases the cost of sustaining marshlands with dredged sediment. With TSS at 20 mg/L, the total costs ($C_T$) to sustain marsh between 2016 and 2100 changed from $128,000/ha in the No-Change scenario to ~$1,010,000/ha in the worst-case scenario, an ~8-fold increase (Fig. 7A). Raising TSS resulted in lower $C_T$ for marsh creation (Figs. 6 & 7). Changing fill elevation also affected costs. Decreasing $E_{fill}$ increased the number of nourishments over time, with the unit costs of marsh nourishment ($P_D$ and $C_{MC}$) getting higher as energy prices increased. In a low sediment and high SLR future this led to very high $C_T$, but resulted in low $C_T$ for short restoration periods and high TSS (Figs. 6 & 7, C & D). Increasing fill height linearly increased $C_{MC}$ but had diminishing lifespan returns because of accelerating SLR; this reduced $C_T$ under high SLR scenarios (Figs. 6 & 7, A & B). At an $E_{fill}$ of 100 cm, increasing TSS from 20 to 160 mg/L did not reduce the average MCCI (across all the energy and SLR scenarios) from 2016 to 2066, but reduced average MCCI 26% from 2016 to 2100. With an $E_{fill}$ of 10 cm, an increase in TSS from 20 mg/L to 160 mg/L reduced the average MCCI by 65% from 2016 to 2066 and 57% from 2016 to 2100.

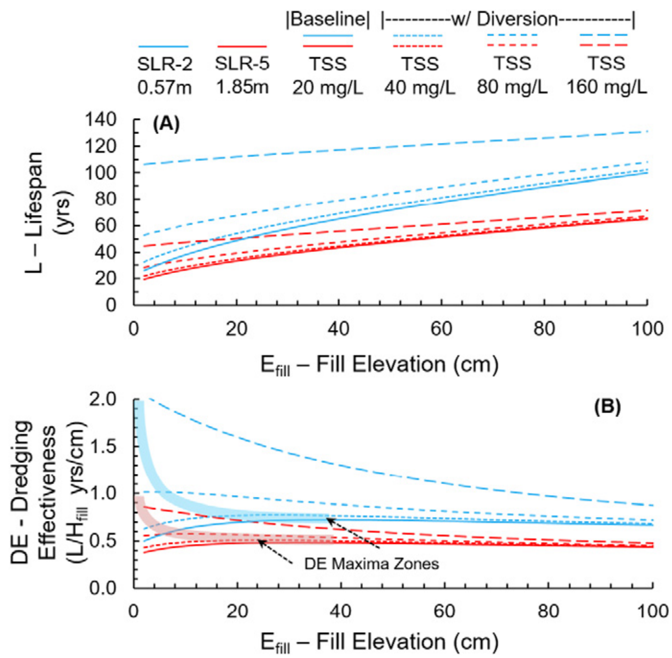


**Fig. 4.** The influence of fill elevation, total suspended sediment (TSS) and sea-level rise (SLR) on created marsh lifespan (A) and dredging effectiveness (B). Red lines are SLR-5 and blue lines are SLR-2 (see Fig. 2A), different line styles denote TSS levels of 20 to 160 mg/L, thick lines represent zones where DE is highest at a given TSS. Every simulation starts with an open bay with an elevation relative to mean water level ERWL of −50 cm.

## 4. Discussion

### 4.1. Summary and implications of results

In WECRM simulations, dredging became more frequent (due to SLR acceleration) and came at a higher unit cost (due to rising energy price) over time. From 2016 to 2100, the average total cost ($C_T$) increased by a factor of 2.6–6.1 (MCCI), depending on TSS and $E_{fill}$ (Fig. 7). Considering the financial constraints on restoration – only half of the $50 billion LACMP budget has been accounted for (Davis et al., 2015) – even a factor increase of 2.0 could render MC unaffordable.

