2017

Modeling the Influence of Energy and Climate Megatrends on Future Costs and Benefits of Marsh Creation in the Mississippi Delta

Adrian R. H. Wiegman
Louisiana State University and Agricultural and Mechanical College

MODELING THE INFLUENCE OF ENERGY AND CLIMATE MEGATRENDS ON FUTURE COSTS AND BENEFITS OF MARSH CREATION IN THE MISSISSIPPI DELTA

A Thesis

Submitted to the graduate faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

in

The Department of Oceanography and Coastal Sciences

by
Adrian R.H. Wiegman
B.S., State University of New York College of Environmental Science and Forestry, 2013
August 2017

ACKNOWLEDGEMENTS

This research was supported by a grant from the Louisiana State University Coastal Sustainability Studio Small Projects Fund [award number 1512] and a grant from the Gulf Research Program of the National Academies of Sciences [award number 2000005991]. John W. Day was the committee co-chair and principle investigator of the project, Dr. Day guided all aspects of the model development, provided day-to-day oversight of the project. Christopher F. D'Elia served as committee co-chair and co-investigator of the project, Dr. D'Elia guided the overall direction of the study. Dr. David E. Dismukes and Dr. Brian Snyder of the LSU Center for Energy Studies served on the committee and were vital in guiding the research and development of the production function for marsh creation cost. Jeffrey S. Rutherford assisted with the review and analysis of energy and sea level rise forecasts, and produced the final sea-level rise scenarios. Dr. James T. Morris served as an expert consultant on marsh elevation modeling; this included two meetings at Louisiana State University, where Dr. Morris provided access to MS Excel macro versions of the Marsh Equilibrium Model, and later a review of the final model produced by Mr. Wiegman. Dr. John Rybczyk provided Mr. Wiegman with access to a STELLA code of the Integrated Wetland Ecosystem Model. Dr. G. Paul Kemp and Dr. Sam Bently guided assumptions on suspended sediments and subsidence. Dr. Beibei Guo gave statistical advice on several aspects of the project. Dr. David Murphy and Dr. Charles Hall guided the approach to energy price forecasting. Dr. James Pahl and Dr. Angelina Freeman of CPRA provided information on coastal restoration. Dr. Eric D. Roy carried out the initial model simulations and documentation before handing the project over to Mr. Wiegman in August 2014. Dr. Roy also provided comments in latter stages of the project. Dr. Robert R. Lane guided the analysis of wetland soil data in addition to day-to-day oversight during model development. Jason Day and Asher Williams provided Mr. Wiegman with many opportunities to do field work, which helped ground the modeling efforts in reality.

TABLE OF CONTENTS

LIST OF ABREVIATIONS

(used in sections 1 – 5)

B:C – benefit to cost ratio of marsh creation

BV –volume of dredging borrow site

C_{MC} – marsh creation construction costs

E_{crit} – critical elevation of marsh collapse, elevation of marsh renourishment

E_{fill} – fill elevation of marsh creation

EROI – energy return on energy invested

E_{RWL} – elevation relative to mean water level

H_{fill} – fill height of marsh creation

IWEM – integrated wetland ecosystem model

L – marsh lifespan

MC – marsh creation

MCCI – marsh creation cost index

MRDP – Mississippi river deltaic plain

MEM – marsh equilibrium model

P_{CO} – unit price of crude oil

P_D – unit price of dredging

RSD – river sediment diversion

RSLR – relative sea-level rise

SLR – eustastic sea-level rise

WECRM – wetland energy and climate restoration model

ABSTRACT

Over 25% of Mississippi delta (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. I modeled hydraulic dredging to sustain marsh from 2016-2066 and 2016-2100 under a range of scenarios for sea level rise, energy price, and management regimes. A marsh elevation model was calibrated to data from MRDP marshes. I developed a model 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^{-1} in the no change scenario to ~\$1,010,000 ha^{-1} in the worst-case scenario in sea level rise and energy price, an ~8-fold increase. Increasing suspended sediment load raised created marsh lifespan and decreased long term dredging costs. Created marsh lifespan changed nonlinearly with dredging fill elevation and suspended sediment level. Costs and benefits of marsh creation can be optimized by adjusting dredging fill elevations based on 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. Marsh creation will likely become unaffordable in the mid to late 21st century, especially if river sediment diversions are not constructed before 2030. Planners must take into consideration coupled energy and climate scenarios for long-term risk assessments and adjust restoration goals accordingly.

1. INTRODUCTION

1.1. Mississippi Delta Restoration and 21st Century Megatrends

About 28% of the wetlands of the Mississippi River Deltaic Plain (MRDP) were lost in the 20th century (Barras et al. 2008, Couvillion et al. 2011) and major restoration effort is needed for the delta be sustained (CPRA 2017). Major forces expected to impact the MRDP and other coastal societies during the 21st century include accelerated 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 (IPCC 2013, Tao et al. 2014, Karl et al. 2015, Tessler et al. 2015, Prein et al. 2016, Day et al. 2016b, Balagaru et al. 2016, Sobel et al. 2016). CO_2 levels are now tracking the highest IPCC scenarios (Friedlingstein et al. 2014, Straus et al. 2015) and sea level is projected to rise by 1-2 meters or more during the 21st century (IPCC 2013, Horton et al. 2014, Deconto & Pollard 2016). World fossil fuel production is projected to peak by 2050 and oil production is projected to begin declining by as early as 2030 (Maggio & Cacciola 2012, Mohr et al. 2015). The net energy ratio, and 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 & 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, barring revolutionary new technology or dramatic reduction in demand (Heun & de Wit 2012, EIA 2015). This will affect petroleum pirce, upon which maritime activities and delta restoration are heavily reliant (McGlade 2014, Bray et al. 1997).

1.2. Wetland Loss and Restoration in the Mississippi Delta

The high wetland loss rates in the MRDP are projected to continue with an additional loss of over 5000 km^2 by 2050 (Blum & 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 aimed at reversing wetland loss in the MRDP and creating a sustainable coast (CPRA 2012a, 2017a). The 2017 LACMP allocated about 50% of its spending to wetland restoration and 50% to risk reduction (e.g. levees and raising structures) (Table 1). I focus paper this paper on coastal restoration. More specifically, I investigate the influence of energy costs, SLR, river input, and construction specifications on the cost and benefits of sustaining coastal marsh ecosystems with hydraulic dredging (i.e. “marsh creation”).

The two main restoration strategies for land building in the MRDP are marsh creation (MC) via pumped sediments and river sediment diversions (RSD) (CPRA 2017a). CPRA divides MC is into two types, “creation” – filling in an open water area typically with a mean elevation of less than -30cm relative to local mean sea level, and “nourishment” – restoration of an area with existing patches of deteriorating marsh, typically with a mean elevation at or just below mean sea level. River diversions range in size and conveyance method (see CPRA 2017b, Kenney et al. 2013, Day et al. 2016a). In terms of land building, MC is a high-power approach with immediate impacts, while RDs, once constructed, are a low-power approach with a long legacy of positive impact (Day et al 2016a, 2016b).

Coastal marsh elevation responds to changes in SLR, suspended sediments, and marsh productivity (Fagherazzi et al. 2014, Mudd et al. 2009). Much early focus on modeling RDs has been on deposition of coarse grain sediment (sand) for delta building, but fine sediments represent at least 75% of the sediment carried by the Mississippi (Allison et al. 2012; Allison & Meselhe 2010), the vast majority of which are 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 that are 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, I model the influence of increased concentrations of total suspended sediments (TSS) from river throughput on sustaining coastal marshes (Figure 2). The analysis is based on data from natural analogs in the MRDP, including new delta lobe development (Roberts et al. 2015, DeLaune et al. 2016, 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 & Day 2014, Tessler et al. 2015). In the 2017 LACMP, $17.1 billion dollars is allocated for MC projects, while $5.1 billion dollars is allocated for RSD projects (Table 1). Altogether, CPRA expects that 2017 LACMP restoration projects will build and/or sustain ~2,000 km^2 of wetlands (CRPA 2017). To deliver sediment, MC requires large machinery such as “cutter-suction” dredges, bulldozers, booster pumps, generator barges and more (Clark et al. 2015, Murphy 2012, CPRA 2012, Day et al. 2015). Diversions vary in their complexity, but in most cases building a RSD is major construction project, concrete, steel, and heavy machinery, are required (Kenney et al. 2013).

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	50%	N/A
"	Barrier Island	1.5	3%	Hydraulic Dredge, Bulldozer
"	Hydrologic	0.4	1%	Pump or Gravity*
"	Marsh Creation	17.1	34%	Hydraulic Dredge, Bulldozer
"	Ridges	0.1	0%	Excavator, Dragline or Bucket Dredge
"	Sediment Diversion	5.1	10%	Gravity*
"	Shoreline Protection	0.2	0%	Barge, Crane or N/A**
Risk Reduction	(Total)	25	50%	N/A
"	Structural (Levees)	18.8	38%	Excavator, Dragline or Bucket Dredge
"	Nonstructural	6.1	12%	Various
Total		50	100%	N/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); **Oyster reefs have various methods of creation; Rock armor shorelines and jetties require barges and cranes

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 & Fan 2012, World Bank 2015). Dredges, like most heavy construction equipment, are almost exclusively powered by diesel fuel and costs of production are sensitive to diesel price (Murphy 2012, Hollinberger 2010). The mean real price of dredging in the U.S. increased 72% between 2000 and 2010 (Cohen 2011), coinciding with a 150% increase in the real price of crude oil (EIA 2015). For cutter suction dredges, total costs of dredging have increased about 17% for each 100% increase in the price of diesel (Belisimo 2000). Fluctuations in oil prices are linked to economic expansions and recessions, which affect material prices as well (Hamilton 2012, Murphy & Hall 2011). Economic volatility also influences the availability of MRDP restoration funding, which comes in part from Gulf of Mexico oil and gas revenue (Davis et al. 2014, 2015, Barnes et al. 2015, CPRA 2015).

Delta restoration in highly developed societies that rely on energy-intensive approaches to management will have high risk for non-sustainable outcomes from climate change in a future with high energy costs (Tessler et al. 2015, Day et al. 2016b). But even without consideration of energy there are significant financial constraints on coastal restoration in Louisiana. Only about $26 billion dollars have been secured for the LACMP, roughly half of the total cost (CPRA 2016). 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 prices. My focus on quantifying the influence of energy prices on hydraulic dredging (for coastal restoration) makes the study important for the MRDP, and developed coastal areas worldwide.

1.4. Objectives & Hypotheses

I hypothesize the following: (H1) Oil prices have a positive linear correlation with the unit costs of dredging for MRDP restoration. (H2) Marshes with higher TSS concentrations due to riverine input will incur lower restoration costs and be more sustainable overtime than areas isolated from river influence. (H3) (a) There are diminishing marginal returns on restored marsh lifespan per unit increase of the dredging fill elevation above mean sea level (Figure 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 decreasing mineral sediment input, and increasing oxidation. These feedbacks are stronger in microtidal regions such as the MRDP (Morris et al. 2002, Kirwan et al. 2010). (b) Costs, however, increase linearly with fill elevation. (c) Therefore, in terms of benefit to cost ratio (B:C, created marsh lifespan divided by cost of MC (volumetric or monetary), an optimal dredging fill height exists at some elevation above mean water level but less than two meters (Figure 1).

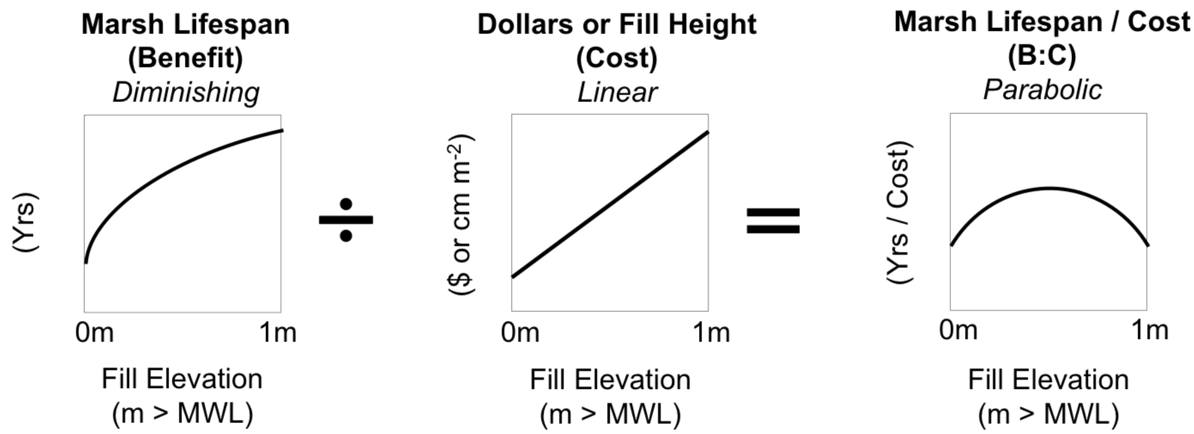

FIGURE 1. The optimum fill elevation hypothesis for marsh creation in the Mississippi Delta. For each increase in marsh creation fill elevation above sea level there is diminishing marginal increase of marsh lifespan, due to biophysical feedbacks with relative elevation. This results in an optimum range for marsh creation in terms of benefit to cost.

The overall objective of this study is to simulate the cost of MC through the addition of hydraulically dredged sediment in coastal marshes of the MRDP with and without river influence for a range of trajectories for future SLR and oil prices. To test the hypotheses, I 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 and benefits of MC efforts to changes in TSS concentration, and Efill – the fill elevation of MC projects.

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 I developed to simulate the costs and benefits of restoring coastal marshes under future trajectories of sea-level rise and energy prices (Figure 2). WECRM is separated into two sub-systems: the wetland system, which simulates the impact of sea-level rise on a wetland ecosystem, and the human system, which simulates restoration and energy costs. The wetland system predicts relative elevation, which feeds back to human system subroutines that determine when to implement restoration. In this paper I use WECRM to simulate the sustainability of a marsh with hydraulically dredged sediments under various regimes of TSS. For example, when a marsh reaches certain threshold in elevation (relative to mean water level), 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. Details follow (also see APPENDICES).

I adapted the Marsh Equilibrium Model (MEM) (Morris et al. 2002, 2012) and the Integrated Wetland Ecosystem Model (IWEM) (Rybczyk & Cahoon 2002, Day et al. 1999, Rybczyk et al. 1998), 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 APPENDIX-A and C). To investigate H1, I developed functional responses of MC costs and oil prices based on CPRA technical documents and data from dredging projects in the Louisiana Coastal Zone (see APPENDIX-B). To investigate H2, I simulated elevation of a prototype MC project that was sustained periodically with re-nourishment starting in 2016 with and without river diversion influence for the full range of SLR and energy forcing scenarios. To investigate the H3, I simulated a series of single marsh creation efforts implemented in 2016 with target fill elevations ranging from 2 to 200 cm (relative to MWL), increasing at 2 cm increments, for each sea level scenario and with TSS levels of 20, 40, 80, and 160 mg/L.

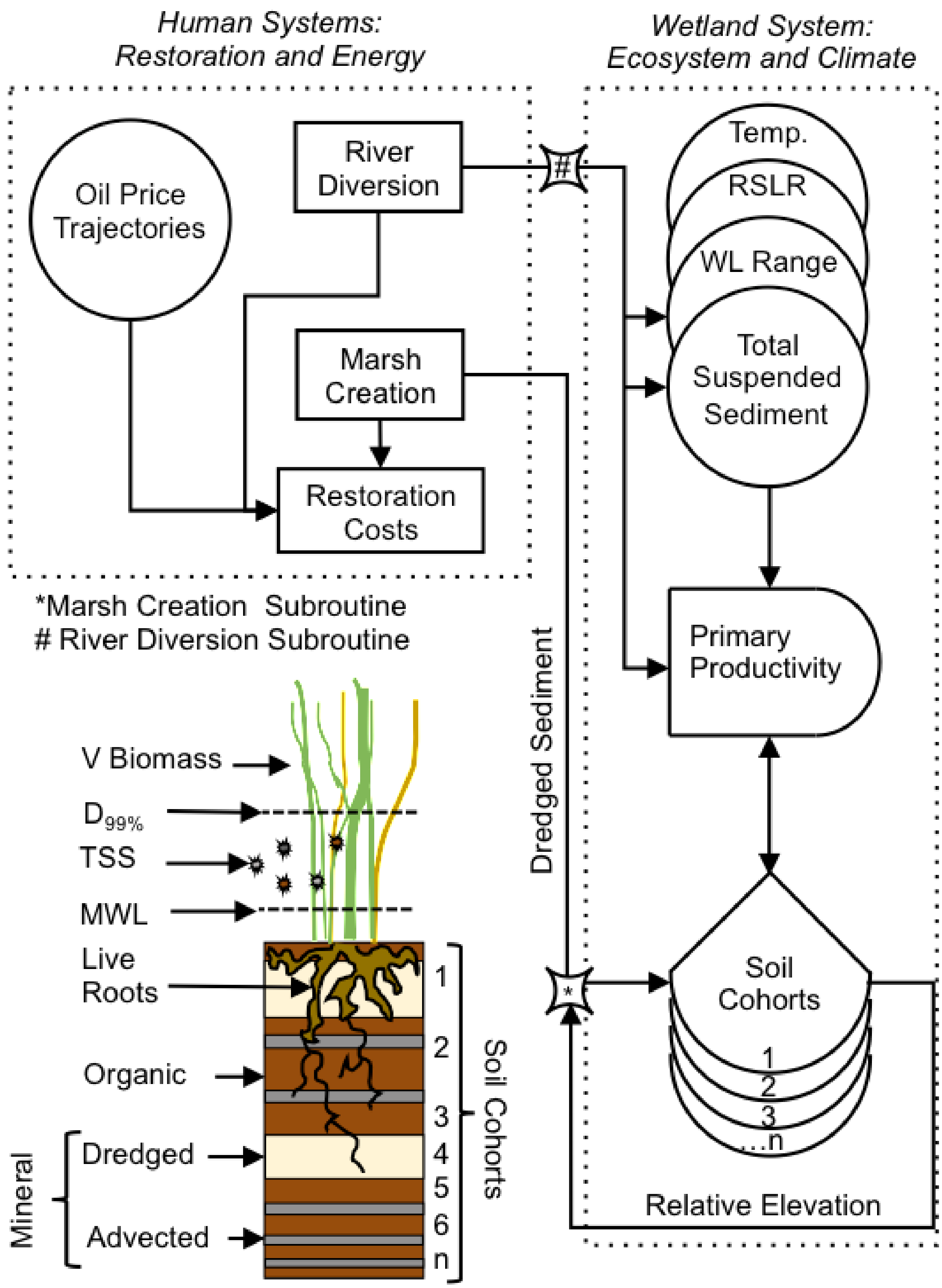

FIGURE 2. Conceptual diagram of the Wetland Energy and Climate Restoration Model (WECRM). The dotted lines show boundaries of the wetland system and human system sub models. A vertical profile of a simulated marsh is depicted on the on the lower left. $D_{99\%}$ - max flooding depth, TSS – total suspended sediments, V – vegetation, MWL – mean water level

2.2. Relative Sea Level Rise

I used five eustatic (global) SLR scenarios (SLR1, SLR-2, SLR-3, SLR-4, SLR-5, Figure 3B, APPENDIX-C) that cover the range of scientific projections to date. The “no-change” scenario (SLR-1) assumes a constant rate of sea-level rise equivalent to the current rate, which is about 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 begin with 3.5 mm yr^{-1} of SLR in 2016, and accelerate according to a second order exponential function towards a specified sea-level in 2100 relative to 2016 (0.57 m, 1.03 m, 1.45 m, and 1.83 m, respectively) (Figure 3B). SLR-5 is consistent with the uppermost sea-level rise reported by semi-empirical models and new findings that indicate greater contributions from polar ice sheets. These studies suggest up to 2 m of sea-level rise (relative to 1992) by 2100 (Pfeffer et al. 2008, Vermeer & Rahmstorf 2009, Deconto & Pollard 2016). Relative SLR (RSLR) is the sum of eustatic SLR and isostatic movement of the crust. Subsidence is the term for isostatic movement that decreases elevation. Most subsidence in deltas is caused by consolidation of Holocene sediment (Meckel et al. 2006). Many of the world’s major deltas, including the MRDP, have also experienced elevated rates of subsidence in certain areas due to fluid withdrawal (Syvitski et al. 2009, Kolker et al. 2011). For simulations presented in this paper, I selected a subsidence rate of 0.87 (mm/yr) based on the median estimate from 25 tidal CRMS sites evaluated in this study (Figure 4, see APPENDIX-C). Note that subsidence estimates in the MRDP can be as high as 29 mm/yr depending on location (Shinkle & Dokka 2004, Zou et al. 2015).

2.3. Oil Prices

I reviewed the energy modeling literature and developed a range of projections for oil prices based on the results of selected models (IEA 2015, EIA 2015, McGlade 2014, Heun & De Wit 2012). Each price scenario (low, central, and high) is an average of five model simulations. I adjusted prices to 2010 dollars using the consumer price index. The model simulations used in each trajectory go to the year 2035. I extrapolated beyond this date to 2100 based on the five-year mean rate of increase from 2030-2035 and an annual decay rate of 5% (see APPENDIX-A). Each scenario starts with an increasing trend as prices rebound from lows after the 2008 financial crisis (Figure 3A). Prices start to decline in 2011 in the Low scenario and in 2012 in the Central and High scenarios. Prices are lowest in 2015 for each scenario (Figure 3A). In both the High and Central scenario prices are significantly higher on average than during the formulation of the LACMP, while the low scenario is not significantly different. After 2020 the Low scenario increases to about $105/bbl by 2050. 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 (Figure 3A). I also included a No Change scenario where prices remain constant at $55/bbl (see APPENDIX-A).

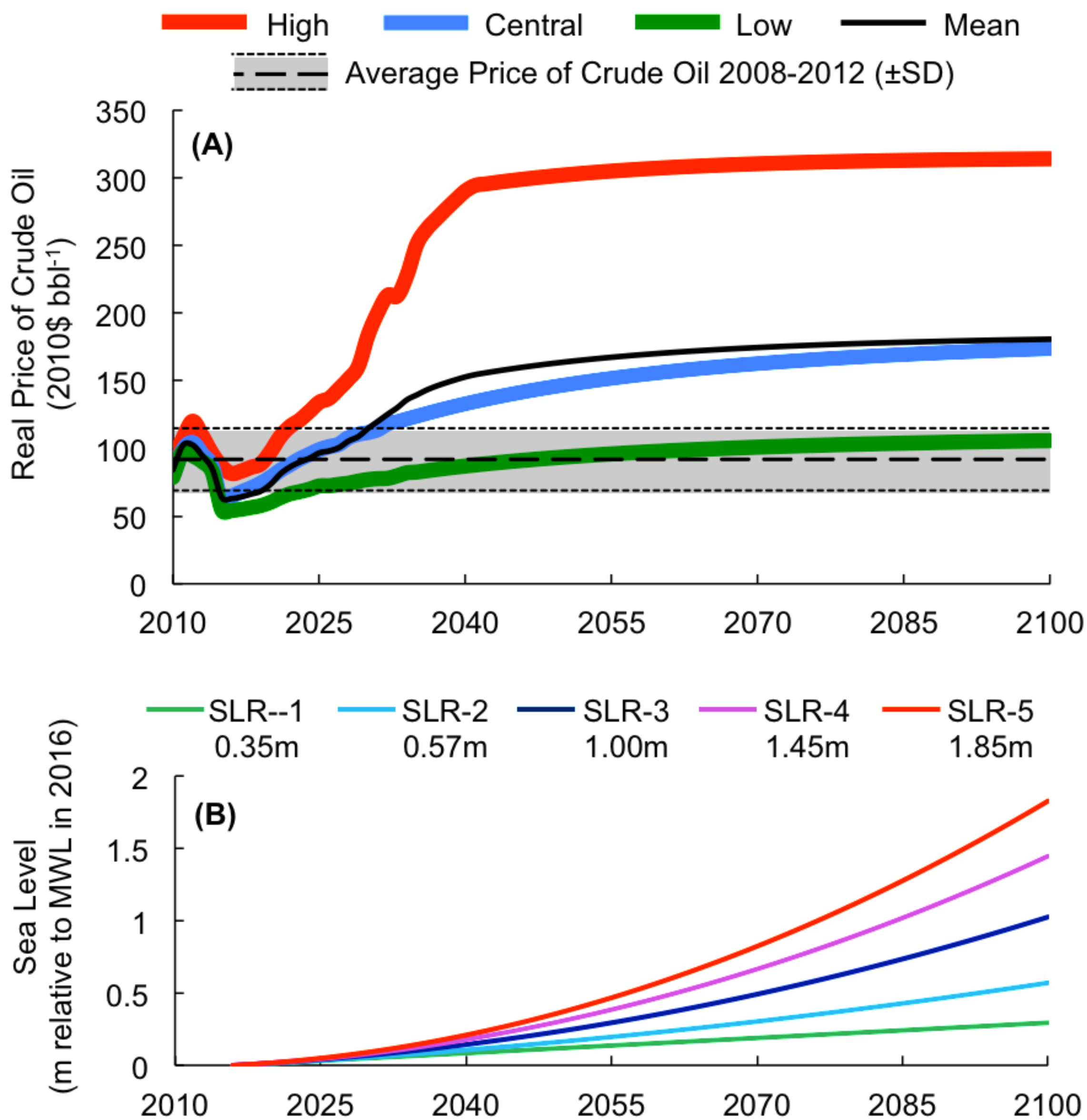

FIGURE 3. Future scenarios for oil price (A) and sea-level (B) (see APPENDIX-A). The low, central, and high, scenarios are composite forecasts for oil prices based on 15 projections from IEA (2015), EIA (2015), McGLade (2014), Heun & De Wit (2012).

The Low, Central, and High scenarios represent different assumptions about future technology, economic growth, and climate policy (Figure 3A, see APPENDIX-A). For example: the Low scenario is associated with adoption of stringent climate policy through a carbon tax, reduced GDP growth in developing countries and reduced market manipulation by the oil cartel "OPEC". The High scenario represents very weak climate restrictions on the energy industry, high short term GDP growth in developing countries through fossil fuel use and high reliance on synthetic liquid fuels from low net energy yielding crude oil substitutes (e.g. biodiesel, bioethanol, bitumen, kerogen, coal liquefaction, natural gas to liquid). The Central scenario represents a partial adoption of climate policies and moderate GDP growth. The Low, Central, and High scenarios all have fossil fuels as a significant portion of the energy supply in 2035, representing no future divestment from petroleum (e.g. Sgouridis et al. 2016). The No Change scenario, represents a future in which improving technology and renewable energy growth decrease demand and production for oil faster than depletion rates (a la Sgouridis et al. 2016) so prices remain constant at \$55 bbl^{-1} (see APPENDIX-A). In reality, there may be fluctuations between the price levels represented by different scenarios driven by a combination of factors.

2.4. Wetland Modeling

WECRM simulates water level, marsh productivity and sediment deposition and resulting elevation dynamics on a weekly time step (Figure 2, see APPENDIX-C). I adapted primary productivity, organic matter and mineral sediment equations from the MEM (Morris et al. 2002, 2012). State equations for biomass and organic sediment were adapted from the IWEM (Rybczyk et al. 1998, Rybczyk & Cahoon 2002). I 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 2016b) (Figure 4, see APPENDIX-C).

Following the MEM, sediment deposition was modeled as a function of the maximum inundation depth, the mean total suspended sediment concentration (TSS, mg/L) of the adjacent water body, and above ground biomass (g d.w. m^{-2}). I parameterized TSS concentrations based on published data from Terrebonne Bay, Fourleague Bay, and the Wax Lake and Atchafalaya Delta areas (Perez et al. 2000, Wang 1997, Murray et al.1993, Allison et al. 2014). I estimated that the mean TSS concentrations for sites with and without river influence ranged from 60-120 mg/L and 20-40 mg/L respectively. Between November and May, passage of semi-weekly/bi-weekly cold fronts can elevate water level substantially, and cause TSS concentrations to exceed

1000 mg/L (Perez et al. 2000, Wang 1997, Murray et al.1993); this is a major pathway for redistribution of river sediment (Roberts et al. 2015, Day et al 2011). 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-2, Table C2). Before the construction of major damns on the Missouri river in the mid 20th century, the Mississippi river had TSS concentrations above 300 mg/L (Allison & Meselhe 2010).

I modeled productivity as a function of percent inundation (e.g. Snedden et al. 2015, Kirwan & Guntenspergen 2012). Soil volume was modeled using the ideal mixing model from Morris et al. (2016). I assumed soil organic matter was comprised of 10% refractory (non-decomposable) material and that decomposition rates of labile material were 40% per year (Lane et al. 2016) (See APPENDIX-C). To validate the wetland system model of WECRM, I conducted 100-year hind-casts of the MEM 5.41 and WECRM. I used the same parameter values and initial conditions in both models and compared Carbon sequestration, accretion, and marsh collapse dates during these simulations (See APPENDIX-D).