Suspended sediments are an essential driver of MRDP marsh sustainability. Raising TSS increased marsh lifespan (Fig. 4) and reduced $C_T$ (Fig. 7). However, the addition of sediment at mean concentrations normally observed near the Mississippi/Atchafalaya Rivers (80–160 mg/L) did not sustain marsh indefinitely with accelerating rates of RLSR (this includes all SLR rates above SLR-1, the "no change" scenario). These findings agree with LACMP models, which indicate that on a delta wide scale net land gain is not possible, regardless of management approach (Wang et al., 2014; CPRA, 2017a).

### 4.2. Production function for marsh creation

The dredging price ($P_D$) and marsh creation cost ($C_{MC}$) functions capture the effect of energy prices ($P_{CO}$), project scale, and difficulty (Ek). We obtained a fairly robust sample of dredging projects (n = 42) over an 18-year time period (1994–2012). The model would likely improve with a larger sample size containing more recent marsh creation projects. But, the model $R^2$ of 0.636 with 39 degrees of freedom ($R^2$ 0.608 when adjusted for additional parameters), is satisfactory considering the amount of variability that can occur from project to project and over two decades in a competitive economic market (Ji and Fan, 2012; Cohen et al., 2011).

A limitation of the $P_D$ model is that many of the variables controlling the price of dredging are time dependent (Cohen et al., 2011; Murphy, 2012). Although the overall $P_D$ model was significant, we needed to log transform $P_D$ and $P_{CO}$ to remove heteroscedasticity, making the relation between $P_{CO}$ and $P_D$ log-linear. The variance of $P_D$ and $P_{CO}$ is likely a function of time (autocorrelation), which is common in economic datasets. A larger, continuous, dataset should be used to investigate autocorrelation. A database that could be used for this in future research is the Navigation Data Center of the U.S. Army Corps of Engineers (http://www.navigationdatacenter.us/dredge/dredge.htm).

There are many factors that could change the relation between $P_D$ and $P_{CO}$ over time, including changes to various forms of "efficiency". Competition for project bids over time can lead to lower bid margins but there are limits to this. Sequential project construction could consolidate mobilization and demobilization efforts. Improved machinery, digital operation technology, and weather forecasts can reduce down time (Cohen et al., 2011). Fuel price volatility makes bidding risky for dredge operators and can lead to higher bid prices. A proactive strategy to reduce bid prices is to negotiate long term contracts with dredgers at a fixed fuel price (Murphy, 2012). However, all of these efficiency measures will have diminishing impact on restoration costs over time due to accelerating SLR and increasing energy costs.

Dredging for MRDP restoration could also become less efficient over time as sediment supplies become scarcer. For example, after exhausting sources of nearby sand, barrier island restoration projects are now sourcing sand from a distant shoal, which has a limited supply of sand of the proper grain size (CPRA, 2015, 2016b; Penland et al., 2003). MC projects that dredge sediment from nearby bays can deepen water, leading to more powerful waves and greater localized erosion (Mariotti and Fagherazzi, 2010, 2013). Taking sediment from farther distances to avoid this feedback, such as from navigation channel dredging spoil or from sandbars on the Mississippi River, is more energy intensive and costly (Clark et al., 2015; CPRA, 2017b). While we have not specifically considered any of these factors, the Ek term (comprised of horsepower