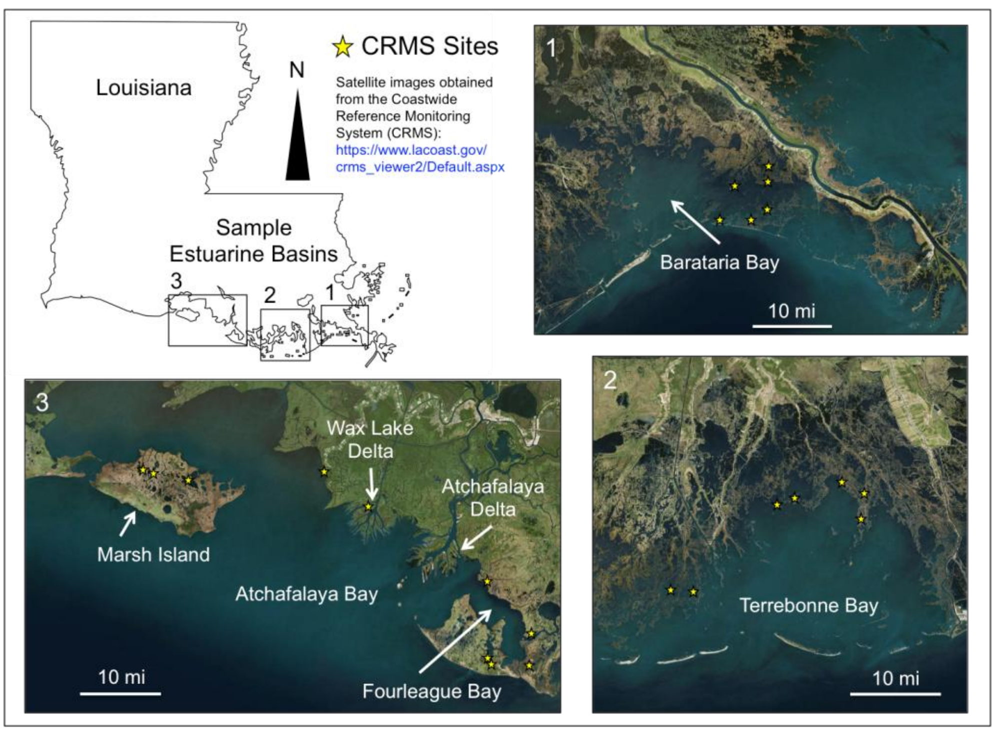

FIGURE 4. Map of Louisiana estuarine basins (1) Barataria, (2) Terrebone and (3) Atchafalaya and the Coastwide Reference Monitoring System sites used to calibrate WECRM. (Modified from LA Coast. 2016b)

2.5. Restoration Subroutines

I built subroutines into the WECRM to simulate the effects of restoration on marsh elevation (Figure 5). When marsh accretion falls behind the rate of SLR, an accommodation space is created that must be filled by the addition of sediment if the marsh is to be sustainable (Paola et al. 2010). Sediment can be added by particles advected onto the marsh surface when it is flooded, or via dredging (Figure 2). When marsh elevation relative to mean water level (E_{RWL}) reaches a threshold (E_{crit}), MC is triggered and dredged sediments are pumped up to the target fill elevation (E_{fill}). Subsequently, total fill height (H_{fill}), mass of dredged sediment per unit area (S), and total borrow volume (BV) are calculated (Eqns. 1-4).

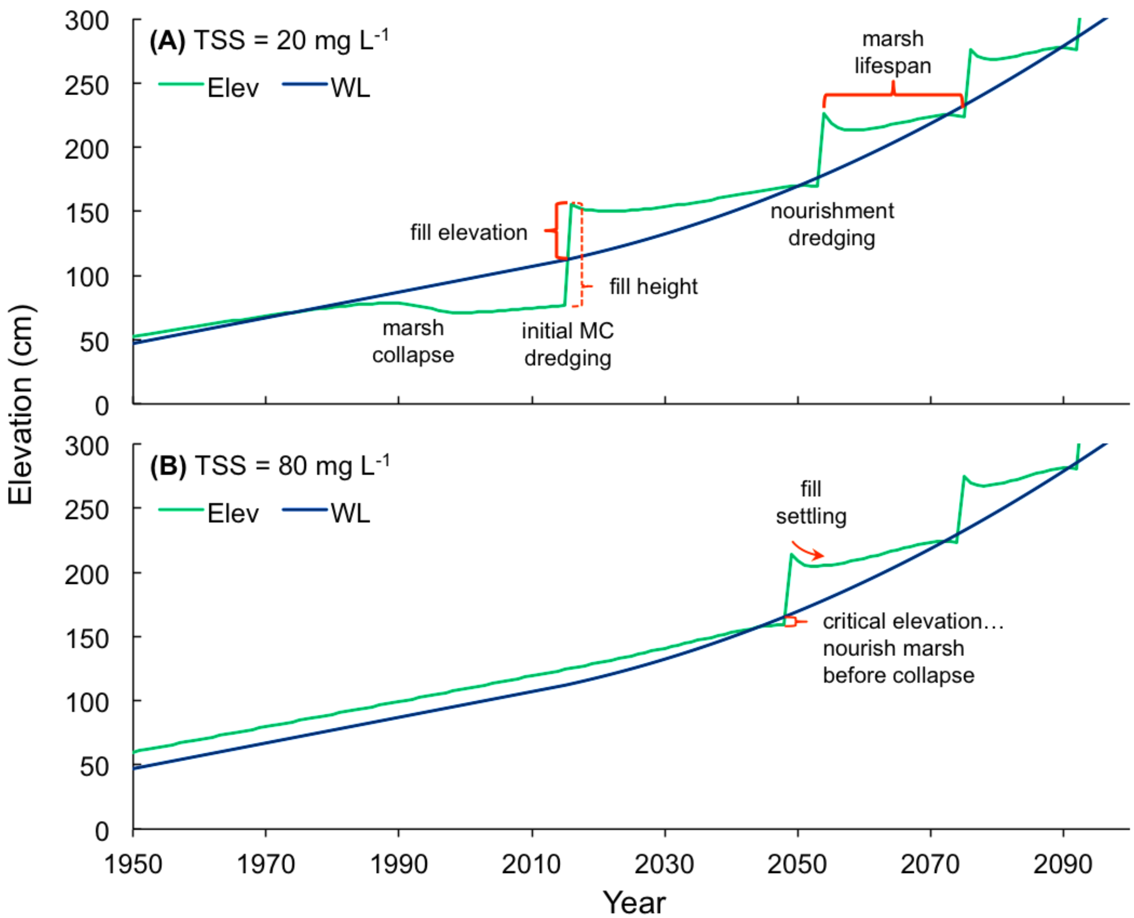

FIGURE 5. WECRM calibration run showing marsh elevation over time with input of dredged materials to sustain marsh for the central sea-level rise scenario (SLR-3). Results are shown for sediment concentrations (TSS) of (A) 20 mg/L and (B) 80 mg/L. Fill elevation (E_{fill}) and the critical elevation at which restoration is triggered (E_{crit}) are adjustable parameters, set here to 50 cm and -10 cm respectively.

(Eqn. 1)

If , $E_{RWL} <= E_{crit}$, Then

MC = 1, "dredge sediment to reach fill target",

proceed to Eqn. 2-4

Else, MC = 0, "do nothing",

set Eqn. 2-4 equal to zero

E_{RWL} is the elevation of the marsh relative to mean water level; E_{crit} is the critical elevation threshold at which marsh creation is triggered.

$$H_{fill} = (E_{fill} – E_{RWL}) \quad \text{(Eqn. 2)}$$

H_{fill} is fill height (m) and E_{fill} is the fill elevation target of marsh creation (m).

$$S = 100*H_{fill}*BD \quad \text{(Eqn. 3)}$$

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).

$$BV = Area*H_{fill}*bf \quad \text{(Eqn. 4)}$$

BV is the total borrow volume (m^3) for the project (i.e., the total material displaced from the borrow site); 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-D); Area is the area (m^2) of the MC project.

The E_{crit} was set to the observed E_{RWL} at which positive physical and biogeochemical feedbacks accelerate marsh submergence. At this elevation, collapse is inevitable without restoration. Once a marsh has reached this elevation further increases in TSS do not save it (e.g. Day et al. 2011, Nyman et al. 1995). The E_{crit} is a function of tidal range, RSLR, and river (freshwater and sediment) input. High tidal range and/or river throughput allow tidal marshes to remain productive at lower E_{RWL} (see APPENDIX-C, Kirwan et al. 2010, Kirwan & Guntenspergen 2012, DeLaune et al. 1983). After analyzing data from CRMS and the literature (Couvillion et al. 2013, Day et al. 2011, Nyman et al. 1995, Rybczyk & Cahoon 2002), and running the MEM v5.41 (Schile et al. 2014) when calibrated for Louisiana, I determined the E_{crit} at current rates of RSLR was about -10 cm. This is a typical average E_{RWL} for a MC project to be considered marsh nourishment.

I ran restoration cost scenarios out to 2066 (50 years) and to 2100 (84 years) starting in 2016. Each model run starts in an open bay with a depth of 50 cm that is restored to the E_{fill}. If marsh accretion falls behind RSLR and the E_{crit} reaches -10 cm, the marsh is nourished with dredged sediment back to the E_{fill} (Figure 7, see APPENDIX-D). I ran sensitivity tests for E_{fill}, year of MC construction, and year of RSD completion. The year of RSD completion is the year that TSS levels are altered from the baseline of 20 mg/L. I ran WECRM while increasing E_{fill} from 2 to 200 cm at 2 cm increments. I ran additional simulations where MC completion year and RSD completion year were delayed from 2016 to 2100 at 1 year increments, each of these tests were repeated at TSS levels of 20, 40, 80, 160 mg/L. During each test, I tracked marsh lifespan (L, Eqn. 5), a physical benefit:cost ratio (B:C), and total project costs (defined below). Marsh lifespan is measured as the number of years after restoration that E_{RWL} of the restored marsh remains above -10 cm (E_{crit}). B:C equals marsh lifespan divided by total height (cm, $H_{fill} = E_{fill} + 50$) added to the bay. (Eqn. 6). The cost of each restoration effort was modeled as a function of projected oil prices in each year using a linear model described in section 2.5 (also see APPENDIX-B).

$$L = Y_{crit} - Y_{MC} \qquad \text{(Eqn. 5)}$$

$$B{:}C = L/(H_{fill}) \qquad \text{(Eqn. 6)}$$

L is the MC project lifespan; Y_{MC} is the year of dredging for MC; Y_{crit} is the year the marsh reaches the E_{crit} (-10 cm relative to MWL); B:C is benefit to cost ratio; H_{fill} is the total fill height of dredging (defined in Eqn. 2).

2.6. Coastal Restoration Costs

I broke down cost forecasting of MC into two components: (1) a production function – a model for the total output (or cost) of a physical economic activity comprised of one or more production units that transform energy and material into final products (e.g. Warr & Ayres 2009, Georgescu-Roegen 1970, 1972, 1979); (2) a commodity market model – a model of supply, demand and subsequent price of a commodity, in this case crude oil (e.g. McGlade & Ekins 2015, Loulou & Labriet 2008).

The production function for the cost of MC projects was developed using data from coastal restoration project completion reports. I compiled a dataset on cutter suction dredging for coastal restoration projects completed in the MRDP (see APPENDIX-B). I 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) in R, using step-wise variable selection (R Core Team 2013, Lumly & Miller 2009). The “reduced” best fit model simulated dredging price as a function of the real (2010 CPI adjusted, https://www.bls.gov/cpi/) mean price of crude oil (P_{CO}) during the 12 months prior to the contract award, a efficiency/scaling factor (Ek), and a binary indicator variable (0/1) for beach and dune restoration to distinguish between dredging for high quality beach sand and muddier substrates used for marsh creation. When the model was in linear form with respect to P_{CO} and P_D the variance was heteroscedastic. It was necessary to log transform P_D and P_{CO} in order to remove heteroscedasticity, resulting in the final model given in Eqn. 7 and Figure 6.

$$P_D = e^{[b_0 + b_1 * LN(P_{CO}) + b_2 * DR + b_3 * Ek]} \quad \text{(Eqn. 7)}$$

P_D is the real (CPI adjusted) unit price of cutter suction dredging (2010$ m^{-3}); P_{CO} is the price of crude oil; Ek is the efficiency/scaling factor, equal to the log of borrow volume over the log of horsepower capacity of the dredge (CY/HP); 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 (Figure 6, See APPENDIX-B).

I modeled the total cost of a single MC effort (C_{MC}) as a function of borrow volume (BV, m^3) and dredging unit price (P_D, $ m^{-3}) (Eqn. 8).

$$C_{MC} = mf * P_D * BV \quad \text{(Eqn. 8)}$$

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; and BV is the borrow volume (m^3) from Eqn 4, and P_D is the function from Eqn. 7 with DR = 0 and Ek = 4.9, the mean value across all observations. Dredging costs are 60-70% of total construction costs for MC projects (CPRA 2012b, Petrolia et al. 2009); accordingly, I set mf to 1.5 (see APPENDIX-B).

The P_D and C_{MC} functions assume the following: (a) The MC project conforms to CPRA specifications (outlined in CPRA 2012b and summarized in APPENDIX-B), (b) the dredge being used is a cutter suction dredge (see APPENDIX-B), (c) changes in the price of diesel and other commodities used in heavy construction (e.g. steel, equipment and labor) follow fluctuations incrude oil markets (Ji & Fan 2012, World Bank 2015); and (d) the dredging contractor modifies the bid price based recent trends in the price of these input commodities, which are impacted by crude oil (see APPENDIX-B).

I used crude oil price forecasts averaged from a suite of energy market models to drive P_D in future simulations (see section 2.2 and APPENDIX-A). For each energy and SLR scenario and sensitivity test, I calculated the total cost (C_T) to restore and sustain coastal marsh using dredging from 2016 to 2066 and from 2016 to 2100 (Eqn. 9). In addition to calculating C_T, I created a metric called the Marsh Creation Cost Index (MCCI). MCCI measures the factor increase in cost of a given scenario relative to the baseline scenario for a given time interval (e.g. 2016-2100), C_{TB} (Eqn. 10). C_{TB} was defined as the C_T for the no change energy and SLR scenarios, with initial E_{RWL} of -50 cm relative to MWL, E_{fill} of 100 cm and TSS of 20 mg/L. The baseline E_{fill} value of 100 cm was based on CPRA specifications for MC projects (CPRA 2012b, see APPENDIX-B).

$$C_T = \Sigma^n_{i=1} [C_{MC},i] \quad \text{(Eqn. 9)}$$

C_T is the total cost to sustain coastal marsh during the time interval, $C_{MC,i}$ is the cost of marsh creation (see Eqn. 7) for the i^{th} restoration effort, and n is the number of restorations required to sustain the marsh during the time interval.

$$MCCI = C_T / C_{TB} \quad \text{(Eqn. 10)}$$

MCCI is equal to C_T for a given scenario divided by C_{TB}, which is the C_T of the baseline scenario (defined above).

3. RESULTS

3.1. Oil Price Impacts on Dredging Costs

The multiple regression model (Eqn. 7) was significant with a p-value of $1.1*10^{-8}$ (f-value 22.76 on 3 parameters and 39 degrees of freedom) and explained 63.6% of the variability in dredging price (Figure 6).

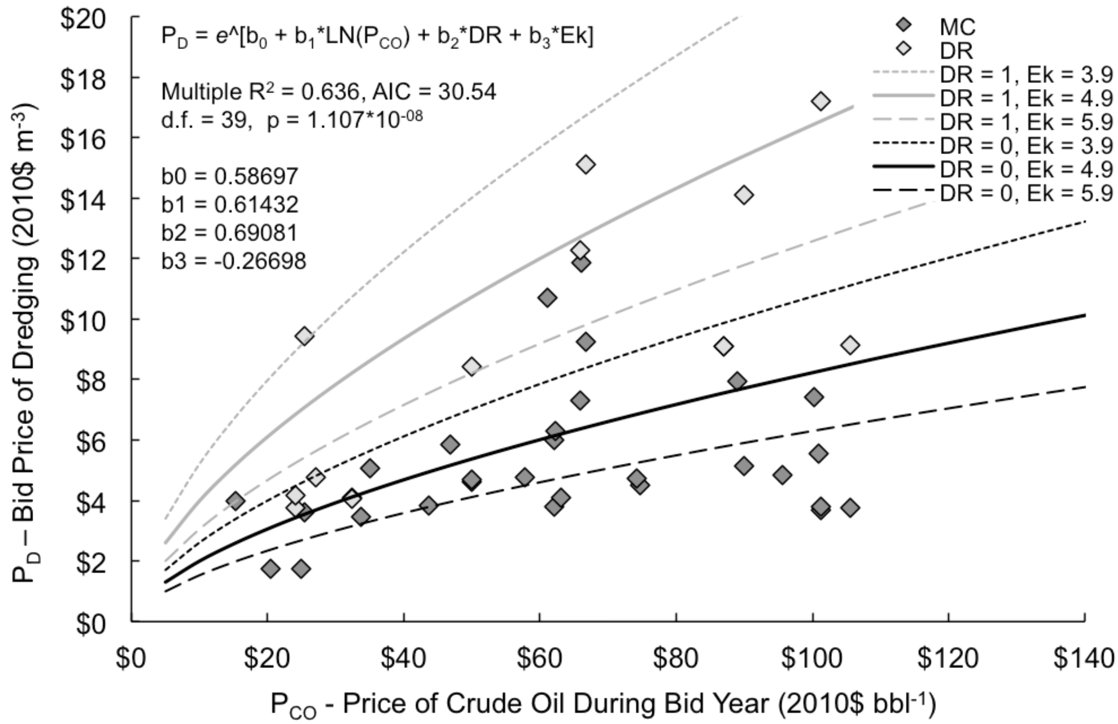

FIGURE 6. The relation between crude oil price (P_{CO}) and the bid price of cutter suction dredging (P_D) for coastal restoration in the Mississippi Delta. Dark grey diamonds indicate marsh creation (MC), light grey diamonds indicate beach/dune restoration (DR). A multiple regression model is plotted on the graph; the equation, results, and parameter estimates are shown in the upper left. According to the regression, three variables control P_D: P_{CO}, DR – an integer that indicates if a project is dune restoration (DR=1) or not (DR=0), and Ek – a project efficiency/scaling factor (see Eqn. 7). Regression lines are plotted for both DR (DR=1) and MC (DR = 0), at the average and ± 1 S.D. of Ek.

All independent parameter estimates were significant at a 99% confidence level (see APPENDIX-B, Table B1). The log-linear model (Figure 6) meets all assumptions of linear regression. There was no significant multicolinearity between independent regressors. According to the Shapiro-Wilk's test (p-value = 0.2271) the data is normal with respect to the model residuals. The Breuch-Pagan test (p-value = 0.691) indicates that the log-linear model has homoscedastic variance. Based on these results, I failed to reject hypothesis that oil and dredging price have a positive linear relation, with the following caveats. Since it was necessary to log transform P_D and P_{CO}, the relation is positive and log-linear. The relation likely changes over time (autocorrelation), or at a certain threshold in oil price (heteroscedasticity), or possibly both.

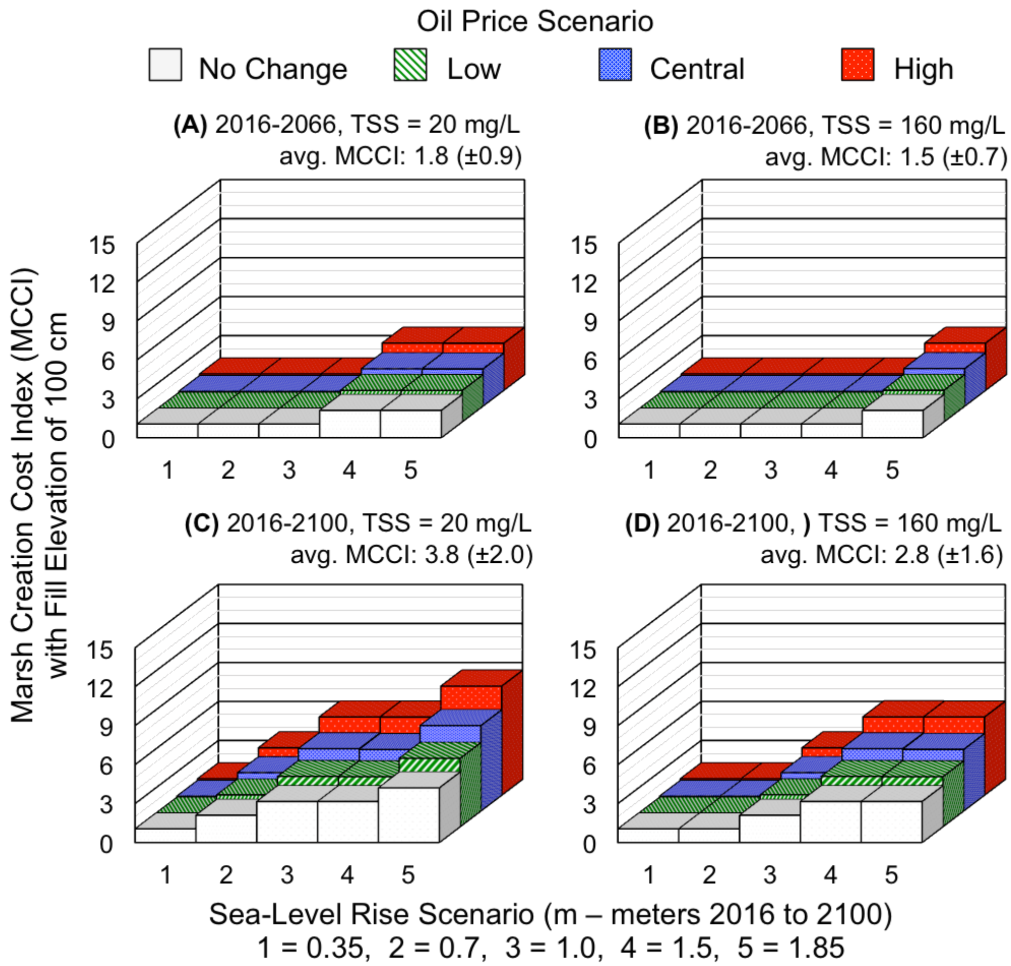

FIGURE 7. The impact of oil price and sea-level rise on the cost of sustaining coastal marsh with hydraulic dredging at a fill elevation of 100 cm. A marsh creation cost index (MCCI) of 1 equals $128,000/ha. MCCI is reported from 2016-2066 (A and B) and from 2016 to 2100 (C and D) with total suspended sediments (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 Figure 3.

3.2. River Sediment and Sustainability of Marsh Creation

Raising TSS resulted in longer created marsh lifespan (see Eqn. 5) (Figure 9A) and lower total cost of marsh creation from 2016 to 2100 (Figure 7). The marginal benefits of increasing TSS were higher at lower fill elevations but decreased with increasing SLR (Figure 9). Changing TSS from 20 to 160 mg/L is the equivalent of going from no river input to the immediate vicinity of a river channel (see section 2.4 in METHODS). For a MC project completed in 2016 with an E_{fill} of 100 cm, a TSS jump 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 (Figure 9 A & D). For a MC project completed in 2016 with an E_{fill} of 10 cm, a TSS jump 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 (Figure 9 A & D). At an E_{fill} of 100cm, increasing TSS from 20 to 160 mg/L did not reduce the average MCCI (across all the energy and SLR scenarios) from 2016-2066, but reduced average MCCI 26% from 2016-2100 (Figure 7). 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 2016-2066 and 57% from 2016-2100 (Figure 8 A & C).

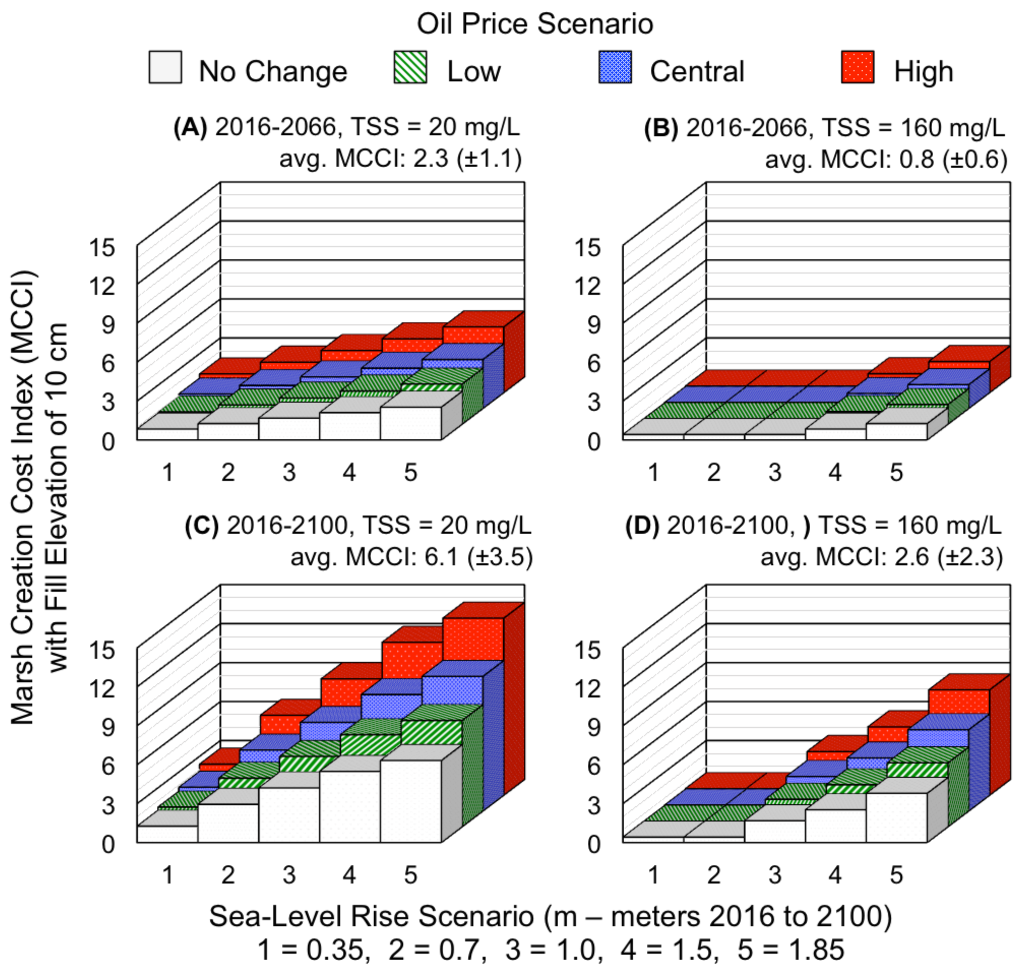

FIGURE 8. The impact of oil price and sea-level rise the cost of sustaining coastal marsh with hydraulic dredging at a fill elevation of 10 cm. A marsh creation cost index (MCCI) of 1 equals $128,000/ha. MCCI is reported from 2016-2066 (A and B) and from 2016 to 2100 (C and D) with total suspended sediments (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 Figure 3.

3.3. Optimal Fill Elevation and Diminishing Returns Over Time

I found diminishing marginal returns on lifespan (benefit) with increasing E_{fill} for open bay marsh creation and existing marsh nourishment (Figure 9). The marginal benefits of increasing E_{fill} varied with TSS level. With TSS at 20 mg/L, the increase in lifespan was increasingly linear above an E_{fill} of 50 cm. As TSS levels increased above 20 mg/L there was greater lifespan change for each increase in E_{fill} at lower E_{fill} than at higher E_{fill} (Figure 9 A-D). When TSS was lower than 40 mg/L, B:C maxima were achieved at E_{fill} values of greater than 30 cm (Figure 9 E & F). At TSS concentrations of 80 mg/L , maxima of B:C occurred at an E_{fill} of roughly 10 cm (Figure 9 G). At TSS concentrations of 160 mg/L, a distinct B:C maxima occurred at E_{fill} below 2 cm (Figure 9 H).

MC suffers diminishing returns on lifespan over time due to accelerating SLR, regardless of TSS level (Figure 10). Projects with an E_{fill} of 50 completed in 2020 had an lifespan from 26 to greater than 100 years depending on SLR and TSS level. When MC completion year was beyond 2050, lifespan for an E_{fill} of 50 cm was frequently below 10 years for SLR-4 and SLR-5, and only greater than 20 years at the highest TSS levels and lowest SLR (Figure 10 A-D). Delaying the RSD completion also year reduced the lifespan for MC projects completed in 2016 (Figure 10 E-H). At an E_{fill} of 50 cm there was no increase in lifespan with RSD completion year greater than 2060 for all SLR scenarios above no change, because the marsh created in 2016 had already collapsed (Figure 10 E-H).

Fill elevation (E_{fill}) is an important parameter when considering energy prices and restoration costs over time. Decreasing fill height increased the number of nourishments over time, with the unit costs of marsh nourishment getting higher and as energy prices increased. Increasing fill height linearly increased costs but yielded diminishing lifespan returns because of accelerating SLR (Figure 9). Figure 7 and Figure 8 show the influence of changing fill elevation of dredging on the total cost of marsh restoration between 2016 and 2100. The E_{fill} with the lowest cost outcome varied depending on future energy and SLR scenarios, and length of restoration period. More optimistic scenarios favored lower E_{fill} while less optimistic scenarios favor higher E_{fill} (Figure 8 and in APPENDIX-F). At Higher TSS levels the lowest cost outcome occurred at lower E_{fill} than at low TSS (Figure F1 and F2).

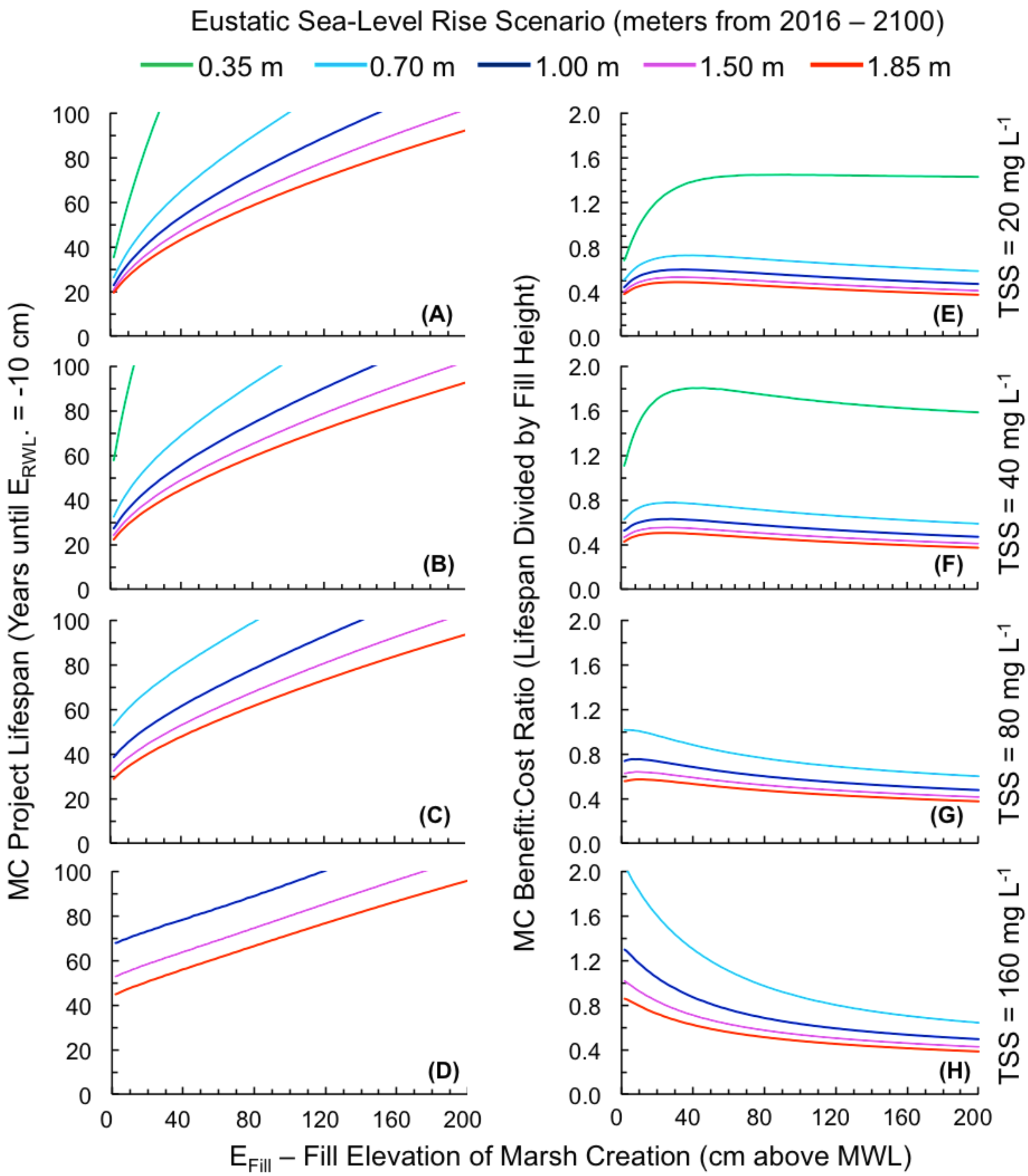

FIGURE 9. The influence of fill elevation, total suspended sediments (TSS) and sea-level rise on (A-D) marsh creation project lifespan (MCPL) and (E-H) benefit:cost ratio (B:C). TSS (shown on the right) increases from top to bottom. lifespan increases nonlinearly relative to fill elevation with increasing TSS (A-D); this leads to an optimum zone where B:C is highest (E-H). The B:C maxima move towards to 0 with increasing TSS levels (G and H).

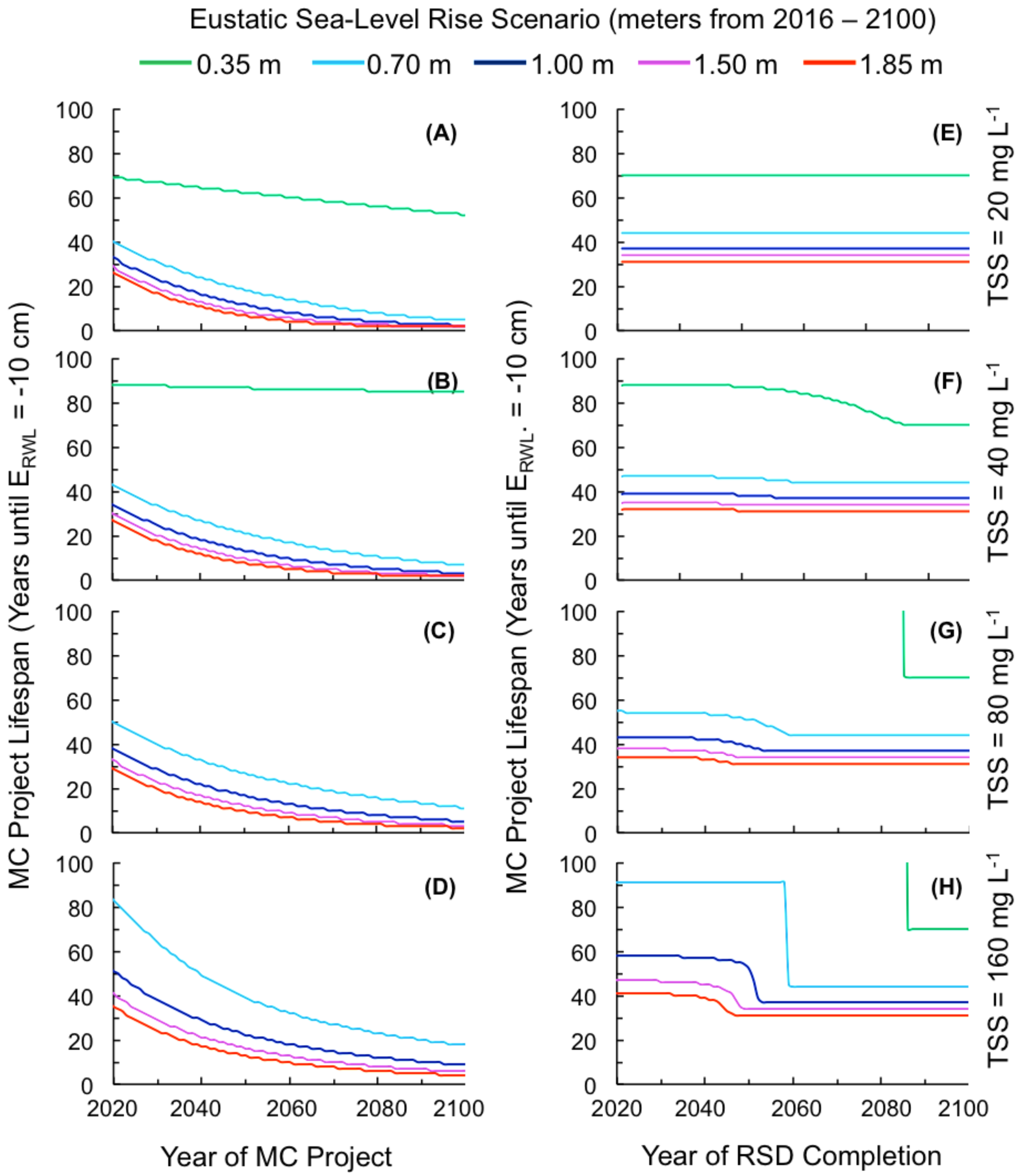

FIGURE 10. Diminishing returns on marsh creation project lifespan (MCPL) with delayed restoration date. (A-D) lifespan verses year of MC project construction; (E-H) lifespan verses year of river diversion (RSD) completion. Total suspended sediments (TSS) (shown on the right) increase from top to bottom. In this figure, every simulation starts with an open bay with an elevation relative to mean water level E_{RWL} of -50 cm that is dredged to an E_{fill} of 50 cm.

3.4. Summary of Findings

A significant positive relationship exists between oil price and the price dredging for MC (Figure 5). I used this relationship in WECRM to simulate the cost of sustaining marshes with MC over time across a range of SLR and oil price forecasts. The results of these simulations show that the combined effect of SLR and oil prices increases the cost to sustain marsh greatly. The costs to sustain marsh between 2016 and 2100 changed from \$128,000 ha^{-1} in the no change scenario to ~\$1,010,000 ha^{-1} in the worst-case scenario, an ~8-fold increase (Figure 7C). Management approaches affect long-term costs to sustain marsh, this was most apparent when evaluating the 2016-2100, time horizon. If a marsh is exposed to higher TSS, lifespan increases, the marsh requires less frequent nourishment with dredged material (e.g. Figure 6), and costs go down (Figure 7 C & D). When considering the less optimistic forecasts for SLR and oil price increasing energy costs, a front-loaded investment strategy yielded the lowest dredging costs between 2016-2100 (Figure 7 C, APPENDIX-F).

I tested the sensitivity of MC project lifespan (MCPL) to various parameters including E_{fill} (Figure 9A), the RSD completion year (the year TSS increases from a baseline of 20 mg/L) (Figure 10 E-H), and MC construction year (Figure 10 A-D). Increasing E_{fill} showed non-linear responses in lifespan, which resulted in optimum B:C zones that tended to become more pronounced and occurred at lower E_{fill} with increasing TSS (Figure 9B). Delaying MC construction reduced lifespan greatly. Delaying RSD completion did not alter lifespan very much (Figure 10), which indicates that sediment input alone cannot explain the low rate of land loss rates seen in the Atchafalaya basin compared to Barataria and Terrebonne (see Twilley et al. 2016). In spite of this, my findings demonstrate that B:C of MC can be optimized by altering dredging protocol depending on the existing marsh conditions, anticipated future river sediment regime, and time horizon of restoration (e.g. Figure 9 E-H, APPENDIX-F). But if RSLR accelerates as projected (Figure 3B), then sustaining marshes with dredged sediments will have diminishing returns over time, regardless of management strategy (Figure 10 A-D).

4. DISCUSSION

4.1. Production Function for Marsh Creation

The price of dredging (P_D) and marsh creation cost (C_{MC}) functions are relatively simple and capture the effect of fuel costs (P_{CO}), project scale and difficulty (Ek), and the type of project, beach and dune restoration or marsh creation (DR). I obtained a robust sample of dredging (n = 42) projects over a 20-year time period (1994-2014), however, the model would be much improved with a larger sample size containing more recent marsh creation projects. In any case, the model R^2, of 0.636 with 39 degrees of freedom (R^2 0.608 when adjusted for additional parameters), is satisfying considering the amount of variability that can occur from project to project and over a 20-year period in a competitive economic market (Ji & Fan 2012).

A limitation of the P_D model is that many of the variables controlling the price of dredging are time dependent (Cohen 2011, Murphy 2012). Although the overall P_D model was significant, H1 was rejected due need to log transform P_D and P_{CO} to remove heteroscedasticity. Thus, the relation between P_{CO} and P_D is more complex than a simple linear relation and likely changes over time, which is common in economic datasets. A larger, continuous, dataset must be used in order 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 form of "efficiency". Competition for projects bids over time can lead to lower bid margins. Sequential project construction could consolidate mobilization and demobilization efforts. Improved machinery, digital operation technology, and weather forecasts can reduce down time (Cohen 2011). In addition to efficiency gains, there is also potential to reduce the impact of fuel price volatility through long-term contracts with a negotiated fixed fuel price (Murphy 2012), a common practice in natural gas markets.

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 Ship Shoal, which has a limited supply of sand of the proper grain size (CPRA 2015, CPRA 2016, Penland et al. 2003). MC projects that take sediment from nearby bays can deepen water, leading to more powerful waves and greater localized erosion (Marriotti & Fagherazzi 2010). 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 (CPRA 2017b, Clark et al. 2015). While I have not specifically considered any of these factors, the Ek term (comprised of horsepower and borrow volume) can be varied to change 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, if a project's borrow volume is very large and the sediment source is shallow and nearby (<5 km) then only one large cutter suction dredge is required (CPRA 2012b, Cohen 2011), the Ek value will be large and P_D will decrease; if the borrow volume is small and the sediment source is very deep or far way (e.g. Mississippi River or offshore, CPRA 2015, CPRA 2012b), then additional horsepower is required (Bray et al. 1997) and the Ek value will be small and P_D will increase (CPRA 2017b).

Engineering input/output (I/O) cost models (e.g. Belesimo 2000, Hollinberger 2010, Wowtschuk 2016) are already used for LACMP cost estimates (CPRA 2012b). I/O models are able to account for project specific variability, such as the influence of substrate type, dredging depth, pipe friction, and more on production rate and cost for a given dredge (Belesimo 2000, Bray et al. 1997). Future research could evaluate the impact of efficiency and other variables (such as pumping distance) on the relation between oil prices and bid price both at the individual project and industry wide levels. This could be approached at the macro-scale by conducting time series analysis a large dataset (as mentioned above), or at the micro-scale using dredging industry I/O models to test parameters for specific projects.

4.2. Diversion Costs

I elected not to quantify the costs of RDs as part of cost modeling for a several reasons. I did not analyze the impact of energy prices on cost of diversion construction. The cost of a diversion must be associated with a discharge capacity and area of impact. I modeled only TSS level, there are many other impacts from a diversion (discussed more below). The cost of a diversion is related to the size of the conveyance channel and complexity of engineering (Kenney et al. 2013); the latter of which can be quite variable for a given capacity. Engineering of RSDs is complicated by positioning on the river, mechanism for diverting sediment, land uses between the river and the outfall area, discharge capacity, and operation flexibility. Diversion design can also be quite simple, such as a crevasse (e.g. Caernarvon 1927 Crevasse, Day et al. 2016b, Davis

Crevasse, Day et al. 2016c) or a breech in a levee using dynamite or a dredged channel (e.g. West Bay, Allison et al. 2015, Kolker et al. 2012). Costs and benefits of a RSD can vary greatly with changes in design and location (Kenney et al. 2013, Wang et al. 2014, CPRA 2017). The impacts of discharge capacity and positioning of diversions on marsh creation projects is currently being analyzed by the LACMP modeling efforts (CPRA 2017). LACMP diversion modeling results and cost estimates will be published in 2017. Future studies should incorporate uncertainty energy costs in a cost benefit analysis of the results of the 2017 LACMP.

4.3. Wetland Model Assumptions and Limitations

WECRM simulates how a uniform unit of marsh responds to changes in mean TSS concentration and RSLR. The most influential parameter on elevation dynamics is primary productivity (APPENDIX-D). Primary productivity influences both organic and mineral sediment accumulation (see APPENDIX-C). Environmental interactions that affect primary productivity are often nonlinear (e.g. salinity and inundation, see Snedden et al. 2015, Couvillon et al. 2013, mineral input, redox, and elevation, Slocum et al. 2005 and Roberts et al.2015), such relations must be test further empirically, then modeled in future studies. Deep subsidence and shallow compaction of sediment during dredged material are also important variables, but their effect is straightforward; increasing subsidence/compaction reduces marsh lifespan linearly, which increases overall cost of sustaining marsh (and vice versa). Subsidence rates range from 2-35 mm/yr in the MRDP (Shinkle & Dokka 2004) and are exacerbated by fluid withdrawal rates, which change over time (Kolker et al. 2011). Subsidence has significant implications for coastal restoration, and MC in areas with high subsidence or highly compressible soils will be much more expensive.

WECRM is integrated weekly, which allows the model to be affected by seasonal and stochastic fluctuations in water level, sediment, etc. However, I used annual averages in this study so that the model could be compared with MEM (Morris et al. 2012, see APPENDIX-D). In reality, marshes are controlled by momentary fluxes in water level, temperature, suspended sediment, nutrient variability, salinity, pH, sheer stress from storm waves, all of which vary over spatial and temporal scales. For example: Water level and TSS fluctuate during river floods and high wind events as a function of shear stress of the bed, flow velocity in the water column and channel geomorphology (Xu et al. 2015). TSS concentrations range from 200-600 mg/L on the rising limb of a Mississippi River flood (Allison et al. 2014). During winter cold fronts, TSS concentrations in bayous and tidal creeks consistently exceed 200 mg/L (sometimes reaching above 1000 mg/L), and water levels can increase over 0.5 m above the astronomical tide (Perez et al. 2000, Murray et al. 1993). Similar examples can be given for other controls variables (e.g. salinity, pH). WECRM has potential to resolve some of this temporal variability (and could also be integrated spatially). Although, others have already developed physical models that resolve many of these forcings (e.g. Huang et al. 2011, Das et al. 2012, Marrioti & Fagherazzi 2013, Meselhe et al. 2013, Mudd et al. 2010).

4.4. Uncertainty Over River Diversion Benefits

A major uncertainty associated with this study is the impact of river input – which alters sediments, nutrients, salinity and water level – on primary productivity. The productivity equations in the model (APPENDIX-C) do not include the effects of minerals, nutrients, or salinity on productivity (Mudd et al. 2009, Mendelsson & Kuhn 2003). There is strong evidence in the literature that primary productivity and organic accretion increase with river throughput. River throughput has been demonstrated to increase longevity of marsh outside the area of land gain from sub-delta formation, through the addition of nutrients, reactive metals and reduction of salinity (Twilley et al. 2016, Roberts 2015, Deluane et al. 2016). Wetlands adjacent to the Wax Lake delta were shown to have higher productivity and carbon sequestration rates after receiving pulses of freshwater and sediment from a flood (DeLaune et al. 2016). The additional organic accretion can subsequently be buried by settling of mineral sediment (Morris et al. 2012). River throughput reduces stress from long periods of inundation and allows marshes to remain productive at lower elevation (Nyman et al. 2006, Couvillion & Beck 2013). A series of recent papers have studied the effects of the Atchafalaya river on marshes in surrounding bays, which include increased soil strength (Day et al. 2011, Roberts et al. 2105); increased productivity and carbon storage (DeLaune et al. 2016, Shields et al. 2016); these factors combine to increase plant resilience during storms and floods resulting in low rates of shoreline erosion and land loss (Twilley et al. 2016).

It is also important to note that prolonged inundation in brackish and saline wetlands negatively affects productivity, leading to higher marsh mortality (Snedden et al. 2015, Deegan et al. 2012, Darby & Turner 2008). This is likely to do sulfides inhibiting root nutrient uptake, low pH, and low redox potential (DeLaune et al. 1983). Inundation has few negative impacts in the Atchafalaya basin because salinities and sulfate concentrations are quite low during floods and water levels are seasonally variable; marshes grow rapidly during period low discharge in the later summer and fall (DeLaune et al. 2016, Roberts et al. 2015, Day et al. 2011). A sediment diversion will be most successful if: (A) the diversion is depositing into an oligohaline area (e.g. Maurepas Basin or Davis Pond) where there are lower sulfate concentrations and vegetation that are more tolerant of inundation, or (B) if water levels are elevated only for short pulses, preferably during dormant seasons (late November – early March) (see Day et al 2016a). Many of the factors influencing productivity occur in concert, making them difficult to parse and model statistically using field studies. This is a ripe area of future study that CRMS dataset is well suited for (LA Coast 2016b).

Restoring and sustaining marsh with higher levels of TSS due to river input was more effective than MC alone (Figure 9) and reduced the cost of MC over the simulation period (Figure 7). While TSS increased the lifespan significantly at low fill elevations, the addition of sediment at mean concentrations normally observed near the Mississippi/Atchafalaya Rivers (80-160 mg/L) did not provide enough sediment to sustain marsh indefinitely with accelerating rates of RLSR (this includes all SLR rates above the "no change" scenario). These findings are in agreement with LACMP models, which indicate that net land gain from RDs will be localized and that on a MRDP wide scale net land gain is not possible, regardless of diversion size (Wang et al. 2014, CPRA 2017a). My estimates of river diversion benefits are conservative; I modeled only the impact of sediment deposition from elevated TSS concentrations. Considering this, this studies results add to a growing body of literature that demonstrates that river sediment input is an essential element of MRDP marsh sustainability (see Nyman et al. 2014, Twilley et al. 2016, Roberts et al. 2015, DeLaune et al. 2016, Day et al. 2016a).

4.5. Optimizing Marsh Creation Benefits and Costs

Changing the depth at which marsh restoration is initiated has a significant impact on both the cost of restoration and the lifespan. I chose to nourish marshes at the E_{crit} (set in this study to -10 cm), before a marsh collapses rapidly and turns into an open bay. Restoring marshes before collapse (see Day et al. 2011) reduces restoration costs by decreasing the sediment load required to reach a desired lifespan. Restoring marshes before they collapse also increases total marsh productivity over the restoration period and has the added benefit of preventing potential release of greenhouse gases (GHGs) from organic matter that is decomposed as vegetation dies and soils erode (Lane et al. 2016, DeLaune & White 2012, see Figure D2).

The optimization analysis of fill elevation (E_{fill}) for a single restoration effort, indicated that sites with high river input (TSS > 80 mg/L) achieved the greatest B:C ratio at elevations lower than 10 cm. The implication is that MC projects completed near RSDs 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. In an area impacted by a RSD, if lower E_{fill} is combined with shallower E_{crit} (i.e. "nourishment" rather than "creation"), a fixed borrow volume could to 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 RSDs, a much greater area of land could be built per dollar (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). While MC projects at sites that are isolated from river influence must be built higher up to achieve a target lifespan. For a fixed borrow volume, there is a steep tradeoff between marsh longevity and spatial extent, especially in areas of low river influence. It is likely more sustainable to restore larger areas of contiguous marsh at low elevation than small patches of marsh at high elevation. 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 (Fagherazzi & Marrioti 2010, Xu et al. 2016, Twilley et al. 2016). There is also potential for local plant recruitment/regrowth if the dredging load is light enough not to kill the existing marsh rhizome network (Mendelssohn & Kun 2003, Slochum et al. 2005).

E_{fill} also has a significant impact on the costs of sustaining marsh with multiple dredging efforts over time under different future energy and SLR scenarios. Generally, the E_{fill} with the lowest cost outcome, increased with increasing energy price, SLR, and restoration period (APPENDIX F). I also found that E_{fill} and cost of the lowest cost outcome was considerably lower under higher TSS levels than under low TSS. These findings indicate that MC projects in areas without river influence have a much lower of return on investment than projects in areas with river influence (See Figure 10) and that marsh creation strategy should adapted based on changes in the likelihood of SLR and energy price scenarios.

4.6. Energy and Climate Path Dependency and Deltaic Sustainability

The decisions made in energy, economic, and climate policy over the next decades will play a role in determining the vulnerability of deltas to climate change and the price of management (Tessler et al. 2015, Day et al. 2016). The models I reviewed converged on similar price and carbon emissions outcomes (see APPENDIX-B). The high oil price scenario is associated with failed climate policy, higher demand for oil and high economic growth resulting in greater carbon emissions. 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, IPCC 2013; IEA 2015; McGlade 2014). The low oil price scenario is more closely associated with the IPCC's low carbon emissions scenarios (e.g. RPC 1.5 and RPC 2.5) due the adoption of a carbon tax, which induces low short-term economic growth, low demand for oil and high investment in renewable energy production. The low oil price scenario is more likely to coincide with the lower end of SLR estimates (IPCC 2013, IEA 2015). However, the oil price trajectory is not necessarily related to future carbon emissions.

When the market is in equilibrium, oil price is a equal to the cost of the marginal unit of production at a given quantity of demand. Production costs are inversely related to the net energy yield of different oil sources, see Heun & de Wit 2012; Berman 2016, Tripathi and Brandt 2016). 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 (Mcollum et al. 2016). Conversely, innovation in the oil sector could increase the efficiency of unconventional oil production, leading to oversupply, low prices, high demand and high carbon emissions (Mcollum et al. 2016); a recent example of this is the 2010-2016 U.S. shale oil boom (Brandt et al. 2016). If the market falls out of equilibrium, a rapid change in price to a new equilibrium level often occurs. If demand greatly exceeds the supply then prices will spike, if supply exceeds demand prices will drop (Hamilton 2012). A low price environment could be sustained by a combination of improving extraction technology and declining demand. Ultimately, the exhaustion of high net energy yielding conventional oil resources within the time frame of the LACMP is likely lead to increasing production costs and higher oil prices (e.g., Maggio & Cacciola 2012, Heun & de Wit 2012).

A low price, high demand situation is unlikely exist for very long. Large oil producers are becoming more risk averse and investing less frivolously in large projects (Berman 2016) and have tended not to invest in innovation until prices are very high (Murphy & Hall 2011). This has led to volatility in recent years. Production rates of existing wells decline over time, and without high prices there will be low investment and declines in old wells will not be offset by new production. Unless demand decreases at the same pace as declines in production, demand will slowly outpace supply leading to high prices (Murphy & Hall 2011). Given the growing demand for personal vehicles in Asia and the pervasive use of the internal combustion engine for cars and trucks in all developed countries, decreasing 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 & Ekans 2015). Unless strict climate policies curb demand for oil faster than declines in production, the oil market is likely return to a high price environment (IEA 2015, McGlade 2014).

Recent publications in both energy and climate science indicate that the lower range of SLR and oil forecasts are less likely than the high scenarios. The Antarctic ice sheet is melting faster than anticipated and could add up to a meter to current SLR projections (DeConto & Pollard 2015). The world economy is still heavily reliant on fossil fuels, which make up more than 80% of total energy use, and over 95% of the energy used for transportation (IEA 2016). A rapid 20-30 year transition from fossil fuels to renewables has been proposed to limit temperature increase to 2°C (Sgouridis et al. 2016; Jacobson et al. 2014), but such a transition is not even guaranteed to prevent/reverse trends in melting of polar land ice (Deconto & Pollard 2016, Horton et al. 2014).

Despite recent growth and efficiency gains in renewable energy (Koppelaar et al. 2016; Louwen et al. 2016), society is projected to remain dependent on fossil fuels, for many decades to come, especially for transportation, heavy industry, and agriculture (McGlade & Ekans 2015). About two-thirds of current fossil fuel reserves, and 90% of low-grade ultimately recoverable resources (URR) would need to remain unburned by 2100 to meet the 2°C target. Anderson (2015) estimates that 650 Gt CO_2 can be emitted from 2015 onward to meet the 2 C threshold, the equivalent of only 12-18 years of projected fossil fuel use (Mohr et al. 2015). Such a rapid transition is highly improbable (Smil 2016); renewables are not presently growing fast enough to reach a 30-year transition target (Hansen et al. 2016, Sgouridis et al. 2016). If solar and wind power growth follows a logistic curve with current growth rates, like every previous energy technology, they would make up only 10% of total energy use in 2030 (Hansen et al. 2016). The projections of Sgouridis et al. (2016) require a ramp up in renewable energy production by more than a hundred fold in less than three decades, far outpacing the growth rate of any fuel in the 20^{th} century (Smil 2016). Renewable energy substitutes also do not provide as much net energy as fossil fuels have historically (Weissbach et al. 2013, Hall et al. 2014). Thus, investing in an accelerated energy transition to meet climate targets could saddle countries with debt and reduce societal EROI greatly having negative implications for political stability and social welfare (Neumeyer & Goldston 2016, Dale et al. 2013, Lambert et al. 2014).

4.7. Recommendations for the Mississippi Delta

Restoration strategies should be designed to minimize the financial risks associated with increasing fossil fuel scarcity and climate change, especially the rate of SLR acceleration. This analysis indicates that energy prices in addition to SLR will impact the affordability of MRDP wetland restoration. Over the long-term, sustainable delta restoration should minimize reliance on energy intensive approaches, such as dredging (Tessler et al. 2015, Day et al. 2016b). This is sustainable management ethics, but things become more complex when funding dynamics are taken into account.