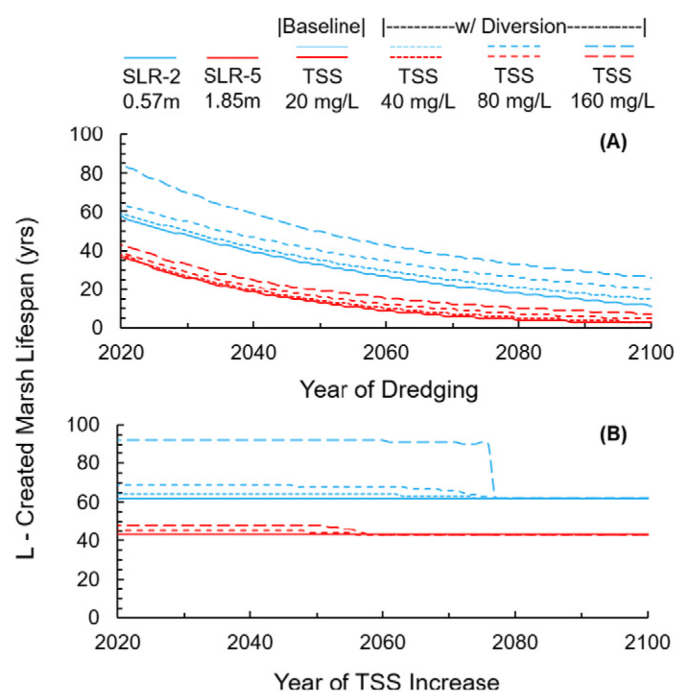


**Fig. 5.** Diminishing returns on created marsh lifespan with delayed restoration date. (A) Lifespan verses year of dredging or marsh creation project construction. (B) Lifespan verses year of total suspended sediment (TSS) increase from a baseline of 20 mg/L, this is analogous to year of diversion completion. Red lines are SLR-5 and blue lines are SLR-2 (see Fig. 2A), different line styles denote TSS levels of 20 to 160 mg/L. Every simulation starts with an open bay with an elevation relative to mean water level $E_{RWL}$ of −50 cm. Fill elevation ($E_{fill}$) is set to 50 cm.

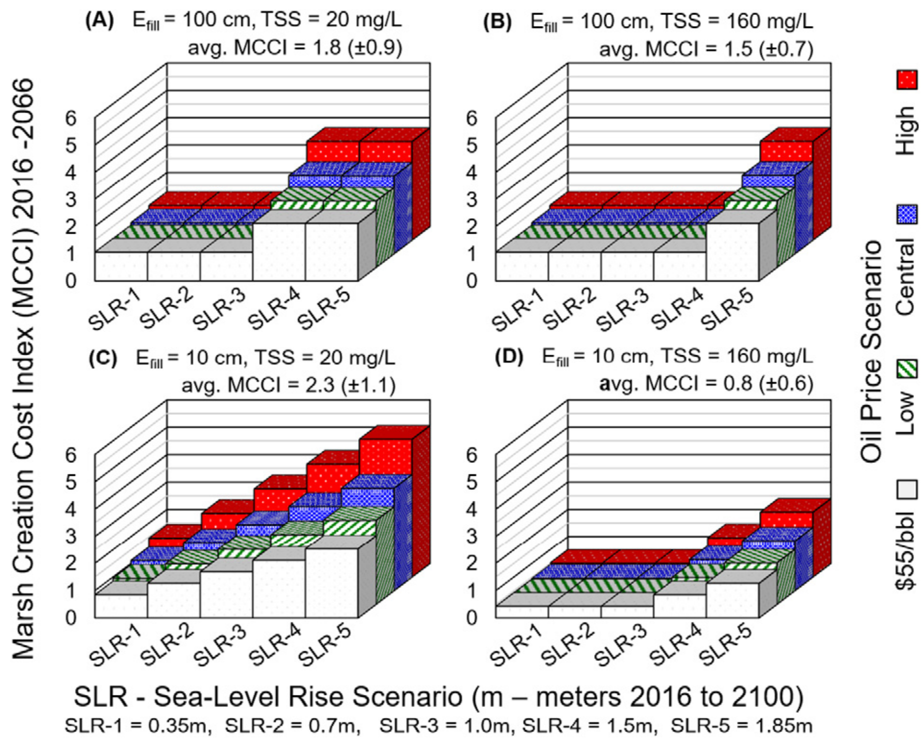


**Fig. 6.** The impact of oil price and sea-level rise on the cost of sustaining coastal marsh with hydraulic dredging from 2016 to 2066. A marsh creation cost index (MCCI) of 1 equals $128,000/ha. MCCI is reported for fill elevation ($E_{fill}$) of 100 cm (A and B) and 10 cm (C and D) with total suspended sediment (TSS) of 20 mg/L (A and C) and 160 mg/L (B and D). Energy and sea-level rise scenarios correspond to those in Fig. 2.

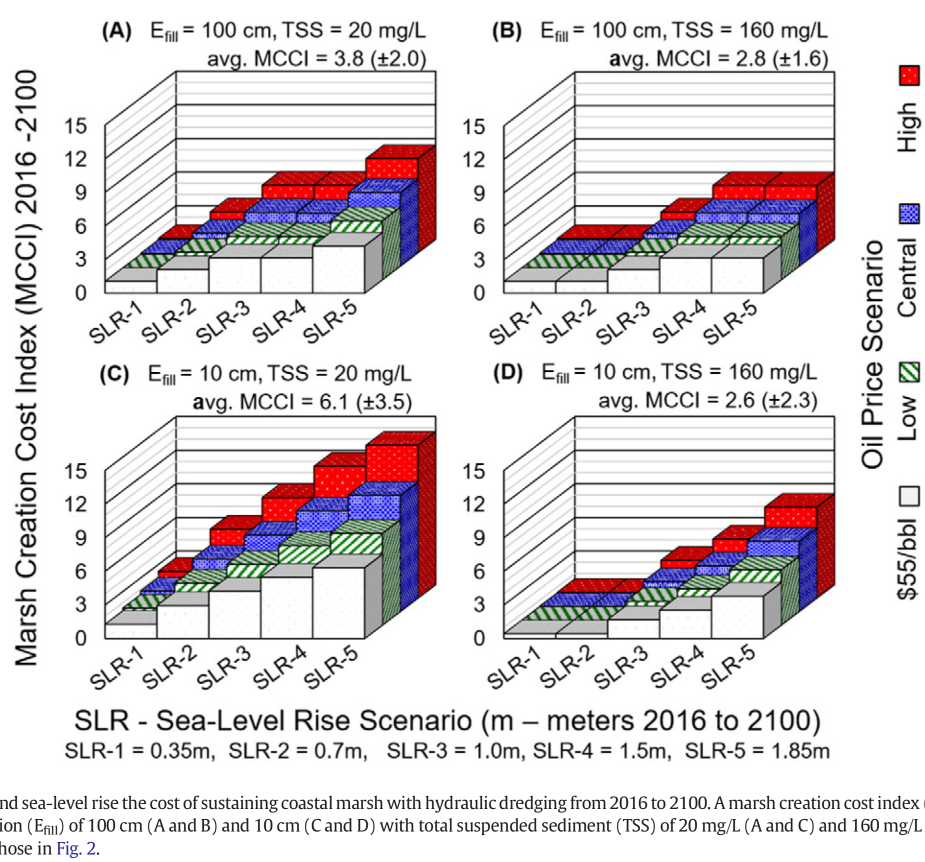


**Fig. 7.** The impact of oil price and sea-level rise the cost of sustaining coastal marsh with hydraulic dredging from 2016 to 2100. A marsh creation cost index (MCCI) of 1 equals $128,000/ha. MCCI is reported for fill elevation ($E_{fill}$) of 100 cm (A and B) and 10 cm (C and D) with total suspended sediment (TSS) of 20 mg/L (A and C) and 160 mg/L (B and D). Energy and sea-level rise scenarios correspond to those in Fig. 2.

and borrow volume) can be varied to investigate the efficiency of a project.

The Ek term is a proxy for efficiency, scale, and difficulty, and brings specificity to the model. With this term one can evaluate how different sediment sources and project sizes would impact $P_D$ at a given oil price. For example, an additional 5000 hp. booster pump is needed roughly every 5 miles of dredge pipeline, so borrow site distance can be specified using Ek in 5 mile, 5000 hp. increments. If a project's borrow volume is very large and the sediment source is shallow and nearby (<5 km) requiring one dredge and no booster pumps (Cohen et al., 2011; CPRA, 2012b), the Ek value will be large and $P_D$ will decrease. If the borrow volume is small and/or the sediment source is very deep or far way requiring booster pumps for additional horsepower, the Ek value will be small and $P_D$ will increase (e.g. Mississippi River or offshore, Clark et al., 2015; CPRA, 2015, 2017b).