On either side of the spectrum for future energy supply, MRDP restoration may be constrained by price and/or funding. If renewable energy, despite its many limitations (Smil 2016, Trainer 2013), were to replace most fossil fuels by midcentury (e.g., Sgouridis et al. 2016), low prices would lead to declining oil and gas production in the northern Gulf of Mexico. A significant portion of Louisiana's tax base is dependent upon petroleum production and refining and associated industries (Davis et al. 2015, CPRA 2015). Successful renewable energy transition might yield low oil prices and lower dredging costs, but may also negatively impact the state's economy and tax budget. Conversely, high oil prices will likely yield higher costs, but might possibly increase the state budget. Further research is needed to quantify how energy-climate pathways influence both the funding and relative costs of restoration for the LACMP. It would be worthwhile to investigate how funding and investment programs could be restructured in response to changes in global markets (e.g. restore the coast when prices are low, save up restoration funds when oil prices are high; use approaches where natural energies are used to the fullest).

Ecological engineering is an approach to natural resource management where natural energies are used to the fullest (Mitsch and Jorgensen 2004). Restoration strategies should focus on restoring natural flow patterns of freshwater and sediments to coastal wetlands in the delta, while maintaining estuarine gradients (Nyman et al. 2014, Day et al. 2016a, Twilley et al. 2016). The Mississippi river is an excellent renewable source of energy and sediment that should be fully exploited through the construction of RSDs. Diversion structures will provide a long-lasting system with low recurring costs in the future. The Bonnet Carré Spillway is an example of this. It will likely be in operation for well over a century and the costs of operation are minimal (Day et al. 2012). Annual operations costs of planned RSDs are estimated to be 1% of total construction costs (CPRA 2017c). A diversion completed in the next 5-10 years will have greater long-term land gains and ecosystem benefit to MC projects than a RSD completed 10 or more years in the future, due to accelerating SLR. Conversely, delaying RSD completion will diminish lifespan (Figure 10 E-H) and likely come at greater cost due to increasing energy prices. This adds on to many reasons why RSDs should be planned and completed between now and 2025.

Marsh creation comes at significant cost and the future affordability of this process will be impacted significantly by energy prices in combination with SLR. MC does, however, provide an immediate and relatively long lasting benefit. Lifespan is projected to be 30 years or more at present (Figure 9A-D). Placing projects near an RSD can increase lifespan in the near term. However, lifespan will also diminish over time regardless of river input due to the acceleration of SLR (Figure 10 A-D). The CPRA should accelerate MC efforts and restore large swaths of the coast as soon and possible. There are several reasons for this: (1) to take advantage of the current period low/stable energy prices and subsequent restoration costs (2) reduce risk of detrimental impacts of future energy price volatility on restoration cost and funding; (3) to maximize the return on investment, which will decline over time as SLR accelerates even if energy prices do not change (e.g. lifespan and B:C, Figure 9, Figure 10 A-D).

To reduce energy use and overall costs, borrow sites for MC should be located as close to the fill areas as possible, reducing the need for booster pumps (Clark et al. 2015); and wherever possible dredged materials for navigation should be used beneficially. River input can reduce the need to re-nourish marsh by providing a long-term supply of suspended sediment. Marsh creation and nourishment should be prioritized in areas that fall within the predicted zone of sediment influence of planned RSDs (Figure 11). To optimize the use of dredge sediment, fill elevation should be modified based on expected TSS level (Figure 9), 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 erosion and more completely shield coastal communities from storms surge.

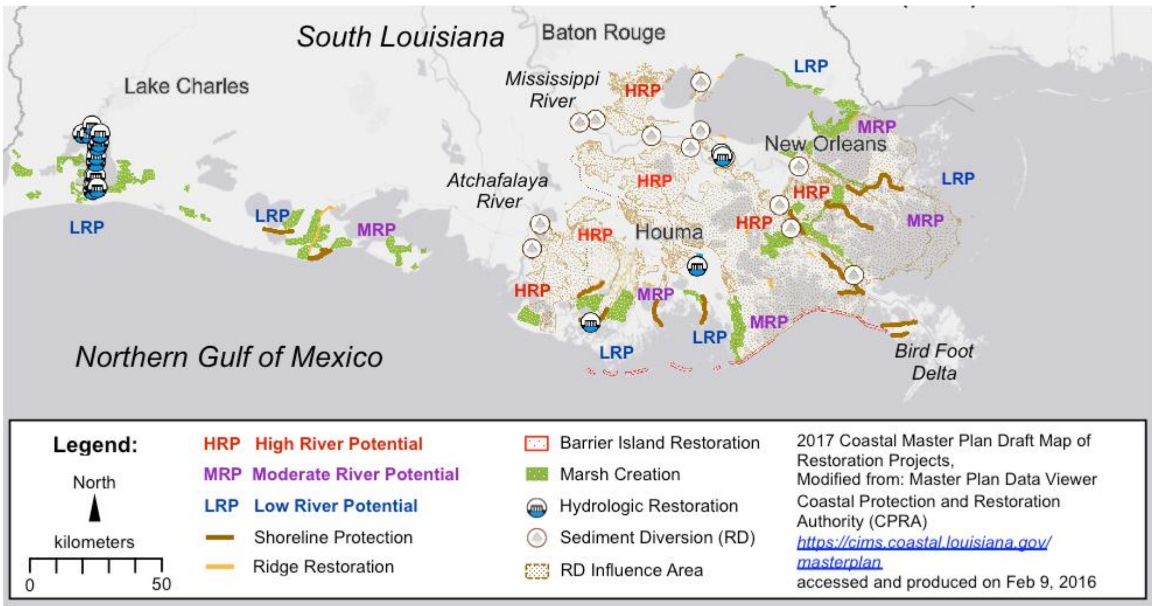

FIGURE 11. Map of coastal Louisiana with planned wetland restoration projects and zones of river potential. River potential zones are classified by the approximate slope (**Δ**) between the wetland and the nearest major river; $\Delta = (E_R - E_W)/x$, where E_R is river elevation, E_W wetland elevation, x is distance between the river and the wetland. Higher **Δ** results in greater river potential. (Modified from CPRA 2017d)

5. CONCLUSION

In this paper I analyzed how SLR and energy prices influence the cost of restoring and sustaining MRDP coastal marsh with hydraulic dredging. I developed the WECRM model, which was calibrated to represent the influence of tides, frontal passages, and river sediment on marsh productivity and mineral accretion in Louisiana. By altering TSS levels, I modeled how suspended sediment input from a river diversion would affect the marsh lifespan and the cost of sustaining marsh. There is a large amount of uncertainty associated with, in any forecasting study, and so is the case with the analysis presented here. The actual costs to sustain Mississippi delta marsh with dredging will inevitably be different from what I have predicted. Nonetheless, this study is important because it identifies the most important drivers influencing costs (e.g. RSLR, Energy Prices, and TSS) and the general magnitude of their impact.

WECRM is a useful model for assessing approaches to coastal wetlands management. It calculates restoration costs, seasonal vegetation dynamics, carbon sequestration, lifespan (years from restoration to collapse), bulk density, and more (see APPENDIX). This analysis only demonstrates a small portion of the model's applicability. The WECRM analysis is being expanded to incorporate forested wetlands, valuation of ecosystem good and services, and the costs of river diversions. One goal is to publish a user-friendly version of the model as an open source decision support tool for coastal managers. In future applications WECRM could be linked to a physical model and used to design restoration plans (timing, fill depth, fill height, etc.) that minimize costs to sustain wetlands with a specific set of environmental conditions (subsidence rate, tidal range, salinity, sediment input, and nutrient availability).

The results of this study indicate that sustaining marshes with future sea-level rise will unequivocally require increasing effort due to declining effectiveness of restoration strategies caused by accelerating SLR and increasing energy costs. Higher TSS levels (from RSDs) reduce the overall cost of sustaining coastal marsh with dredging. Dredging fill specifications can be optimized based on expected sediment load from an RSD at a given location. If a marsh must be sustained out to 2100, then a high upfront investment in marsh creation is more favorable to an incremental approach given future projections for oil price (all other things being equal). Since the model does not incorporate the impacts of river throughput on primary productivity, which have been demonstrated recently in the literature (Roberts et al. 2015, DeLaune et al. 2016), the results are conservative.

What is unique about this study is the consideration of changes in the cost of energy, which will be impacted by future climate policy, economic growth, and rate of fossil fuel depletion (IEA 2015). Oil price has a significant effect on the costs of dredging for MC. The majority of oil models predict that real oil prices will increase in the future if oil production is to be sustained (Figure 3A, EIA 2015, McGlade 2014, IEA 2015, Shafiee & Topal 2010, Heun & De Witt 2012, Mcollum et al. 2016). Given future increases in energy costs predicted by these models, energy prices will affect and likely limit the affordability of restoration.

Due to the convergence of energy and climate megatrends, conventional energy-intensive approaches to restore the Mississippi delta are likely to become cost prohibitive by the mid-21st century or possibly even sooner, especially if large sediment diversions are not constructed. Synergistic approaches that put MC projects near the outfall of RSDs should be prioritized in the LACMP. I 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. CPRA and other coastal planners should consider coupled climate policy and energy supply/price forecasts in funding projections, cost estimates, and decision frameworks (e.g. this study, Tessler et al. 2015).

LITERATURE CITED

Achim Zeileis, Torsten Hothorn 2002. Diagnostic Checking in Regression Relationships. R News 2(3), 7-10. URL https://CRAN.R-project.org/doc/Rnews/

Allison, M. A., and Meselhe, E. A. 2010. The use of large water and sediment diversions in the lower Mississippi River (Louisiana) for coastal restoration.Journal of Hydrology, 387(3), 346-360.

Allison, M.A., Demas, C.R., Ebersole, B.A., Kleiss, B.A., Little, C.D., Meselhe, E.A., Powell, N.J., Pratt, T.C. and Vosburg, B.M., 2012. A water and sediment budget for the lower Mississippi–Atchafalaya River in flood years 2008–2010: implications for sediment discharge to the oceans and coastal restoration in Louisiana. Journal of Hydrology, 432, pp.84-97.

Allison, M. A., Ramirez, M. T., & Meselhe, E. A. 2014. Diversion of Mississippi River Water Downstream of New Orleans, Louisiana, USA to Maximize Sediment Capture and Ameliorate Coastal Land Loss. Water Resources Management, 28(12), 4113-4126.

Balaguru, K., Foltz, G.R., Leung, L.R. and Emanuel, K.A., 2016. Global warming-induced upper-ocean freshening and the intensification of super typhoons. Nature communications, 7.

Barnes, S., Bond, S., Burger, N, Anania, K., Strong, A., Weilant, S., and Virgets, S., 2015. Economic Evaluation of Coastal Land Loss in Louisiana. Lousiana State University and the Rand Corporation. Published online: (http://coastal.la.gov/economic-evaluation-of-land-loss-in-louisiana/)

Barras, J., Beville, S., Britsch, D., Hartley, S., Hawes, S., Johnston, J., Kemp, P., Kinler, Q., Martucci, A., Porthouse, J., Reed, D., Roy, K., Sapkota, S., and Suhayda, J., 2003, Historical and projected coastal Louisiana land changes: 1978- 2050: USGS Open File Report 03- 334, 39 p.

Berman A. 2016. Returning To Market Balance: How High Must Prices Be To Save The Oil Industry? Art Berman Blog: http://www.artberman.com/returning-to-market-balance-how-high-must-prices-be-to-save-the-oil-industry/, accessed Feb 15, 2016

Belesimo, F.J., 2000. Cost estimating projects for large cutter and hopper dredges (Doctoral dissertation, Texas A&M University).

Blum, M.D., Roberts, H.H., 2009. Drowning of the Mississippi Delta due to insufficient sediment supply and global sea level rise. Nature Geoscience 2:488- 491.

Brandt, A.R., Yeskoo, T., McNally, M.S., Vafi, K., Yeh, S., Cai, H. and Wang, M.Q., 2016. Energy intensity and greenhouse gas emissions from tight oil production in the Bakken formation. Energy & Fuels, 30(11), pp.9613-9621.

Bray, R.N., Bates, A.D. and Land, J.M., 1997. Dredging: a handbook for engineers.

Cohen, B., Collins, G., Escude, D., Garbaciak, S., Hassan, K, Lawton, D., Perk, L., Simoneaux, R., Spadaro, P.,Newman M., 2011. Evaluating Alternatives to improve dredging efficiency and cost effectiveness for inland marsh restoration projects. Proceedings of the Western Dredging Association (WEDA XXXI) Technical Conference and Texas A&M University (TAMU 42) Dredging Seminar, Nashville, Tennessee, June 5-8, 2011.

Couvillion, B.R.; Barras, J.A.; Steyer, G.D.; Sleavin, William; Fischer, Michelle; Beck, Holly; Trahan, Nadine; Griffin, Brad; and Heckman, David, 2011, Land area change in coastal Louisiana from 1932 to 2010: U.S. Geological Survey Scientific Investigations Map 3164, scale 1:265,000, 12 p. pamphlet.

CPRA 2012a. Louisiana's Comprehensive Master Plan for a Sustainable Coast. 2012 Coastal Master Plan. Louisiana Coastal Protection and Restoration Authority (CPRA). Baton Rouge, Louisiana.

CPRA, 2012b. Appendix A: 1 Project Definitions. 2012 Coastal Master Plan. Louisiana Coastal Protection and Restoration Authority, Baton Rouge, Louisiana.

CPRA, 2012d. Appendix A: 2 Project Fact Sheets. 2012 Coastal Master Plan. Louisiana Coastal Protection and Restoration Authority, Baton Rouge, Louisiana.

CPRA, 2012e. Appendix C: Environmental Scenarios. 2012 Coastal Master Plan. Louisiana Coastal Protection and Restoration Authority, Baton Rouge, Louisiana.

CPRA, 2015. Barrier Island Status Report Draft Fiscal Year 2016 Annual Plan. Louisiana Coastal Restoration and Protection Authority. Baton Rouge, LA, USA. http://coastal.la.gov/wp-content/uploads/2015/01/BARRIER_ISLAND_STATUS_RPT_FY16_20150128.pdf accessed: Feb 15, 2017

CPRA, 2016a. Barrier Island Status Report Draft Fiscal Year 2017 Annual Plan. Louisiana Coastal Restoration and Protection Authority. Baton Rouge, LA, USA. Available online http://coastal.la.gov/wp-content/uploads/2016/01/BARRIER_ISLAND_STATUS_RPT_AP_FY17_Web.pdf accessed: Feb 15, 2017

CPRA. 2016b. Integrated Ecosystem Restoration & Hurricane Protection in Coastal Louisiana: Fiscal Year 2016 Annual Plan. Louisiana Coastal Protection and Restoration Authority, Baton Rouge, Louisiana.

CPRA 2017a. Louisiana's Comprehensive Master Plan for a Sustainable Coast. 2017 Coastal Master Plan. Louisiana Coastal Protection and Restoration Authority (CPRA). Baton Rouge, Louisiana.

CPRA, 2017b. Appendix A: Project Definitions. 2017 Coastal Master Plan. Louisiana Coastal Protection and Restoration Authority, Baton Rouge, Louisiana.

CPRA, 2017c. Appendix A: 2 Project Fact Sheets. 2017 Coastal Master Plan. Louisiana Coastal Protection and Restoration Authority, Baton Rouge, Louisiana.

CPRA, 2017d. 2017 Draft Coastal Master Plan. http://cims.coastal.louisiana.gov/masterplan/

Accessed: Feb 10, 2015

CPRA, 2017e. Appendix C: Environmental Scenarios. 2017 Coastal Master Plan. Louisiana Coastal Protection and Restoration Authority, Baton Rouge, Louisiana.

CUSLRG, 2016. 2016_rel4: Global Mean Sea Level Time Series (seasonal signals removed). Colorado University Sea Level Research Group. http://sealevel.colorado.edu/, Accessed: Dec 15, 2016

Darby, F.A., Turner, R.E., 2008. Effects of eutrophication on salt marsh root and rhizome accumulation. Marine Ecology Progress Series 363, 63-70.

Das, A., Justic, D., Inoue, M., Hoda, A., Huang, H. and Park, D., 2012. Impacts of Mississippi River diversions on salinity gradients in a deltaic Louisiana estuary: Ecological and management implications. Estuarine, Coastal and Shelf Science, 111, pp.17-26.

Davis M, Vorhoff, H., Boyer, D., 2015. Financing the Future: Turning Coastal Restoration and Protection Plans into Realities: How Much Is Currently Funded? Second in an Occasional Series An Issue Paper of the Tulane Institute on Water Resources Law and Policy. Tulane Institute on Water Resources Law & Policy, New Orleans, LA

Day, J. W., Barras, J., Clairain, E., Johnston, J., Justic, D., Kemp, G. P. and Yanez-Arancibia, A. 2005. Implications of global climatic change and energy cost and availability for the restoration of the Mississippi delta. Ecological Engineering, 24(4), 253-265.

Day, J.W., Kemp, G.P., Reed, D.J., Cahoon, D.R., Boumans, R.M., Suhayda, J.M. and Gambrell, R., 2011. Vegetation death and rapid loss of surface elevation in two contrasting Mississippi delta salt marshes: The role of sedimentation, autocompaction and sea-level rise. Ecological Engineering, 37(2), pp.229-240.

Day, J., R. Hunter, R.F. Keim, R. DeLaune, G. Shaffer, E. Evers, D. Reed, C. Brantley, P. Kemp, J. Day, and M. Hunter. 2012. Ecological response of forested wetlands with and without large-scale Mississippi River input: implications for management. Ecological Engineering 46: 57–67.

Day, J.W., Lane, R., Moerschbaecher, M., DeLaune, R., Mendelssohn, I., Baustian, J., Twilley, R., 2013. Vegetation and soil dynamics of a Louisiana estuary receiving pulsed Mississippi River water following hurricane Katrina. Estuaries & Coasts 36, 1-18.

Day, J.W., Moerschbaecher, M., Pimentel, D., Hall, C. and Yáñez-Arancibia, A., 2014. Sustainability and place: How emerging mega-trends of the 21st century will affect humans and nature at the landscape level. Ecological Engineering, 65, pp.33-48.

Day, J.W., Lane, R.R., D'Elia, C.F., Wiegman, A.R., Rutherford, J.S., Shaffer, G.P., Brantley, C.G. and Kemp, G.P., 2016a. Large infrequently operated river diversions for Mississippi delta restoration. Estuarine, Coastal and Shelf Science, 183, pp.292-303.

Day, J.W., Agboola, J., Chen, Z., D'Elia, C., Forbes, D.L., Giosan, L., Kemp, P., Kuenzer, C., Lane, R.R., Ramachandran, R. and Syvitski, J., 2016b. Approaches to defining deltaic sustainability in the 21st century. Estuarine, Coastal and Shelf Science, 183, pp.275-291.

Day, J.W., J.E. Cable, R.R. Lane, and G.P. Kemp. 2016c. Sediment Deposition at the Caernarvon Crevasse during the Great Mississippi Flood of 1927: Implications for Coastal Restoration. Water 3(38): 1-12.

Deegan, L.A., Johnson, D.S., Warren, R.S., Peterson, B.J., Fleeger, J.W., Fagherazzi, S., Wollheim, W.M., 2012. Coastal eutrophication as a driver of salt marsh loss. Nature 490, 388-392.

DeConto, R.M. and Pollard, D., 2016. Contribution of Antarctica to past and future sea-level rise. Nature, 531(7596), pp.591-597.

DeLaune, R.D. and White, J.R., 2012. Will coastal wetlands continue to sequester carbon in response to an increase in global sea level?: a case study of the rapidly subsiding Mississippi river deltaic plain. Climatic Change, 110(1), pp.297-314.

DeLaune, R.D., M. Kongchum, J.R. White, and A. Jugsujinda. 2013. Freshwater diversions as an ecosystem management tool for maintaining soil organic matter accretion in coastal marshes. Catena 107: 139-144.

DeLaune, R.D., Sasser, C.E., Evers-Hebert, E., White, J.R. and Roberts, H.H., 2016. Influence of the Wax Lake Delta sediment diversion on aboveground plant productivity and carbon storage in deltaic island and mainland coastal marshes. Estuarine, Coastal and Shelf Science, 177, pp.83-89.

EIA (Energy Information Administration), 2015. Annual Energy Outlook with projections to 2040. Washington D.C: EIA Independent Statistics and Analysis, United States Department of Energy, 154p.

EIA 2016. Spot Prices. Petroleum & Other Liquids http://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm, accessed Feb 14, 2016

Fagherazzi, S., Kirwan, M.L., Mudd, S.M., Guntenspergen, G.R., Temmerman, S., D'Alpaos, A., Koppel, J., Rybczyk, J.M., Reyes, E., Craft, C. and Clough, J., 2012. Numerical models of salt marsh evolution: Ecological, geomorphic, and climatic factors. Reviews of Geophysics, 50(1).

FitzGerald, D.M., M.S. Fenster, B.A. Argow, and I.V. Buynevich. 2008. Coastal impacts due to sea-level rise. Annual Revue Earth & Planetary Sciences 36: 601-647.

Fizaine, F. and Court, V., 2016. Energy expenditure, economic growth, and the minimum EROI of society. *Energy Policy*, *95*, pp.172-186.

Friedlingstein, P., M. Meinshausen, V. K. Arora, C. D. Jones, A. Anav, S. K. Liddicoat, and R. Knutti. 2014. Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks. Journal of Climate 27(2): 511-526.

Georgescu-Roegen, N., 1970. The economics of production. The American Economic Review, 60(2), pp.1-9.

Georgescu-Roegen, N., 1972. Process analysis and the neoclassical theory of production. American Journal of Agricultural Economics, 54(2), pp.279-294.

Georgescu-Roegen, N., 1979. Methods in economic science. Journal of economic issues, 13(2), pp.317-328.

Hamilton, J.D., 2012. Oil prices, exhaustible resources, and economic growth (No. w17759). National Bureau of Economic Research.

Hall, C.A., Lambert, J.G. and Balogh, S.B., 2014. EROI of different fuels and the implications for society. Energy policy, 64, pp.141-152.

Heun, M.K. and de Wit, M., 2012. Energy return on (energy) invested (EROI), oil prices, and energy transitions. Energy Policy, 40, pp.147-158.

Hollinberger, T.E., 2010. Cost Estimation and Production Evaluation for Hopper Dredges (Doctoral dissertation, Texas A&M University).

Hopkinson, C.S., Gosselink, J.G. and Parrando, R.T., 1978. Aboveground production of seven marsh plant species in coastal Louisiana. Ecology, 59(4), pp.760-769.

Horton, B.P., S. Rahmstorf, S.E. Engelhart, and A.C. Kemp. 2014. Expert assessment of sea-level rise by AD 2100 and AD 2300. Quaternary Science Reviews 84: 1-6.

Huang, H., Justic, D., Lane, R.R., Day, J.W. and Cable, J.E., 2011. Hydrodynamic response of the Breton Sound estuary to pulsed Mississippi River inputs. Estuarine, Coastal and Shelf Science, 95(1), pp.216-231.

IEA (International Energy Agency), 2015. 2015 World Energy Outlook. International Energy Agency, Organization of Economic Coordination and Development, Paris, France. ISBN: 978-92-64-24366-8

IPCC (Intergovernmental Panel on Climate Change). 2013. Climate change 2013: The physical science basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (ed. T.F. Stocker, D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P. M. Midgley) Cambridge, United Kingdom and New York, NY, USA, 1535 pp

Ji, Q., and Fan, Y. (2012). How does oil price volatility affect non-energy commodity markets?. Applied Energy, 89(1), 273-280.

Karl, T. R., A. Arguez, B. Huang, J. H. Lawrimore, J. R. McMahon, M. J. Menne, T. Peterson, R. Vose, and H. M. Zhang. 2015. Possible artifacts of data biases in the recent global surface warming hiatus. Science. 348(6242): 1469-1472.

Kenney, M.A., Hobbs, B.F., Mohrig, D., Huang, H., Nittrouer, J.A., Kim, W. and Parker, G., 2013. Cost analysis of water and sediment diversions to optimize land building in the Mississippi River delta. Water Resources Research, 49(6), pp.3388-3405.

Kirwan, M.L. and Guntenspergen, G.R., 2010. Influence of tidal range on the stability of coastal marshland. Journal of Geophysical Research: Earth Surface, 115(F2).

Kirwan, M.L. and Guntenspergen, G.R., 2012. Feedbacks between inundation, root production, and shoot growth in a rapidly submerging brackish marsh. Journal of Ecology, 100(3), pp.764-770.

Kirwan, M.L. and Guntenspergen, G.R., 2015. Response of plant productivity to experimental flooding in a stable and a submerging marsh. Ecosystems, 18(5), pp.903-913.

Kolker, A.S., Allison, M.A. and Hameed, S., 2011. An evaluation of subsidence rates and sea-level variability in the northern Gulf of Mexico. Geophysical Research Letters, 38(21).

Kolker, A.S., Miner, M.D. and Weathers, H.D., 2012. Depositional dynamics in a river diversion receiving basin: The case of the West Bay Mississippi River Diversion. Estuarine, Coastal and Shelf Science, 106, pp.1-12.

LA Coast. 2016a. Projects Lists. Coastal Wetlands Planning Protection Restoration Act. Available online: http://lacoast.gov/new/Projects/List.aspx accessed: Nov, 1, 2016

LA Coast. 2016b. Coastwide Reference Monitoring System. Coastal Wetlands Planning Protection Restoration Act. Available online: http://lacoast.gov/crms2/home.aspx accessed: June 1, 2016

LDL 2016. Louisiana Digital Library. http://louisianadigitallibrary.org/ accessed: Dec 1, 2016

CPRA 2017. Projects http://cims.coastal.louisiana.gov/outreach/OPL_Full_page.html accessed: Feb 15, 2017

Lambert, J.G., Hall, C.A., Balogh, S., Gupta, A. and Arnold, M., 2014. Energy, EROI and quality of life. Energy Policy, 64, pp.153-167.

Lane, R.R., J.W. Day Jr., B. Marx, E. Hyfield, J.N. Day. E. Reyes. 2007. The effects of riverine discharge on temperature, salinity, suspended sediment and chlorophyll a in a Mississippi delta estuary measured using a flow-through system. Estuarine Coastal & Shelf Science 74: 145-154.

Lumley, T. and Miller, A., 2009. Leaps: regression subset selection. R package version 2.9. *See http://CRAN. R-project. org/package= leaps*.

Loulou, R. and Labriet, M., 2008. ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure. Computational Management Science, 5(1-2), pp.7-40.

Maggio, G. and Cacciola, G., 2012. When will oil, natural gas, and coal peak?. Fuel, 98, pp.111-123.

Mariotti, G. and Fagherazzi, S., 2010. A numerical model for the coupled long- term evolution of salt marshes and tidal flats. Journal of Geophysical Research: Earth Surface, 115(F1).

Mariotti, G. and Fagherazzi, S., 2013. A two- point dynamic model for the coupled evolution of channels and tidal flats. Journal of Geophysical Research: Earth Surface, 118(3), pp.1387-1399.

McCollum, D.L., Jewell, J., Krey, V., Bazilian, M., Fay, M. and Riahi, K., 2016. Quantifying uncertainties influencing the long-term impacts of oil prices on energy markets and carbon emissions. Nature Energy, 1, p.16077.

McGlade, C. and Ekins, P., 2014. Un-burnable oil: an examination of oil resource utilisation in a decarbonised energy system. Energy Policy, 64, pp.102-112.

McGlade, C. and Ekins, P., 2015. The geographical distribution of fossil fuels unused when limiting global warming to 2 [deg] C. Nature, 517(7533), pp.187-190.

McGlade, C.E., 2014. Uncertainties in the outlook for oil and gas (Doctoral dissertation, UCL (University College London)).

Mei, W., Xie, S.P., Primeau, F., McWilliams, J.C. and Pasquero, C., 2015. Northwestern Pacific typhoon intensity controlled by changes in ocean temperatures. Science advances, 1(4), p.e1500014.

Mendelssohn, I.A. and Kuhn, N.L., 2003. Sediment subsidy: effects on soil–plant responses in a rapidly submerging coastal salt marsh. Ecological Engineering, 21(2), pp.115-128.

Meselhe, E., McCorquodale, J. A., Shelden, J., Dortch, M., Brown, T. S., Elkan, P. and Wang, Z. 2013. Ecohydrology component of Louisiana's 2012 Coastal Master Plan: mass-balance compartment model. Journal of Coastal Research,67(sp1), 16-28.

Moerschbaecher, M., and Day, J.W., 2014. The impact of global climate change and energy scarcity on Mississippi delta restoration. In Perspectives on the Restoration of the Mississippi Delta (pp. 175-184). Springer Netherlands.

Morris, J.T., Sundareshwar, P.V., Nietch, C.T., Kjerfve, B. and Cahoon, D.R., 2002. Responses of coastal wetlands to rising sea level. Ecology, 83(10), pp.2869-2877.

Morris, J.T., Edwards, J., Crooks, S. and Reyes, E., 2012. Assessment of carbon sequestration potential in coastal wetlands. In Recarbonization of the Biosphere (pp. 517-531). Springer Netherlands.

Morris, J.T., G.P. Shaffer, and J.A. Nyman. 2013a. Brinson review: perspectives on the influence of nutrients on the sustainability of coastal wetlands. Wetlands 33: 975-988.