### 4.3. Wetland modeling

WECRM simulates a uniform unit of marsh with no spatial resolution. We modeled only the impact of changing TSS and RSLR on marsh elevation. As an empirical model, WECRM has many parameters that contribute to uncertainty. In Appendix-D we provide a table of parameters and results of validity assessments and sensitivity tests. The model compares well with data collected in the MRDP. Jankowski et al. (2017) reported that the mean RSLR across all 274 CRMS sites is 12.0 mm/yr (±8.8), and the mean vertical accretion rate is 10.7 mm/yr. With an RSLR of 12.0, and TSS of 40 mg/L – the rough average TSS in MRDP estuaries (Wang, 1997) – WECRM predicted an average accretion over ten years of 10.1 mm/yr (Appendix-D).

Sensitivity tests indicated that elevation dynamics were most affected by primary productivity (Appendix-D). Biomass production influences refractory organic matter accumulation and also mineral sediment accumulation via friction and particle trapping (see Appendix-C). Interactions between environmental factors (e.g. salinity, TSS, redox potential, nutrients and water level) affect primary productivity and accretion, leading to variability (Roberts et al., 2015; Slocum et al., 2005; Snedden et al., 2015). For example, passage of cold fronts can elevate water level up to almost a meter above the astronomical tide, and cause TSS concentrations to exceed 1000 mg/L (Murray et al., 1993; Perez et al., 2000; Wang, 1997); this is a major pathway for input of sediments to coastal marshes (Day et al., 2011; Roberts et al., 2015). Freshwater, sediments and nutrients alleviate many of the stresses of RSLR and recent studies report enhanced productivity and accretion in areas with sediment-rich river throughput (Day et al., 2013; Day et al., 2016b; DeLaune et al., 2016; Nyman, 2014; Roberts et al., 2015; Twilley et al., 2016). However, interactions of this kind are complicated by local conditions and are often nonlinear (Roberts et al., 2015; Slocum et al., 2005; Snedden et al., 2015). Further research is needed before additional modeling is pursued in this area.

Diversion impacts will be uneven over space and time, and will relate to operation, location, channel design, and the initial conditions and future changes in the estuarine outfall basin (Das et al., 2012; Huang et al., 2011; Roy et al., 2013; Wang et al., 2014). The average cost per area of land gained or maintained over 50 years for diversions selected in the 2017 LACMP was $55,100/ha (2010$), but costs can vary greatly with discharge capacity, complexity of design and location (see Appendix-E). The area of land gained or maintained is affected by the environmental scenario and by other proposed restoration projects (e.g. marsh creation) that fall within the diversion impact area. For example, 2012 LACMP reports area estimates for the moderate environmental scenario while the 2017 LACMP uses the high environmental scenario. This makes estimating diversion costs per unit area while also accounting for SLR and TSS changes quite complex. For these reasons, we did not factor the costs of diversion construction and operation in our study. This should be pursued in future research.

Deep subsidence and compaction of shallow sediment after addition of dredged material are also important variables. Their effect, however, is straightforward. Increasing subsidence/compaction reduces marsh lifespan linearly, which increases overall cost of sustaining marsh (and vice versa). Many of the world's major deltas, including the MRDP, also experience elevated rates of subsidence in certain areas due to fluid withdrawal, this leads to high spatiotemporal variability (Kolker et al., 2011; Syvitski et al., 2009). For example: total subsidence estimates in the MRDP have mean of 10 mm/yr (±8.4) and a range of −39.4 to 65.8 mm/yr (Jankowski et al., 2017). Sustaining marsh in areas with high subsidence or highly compressible soils will be much more expensive.