Mudd, S.M., Howell, S.M. and Morris, J.T., 2009. Impact of dynamic feedbacks between sedimentation, sea-level rise, and biomass production on near-surface marsh stratigraphy and carbon accumulation. Estuarine, Coastal and Shelf Science, 82(3), pp.377-389.

Mudd, S. M., D'Alpaos, A., and Morris, J. T. 2010. How does vegetation affect sedimentation on tidal marshes? Investigating particle capture and hydrodynamic controls on biologically mediated sedimentation, J. Geophys. Res., 115, F03029, doi:10.1029/ 2009JF001566.

Murphy, D.J. and C.A.S. Hall. 2011. Adjusting the economy to the new energy realities of the second half of the age of oil. Ecological Modeling 223: 67-71.

Murphy, J. T., 2012. Fuel provisions for dredging projects. Proceedings of the Western Dredging Association (WEDA XXXII) Technical Conference and Texas A&M University (TAMU 43) Dredging Seminar, San Antonio, Texas, June 10-13, 2012.

Murray, S.P., Walker, N.D. and Adams, C.E., 1993. Impacts of winter storms on sediment transport within the Terrebonne Bay marsh complex. In Coastlines of the Gulf of Mexico: (pp. 56-70). ASCE.

Nyman, J.A., DeLaune, R.D., Roberts, H.H., and Patrick Jr. W.H., 1993. Relationship between vegetation and soil formation in a rapidly submerging coastal marsh. Marine Ecology Progress Series 96:269- 279.

Nyman, J.A., Walters, R.J., DeLaune, R.D., and Patrick Jr., W.H., 2006. Marsh vertical accretion via vegetative growth. Estuarine, Coastal and Shelf Science 69:370- 380.

Nyman, J.A., 2014. Integrating successional ecology and the delta lobe cycle in wetland research and restoration. Estuaries and coasts, 37(6), pp.1490-1505.

Paola, C., R.R. Twilley, D.A. Edmonds, W. Kim, D. Mohrig, G. Parker, E. Viparelli, and V.R. Voller., 2010. Natural processes in delta restoration: application to the Mississippi delta. Annual Review of Marine Science 3: 67-91.

Penland, S., Connor, P., Cretini, F., and Westphal, K., 2003. CWPPRA Adaptive Management: Assessment of Five Barrier Island Restoration Projects In Louisiana. A Report Submitted To: Louisiana Department of Natural Resources Office of Coastal Restoration and Management. Pontchartrain Institute for Environmental Sciences University of New Orleans. New Orleans, LA, USA

Petrolia, D.R., Kim, T.G., Moore, R.G. and Caffey, R.H., 2009, January. A Cost Analysis of Rapid Land-Building Technologies for Coastal Restoration in Louisiana. In *Southern Agricultural Economics Association Annual Meeting (SAEAA), Atlanta, Georgia*.

Pfeffer, W.T., Harper, J.T. and O'Neel, S., 2008. Kinematic constraints on glacier contributions to 21st-century sea-level rise. Science, 321(5894), pp.1340-1343.

Prein, A.F., Rasmussen, R.M., Ikeda, K., Liu, C., Clark, M.P. and Holland, G.J., 2016. The future intensification of hourly precipitation extremes. Nature Climate Change.

R Core Team. 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Roberts, H.H., R.D. DeLaune, J.R. White, C. Li, C.E. Sasser, D. Braud, E. Weeks and S. Khalil, 2015. Floods and Cold Front Passages: Impacts on Coastal Marshes in a River Diversion Setting (Wax Lake Delta Area, Louisiana). Journal of Coastal Research, 31(5): 1057-1068.

Roy, E.D., J.R. White, E.A. Smith, S. Bargu, and C. Li. 2013. Estuarine ecosystem response to three large-scale Mississippi River flood diversion events. Science of the Total Environment 458: 374-387.

Rybczyk, J., Callaway, J.C., Day Jr., JW. 1998. A relative elevation model for a subsiding coastal forested wetland receiving wastewater effluent. Ecological Modeling 112:23- 44.

Rybczyk, J.M., and D.R. Cahoon. 2002. Estimating the potential for submergence for two wetlands in the Mississippi River Delta. Estuaries 25:985- 998.

Schile, L. M., Callaway, J. C., Morris, J. T., Stralberg, D., Parker, V. T., and Kelly, M. 2014. Modeling tidal marsh distribution with sea-level rise: Evaluating the role of vegetation, sediment, and upland habitat in marsh resiliency. PloS one, 9(2), e88760.

Sgouridis, S., Csala, D. and Bardi, U., 2016. The sower’s way: quantifying the narrowing net-energy pathways to a global energy transition. Environmental Research Letters, 11(9), p.094009.

Shafiee, S., and Topal, E. 2010. A long-term view of worldwide fossil fuel prices. Applied Energy, 87(3), 988-1000.

Shields, M.R., Bianchi, T.S., Gélinas, Y., Allison, M.A. and Twilley, R.R., 2016. Enhanced terrestrial carbon preservation promoted by reactive iron in deltaic sediments. Geophysical Research Letters, 43(3), pp.1149-1157.

Shinkle, K.D. and Dokka, R.K., 2004. Rates of vertical displacement at benchmarks in the lower Mississippi Valley and the northern Gulf Coast (p. 135). US Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, National Geodetic Survey.

Slocum, M.G., Mendelssohn, I.A. and Kuhn, N.L., 2005. Effects of sediment slurry enrichment on salt marsh rehabilitation: plant and soil responses over seven years. Estuaries and Coasts, 28(4), pp.519-528.

Snedden, G.A., K. Cretini, and B. Patton. 2015. Inundation and salinity impacts to above-and belowground productivity in Spartina patens and Spartina alterniflora in the Mississippi

River deltaic plain: Implications for using river diversions as restoration tools. Ecological Engineering 81: 133-139.

Smil, V., 2016. Examining energy transitions: A dozen insights based on performance. *Energy Research & Social Science*, *22*, pp.194-197.

Sobel, A.H., Camargo, S.J., Hall, T.M., Lee, C.Y., Tippett, M.K. and Wing, A.A., 2016. Human influence on tropical cyclone intensity. Science, 353(6296), pp.242-246.

Strauss, B.H., Kulp, S. and Levermann, A., 2015. Carbon choices determine US cities committed to futures below sea level. Proceedings of the National Academy of Sciences, 112(44), pp.13508-13513.

Syvitski, J.P., Kettner, A.J., Overeem, I., Hutton, E.W., Hannon, M.T., Brakenridge, G.R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L. and Nicholls, R.J., 2009. Sinking deltas due to human activities. Nature Geoscience, 2(10), pp.681-686.

Tao, B., H.Tian, W. Ren, J. Yang, Q. Yang, R. He, W. Cai, and S. Lohrenz. 2014. Increasing Mississippi river discharge throughout the 21st century influenced by changes in climate, land use, and atmospheric CO2. Geophysical Research Letters 41: 4978-4986.

Tessler, Z.D., Vörösmarty, C.J., Grossberg, M., Gladkova, I., Aizenman, H., Syvitski, J.P.M. and Foufoula-Georgiou, E., 2015. Profiling risk and sustainability in coastal deltas of the world. Science, 349(6248), pp.638-643.

Tripathi, V.S. and Brandt, A.R., 2017. Estimating decades-long trends in petroleum field energy return on investment (EROI) with an engineering-based model. PloS one, 12(2), p.e0171083.

Turner, R.E., Swenson, E.M., Milan, C.S., Lee, J.M. and Oswald, T.A., 2004. Below- ground biomass in healthy and impaired salt marshes. Ecological Research, 19(1), pp.29-35.

Tverberg, G.E., 2012. Oil supply limits and the continuing financial crisis. *Energy*, *37*(1), pp.27-34.

Twilley, R.R. and Nyman, A. 2005. The role of biogeochemical processes in marsh restoration: implications to freshwater diversions. Final Report to Louisiana Department of Natural Resources. Baton Rouge, LALouisiana. DNR Contract No. 2512- 98- 06. 99pp.

Twilley, R.R., Bentley, S.J., Chen, Q., Edmonds, D.A., Hagen, S.C., Lam, N.S.N., Willson, C.S., Xu, K., Braud, D., Peele, R.H. and McCall, A., 2016. Co-evolution of wetland landscapes, flooding, and human settlement in the Mississippi River Delta Plain. Sustainability Science, 11(4), pp.711-731.

Vermeer, M. and Rahmstorf, S., 2009. Global sea level linked to global temperature. Proceedings of the National Academy of Sciences, 106(51), pp.21527-21532.

Wang, F.C., Sikora, W.B. and Wang, M., 1994. Hydrologic regimes of tidal channel-salt marshes flow systems, Fourleague Bay, Louisiana, USA. Journal of coastal research, pp.809-824.

Wang, F. C. 1997. Dynamics of intertidal marshes near shallow estuaries in Louisiana. Wetlands Ecology and Management, 5(2), 131-143.

Wang, H., G.D. Steyer, B.R. Couvillion, J.M. Rybczyk, H.J. Beck, W.J. Sleavin, E.A. Meselhe, M.A. Allison, R.G. Boustany, C.J. Fischenich, and V.H. Rivera-Monroy. 2014. Forecasting landscape effects of Mississippi River diversions on elevation and accretion in Louisiana deltaic wetlands under future environmental uncertainty scenarios. Estuarine, Coastal & Shelf Science 138: 57-68.

Warr, B.S. and Ayres, R.U., 2010. Evidence of causality between the quantity and quality of energy consumption and economic growth. Energy, 35(4), pp.1688-1693.

World Bank. 2015. Commodities Price Forecast. Released October 20, 2015.

Wowtschuk, B.M., 2016. Production and Cost Estimating for Trailing Suction Hopper Dredge (Doctoral dissertation, Texas A&M University).

Xu, K., Bentley, S.J., Robichaux, P., Sha, X. and Yang, H., 2016. Implications of texture and erodibility for sediment retention in receiving basins of coastal Louisiana diversions. *Water*, *8*(1), p.26.

Zou, L., Kent, J., Lam, N.S.N., Cai, H., Qiang, Y. and Li, K., 2015. Evaluating land subsidence rates and their implications for land loss in the Lower Mississippi River Basin. Water, 8(1), p.10.

APPENDIX-A. MEGATRENDS

A.1. Oil Price Forecasts

Composite forecasts for oil price, containing three market trajectories (Low, Central and High), were developed using scenarios from four models (EIA 2015, IEA 2015, McGlade 2014, Heun & de Wit 2012). A total of 15 scenarios were included in the composite forecasts, which were extrapolated out to 2100. Real Price adjustments were done on price data using the consumer price index (the method used by the EIA), for the year 2010. From IEA (2015), the Low Oil Price, 450ppm, NPS, CPS scenarios were included; from EIA (2015), the Low, Reference, and High scenarios from were included; from McGlade (2014), the Lybia, OPEC, and Institutions sensitivity scenarios were included for both the NPS and LCS (Defined below). For the Heun and De Wit model, we extrapolated two model fits of historical EROI data to simulate price. After selecting projections, we separated the 15 forecasts into three bins, Low, Central and High price, based on projected price in 2035. The five highest prices were put into the high bin, the five lowest prices were put into the low bin and the remaining forecasts were put into the central bin. In the composite forecast, each year up to 2035-projected value is equal to the average of the five forecasts in the low, central, and high bins (Table A1).

The model projections were extrapolated conservatively and we bounded the scenarios with a uniform assumption for extrapolating all models. Beyond 2035 (the last year displayed by McGlade 2014), each model scenario was given a declining slope so it approached a vertical asymptote (Figure A1 A). The initial rate of change was based on the five-year average slope between 2030 and 2035. Each ensuing year the rate of change in price decayed at a prescribed rate of 5% per year (See section 1.4). For the NPS scenarios (McGlade 2014), which projected very steep price increase of up to 500$ per barrel by 2035, price caps were installed at $350/bbl (See Figure A1, A and B). The assumption implicit here is that beyond 2035 the oil market will reach equilibrium as market imperfections are reduced by improved information technology, which will have the effect of reducing volatility of demand and supply. Since the projections past 2035 are so far in the future, any market assumptions that are made become somewhat arbitrary. Therefore, we consider the assumption that oil markets will trend towards constant price equilibrium to be as valid as any other, in additional to being conservative.

The scenarios developed in the composite forecast represent the full range of trajectories for oil prices presented in the literature. Because energy market models (commonly called integrated assessment models) are used primarily as tools for climate policy (Loulou & Labriet 2008), each composite forecast has general economic and climate outcomes associated with it (Table A1). The Low scenario is associated with adoption of stringent climate policy through a carbon tax, reduced GDP growth in developing countries and low oil demand. The high scenario represents little to no climate restrictions on the energy industry, high short term GDP growth in developing countries through fossil fuel use and high exploitation of synfuels. The central scenario represents a moderate transition from fossil fuels to renewable technology through partial adoption of climate policies. Therefore, the composite model scenarios, or any of the 15 projections for that matter, could be used for cost modeling in response to energy and climate policy and to compare with society's current trajectory. For example, the Low scenario is closest to the actual 2015 price of oil at around $58/bbl, because OPEC (principally, Saudi Arabi) and U.S. shale producers flooded the market, while US and European demand stagnated due in part to efficiency gains and lower than expected economic growth occurred in emerging markets in Asia. The Low scenario however, projects prices below 100 dollars per barrel well past 2035 (Table A1, Figure A1). Although, the carbon tax that is necessary to reduce oil demand would raise the actual price of oil from $7/bbl to $15/bbl in 2020 and 2040 respectively (IEA 2015, See Table A2). The remainder of APPENDIX-A reviews the assumptions of the composite oil forecast.

A.2. Energy Market Models & Supply Demand Equilibrium Calculation

In supply demand equilibrium (SDEQ) modeling, each year producers seek profits through the development of oil reserves; the choice to invest in production is made if net present value (NPV) is positive. Price and demand at a given price are adjusted iteratively until equilibrium is satisfied at the level of production in a given time step (McGlade 2014). In order to calculate SDEQ, energy market models require a demand module that contains energy-consuming capital stock and a supply module that contains a database of oil capital stock, reserves, production characteristics and price to add a unit of production. SDEQ and the principles of energy market modeling are explained in detail by McGlade (2014) and Loulou & Labriet (2008).

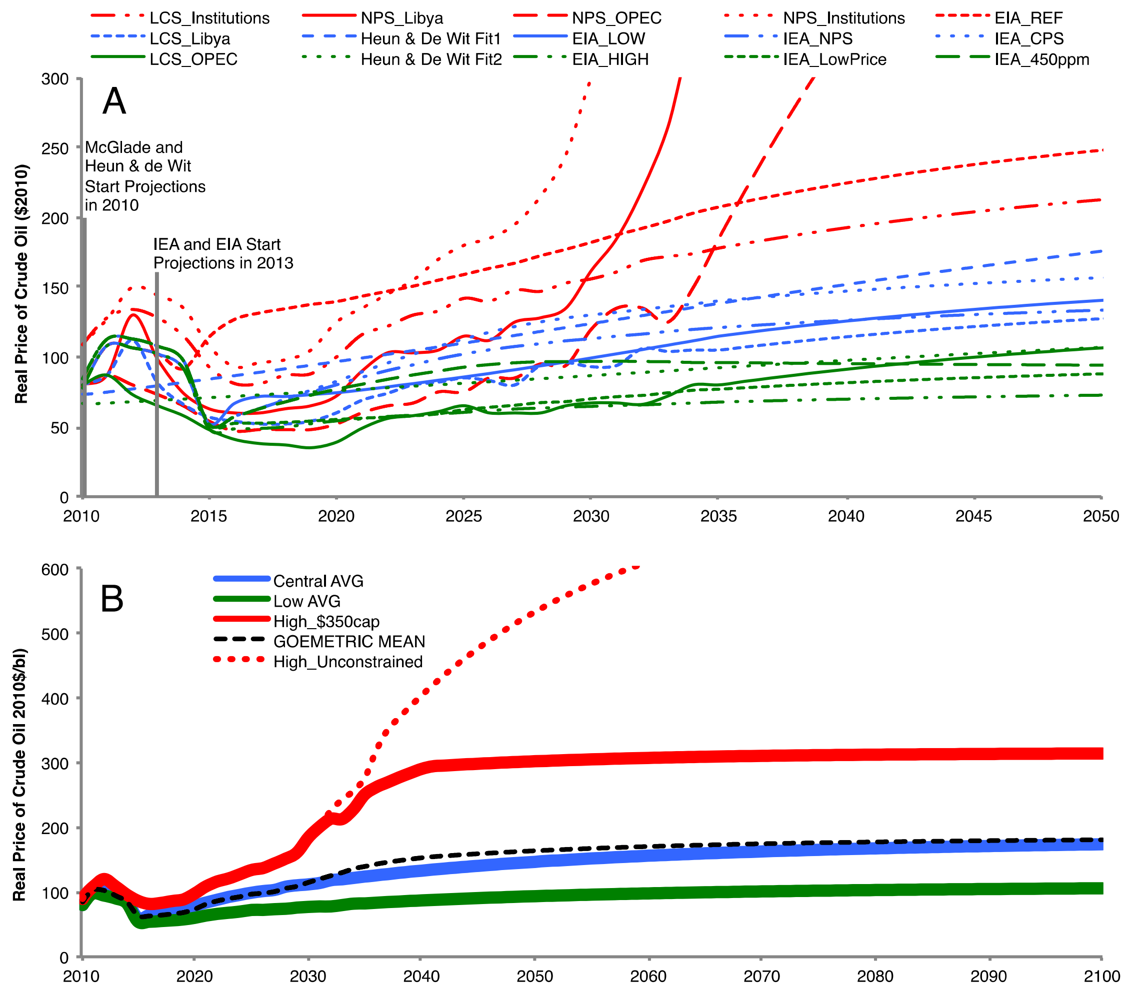

FIGURE A1. (A) 15 model projections for oil price and (B) composite forecasts extrapolated out to 2100. Green projections are grouped into the low scenario, Blue projections are in the central scenario, and Red projections are in the high scenario. The composite forecast shows the average value for the Low (green), Central (blue) High (red) scenarios, and the geometric mean (black dashes) of the 15 forecasts. Forecasts are extrapolated out beyond 2035 using a decay rate in price increase of 5% out to 2100. The dotted red line shows the high scenario without a $350/bbl price cap.

TABLE A1. Generalized assumptions of the oil price scenarios. The projected price (real 2010 $/bbl) in 2025 and 2035 is given with the half standard deviation value in parentheses. See TABLE A2 for more on model runs.

Name	Model Runs Included	Generalized Assumptions of the Scenario	Projected Price $/bbl (±0.5 SD.) 2025	2035
No Change	N/A	Techno optimist scenario: sustained rapid renewable energy growth, high efficiency gains and changes in end use, drastically decrease demand for oil in the residential, commercial, and transportation sectors; drilling technology improves recovery of unconventional fuels; a small amount of oil is used for chemical feedstock, heavy construction and industry.	55 (±0)	55 (±0)
Low	LCS_OPEC IEA_LOW IEA_450 EROI_Fit1 EIA_LOW	Stringent energy and climate policies: low oil demand and low short term GDP growth in developing countries, break up of OPEC, low cost oil floods the market, high renewable energy investment, adoption of carbon tax curbs demand.	$73 (±7)	$83 (±6)
Central	IEA_CPS LCS_Lybia EROI_Fit2 IEA_NPS EIA_REF	Moderate energy and climate policy: moderate oil demand and GDP growth, OPEC operates as a swing producer to control price, moderate renewable investment, stated emissions targets are upheld, no further climate policies initiated.	$99 (±6)	$124 (±7)
High	LCS_Inst. NPS_Lybia NPS_OPEC NPS_Inst. EIA_HGH	Business as usual energy and climate policy: high oil demand and high short term GDP growth in developing countries, conservative investment practices from oil producers causes demand to exceed supply, low renewable investment, significant climate policies not adopted.	$134 (±20)	$251 (±44)

TABLE A2. Energy model developer information

Developing Institution	Model	Supply Data	Year Published	Relavent Links and Citations
U.S. Energy Information Administration	EIA NEMS	Field level in U.S. regional in rest of world	2015	EIA 2015; https://www.eia.gov/outlooks/aeo
International Energy Agency	ETSAP-TIAM	Regional	2015	Loulou & Labriet 2008; IEA 2015; https://www.iea.org/bookshop720-World_Energy_Outlook_2016
University College London, U.K.	TIAM-UCL & BUEGO	Field level globally, Regional for U.S. tight/shale oil and gas	2014	McGlade 2014; McGlade & Ekins 2014; McGlade & Ekins 2015
N/A Academic	EROI	Empirical	2012	Heun & de Wit 2012; King & Hall 2011; King 2015

TABLE A3. Assumptions of energy market model projections used in composite oil price scenarios.

Devel-oper	Model Acronym	Scenario Name	1P reserves (10^9 bbl)	Geopolitics and Producer Behavior	Climate Policies	ΔGDP/yr 2010-40 (%)	Composite Scenario
EIA	NEMS	Ref	1647	OPEC acts as swing producer (market share ~40%)	Current U.S. & international regulations only	2.4	Central
		Low		OPEC maximizes revenue (market share ~50%)	""	1.8	Low
		High		OPEC cuts production maximizes profit (market share ~30%)	""	2.9	High
IEA	ETSAP-TIAM	NPS	1706	Geopolitics & producer behavior not considered or mentioned	Currently active COP21 policies and those yet to be implemented	3.5	Central
		Low		OPEC pursues higher market share, technology lowers production costs	Same as NPS	""	Low
		CPS		Geopolitics & producer behavior not considered or mentioned	Only active carbon policies, no future policies activated	""	Central
		450		Geopolitics & producer behavior not considered or mentioned	450ppm and 2C goal, carbon tax $22/ton C in 2020, $50/ton in 2040	""	Low

Devel-oper	Model Acronym	Scenario Name	1P reserves (10^9 bbl)	Geopolitics and Producer Behavior	Climate Policies	ΔGDP/yr 2010-40 (%)	Composite Scenario
UCL	TIAM-UCL & BUEGO	LCS_Inst	1294	Relucance of institutions to invest in new capacity, double the discount rate in NPV	CO2 concentrations do not exceed 425 ppm by 2100	Roughly 3.3 and declining	High
		LCS_Libya		Supply cut 1.5 mmbbl/day in 2012 due to Lybian uprising, gradual production return	CO2 concentrations do not exceed 425 ppm by 2100	""	Central
		LCS_OPEC		Dissolution of OPEC, countries operate independantly to maximize profit	CO2 concentrations do not exceed 425 ppm by 2100	""	Low
		NPS_Inst		Relucance of institutions to invest in new capacity, double the discount rate in NPV	CO2 remains below 570 ppm by 2100, gradually increasing carbon tax initiated in 2020	""	High
		NPS_Libya		Supply cut 1.5 mmbbl/day in 2012 due to Lybian uprising, gradual production return	CO2 remains below 570 ppm by 2100, gradually increasing carbon tax initiated in 2020	""	High
		NPS_OPEC		Dissolution of OPEC, countries operate independantly to maximize profit	CO2 remains below 570 ppm by 2100, gradually increasing carbon tax initiated in 2020	""	High

A.3. National Energy Modeling System (EIA 2015)

The Unites States Energy Information Administration (EIA) uses the National Energy Modeling System (NEMS) to simulate the response of energy markets to global trends and policies. The EIA publishes forecasts for the energy industry in the Annual Energy Outlook (AEO). The AEO presents scenarios which tests the influence of changes in economic growth rates on price of oil and production volume of oil, and gives projections out to 2040. Three scenarios are summarized in the AEO 2015, Low (EIA_Low), reference (EIA_Ref), and high (EIA_High) (see Figure A1 and Table A1). In EIA_Ref, world GDP grows at an annual rate of 2.4% which is assumed to be a continuation of historic trends. OPEC continues to operate as a swing producer with a market share of about 40%. World oil demand growth is 1.09%, with the majority coming from non-OECD countries, where demand grows at 2.07%. In EIA_High, world GDP grows a rate of 2.9% per year which is attributed to high non-OECD growth. Low investment into new production decreases OPEC's market share to about 30%. In EIA_LOW, world GDP grows at a rate of 1.8%, which is attributed low non-OECD growth. OPEC invests in new production at a higher rate and does not act as a swing producer, and as a result their market share increases to 50% by 2040.

A.4. ETSAP-TIAM - Times Integrated Assessment Model (IEA 2015)

The TIMES Integrated Assessment Model (TIAM) is a linear programming partial equilibrium model developed and maintained by the IEA's Energy Technology Systems Analysis Programme (ETSAP) (Loulou and Labriet 2008). This model will be referred to as ETSAP-TIAM. ETSAP-TIAM simulates global economic activity and tracks energy related carbon emissions under various future regimes of energy and climate policy. The model runs on 5-year increments, which makes it less capable of simulating market cycles (McGlade 2014). The IEA publishes updated outputs of the ETSAP-TIAM annually in the World Energy Outlook (WEO). In the 2015 outlook, the IEA assumes world average GDP growth rate of 3.5% from 2013-2040, higher than EIA, this is due to high estimates of GDP growth in Asia at about 6%. Four scenarios are presented in the WEO 2015: a new climate policy scenario based on promised climate goals of the Paris Accord and other agreements (IEA_NPS), a low price scenario (IEA_Low), a low carbon scenario associated with a 2°C climate limit (IEA_450), and current a policies scenario representing no significant climate action (IEA_CPS).

The New Policies Scenario (IEA_NPS) is the reference scenario in the WEO. This scenario assumes full adoption of all policies and emissions targets that were announced by countries as of 2015. The IEA_Low investigates the impact of lower oil prices than the IEA_NPS. The scenario operates with the same climate policies from the NPS, but alters the assumptions for oil supply and demand. On the supply side, the OPEC shifts behavior to pursue higher market share and a lower oil price. Marginal oil producers such as heavy oil and shale oil are assumed to be able to adapt and cut costs enabling them to be more resilient to lower prices. On the demand side, the rate of GDP growth is slightly subdued due to climate policies aimed at limiting long term global temperature increase to 2°C. The Current Policies Scenario (CPS) is the business as usual projection with respect to climate policy and energy use patterns. The scenario applies only climate policies that had been formally adopted as of 2015 and makes the assumption that these policies persist unchanged.

A.5. TIAM-UCL & BUEGO (McGlade 2014, McGlade & Ekins 2015)

Researchers at University College London (UCL) have modified the ETSAP-TIAM model described above in order to provide more detail on the supply side (McGlade 2014). The UCL revision of the EIA TIAM model will be referred to as TIAM-UCL. To model oil production in response to climate policy, McGlade (2014) developed the Bottom Up Economic Geological Oil Model (BUEGO) (McGlade & Ekins 2014). BUEGO investigates shorter term market interactions (annual time step) and provides higher resolution (field level in each producing region) for the oil and gas resources than TIAM. BUEGO is linked to the TIAM-UCL demand output and simulates oil production and price setting via SDEQ (McGlade 2014).

McGlade modeled two policy scenarios for climate change based on IPCC (2014): a low carbon scenario (LCS) and a new policies scenario (NPS) (McGlade 2014). Achieving climate objectives involves setting regional emissions caps using the TIAM-UCL climate module. In the LCS, demand reduction policies limit emissions from global fossil fuel consumption so that CO_2 concentrations do not exceed to 425 ppm by 2100. Regional emission constraints in 2020 are based on the maximum targets of the Copenhagen accord. In the NPS, demand reduction policies were less aggressive, concentrations of CO_2 are constrained to remain below 570 ppm by 2100; this equates to 50% chance of remaining below a 3.5°C global temperature increase.

2020 emissions targets are based on the Copenhagen pledges in countries of each region. From 2020 to 2050 emissions in developed countries decrease to 5.7 t/capita. For developing countries, emissions increase to 3.2 t/capita.

Within each climate scenario McGlade also conducted several sensitivity tests within the NPS and LCS including a supply shock such as the Libyan uprising (this test will be referred to as Libya), producer caution in risk assessments for oil investments (this test will be referred to as Institutions), and the breakup of OPEC resulting in increased production in respective regions (this test will be referred to as OPEC) (McGlade 2014, for details see Table A1 and Figure A1).

The Libya sensitivity test simulates supply shortage from the Libyan uprising. Libya demonstrates the influence of a major politically-motivated supply disruption that resulted in the immediate loss of 1.5 mbbl/day of production. Since this sensitivity test was simulating an actual historical event we use it as the baseline model run. The OPEC sensitivity test simulates the dissolution of the oil cartel OPEC. The supply cap for OPEC members removed and OPEC members no long act as a swing producers. Instead, OPEC countries operate to maximize net present value using the same protocol as other non-cartel producers. The resulting decrease in oil prices between LCS_Lybia and LCS_OPEC was of $25/bbl in the LCS and a $35/bbl in NPS. The Institutions sensitivity test simulates a reluctance of institutions to invest in new capacity. Oil producers double the discount rate during net present value assessments before initiating well development. This behavior led to 40% higher overall prices above the Libya scenario throughout the model horizon in both LCS and NPS scenarios. A number of potential production capacity additions (new oil rigs) in marginal areas, such as ultra deep-water or arctic, also failed to become economic at any price; meaning that it was harder to satisfy demand in later periods (McGlade 2014). For the remainder of the paper each of these sensitivity tests, will refered to as the name of the climate scenario followed by the name of the sensitivity test (e.g. NPS_Libya).