### 4.4. Optimizing marsh creation benefits

We estimate that a change from the low to high oil price scenario would roughly half the volume of dredging for MC that could be paid for over 50 years with the $17.8 budget in the LACMP (Appendix-F). This makes it imperative to search for ways to maximize the cost effectiveness of MC. Changing the depth at which marsh restoration is initiated ($E_{crit}$) has a significant impact on both the cost of restoration and marsh lifespan. The model nourished marshes when relative elevation $E_{RWL}$ dropped to −10 cm, just before a marsh collapses rapidly and turns into open water. The elevation of collapse is a function of tidal range, RSLR, and river (freshwater and sediment) throughput. High tidal range and river throughput allow tidal marshes to remain productive at lower $E_{RWL}$ (see Appendix-C, DeLaune et al., 1983; Kirwan and Guntenspergen, 2010, 2012, 2015). At low TSS and current rates of RSLR (10–12 mm/yr for much of the deltaic plain), our analysis indicates that having $E_{RWL}$ below −10 cm leads to positive biogeochemical feedbacks that accelerate marsh submergence (Appendix-D), which is consistent with data from CRMS and the literature (Couvillion and Beck 2013; Day et al., 2011; Nyman et al., 1993; Rybczyk and Cahoon, 2002). Restoring marshes before collapse reduces restoration costs by decreasing the sediment input required to reach a desired lifespan. It also increases total marsh productivity over the restoration period and has the added benefit of preventing potential release of greenhouse gases from organic matter that is decomposed as vegetation dies and soils erode (DeLaune and White, 2012; Lane et al., 2016, see Appendix-D).

Our analysis of fill elevation ($E_{fill}$) for a single restoration effort (Fig. 4) indicates that sites with high river input (TSS > 80 mg/L) achieved the greatest dredging effectiveness at elevations lower than 10 cm. MC projects completed near an existing river channel or planned diversion could be restored to lower $E_{fill}$ and achieve the same lifespan as projects that are isolated from river sediment and restored to higher elevation. With high TSS, if lower $E_{fill}$ is combined with shallower restoration depth (i.e. "nourishment" rather than "creation"), a fixed borrow volume could be distributed over a significantly larger area than under conventional MC specifications. This is an interesting finding because it indicates that cost savings and/or better use of available sediment borrow sources could be achieved if restoration strategies are altered based on the local TSS regime.

Near diversions, a much greater area of land could be built per unit cost (or unit of sediment) by restoring deteriorating marshes to lower $E_{fill}$ and allowing river sediment to further build and sustain the marsh (e.g. Twilley et al., 2016). MC projects at sites that are isolated from river influence must be built at a higher elevation to achieve a target lifespan. It is likely more sustainable to restore larger areas of contiguous marsh at low $E_{fill}$ than small patches of marsh at high $E_{fill}$. Having a higher land-water ratio yields lower fetch in adjacent ponds and bays and reduces potential for wind wave erosion of the marsh edge (Mariotti and Fagherazzi, 2010, 2013; Twilley et al., 2016; Xu et al., 2016), reducing the need for expensive shoreline armoring. There is also potential for local macrophyte recruitment/regrowth if the dredging load is light enough not to kill the existing rhizome network (Mendelssohn and Kuhn, 2003; Slocum et al., 2005).

### 4.5. Oil price and climate path dependency and deltaic sustainability

The decisions made in energy, economic, and climate policy over the next decades will be important in determining the vulnerability of deltas and other coastal areas to climate change and the price of management (Day et al., 2016a; Strauss et al., 2015; Tessler et al., 2015). The energy models we reviewed converged on similar oil prices for different carbon emissions outcomes (see Appendix-A). The High scenario is more closely associated with IPCC's highest carbon scenarios and the higher end of the sea-level rise projections (e.g. RPC 4.5 and RPC 8.5) (IEA, 2015; IPCC, 2013; McGlade, 2014). The No-Change scenario represents a future in which improved technology and renewable energy investment cause demand for oil to decrease faster than depletion rates, allowing prices remain constant at $55/bbl (see Appendix-A). The Low and No-Change scenarios are more closely associated with the IPCC's low carbon emissions scenarios (e.g. RPC 1.5 and RPC 2.5).

The oil price trajectory is not necessarily related to future carbon emissions. When the market is in equilibrium, oil price is equal to the cost of the marginal unit of production at a given quantity of demand. A low or high price environment could occur at low or high production levels. For example, low fossil fuel investment and lack of innovation could also lead to high prices, even in a future with very low oil demand and low carbon emissions (McCollum et al., 2016). Conversely, innovation in the oil sector could increase the efficiency of unconventional oil production, leading to low prices, high demand and high carbon emissions (McCollum et al., 2016). A recent example of this is the 2010–2016 U.S. shale oil boom (Brandt et al., 2016). In reality, there may be fluctuations between the price levels represented by different scenarios driven by a combination of factors.