A.6. Composite Model Extrapolation

The assumption implicit in the projections extrapolated beyond 2035 is that the oil market will reach a long-term equilibrium; and presumably at this time the economy will be forced to shift towards society with low oil throughput. This represents a future scenario where the mean marginal cost of production over time is stable because consumption rate has declined considerably. In the interim, it is likely that prices will oscillate around these points in response to supply disruptions and the cycles of investment. Since the projections past 2035 are so far in the future, the market assumptions become somewhat trivial. Therefore, we consider the assumption that oil markets will trend towards equilibrium of the long term average price to be as valid as any other, in additional to being quite conservative. The initial slope was based on the five-year average slope between 2030 and 2035, each year, the rate of change decayed at a rate of 5% per year (Eqn. A1).

(Eqn. A1)

$$\mathrm{dPrice}(2036) = \mathrm{r} * \frac{\left(\mathrm{Price}(\mathrm{t}-2035) - \mathrm{Price}(\mathrm{t}-2030)\right)}{2035-2030}$$

$$\mathrm{dPrice}(2036+\mathrm{n}) = \mathrm{r} * \mathrm{dPrice}(2036+\mathrm{n}-1)$$

dPrice (year) is the change in price of a given year, and r is the decay rate 0.95, n is the time step.

Several of McGlade's scenarios included periods of rapid price increase, which might in reality lead to a crash. Though the BUEGO model is quite robust, the lack of response to price increases with peaks reaching $500/bbl, indicates that the negative feedbacks of oil price on economic activity (Murphy & Hall 2011, Hamilton 2012) are not well defined. This can be attributed to the consideration of GDP as an exogenous forcing variable, an assumption also held by EIA and IEA. Since the TIAMS-UCL model does not incorporate energy prices as a feedback into its calculation of GDP growth, the model is doesn't have an upper bound for oil prices (the point where the economy fails due to energy limitation). To adjust for this we capped the NPS scenario, which projects a very steep price increase up to about $500/bbl by 2035, at $350/bbl (See figure A3 A and B). This is because the economy would be fundamentally changed if such a high portion of energy were allocated to obtaining oil. Price increases cannot continue indefinitely, they can only increase if there is enough money remaining to continue running the economy and for growth to pay off debt (Tverberg 2012, Fizaine & Court 2016). More research is needed to determine the energetic and financial limits of oil production in the economy.

Literature Cited

EIA (Energy Information Administration), 2015. Annual Energy Outlook with projections to 2040. Washington D.C: EIA Independent Statistics and Analysis, United States Department of Energy, 154p.

Fizaine, F. and Court, V., 2016. Energy expenditure, economic growth, and the minimum EROI of society. *Energy Policy*, *95*, pp.172-186.

Hamilton, J.D., 2012. Oil prices, exhaustible resources, and economic growth (No. w17759). National Bureau of Economic Research.

Heun, M.K. and de Wit, M., 2012. Energy return on (energy) invested (EROI), oil prices, and energy transitions. Energy Policy, 40, pp.147-158.

IEA (International Energy Agency), 2015. 2015 World Energy Outlook. International Energy Agency, Organization of Economic Coordination and Development, Paris, France. ISBN: 978-92-64-24366-8

King, C.W. and Hall, C.A., 2011. Relating financial and energy return on investment. *Sustainability*, *3*(10), pp.1810-1832.

King, C.W., Maxwell, J.P. and Donovan, A., 2015. Comparing world economic and net energy metrics, Part 1: Single Technology and Commodity Perspective. *Energies*, *8*(11), pp.12949-12974.

Loulou, R. and Labriet, M., 2008. ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure. Computational Management

McGlade, C. and Ekins, P., 2014. Un-burnable oil: an examination of oil resource utilisation in a decarbonised energy system. Energy Policy, 64, pp.102-112.

McGlade, C. and Ekins, P., 2015. The geographical distribution of fossil fuels unused when limiting global warming to 2 [deg] C. Nature, 517(7533), pp.187-190.

McGlade, C.E., 2014. Uncertainties in the outlook for oil and gas (Doctoral dissertation, UCL (University College London)).

Murphy, D.J. and C.A.S. Hall. 2011. Adjusting the economy to the new energy realities of the second half of the age of oil. Ecological Modeling 223: 67-71.

Tverberg, G.E., 2012. Oil supply limits and the continuing financial crisis. Energy, 37(1), pp.27-34.

APPENDIX-B. COSTS OF MARSH CREATION

B.1. Marsh Creation Projects

I developed a production function of the cost of hydraulic dredging for coastal restoration using data from restoration projects completed in the Louisiana coastal zone. The following information was used to inform the development of the cost model. The most important factors controlling the hydraulic dredging are the size of the project and the distance between the borrow site and fill site. Project volume influences economy of scale and is inversely correlated with price (Clark et al. 2015). Pumping distance, depth and substrate type influence the total horsepower capacity and energy requirements for the project (Clark et al. 2015, Bray et al. 1997). Fuel costs make up between 15 – 30% of the dredging unit cost. The other portions being lubricant (10% of fuel costs), maintenance (10%), and labor and rentals (the remainder) (Bray et al. 1997). CPRA lists the assumptions for design and cost of marsh creation projects in appendix A-1 of the 2012 coastal master plan (CPRA 2012). According to CPRA, costs for hydraulic dredging are 60-70% of the total marsh creation project construction cost (see excerpt 1 below). CPRA also defines many of the terms related to each type of restoration project and provides assumptions for the material needs, cost and duration of various aspects of a marsh creation project. The CPRA defines these project attributes for all types of restoration project in section 3.0 the LACMP Appendix A-1 (CPRA 2012b), see excerpt 2 below (CPRA 2012b, section 3.5). Production rate depends on project size, equipment, and crew. Figure B1 presents a conceptualized view of a marsh creation project.

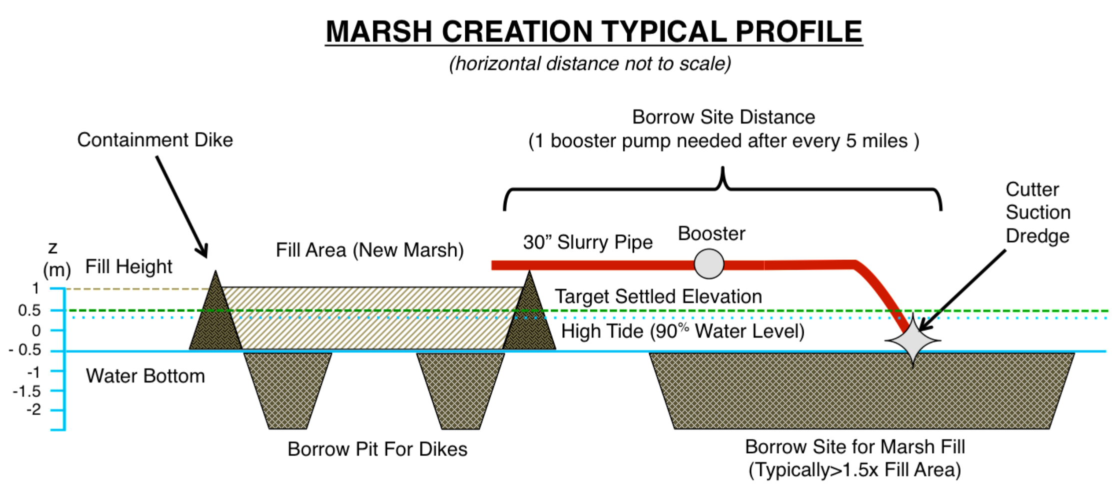

FIGURE B1. Transect of a typical marsh creation project showing the key construction elements.

B.2. Data Collection

We compiled a spreadsheet with data on costs of dredging from all search results available through the following online resources: Coastal Protection and Restoration Authority – CPRA (http://coastal.la.gov/our-work/projects/), Coastal Wetlands Planning, Protection, and Restoration Act – CWPPRA (https://lacoast.gov/new/Projects/List.aspx), and the Louisiana Digital Library – LDL (http://louisianadigitallibrary.org/). We filtered the CPRA map for completed projects and collected completion reports for marsh creation and barrier island restoration. We filtered the CWPPRA database for all completed projects and collected all relevant completion reports. We queried the LDL for the search terms "project completion report" and "dredge". From the completion reports, we collected all cost data that contained a unit price estimate in \$/CY for dredging.

For each unit cost estimate, we recorded the project ID number, the primary dredging contractor(s), the date of the report, the date of the contract award (which typically occurs one to three months after a bid opening), the type of activity (e.g. marsh creation, barrier island restoration, beneficial navigation dredging), the general location and type of project the activity is associated with, the type of dredges and machinery used for the specific activity (as stated in the project completion report), the total volume of material to be displaced by that activity (CY), the estimated horsepower capacity of the machines used for dredging, and where available the daily production rate (CY/day). The data is given in table 1.

A spreadsheet was used to compile information from project completion reports. The name, specific type and number of machines dedicated to an activity were inferred (e.g. 30" cutter suction dredge named "Tom James") based on the information reported in the "major equipment used" and "construction sequence and activities" sections. The horsepower capacity (hp) dedicated to an activity was estimated with a Google internet search for the name of the dredge and/or type of machine (e.g. CAT 325 marsh buggy) along with the name of the contractor (e.g. Weeks Marine). In all cases for cutter suction dredges this yielded a webpage for the dredge contractor with the specifications of the dredge or machine in question. The horsepower rating of the machine was logged in the spreadsheet. If more than one machine was required for an activity the horsepower capacity was set equal to the sum of horsepower for each machine.

I developed an indicator for the scaling efficiency/ energy intensity of dredging called the efficiency factor – Ek, This metric was obtained by taking the log of the volume of displaced borrow material (q) divided by the horsepower capacity (hp) for the activity. Ek serves as a proxy for the scale efficiency and/or energy intensity (1/efficiency) and production rate of the project. These are affected by borrow site distance, depth of borrow material, and the density or shear strength of the borrow material (Ek is discussed more sections 2. METHODS and 4. DISCUSSION).

B.3. Oil Prices

The price of oil was estimated for each bid using a vlookup function in MS Excel software. In order to relate the date of the contract with the price of fuel, the month and year of the contract award, report date, and monthly mean price fuel were converted into decimal years. The vlookup function returns a fuel price parameter from a separate spreadsheet for a given date. Fuel price was either presented as the spot price of Brent crude oil ($/barrel $/bbl or $/42 gallons), or the price of diesel ($/gallon).

I calculated several fuel price metrics from U.S. Energy Information Administration (EIA 2016) to test a regression against the unit cost of dredging. Fuel price metrics were calculated in both nominal and real terms. Real prices were calculated using the consumer price index for all expenditures. Fuel price metrics included: (m1) the fuel price during the month of the contract award, (m2) the mean price for the six months prior to the contract award, (m3) the mean fuel price for the six months prior and six months post of the contract award, (m4) the fuel price for the 12 months prior to the contract award, (m5) the change in fuel price over the six months prior to the contract award, (m6) the change in fuel price over the twelve months prior to the contract award, and (m7) the volatility or absolute value of the delta fuel price over the six months prior to the contract award. Preliminary regressions were developed for the fuel price metrics against bid price of dredging. All fuel price metrics showed a significant relation with the price of dredging. m4, the mean price of crude and diesel 12 months prior to the contract award was the best predictor of bid price. we elected to use the mean price of crude oil 12 months prior to contract award as the predictor variable in this study rather than diesel because crude oil price projections are given in the results of most composite oil price forecast (crude oil and diesel price correlate very well).

B.4. Results

Figure B2 shows dredging price verses the log of borrow volume divided by horsepower (Ek). Table B1 shows the parameters and statistical results for the production function for hydraulic dredging. Figures B3 and B4 show regression diagnostics.

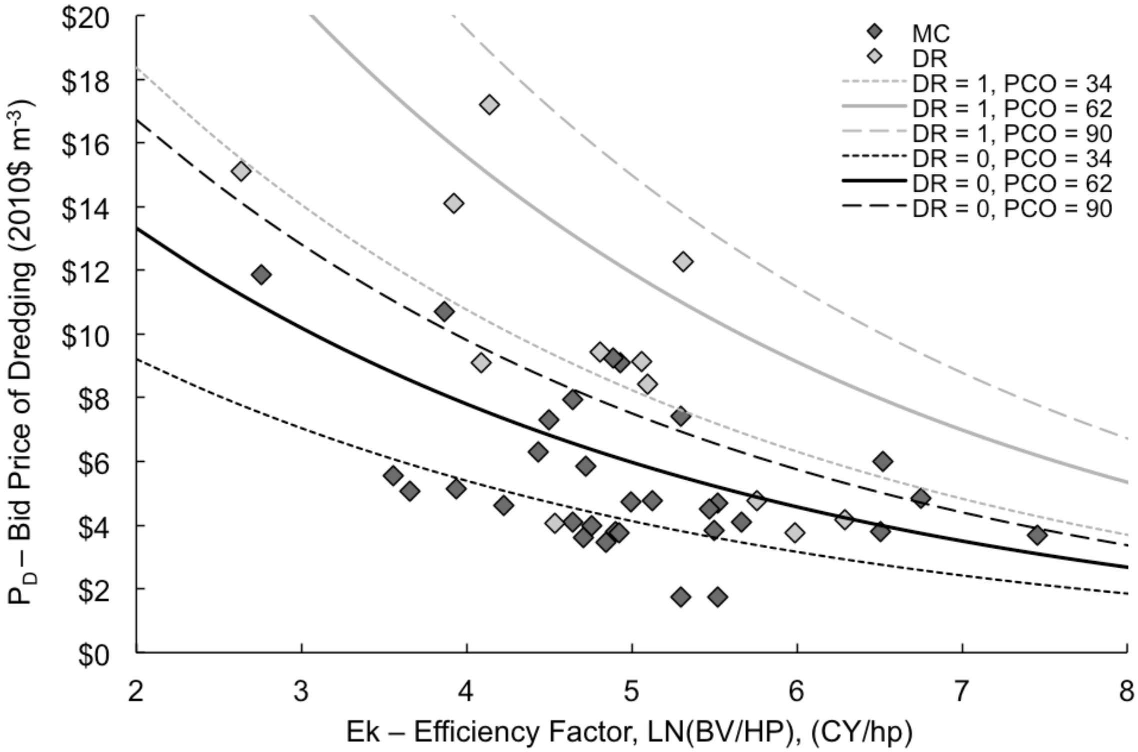

FIGURE B2. Multiple regression model for the price of cutter suction dredging plotted verses efficiency factor – Ek, for dune restoration (DR) (light grey) and marsh creation projects (dark grey) at the mean price of crude oil across all samples (solid lines) and ±1.0 S.D. (dashed lines).

TABLE B1. Multiple regression results summary

Equation
$P_D = e$^[$b_0 + b_1$*LN(P_{CO}) + b_2*DR + b_3*Ek] (Units are 2010 $/CY, divide parameters by 0.76455 to convert to $/m^3)
Model Summary
Residual standard error: 0.3227 on 3 and 39 degrees of freedom; Multiple R-squared: 0.6365, Adjusted R-squared: 0.6085; F-statistic: 22.76, p-value: 1.107e-08; AIC score: 30.54

Parameter estimates

variable	param.	Estimate	Std. Error	Pr(>|t|)	Signif.[1]
(Int.)	b0	0.44877	0.49684	0.37194	
$LN(P_{CO})$	b1	0.46968	0.09488	1.47E-05	***
DR	b2	0.52816	0.11095	2.66E-05	***
Ek	b3	-0.2041	0.05173	0.00032	***

Type III Partial Sum of Squares

variable	Df	Sum Sq	F value	Pr(>F)	Signif.[1]
(Int.)	1	2.683	25.77	9.83E-06	***
DR	1	2.804	26.94	6.86E-06	***
Ek	1	1.621	15.57	0.00032	***
Residuals	39	4.06			

Type II Sequential Sum of Squares

variable	Df	Sum Sq	F value	Pr(>F)	Signif.[1]
$LN(P_{CO})$	1	2.5511	24.505	1.47E-05	***
DR	1	2.3593	22.663	2.66E-05	***
Ek	1	1.6208	15.569	0.00032	**

[1]: Significance codes 0 > '***' > 0.001> '**'> 0.01 > '*'> 0.05 > '.' > 0.1 >' '>1

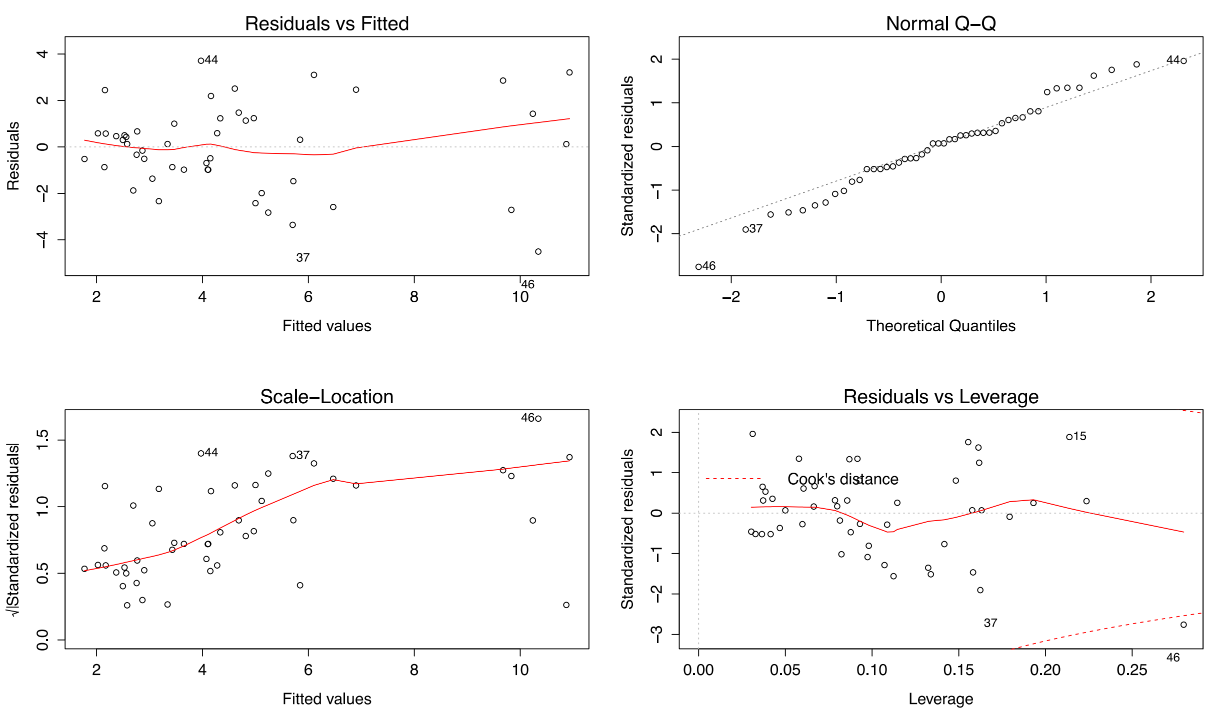

FIGURE B3. Regression diagnostic plots for the model in Table B1.

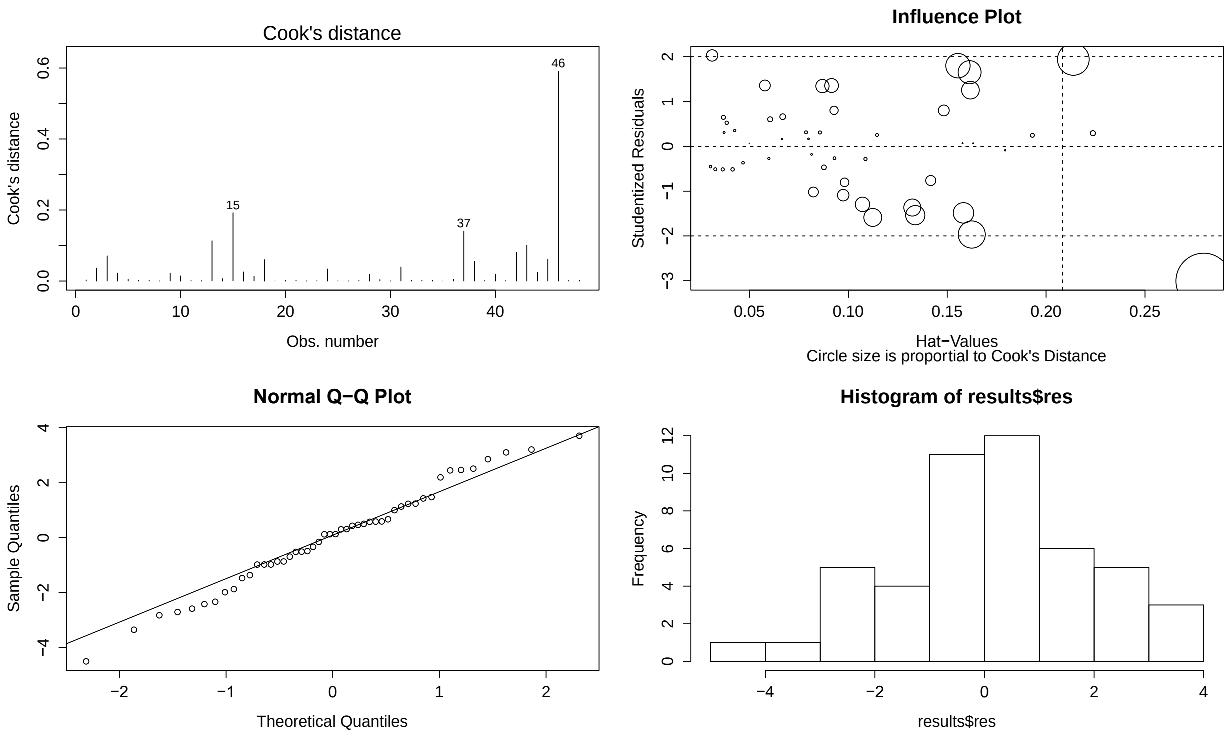

FIGURE B4. Regression diagnostic plots for the model in Table B1.

EXCERPT 1 (copied from CPRA 2012b):

> "…Approximately 60% to 70% of the total construction cost of this [marsh creation] is dictated by the unit cost of the marsh fill material. This marsh fill unit cost is typically influenced by the type of material to be dredged, the dredging distance, payment method, fuel costs, and dredging experience. Approximately 20% to 30% of the total construction cost is derived from the mobilization and demobilization of construction equipment. This cost is influenced by the project size, borrow source, dredging distance, pipeline corridor, dredging equipment, dredging volume, manpower, and contractor risk…"

EXCERPT 2 (copied from CPRA 2012b):

> "3.5 MARSH CREATION
> Created Acres: Total acres of land created or nourished by project.
> Fill Volume: The total estimated volume of marsh fill material required to construct the project feature using one initial lift based on the target marsh elevation at TY0.
> Cut Volume: Total dredge volume required for project.
> Borrow Source: The borrow area(s) required to construct the feature(s). For further project development, the source of material should be optimized using material from shoals, relic channels, the Mississippi River, or other. A 500-foot

buffer should be used near existing inland pipelines and a 1,500-foot buffer for offshore pipelines.
Fill Source: The borrow area(s) required to construct the marsh feature(s). For further project development, the source of material may be optimized using offshore and river sources. A hydraulic dredge cut of 10 feet may be used to determine the borrow area acreage. A 500- foot buffer may be used near existing inland pipelines and a 1,500-foot buffer for offshore pipelines.
[E_{Fill}] Elevation at Target Year 0: Refers to marsh elevation at target year 0.
Louisiana's Comprehensive Master Plan for a Sustainable Coast Page A-60
Appendix A – Project Definitions
Estimated Construction Cost (2010): Includes construction and construction management
costs. It includes the following bid items: mobilization and demobilization, marsh fill, earthen
containment dikes, surveys, and vegetative plantings. 11.
Estimated Operation and Maintenance Cost: This cost includes the O&M costs for a 50-year
project lifespan. It includes the following bid items: vegetative plantings (TY5, TY15, and TY25), containment dike gapping (TY1, TY3, and TY5), and profile surveys (TY5, TY15, TY25, TY35, and TY50).
[Marsh Creation Features]
Marsh Creation Fill Area: One initial marsh fill lift placed to the target marsh fill elevation at TY0 as derived from the regional settlement curves; maximum target marsh fill elevation of +3.2 ft NAVD88.
Earthen Containment Dikes: A crest width of 5 feet, side slopes of 4(H):1(V); crown elevation of +4.5 ft NAVD88 assumed to be maintained during construction; constructed using in-situ material. Interior earthen containment dikes utilized for marsh fill placement as required for acceptance and dewatering using 1,000-acre cells.
…
Marsh Creation Project Cost Assumptions:
Borrow Source and Pipeline Corridor:
Borrow Source Quantity: Sufficient borrow source volume to build each conceptual candidate project was assumed. However, a borrow source evaluation will be required to identify potential borrow source location(s) and available sediment for portfolio or preliminary project development.
Borrow Source Material Type: Unit costs for marsh fill adjusted accordingly based on the source location and material type. The following assumptions were used to develop marsh fill unit costs:

- Dredge cut depth of 30 feet.
- Fuel cost of $3.50/gallon.
- Mississippi River: included 5 additional miles of pumping distance for projects needing in excess of 4 million cubic yards of material.
- Dredge Material: 85% sand, 5% mud.
- Pipeline: 1% flow line, 49% submerged, 50% shoreline pipe.

…Dredge Types: A 30-inch hydraulic cutter suction pipeline dredge was assumed for river and offshore dredging. A 20-inch hydraulic cutter suction pipeline dredge was assumed for interior waterbody dredging. 1 dredge utilized for projects < 2,000 acres. □□2 dredges utilized for projects 2,000-5,000 acres. 3 dredges utilized for projects > 5,000 acres.

…Pumping Distance: The maximum distance from the proposed marsh fill area(s) to the
borrow source.

- A maximum pumping distance of 19 miles for both a 20-inch and 30-inch dredge with a minimum of four booster pumps. A 30-mile maximum was also used in specific locations.
- A maximum pumping distance of 5 miles without a booster pump.

Marsh Creation Fill Area(s): - Marsh fill volume determined by the Wetland Morphology model from GIS shapefiles of project footprints using the following rules:

Open water areas within the project polygon were filled to 100% land; this new land was then built to a project-specific target elevation of either 2.5 ft or 3.2 ft NAVD88 as specified in the Project Attributes Table column Elev_TY0…Open water areas with water bottom elevations lower than -5.0 feet NAVD 88 were excluded.

Nourishment of existing land within the project polygon was not considered in the computations…

Earthen Containment Dike:

- Containment dikes placed along the perimeter of the proposed marsh fill areas and in the interior to create cells; 1,000-acre cells utilized for projects.
- Constructed using marsh buggy hoe and in-situ material.

Optimized marsh buggy quantity based on project size and production rates.

Marsh Creation Project Duration Assumptions:

Dredging of Marsh Creation Fill Area(s):

- 30 days/year for maintenance downtime.
- 15 days/ year for weather delay downtime.
- 12,000 CY/day production rate for a 20-inch dredge.
- 20,000 CY/day production rate for a 30-inch dredge."