A low price, high demand situation is not likely to exist very long. Production rates of existing wells decline over time, and without high prices there will be low investment and declining production. Unless demand declines at the same pace as production, demand will slowly outpace supply leading to investment in low quality fuels to meet demand and a return to high prices (Heun and de Wit, 2012; McGlade, 2014; Murphy and Hall, 2011). Internal combustion engines are used pervasively for vehicles and machines in all developed countries, and there is growing demand for personal vehicles in Asia (IEA, 2015). Given this, declining demand for oil does not seem very likely in the near future, and is not projected by major global energy models (EIA, 2015; IEA, 2015; McGlade and Ekins, 2015). There is no major divestment in petroleum in the Low, Central, and High scenarios (Appendix-A).

### 4.6. Recommendations for the MRDP and deltas worldwide

Most of the world's large delta's do not receive sufficient sediment to maintain their area at current RLSR (Giosan et al., 2014). Projected increases in SLR almost guarantee that large deltas will suffer high rates of land loss in the 21st century, creating immense pressure on governments to mitigate land loss in deltas. Marsh creation (MC) is one of a suite of methods that delta managers will employ to forestall deltaic retreat (Table 1). Although wetland productivity, subsidence rate, availability of sediment and cost of dredging vary in deltas around the world, the management implications for MC drawn from our study are broadly applicable to other deltas.

Creating and nourishing marsh with hydraulic dredging provides an immediate and relatively long-lasting benefit and is compatible with most coastal industries. MC comes at significant cost and projected trends in energy and SLR raise serious concerns over its future sustainability. Created marsh lifespan will decrease as the rate of SLR increases (Fig. 4A). Delta managers must pursue all possible measures to reduce dredging price, this will allow for a larger volume of sediment to be dredged for a fixed amount of funding (e.g. the $17.8 billion allocated for MC by the 2017 LACMP). Considering this and the current period of low/stable energy prices, it would be wise for Louisiana to accelerate MC efforts and restore large swaths of the MRDP as soon as possible. Given future projections for oil price (all other things being equal), if a marsh must be sustained out to 2100, then dredging initially to high fill elevation ($E_{fill}$) followed by incremental dredging to low $E_{fill}$ may be a favorable cost reduction approach. Dredging price can also be lowered by using sediment from navigation dredging and placing borrow sites as close to the fill areas as possible, reducing the need for booster pumps (Clark et al., 2015).

Ecological engineering is an approach to natural resource management where natural energies are used to the fullest (Mitsch and Jørgensen, 2004). Consistent with this approach, delta restoration strategies should be designed to minimize the risks associated with increasing fossil fuel scarcity and climate change, especially the rate of SLR acceleration. Over the long-term, sustainable delta restoration should minimize reliance on energy intensive approaches, such as dredging (Day et al., 2016a; Tessler et al., 2015), and should focus on restoring