TABLE B2. Raw data collected on dredging for coastal restoration in the Mississippi delta

Project ID	Date of contract award	[1]Project Type	[2]Dredge Type	Nominal Dredging Bid Price	Real Dredging Price (2010$)	Real Crude Oil Price (2010$)	Quantity of Borrow Material	Dredging Power Capacity
(n/a)	(yr)	(n/a)	(n/a)	($/CY)	($/CY)	($/CY)	CY	HP
BA-30	2009.42	MC	cs0	5.5	5.58	65.92	965211	10722
BA-30	2009.42	DR	cs0	9.25	9.38	65.92	2179039	10722
BA-35	2008.33	DR	cs1	7.05	6.95	87.03	891580	14915
BA-35	2008.33	MC	cs1	7.05	6.95	87.03	2066472	14915
BA-36	2008.67	MC	cs0	3.05	2.83	101.19	6500000	3750
BA-37	2005.42	MC	cs0	2.45	2.89	62.07	2512432	3750
BA-37	2007.33	MC	cs0	4.25	4.47	46.85	422361	3750
BA-38-1	2011.5	DR	cs2	12.1	10.80	90.00	1400000	27630
BA-38-1	2011.5	MC	cs2	4.4	3.93	90.00	1419000	27630
BA-38-2	2005.58	MC	cs0	3.05	3.54	49.96	735206	10722
BA-38-2	2005.58	DR	cs0	5.55	6.45	49.96	1748443	10722
BA-39	2010.08	MC	cs1	9.2	9.08	66.04	340471	21600
BA-39	2009	MC	cs1	6.05	6.08	88.94	2237769	21600
BA-40	2012.25	DR	cs2	14.9	13.14	101.29	1889310	30200
BA-40	2012.25	MC	cs0	3.3	2.91	101.29	1483146	11000
BA-42*	2008.75	MC	cs1	6.15	5.68	100.29	4000000	20000
CS-01	2002.42	DR	cs1	5.25	7.22	25.34	1750000	14322
CS-01	2002.42	BU	cs0	2	2.75	25.34	1000000	9000
CS-28-1	2001.25	MC	cs0	1.94	2.66	33.64	2400000	18900
CS-28-3	2006.75	MC	cs0	2.9	3.12	63.11	585000	5650.78
LA-01-D	2005.58	MC	cs0	3.1	3.60	49.96	747700	3000
LA-01-E	2007.5	MC	cs0	4.4	4.59	62.15	289629	425
LA-01-F	2007.58	MC	cs0	4.65	4.82	62.20	295000	3500

Project ID	Date of contract award	1Project Type	2Dredge Type	Nominal Dredging Bid Price	Real Dredging Price (2010$)	Real Crude Oil Price (2010$)	Quantity of Borrow Material	Dredging Power Capacity
(n/a)	(yr)	(n/a)	(n/a)	($/CY)	($/CY)	($/CY)	CY	HP
BA-30	2009.42	MC	cs0	5.5	5.58	65.92	965211	10722
BA-30	2009.42	DR	cs0	9.25	9.38	65.92	2179039	10722
BA-35	2008.33	DR	cs1	7.05	6.95	87.03	891580	14915
BA-35	2008.33	MC	cs1	7.05	6.95	87.03	2066472	14915
BA-36	2008.67	MC	cs0	3.05	2.83	101.19	6500000	3750
BA-37	2005.42	MC	cs0	2.45	2.89	62.07	2512432	3750
BA-37	2007.33	MC	cs0	4.25	4.47	46.85	422361	3750
BA-38-1	2011.5	DR	cs2	12.1	10.80	90.00	1400000	27630
BA-38-1	2011.5	MC	cs2	4.4	3.93	90.00	1419000	27630
BA-38-2	2005.58	MC	cs0	3.05	3.54	49.96	735206	10722
BA-38-2	2005.58	DR	cs0	5.55	6.45	49.96	1748443	10722
BA-39	2010.08	MC	cs1	9.2	9.08	66.04	340471	21600
BA-39	2009	MC	cs1	6.05	6.08	88.94	2237769	21600
BA-40	2012.25	DR	cs2	14.9	13.14	101.29	1889310	30200
BA-40	2012.25	MC	cs0	3.3	2.91	101.29	1483146	11000
BA-42*	2008.75	MC	cs1	6.15	5.68	100.29	4000000	20000
CS-01	2002.42	DR	cs1	5.25	7.22	25.34	1750000	14322
CS-01	2002.42	BU	cs0	2	2.75	25.34	1000000	9000
CS-28-1	2001.25	MC	cs0	1.94	2.66	33.64	2400000	18900
CS-28-3	2006.75	MC	cs0	2.9	3.12	63.11	585000	5650.78
LA-01-D	2005.58	MC	cs0	3.1	3.60	49.96	747700	3000
LA-01-E	2007.5	MC	cs0	4.4	4.59	62.15	289629	425
LA-01-F	2007.58	MC	cs0	4.65	4.82	62.20	295000	3500

Literature Cited

Bray, R.N., Bates, A.D. and Land, J.M., 1997. Dredging: a handbook for engineers.

Clark, F.R., Bienn, H.C., and Willson, C.S. 2015. Assessing the Cost of Coastal Land Creation Using Dredged Material. The Water Institute of the Gulf. Science & Engineering Plan – Project Implementation Support Task. Baton Rouge, LA.

CPRA, 2012b. Appendix A: 1 Project Definitions. 2012 Coastal Master Plan. Louisiana Coastal Protection and Restoration Authority, Baton Rouge, Louisiana.

Ji, Q., and Fan, Y. (2012). How does oil price volatility affect non-energy commodity markets?. Applied Energy, 89(1), 273-280.

Murphy, D.J. and C.A.S. Hall. 2011. Adjusting the economy to the new energy realities of the second half of the age of oil. Ecological Modeling 223: 67-71.

World Bank. 2015. Commodities Price Forecast. Released October 20, 2015.

APPENDIX-C. MARSH ELEVATION MODELING

C.1. The Wetland System

The wetland system subroutines of WECRM simulates water level, marsh productivity, sediment deposition and resulting elevation dynamics using a weekly time step. To simulate marsh elevation with varying RSLR and river influence, I adapted the primary productivity, organic matter and mineral sediment equations from the Marsh Equilibrium Model (MEM) (Morris et al. 2002) and the integrated wetland ecosystem model (IWEM) (Rybczyk & Cahoon 2002). The model was calibrated using data from a selection of Louisiana Coastwide Reference Monitoring System (CRMS, https://www.lacoast.gov/crms2/home.aspx) sites with similar tidal range from the Western Atchafalaya and Wax Lake Region, Fourleague Bay, Upper Terrebonne Bay, and Southeast Barataria (see Table S5). Described in this section are the modifications and procedures that were executed calibrate WECRM for simulation of marsh creation. I wrote the model in FORTRAN 95 and the code provided in APPENDIX-H.

C.2. Eustatic Sea-Level Rise

The rate equations (m/year) for SLR are given in the following equations, SLR 1 – 5. These fits meet the current rate of sea level rise (3.5 mm/year, http://climate.nasa.gov/vital-signs/sea-level/) and are constrained to fit the sea level projected for 2100.

$$dSL = 0.0035 \quad (\mathrm{SLR}-1)$$
$$dSL = 0.00007823\mathrm{t} + 0.0035 \quad (\mathrm{SLR}-2)$$
$$dSL = 0.00020721\mathrm{t} + 0.0035 \quad (\mathrm{SLR}-3)$$
$$dSL = 0.00032648\mathrm{t} + 0.0035 \quad (\mathrm{SLR}-4)$$
$$dSL = 0.00043445\mathrm{t} + 0.0035 \quad (\mathrm{SLR}-5)$$

dSL is delta sea level per year and t is the year t = 0 is 2016

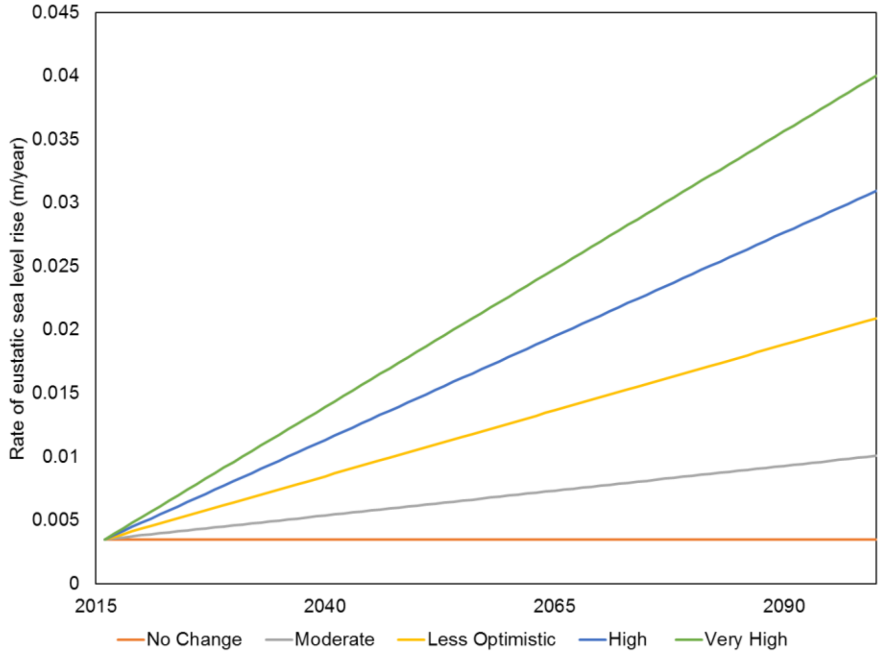

FIGURE C1. Projections for rate of eustatic sea-level rise used in this study. No Change corresponds with SLR-1, Very High corresponds with SLR-5.

C.3. Water Level, Elevation, Subsidence and Compaction

In WECRM, relative sea level rise (RLSR) is the sum of the rate of deep subsidence (SubR) and eustatic sea level rise (Eqn. C1a). RSLR is added to water level at each time step (Eqn. C1b). Elevation relative to mean water level (E_{RWL}, used interchangeably with Relev) is the difference between elevation and water level (WL) during a given time step (Eqn. C1c).

$$RSLR = dSL + SubR \qquad \text{(Eqn. C1a)}$$

$$WL = WL + RSLR - InitRelev \qquad \text{(Eqn. C1b)}$$

$$E_{RWL} = Relev = E - WL \qquad \text{(Eqn. C1c)}$$

dSL is change in eustatic sea level (cm/yr), SubR is the regional rate of deep subsidence below the soil column being modeled (cm/yr) (explained below), WL is mean water level (cm), InitRelev is the initial relative elevation of the marsh specified by the modeler, E is the elevation of the soil surface (cm) calculated in Eqn. C5.

Local deep subsidence rates relate to the thickness of the Holocene sediment layer (Meckel et al. 2006), the age of the delta basin, the distance of a site from a distributary channel, and the rate of subsurface fluid extraction, all of which vary greatly throughout the Mississippi delta (Kolker et al. 2011). I estimated subsidence rates from sediment elevation table data (Cahoon et al. 2002) from CRMS sites by subtracting the long-term accretion rate above a feldspar marker horizon from the long-term elevation change of the benchmark (see Table C2 at end of APPENDIX-C). For simulations, I used a deep subsidence value of 0.87 (mm/yr) based on the median estimate from CRMS sites in Table C2. Subsidence rates reported in the Mississippi delta range between 4-12 (mm/yr) in the Atchafalaya and Terrebonne basins, 5-25 (mm/yr) in Barataria and Breton basins, and are as high as 35 mm in the recently formed Bird's Foot delta (Shinkle & Dokka 2004, CPRA 2012c). Sensitivity tests performed on the subsidence rate are provided in APPENDIX-D.

Another factor influencing subsidence is compression of recently deposited sediment due do autocompaction and surface loading (Day et al. 2011; Rybczyk & Cahoon 2002). WECRM does not model the compaction of marsh sediments because of the difficulty in calibration and the need to derive site-specific parameters, which limits model applicability for simulating multiple locations (see Rybczyck et al. 1998; Rybczyk & Cahoon 2002). Rather, I employ the "ideal mixing model", which developed across a wide range of marsh sediments, this model does not require additional calibration (Adams 1973; Morris et al. 2016). The model assumes that organic matter and mineral matter have discrete self-packing densities (k1 and k2), and that bulk density (BD) (Eqn. C2), vertical accretion (cm/yr) (Eqn. C3) or soil height (cm) (Eqn. C4), can be modeled by treating mineral and organic matter as separate entities. With this model, loss of soil volume can only be attributed to decomposition of organic matter.

$$BD = 1/ [LOI/k1 + (1-LOI)/k2] \qquad \text{(Eqn. C2)}$$

LOI is loss on ignition or the organic fraction of soil (g/g), k1 is the self-packing density of organic matter, given a value of 0.085 (g/cm^3) (from Morris et al. 2016), k2 is the self-packing density of mineral matter, given a value of 1.99 (g/cm3) (from Morris et al. 2016).

$$A = dO/k1 + dM/k2 \qquad \text{(Eqn. C3)}$$

A is the accretion rate (cm/yr), dO is the rate of change in organic mass ($g/cm^2/yr$), dM is the rate of change in Mineral matter ($g/cm^2/yr$), k1 and k2 are the respective self-packing densities for organic and mineral matter (g/cm^3) from Eqn. C2.

$$H = O/k1 + M/k2 \qquad \text{(Eqn. C4)}$$

H is the soil column height (cm), O is the organic mass (g/cm^2), M is the mineral mass (g/cm^2). I calculated elevation (E) as the difference between the soil column height (H) and elevation loss from compaction of sediments below the modeled soil column from surface loading of hydraulically dredged sediments (Eqn. C5).

$$E = H - J \qquad \text{(Eqn. C5)}$$

H is the height of the soil column as modeled by Eqn. C4, J is compaction of subsurface sediment below the soil column from loading of dredged sediments (all units in cm).

Large pulses of sediment that occur during the addition of hydraulically dredged sediments at a marsh creation project or after a storm surge results in significant compaction of subsurface sediments. The compaction caused from surface loading is non-linear with respect to time and has significant impacts on the evaluation of benefits of a marsh creation project. In the tidal reaches of the Mississippi delta, compaction estimates from loading of dredged sediments range from a few centimeters up to a meter, depending on the characteristics subsurface Holocene sediments and the amount of fill material (Furgo Consultants Inc. 2011; Thompson 2007; Simoneaux et al. 2008). It was not feasible to simulate compaction due to loading of dredged sediment mechanistically. Estimating compaction of subsurface sediments due to surface loading requires geotechnical surveys that involve deep (10s of meters) soil borings and laboratory tests. A geotechnical analysis commonplace procedure and is often required for large construction projects, however, it is expensive and time consuming and beyond the scope of the study. Geotechnical surveys are used in marsh creation projects to produce settlement curves that predict elevation loss over time due to surface loading (Furgo Consultants Inc. 2011). Settlement curves can be found in graphical and tabular form in design and/or geotechnical reports for marsh creation projects.

I calculated a parameter called the settling ratio using data that are typically given on a settlement curve/table in a geotechnical report (Eqn. C6).

$$sl = (E_0 - E_{20})/(H_{fill}) \qquad \text{(Eqn. C6)}$$

sl (cm/cm) 20 year settling ratio or the 20 year settling distance ($E_0 - E_{20}$) divided by the fill height (H_{fill}), H_{fill} is taken as the elevation at time zero minus the average elevation of the site before addition of sediment (see Eqn. 2 in section 2. METHODS), E_0 is the elevation 0 years after the fill quantity has been placed, E_{20} is the elevation 20 years after sediment placement of fill (all using equivalent units of distance). I chose a settling ratio of 0.25, which is on the lower end of 20 year settling ratios from the marsh creation projects we reviewed BA-39, BA-42, and BA-43B (Table C1).

TABLE C1. Calculation of 20 year settlement ratios. Data is derived from geotechnical engineering for Lake Hermitage (BA-42, Simoneaux et al. 2008) and Bayou Dupont (BA-39, Thompson 2007) Marsh Creation Projects and the Mississippi River Long Distance Sediment Pipeline BA-43B (FUGRO CONSULTANTS, INC. 2011) (See Eqn. C6)

Project	H_{fill} (ft)	Relev (ft)[1]	E_0 (ft)	E_{20} (ft)	sl
BA-42	5	-2.105	2.895	2.2	0.14
BA-42	3.5	-2.105	1.395	0.85	0.16
BA-39	6	-0.5	5.5	3.06	0.41
BA-39	4	-0.5	3.5	1.84	0.42
BA-39	2	-0.5	1.5	0.76	0.37
BA-43B	7	-2.5	4.5	2.04	0.36
BA-43B	5.5	-2.5	3.5	1.23	0.34
BA-43B	5.5	-1	4.5	2.03	0.32
BA-43B	4.5	-1	3.5	1.39	0.3

[1] Relev is the initial mean soil surface elevation of the site before dredging, commonly referred to in technical reports as the “mudline elevation”.

Multiple marsh creation efforts were needed to sustain marsh from 2016 to 2100. Compaction from each addition of hydraulically dredged sediment was modeled discretely for each effort with respect to time using a Michaelis-Menten function (Eqn. C7) and summed to get the total amount of compaction (Eqn. C8).

$$Jf_i = sl*[(Yr-Yr_i)/(pk+(Yr-Yr_i)] \qquad \text{(Eqn. C7)}$$

Jf_i is amount of compaction from the i^{th} marsh creation effort (0-sl, unitless), a function of time, the sl is the settling ratio from Eqn. C6 with an intermediate value of 0.25 (see Table C1 and Table D2), Yr is the current decimal year in the model run, Yr_i is the year of the i^{th} marsh creation effort, pk is the half settling period or the amount of time between initial restoration and the time at which half of the total settling has occurred (all parameters can be derived from a settling curve, see Thompson 2007, page 15).

$$J = \Sigma^n_{i=1} [Jf_i * H_{fill,i}] \qquad \text{(Eqn. C8)}$$

J is the total compaction due to addition of dredged sediment and Jf_i is the compaction of the i^{th} marsh creation effort over time from Eqn. C7, $H_{fill,i}$ is the height (cm) of dredge sediment addition.

C.4. Calibration to Deltaic Accretion Rates

I calibrated productivity and sediment deposition functions, using a selection of CRMS sites with similar tidal range from the Western Atchafalaya and Wax Lake Region, Fourleague

Bay, Upper Terrebonne Bay, and Southeast Barataria (see Table C2). I collected the following information for each CRMS site: the marsh elevation, mean water level, 90th percentile water level (90$^{\%}$WL), the organic matter fraction (LOI) and bulk density (BD) of the top 0-4 cm of the soil, the estimated long term accretion rate, the long term elevation change (accretion minus subsidence), the mean annual salinity of the site. I estimated the mass contribution (g cm^{-2} yr^{-1}) of minerals and organic matter using the long-term accretion rate (cm yr^{-1}), LOI (g cm^{-3}), and BD (g/g) (Eqn. C9, Eqn. C10) (see Figure C2).

$$dM = A*BD*(1-LOI) \qquad \text{(Eqn. C9)}$$

$$dO = A*BD*LOI \qquad \text{(Eqn. C10)}$$

dM is accumulation rate of mineral matter (g cm^{-2} yr^{-1}), dO is accumulation rate of organic matter (g cm^{-2} yr^{-1}), A is the accretion rate (cm yr^{-1}).

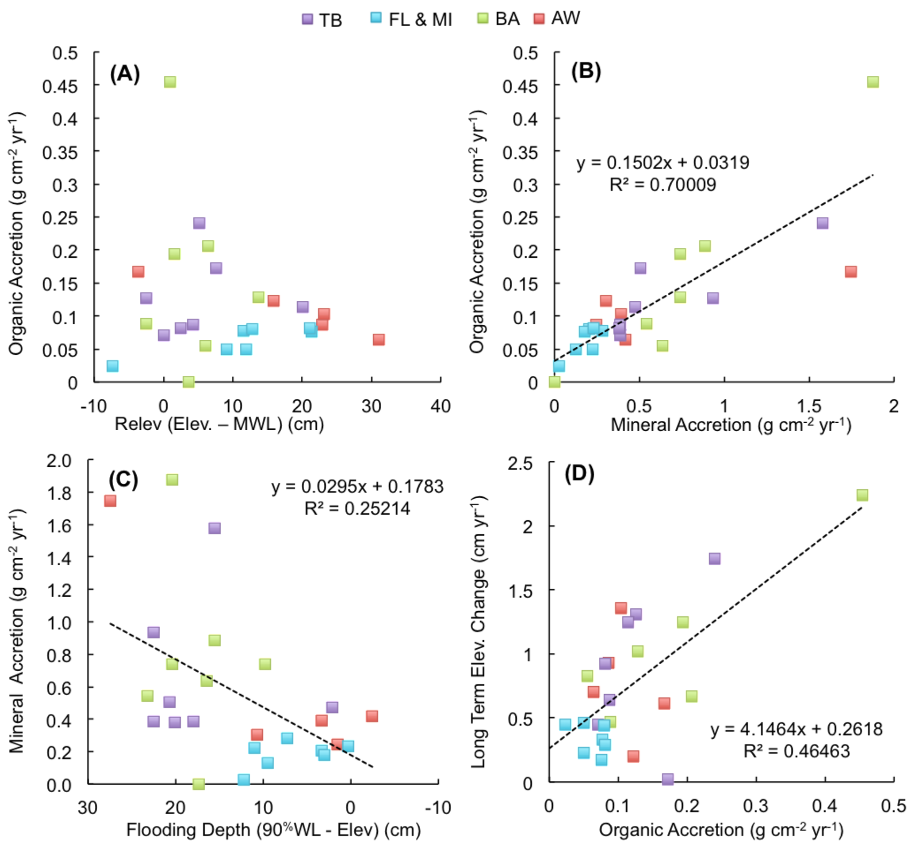

FIGURE C2. Mineral and organic accretion rates from CRMS sites in Upper Terrebonne Bay, Fourleague Bay, Southeast Barataria Bay, and marshes surrounding Atchafalaya and Wax Lake Detlas. Shown here: (A) organic accretion verses elevation relative to mean water level showing a parabolic type relationship (see figure C5), (B) organic accretion verses mineral accretion with a linear trend line, (C) mineral accretion verses elevation relative to 90% water level or high tide with a linear trend line, (D) Long term elevation change (accretion minus shallow and deep subsidence) verses organic accretion with a linear trendline.

C.5. Mineral Sediment Deposition

I assume that erosion is not a factor. Mineral mass balance is controlled only by sedimentation (Eq. C11).

$$M = M + S*(1-xo) \qquad \text{(Eqn. C11)}$$

M is mineral matter in the soil column (g cm^{-2}), S is sedimentation (g cm^{-2} $week^{-1}$), xo is the fraction of suspended sediment made of refractory organic matter. I use an xo value of 0.03, sensitivity tests for xo are provided in APPENDIX-D.

Sediment deposition was modeled as a function of the maximum inundation depth (99^{th} percentile water level, $99^{\%}$WL), percent inundation, the mean total suspended sediment (TSS) concentration, (mg L^{-1}) and above ground biomass (g d.w m^{-2}) (Eqn. C12 and Eqn. C13). The parameters were calibrated to match accretion and water level data from CRMS sites (LA Coast 2016b). Based on data published in Terrebonne Bay, Fourleague Bay, and the Wax Lake and Atchafalaya delta areas, we estimated that the mean TSS concentrations for sites with and without river influence ranged from 60-120 mg/L and 20-40 mg/L respectively (Perez et al. 2000, Wang 1997, Murray et al. 1993). I did not have site-specific TSS estimates; instead the model accretion rates were calibrated to fit this range of suspended sediment concentrations (Figure C3).

$$S = TSS*(q + ks*AGB)*\omega* f *(99^{\%}WL - Relev)/2 \qquad \text{(Eqn. C12)}$$

S is sediment deposition (g cm^{-2} $week^{-1}$); TSS (g/cm^{-3}, which is equal to mg/L divided by 10,000) is the sediment concentration in the adjacent water bodies; ω is the fraction of time the marsh is inundated (see Eq. C13); $99^{\%}$WL is the 99^{th} percentile high water level, estimated from CRMS data for the water year 2010 ($99^{\%}$WL is roughly double $90^{\%}$WL); Relev is the marsh elevation relative to mean water level; q is the settling velocity of sediment particles (cm^{-1} $week^{-1}$); ks is a coefficient for the efficiency of above ground biomass, AGB (g/cm^2), at trapping sediment (g g^{-1} $week^{-1}$); *f* is the frequency of inundation during the time step (Morris et al. 2002; Morris et al 2012).

$$\omega = 1/[1+e^{-ki*kii/Tamp*(Relev - kii)}] \qquad \text{(Eqn. C13)}$$

ω is the fraction of time the marsh is inundated; Tamp is the tidal amplitude measured as the $90^{\%}$WL – MWL; ki is a fitted parameter for the slope; kii is a fitted parameter for the inflection point (Figure S11).

In microtidal settings, the function in Eqn. C13 is favorable to unitless elevation [Tamp-Relev)/(Tamp*2)], which is used by Morris & Callaway (2017 [Submitted]). This function can also simulate percent inundation for any tidal range.

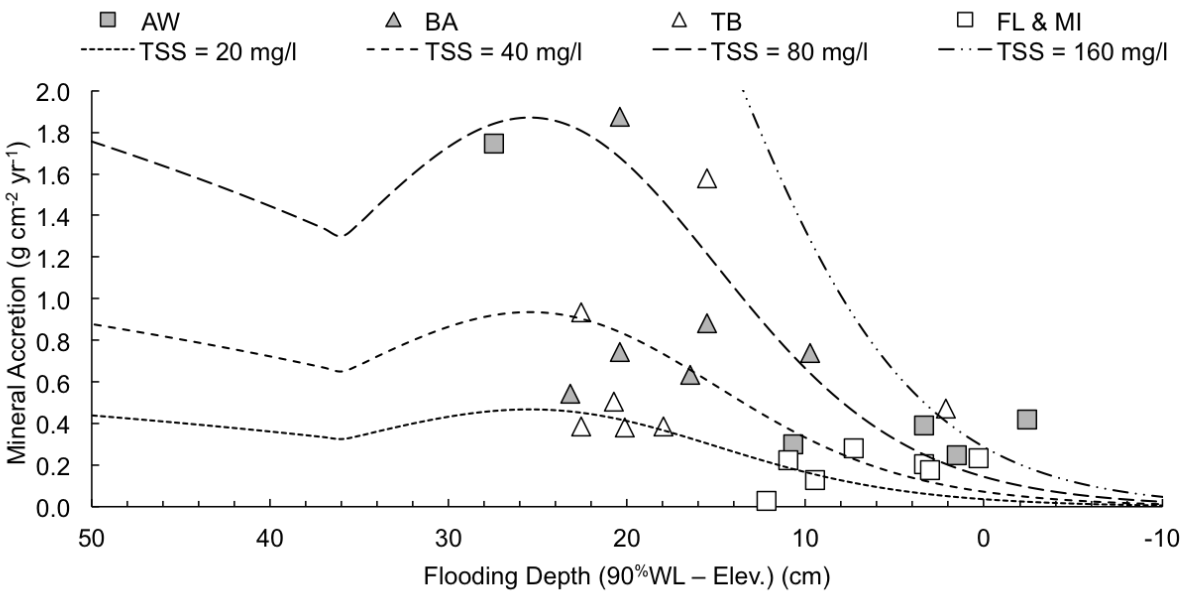

FIGURE C3. Observed mineral accretion verses modeled mineral sediment deposition. (see table and eqn. C12). Field data is sorted by sample regions: AW – Atchafalaya Wax Lake, FL & MI – Fourleague Bay and Marsh Island, TB – Terrebonne Bay, BA – Barataria Bay.

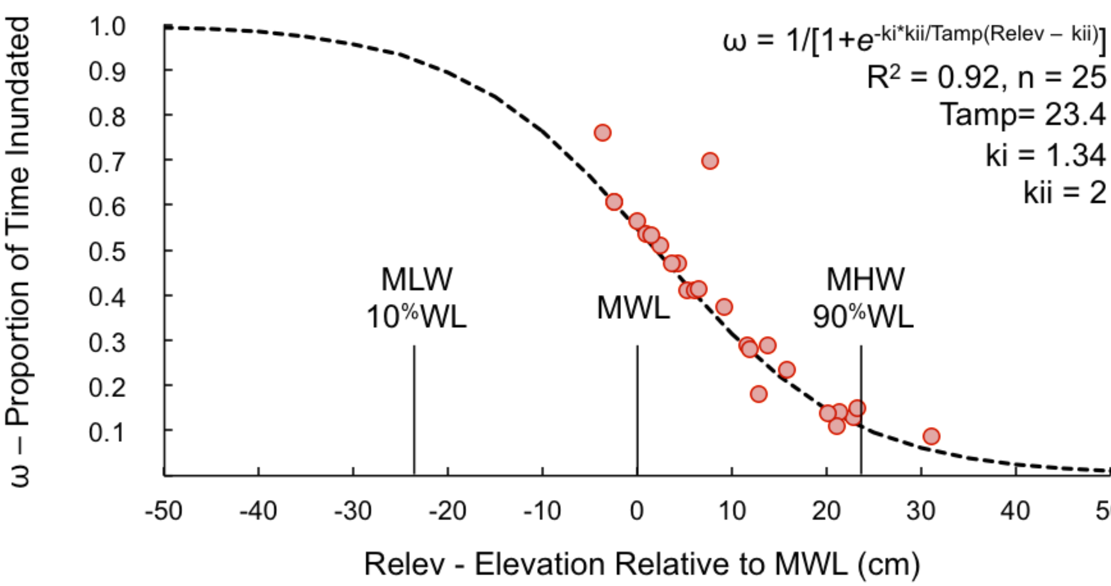

FIGURE C4. Proportion of time inundated inundation (ω) as a function of relative marsh elevation for a tidal amplitude (Tamp) of 23.4 ($90^{\%}$WL – MWL). Raw data is provided in Table C2.