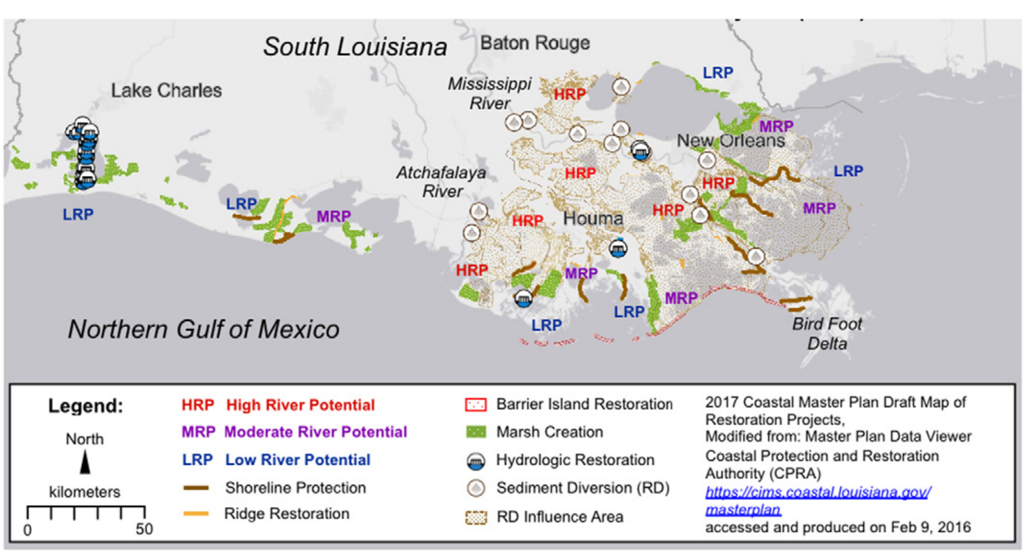


**Fig. 8.** Map of coastal Louisiana with planned wetland restoration projects and zones of river potential. River potential zones are classified by the approximate slope (Δ) between the wetland and the nearest major river; $\Delta = (E_R - E_W) / x$, where $E_R$ is river elevation, $E_W$ wetland elevation, x is distance between the river and the wetland. Higher Δ results in greater river potential. (Modified from CPRA, 2017c).

natural flow patterns of freshwater and sediments to coastal wetlands, while maintaining estuarine gradients (Day et al., 2016b; Nyman, 2014; Twilley et al., 2016).

Rivers are an excellent renewable source of energy and sediment that can be exploited through the construction of diversions, which have low recurring energy cost. River input can reduce the need to renourish marsh by providing a long-term supply of suspended sediment. We recommend that marsh creation and nourishment be prioritized in areas that fall within the predicted zone of sediment influence of planned diversions (Fig. 8). To optimize the use of dredge sediment, $E_{fill}$ should be modified based on expected TSS level (Fig. 4), and existing marsh nourishment should be prioritized over marsh creation. In the areas where river sediment is plentiful, marshes should be restored to lower elevations, in favor of larger contiguous areas that are less susceptible to wave erosion and more completely shield coastal communities from storm surge.

## 5. Conclusions

In this paper, we analyzed how SLR and energy prices influence the cost of sustaining MRDP coastal marshes with hydraulic dredging by developing the WECRM model, which we calibrated to incorporate the influence of tides, frontal passages, and river sediment on marsh productivity and mineral accretion. By altering TSS levels, we modeled how suspended sediment input affects marsh lifespan and the cost of sustaining marsh. As is the case with any forecasting study, our analysis has uncertainty that grows with the time horizon. The actual costs to sustain Mississippi delta marsh with dredging will inevitably be different from what we have predicted. Nonetheless, this study is important because it identifies the key drivers influencing costs (e.g. RSLR, energy prices, and TSS) and the general magnitude of their impact.

What is most unique about this study is the consideration of changes in the price of energy. Energy prices, oil in particular, will affect and could likely limit the affordability of MRDP restoration. Oil price will be impacted by future climate policy, economic growth, and rate of fossil fuel depletion (IEA, 2015; Mohr et al., 2015). The majority of models indicate that real oil prices must increase if oil production is to be sustained long into the future (Fig. 2B, EIA, 2015; IEA, 2015; Heun and de Wit, 2012; McGlade, 2014; McCollum et al., 2016; Shafiee and Topal, 2010).

The combined impact of SLR and fossil fuel scarcity will likely reduce the amount of dredging that is possible with a fixed budget and render energy-intensive approaches to restore the Mississippi delta (as well as other large deltas) cost prohibitive by the mid-21st century. We strongly recommend that a greater effort be undertaken to quantify and understand the influence of short and long-term changes in energy and material resource availability on the costs and sustainability of large-scale deltaic engineering. We recommend that coastal planners consider climate policy and energy supply/price uncertainty in future cost estimates and risk assessments.

## Acknowledgements

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## Appendix. Supplementary data

Supplementary data and appendices to this article can be found online at https://doi.org/10.1016/j.scitotenv.2017.09.314.

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