C.6. Biomass, Primary Production and Decomposition

Net primary productivity (NPP) and decomposition state equations were modified from IWEM (Rybzyck et al. 1998). Productivity of above ground marsh vegetation and roots were modeled as a function of elevation relative to sea level using published data on seasonal above and belowground biomass (Hopkinson et al 1978, Nyman et al. 1993, Nyman et al. 1995, Darby & Turner 2008a, 2008b). I added the simulation of dead above ground biomass and export of dead biomass from the marsh before it becomes leaf litter. Export can occur either from standing decomposition predation or advection from wind or floods (Nyman et al. 1995). I simulated marsh productivity as a function of proportion of time inundated (see Figure C5 and Eq. C22). A relative productivity factor was fit to data for organic accretion rates from tidal marsh data from CRMS sites, with guidance from published studies Mississippi delta marshes (Day et al. 2011, Couvillion & Beck 2013, DeLaune et al. 1983, 2016, Snedden et al. 2015). Differential equations for above and below ground biomass are given below.

$$AGB = V + D \qquad \text{(Eqn. C14)}$$

AGB is total above ground biomass, V is the live above ground biomass (g/m^2), D is the dead and senescent above ground biomass (g/m^2). For use in Eqn. C12, AGB is divided by 10000 to convert from g/m^2 to g/cm^2.

$$V = V + dV \qquad \text{(Eqn. C15)}$$

dV is the change in live above ground vegetation ($g\ m^{-2}\ week^{-1}$).

$$dV = (G_{max} / 52) * RP * Tf – V*Mort \qquad \text{(Eqn. C16)}$$

G_{max} is maximum annual NPP at a typical LA tidal marsh divided by 52 (weeks/yr), RPf (no units) is a factor for relative productivity with inundation (see Eqn. C20), Tf (no units) is a temperature factor (Eqn. C21), Mort is seasonably variable morality rate calibrated to data on *Spartina spp.* in Terrebonne Bay (Hopkinson et al. 1978).

$$D = D + dD \qquad \text{(Eqn. C17)}$$

dD is the change in dead or senescent above ground vegetation ($g\ m^{-2}\ week^{-1}$)

$$dD = V*Mort – D*(Leaflit + Export) \qquad \text{(Eqn. C18)}$$

V is live above ground biomass from Eqn. C15; Mort is seasonably variable morality rate from Eqn. C16, Leaflit is the rate of leaf litter fall onto the soil surface. Export is the rate of predation, standing decay, and physical removal of vegetation from the marsh, measured as the difference between live production and leaf litter (Hopkinson et al. 1978; Nyman et al. 1995).

$$R = R + dR \qquad \text{(Eqn. C19)}$$

dR is the change in root and rhizome biomass (g m^{-2} $week^{-1}$), R is the total root and rhizome biomass (g/m^2).

$$dR = (G_{max} / 52)*R{:}S *RPf – R * Rootlit \qquad \text{(Eqn. C20)}$$

G_{max} is maximum annual NPP at a typical LA tidal marsh divided by 52 (weeks/yr), RPf is a factor for relative productivity from Eqn. C22, R:S is the root and rhizome productivity to shoot productivity ratio, Rootlit is the rate of root senescence.

$$Tf = T*(1/(T_{opt} – T_{min}))*(T_{min}/ (T_{opt} - T_{min})) \qquad \text{(Eq. C21)}$$

Tf is a unitless multiplier to alter productivity as a function of tempurature, T_{opt} is the optimum temperature for growth, T_{min} is the observed minimum temperature. T_{opt} and T_{min} were calibrated to fit seasonal live and dead biomass data for *Spartina spp.* from Hopkinson et al. 1978.

$$RPf = b_0 – b_1 * \omega + b_2 * \omega^2 \qquad \text{(Eqn. C22)}$$

RPf is a function for relative productivity (no units), ω is the proportion of time the marsh is inundated, b_0, b_1 and b_2 are model parameters (given in Figure C5). I used the organic accretion rate to simulate relative productivity. The RPf function can be substituted with an equivalent measure of productivity such as NDVI(e.g. Couvillion & Beck 2013) or peak standing biomass (Morris et al. 2002).

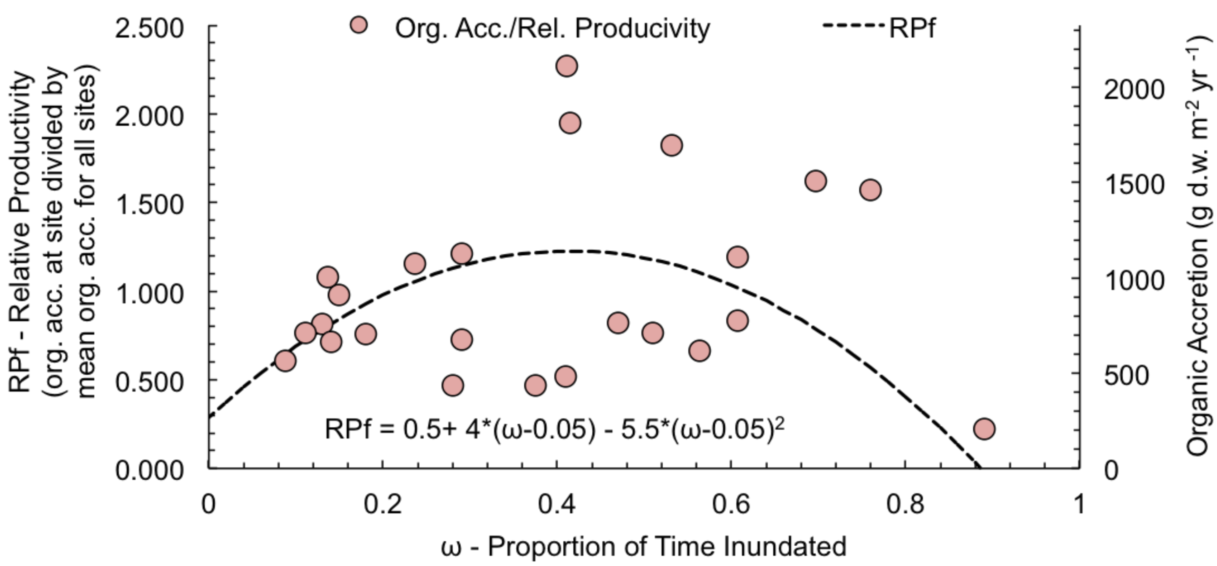

FIGURE C5. Relative productivity (RPf) of marsh as a function of inundation fration (ω).

Organic matter can be categorized into refractory and labile fractions (Rybczyk et al 1998). Following Morris & Calleway (Submitted), I define refractory mater as complex organic molecules (e.g. lignin, tannins, waxes), that not to decay under anaerobic conditions. Labile OM will decay under anaerobic conditions. I assume a constant refractory fraction of organic production of 0.1, therefore the labile fraction is 0.9 (Morris pers. comm.; Morris & Callaway Submitted). I assume that above ground production, does not contribute significantly to refractory matter accumulation in the soil (Morris pers. comm.; Wigand et al 2014). The long-term accretion rate is controlled by accumulation of refractory organic matter from below ground production (Morris & Calleway submitted). I selected a labile organic matter decay rate of 0.4 (yr^{-1}) (Lane et al. 2016). Decay rates of labile organic matter do not affect the long-term dynamics of the marsh. Root biomass and labile organic matter accumulation/decomposition control short-term elevation dynamics when the marsh productivity or community structure is changing rapidly. Examples of this include colonization of a mud flat at a marsh creation project or prodelta (Edwards & Proffit 2003), rapid die off from inundation stress (Day et al. 2011), or change in the nutrient status (Morris et al. 2013). Differential equations for soil organic matter are given below.

$$B = B + dB \qquad \text{(Eqn. C23)}$$

dB is the change in refractory organic matter (g m^{-2} $week^{-1}$), B is total soil refractory organic matter (g/cm^2).

$$dB = S*xo + R*rootlit*(1-lf_R) \qquad \text{(Eqn. C24)}$$

R is root and rhizome biomass (g/cm^2), S is the sedimentation rate and xo is the fraction of refractory organic matter in suspended sediment, rootlit is the litter rate of roots and rhizomes, lf_R is the labile fraction of root and rhizome biomass.

$$Q = Q + dQ \qquad \text{(Eqn. C25)}$$

dQ is the change labile organic matter (g m^{-2} $week^{-1}$), Q is total soil labile organic matter (g/m^2).

$$dQ = D*Leaflit + R*rootlit*lf_R - Q*k_l \qquad \text{(Eqn. C26)}$$

k_l is the decay rate of labile organic matter; D is dead biomass and Leaflit is the leaf litter rate from (Eqn. C18); R is root biomass and rootlit is the root litter rate from (Eqn. C20). I assume that labile organic matter deposited in suspended sediments are fully metabolized at under aerobic conditions at the soil surface, and does not contribute to the stock of labile organic matter below the soil surface.

C.7. Depth Integration

The constituents of marsh soil, minerals (M), refractory organics (B), labile organics (Q), and live roots (R), can be integrated with depth to give better resolution in comparing model outputs with soil cores (e.g. Rybzyck & Cahoon 2002). This is important if compaction of the marsh soil column is being modeled. WECRM does not incorporate compaction of the marsh soil strata or cohorts (see Rybczyk et al. 1998), so the method of depth integration does not affect the outcome of the model. In fact, with the ideal mixing model (Morris et al. 2016) depth integration is not necessary for simulating elevation dynamics. However, integrating the soil profile with depth is useful for calibration/validation and especially when performing hind-casts against soil cores. I used 18 soil cohorts (similar to Rybczyck et al. 1998) to discretize the soil column during calibration and validation to compare results with soil core data from Rybzyck & Cahoon 2002 and CRMS data. High resolution of depth increases calculation time, minimize number cohorts of for spatial applications and sensitivity tests.

C.8. Soil Carbon Budget

Organic matter is given in terms of oven dry weight (d.w.) and can be converted to carbon using a ratio of 0.45 (g C / g d.w.) (Steyer et al. 2012). Soil organic carbon can be estimated by multiplying below ground biomass, Q, B, R, by the carbon to dry weight ratio (Eqn. C24).

$$SOC_t = 0.45*(Q+B+R)*10000 \qquad \text{(Eqn. C27)}$$

SOC_t is the soil organic carbon at a given time step (g/m^2); 0.45 converts grams of organic matter in dry weight to grams of carbon; 10000 converts cm^2 to m^2. Subsequently the annual carbon accumulation/loss from the soil can be estimated (Eqn. C25).

$$dSOC = SOC_t - SOC_{t-1} \qquad \text{(Eqn. C28)}$$

dSOC is the change in soil organic carbon between time intervals t and t – 1.

Carbon accumulation rates from WECRM can be compared with estimates from field studies. With the default parameters (listed in table D2), WECRM accumulates carbon at a rate of 200-350 $g/m^2/yr$ depending on marsh elevation, RSLR, TSS, and xo (see APPENDIX-D). These rates are comparable to those reported in field studies across a range of Mississippi delta coastal marshes (DeLaune & White 2012).

TABLE C2. Hydrologic and soil data and summary statistics for selected coastal marsh sites from the Louisiana Coastwide Reference Monitoring System (CRMS). Basins include AW – Atchafalaya Wax Lake, FL– Fourleague Bay and Marsh Island, TB – Terrebonne Bay, BA – Barataria Bay.

CRMS Site #	Basin	Elev. Rel.WL (cm)	90%WL Tide amp. (cm)	Mean Salinity (g/L)	Inund-ation (%)	% Org. 0-4 cm	Bulk Dens. 0-4cm (g/cm3)	A: Accr. Surface (cm/yr)	L: Long-term dElev. (cm/yr)	Mineral depos. ($g/m^2/yr$)	Organic depos. ($g/m^2/yr$)	Subidence A - L (cm/yr)
305	AWL	22.9	24.4	1	13	26.1	0.24	1.38	0.93	2449	863	0.45
479	AWL	-3.7	23.8	0.2	76	8.7	0.54	3.54	0.61	17447	1669	2.93
489	AWL	23.2	26.5	0.9	15	21	0.31	1.59	1.36	3894	1035	0.23
496	AWL	15.8	26.5	0.5	23.6	28.9	0.4	1.06	0.2	3017	1223	0.86
517	AWL	31.1	28.7	0.8	8.7	13.4	0.34	1.42	0.7	4182	646	0.72
399	FL	11.6	18.9	3.7	29	21.5	0.28	1.28	0.33	2814	770	0.95
322	FL	9.1	18.6	10.8	37.5	28.1	0.29	0.61	0.46	1272	497	0.15
309	FL	11.9	22.9	7.3	28.1	18.2	0.33	0.83	0.23	2240	499	0.6
293	FL	12.8	16.2	7	18	28	0.44	0.65	0.44	2059	801	0.21
523	MI	21.3	24.4	4.2	14	30	0.22	1.15	0.17	1771	759	0.98
529	MI	-7.3	4.9	5	89	46.5	0.09	0.57	0.45	274	239	0.12
520	MI	21	21.3	4.4	11	26	0.26	1.2	0.29	2308	812	0.91
345	TB	-2.4	20.1	17.5	60.7	11.9	0.43	2.47	1.31	9357	1264	1.16
347	TB	5.2	20.7	18.3	41.2	13.2	0.48	3.79	1.74	15787	2405	2.05
355	TB	20.1	22.3	17.7	13.7	19.4	0.26	2.26	1.25	4734	1142	1.01
341	TB	0	22.6	17	56.3	15.4	0.4	1.14	0.45	3857	703	0.69
338	TB	7.6	28.3	16.8	69.6	25.4	0.29	2.33	0.02	5039	1718	2.31
336	TB	4.3	22.3	17	47	18.5	0.43	1.1	0.64	3857	873	0.46
335	TB	2.4	22.6	17.7	51	17.6	0.32	1.44	0.92	3798	810	0.52
171	BA	6.1	22.6	17	41	8	0.49	1.41	0.83	6356	553	0.58
172	BA	-2.4	20.7	16.3	60.8	14	0.4	1.58	0.47	5436	884	1.11
181	BA	13.7	23.5	17	29	14.8	0.46	1.89	1.02	7410	1284	0.87
179	BA	6.4	21.9	13.7	41.5	18.9	0.46	2.37	0.67	8838	2064	1.7
174	BA	0.9	21.3	14.8	53.6	19.5	0.3	7.76	2.24	18740	4540	5.52
272	BA	1.5	21.9	13.3	53.2	20.7	0.34	2.75	1.25	7414	1936	1.5

CRMS Site #	Basin	Elev. Rel.WL (cm)	90%WL Tide amp. (cm)	Mean Salinity (g/L)	Inund-ation (%)	% Org. 0-4 cm	Bulk Dens. 0-4cm (g/cm3)	A: Accr. Surface (cm/yr)	L: Long-term dElev. (cm/yr)	Mineral depos. (g/m^2/yr)	Organic depos. (g/m^2/yr)
Mean	9.324	21.916	10.396	39.26	20.548	0.352	1.9028	0.7592	5774	1199.56	1.1436
Median	7.6	22.3	13.3	41	19.4	0.34	1.42	0.64	3894	873	0.87
25% Percentile	1.5	20.7	4.2	18	14.8	0.29	1.14	0.44	2449	759	0.52
75% Percentile	15.8	23.8	17	53.6	26	0.43	2.33	1.02	7410	1284	1.16

Literature Cited

Adams, W. A. 1973. The effect of organic matter on the bulk and true densities of some uncultivated podzolic soils, *J. Soil Sci.*, *24*, 10–17.

Cahoon, D.R., Lynch, J.C., Perez, B.C., Segura, B., Holland, R.D., Stelly, C., Stephenson, G. and Hensel, P., 2002. High-precision measurements of wetland sediment elevation: II. The rod surface elevation table. *Journal of Sedimentary Research*, *72*(5), pp.734-739.

Couvillion, B.R. and Beck, H., 2013. Marsh collapse thresholds for coastal Louisiana estimated using elevation and vegetation index data. Journal of Coastal Research, 63(sp1), pp.58-67.

Darby, F.A. and Turner, R.E., 2008a. Below-and aboveground biomass of Spartina alterniflora: Response to nutrient addition in a Louisiana salt marsh. Estuaries and Coasts, 31(2), pp.326-334.

Darby, F.A. and Turner, R.E., 2008b. Below-and aboveground Spartina alterniflora production in a Louisiana salt marsh. Estuaries and Coasts, 31(1), pp.223-231.

Day, J.W., Kemp, G.P., Reed, D.J., Cahoon, D.R., Boumans, R.M., Suhayda, J.M. and Gambrell, R., 2011. Vegetation death and rapid loss of surface elevation in two contrasting Mississippi delta salt marshes: The role of sedimentation, autocompaction and sea-level rise. *Ecological Engineering*, *37*(2), pp.229-240.

Day, J.W., Cable, J.E., Lane, R.R. and Kemp, G.P., 2016. Sediment deposition at the Caernarvon crevasse during the great Mississippi flood of 1927: implications for coastal restoration. *Water*, *8*(2), p.38.

DeLaune, R.D., Smith, C.J. and Patrick, W., 1983. Relationship of marsh elevation, redox potential, and sulfide to Spartina alterniflora productivity. *Soil Science Society of America Journal*, 47(5), pp.930-935.

DeLaune, R.D. and White, J.R., 2012. Will coastal wetlands continue to sequester carbon in response to an increase in global sea level?: a case study of the rapidly subsiding Mississippi river deltaic plain. *Climatic Change*, *110*(1), pp.297-314.

DeLaune, R.D., Sasser, C.E., Evers-Hebert, E., White, J.R. and Roberts, H.H., 2016. Influence of the Wax Lake Delta sediment diversion on aboveground plant productivity and carbon storage in deltaic island and mainland coastal marshes. *Estuarine, Coastal and Shelf Science*, *177*, pp.83-89.

Edwards, K.R. and Proffitt, C.E., 2003. Comparison of wetland structural characteristics between created and natural salt marshes in southwest Louisiana, USA. *Wetlands*, *23*(2), pp.344-356.

Furgo Consultands, Inc. 2011. Appendix G: Design Geotechnical Data. Draft Geotechnical Study Mississippi River Long Distance Sediment Pipeline (BA-43 EB) Mississippi to Barataria Waterway LDNR RSIQ No. 2503-08-22. Jefferson Parish, Louisiana. Report No. 04.55084005 - DRAFT November 29, 2011.

Hopkinson, C.S., Gosselink, J.G. and Parrando, R.T., 1978. Aboveground production of seven marsh plant species in coastal Louisiana. *Ecology*, *59*(4), pp.760-769.

Mattson G. A. 2014. Characterization of Dredged Sediment Used in Coastal Restoration and Marsh Creation Projects. Master's Thesis. University of New Orleans.

Meckel, T.A., ten Brink, U.S. and Williams, S.J., 2006. Current subsidence rates due to compaction of Holocene sediments in southern Louisiana. *Geophysical Research Letters*, *33*(11).

Mendelssohn, I.A. and Kuhn, N.L., 2003. Sediment subsidy: effects on soil–plant responses in a rapidly submerging coastal salt marsh. *Ecological Engineering, 21*(2), pp.115-128.

Morris, J.T., Sundareshwar, P.V., Nietch, C.T., Kjerfve, B. and Cahoon, D.R., 2002. Responses of coastal wetlands to rising sea level. *Ecology*, 83(10), pp.2869-2877.

Morris, J.T., Barber, D.C., Callaway, J.C., Chambers, R., Hagen, S.C., Hopkinson, C.S., Johnson, B.J., Megonigal, P., Neubauer, S.C., Troxler, T. and Wigand, C., 2016. Contributions of organic and inorganic matter to sediment volume and accretion in tidal wetlands at steady state. Earth's future, 4(4), pp.110-121.

Morris J.T., and Callaway J.C. (Submitted). Physical and biological regulation of carbon sequestration in salt marshes.

Morris, J.T. 2017. Personal Communication. Email correspondence between 2015 and 2017 and in person meeting on March 30, 2017.

Nyman, J.A., DeLaune, R.D., Pezeshki, S.R. and Patrick, W.H., 1995. Organic matter fluxes and marsh stability in a rapidly submerging estuarine marsh. *Estuaries*, *18*(1), pp.207-218.

Nyman, J.A., DeLaune, R.D., Roberts, H.H., and Patrick Jr. W.H. 1993. Relationship between vegetation and soil formation in a rapidly submerging coastal marsh. Marine Ecology Progress Series 96:269-279.

Perez, B.C., Day, J.W., Rouse, L.J., Shaw, R.F. and Wang, M., 2000. Influence of Atchafalaya River discharge and winter frontal passage on suspended sediment concentration and flux in Fourleague Bay, Louisiana. *Estuarine, Coastal and Shelf Science*, *50*(2), pp.271-290.

Rybczyk, J.M. and Cahoon, D.R., 2002. Estimating the potential for submergence for two wetlands in the Mississippi River Delta. *Estuaries*, *25*(5), pp.985-998.

Simoneaux, R., Beall, A., & Roy, K 2008. Lake Hermitage Marsh Creation Project (BA-42) Final (95%) Design Report, October 2008. Plaquemines Parish, LA.

Snedden, G.A., Cretini, K. and Patton, B., 2015. Inundation and salinity impacts to above-and belowground productivity in Spartina patens and Spartina alterniflora in the Mississippi River Deltaic Plain: implications for using river diversions as restoration tools. Ecological Engineering, 81, pp.133-139.

Steyer, G., Couvillion, B., Wang, H., Sleavin, B., Rybczyk, J., Trahan, N., Beck, H., Fischenich, C., Boustany, R., and Allen, Y. 2012. APPENDIX D: 2 WETLAND MORPHOLOGY MODEL TECHNICAL REPORT. Coastal Protection and Restoration Authority. Baton Rouge, LA.

Thompson, W.C. 2007. Final Design Report. Mississippi River Sediment Delivery System – Bayou Dupont (BA-39). Coastal Engineering Division Engineering and Design Section, Louisiana Department of Natural Resources. Plaquemines/Jefferson Parishes, Louisiana.

APPENDIX-D: PARAMETER VALUES AND SENSITIVITY TESTS

D.1. Model Comparison

Figure D1 and D2 Show a comparison of WECRM and MEM v6.0 runs using equivalent parameter values. The results shown in Figure D2 use a refractory organic fraction in TSS (xo) of 0.03, while Figure D1 used an xo of 0. MEM parameters are given in Table D1, WECRM Parameters are given in Table D2. The RSLR is set to 1 cm/yr and TSS levels of 20 and 40 mg/L are shown. WECRM outputs correlate very well with MEM v6.0 when equivalent model parameters are used, with WECRM marshes being slightly longer lived in most cases. WECRM shows net carbon loss during marsh collapse while MEM does not (see Lane et al. 2016). Deviations in predicted marsh trajectories between the models are related to the following differences: WECRM's inclusion of a vegetation trapping feedback (ks) for TSS deposition that is not included in MEM v6.0 (see FIGURE C3), WECRM's calibration to $99^{\%}$WL compared to MEM's calibration to $90^{\%}$WL, and the 18.6 year lunar tidal amplitude cycles used in the MEM that are not included in WECRM (note the wobbles in MEM runs compared to smooth lines in WECRM in Figure D1). These differences highlight the importance of both meteorological forcing's (cold fronts, floods and hurricanes) in the northern Gulf of Mexico and multidecadal patterns on the outcome of model results. The lunar declination cycle is one of the only examples of this kind of phenomenon that is not stochastic.

D.2. Wetland Model Sensitivity

The remaining figures and tables in this section pertain to sensitivity tests on wetland parameters. All sensitivity tests on marsh parameters were conducted with a subsidence rate of 0.87 (cm/yr) and eustatic sea level rise rate of 0.20 (cm/yr). Initial elevation relative to mean water level (Relev) was set to 10cm. Sensitivity tests report the 10-year average rates of change in a response variable (e.g. long term elevation change, and soil organic carbon accumulation) from model year 20 to model year 30. Figure D2 shows the change in response variables against selected parameters. Tables D3, D4 and D5 show sensitivity test results on WECRM wetland system parameters.

Across all sensitivity tests, the average percent change in long-term elevation change (dElev/dt, cm/yr) was +17% and -28%; the average percent change for soil organic carbon accumulation (dSOC/dt, g C m^{-2} yr^{-1}) was +13% and -24%. Gmax (primary productivity) was by

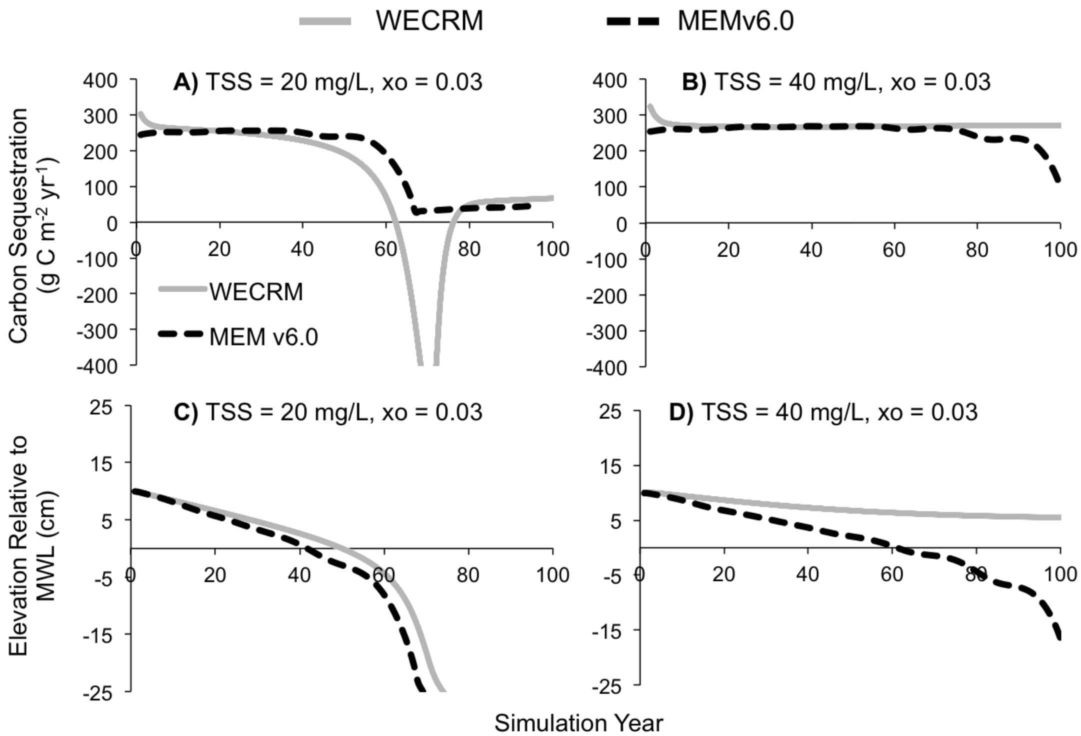

FIGURE D1. Calibration runs showing MEM v6.0 and WECRM results with relative sea level rise of 1 cm/yr at varying total suspended sediment (TSS) concentrations, xo is the fraction of TSS that is comprised of refractory organic material, set here to 0.03.

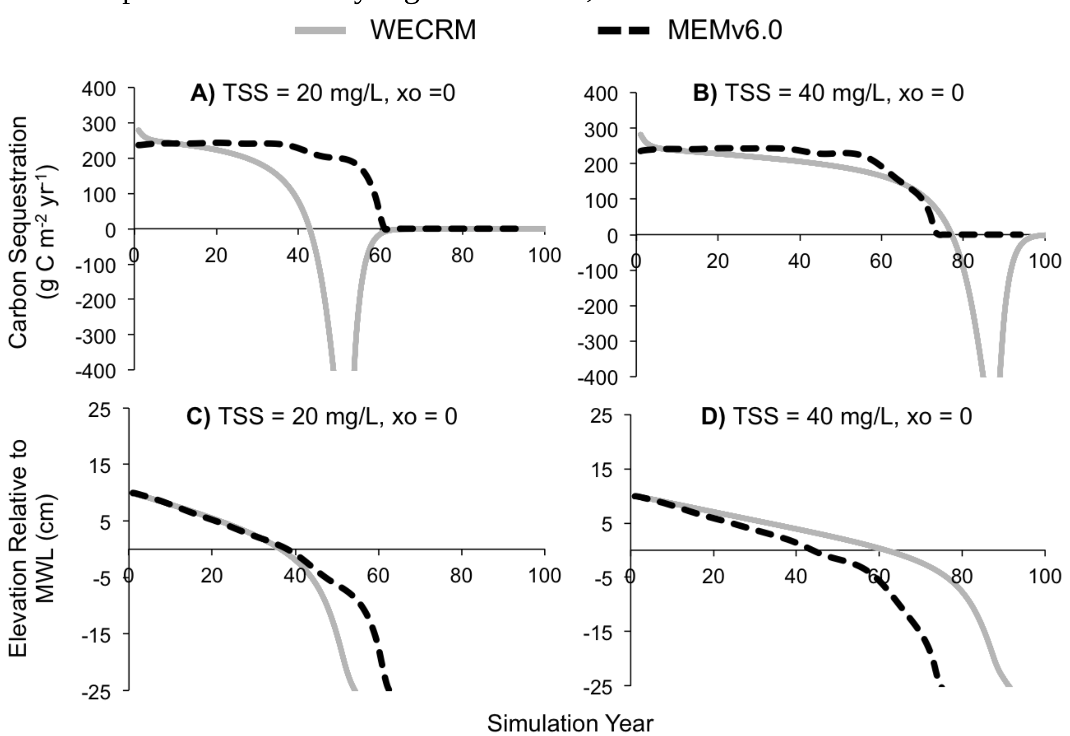

FIGURE D2. Calibration runs showing MEM v6.0 and WECRM results with relative sea level rise of 1 cm/yr at varying total suspended sediment (TSS) concentrations, xo is the fraction of TSS that is comprised of refractory organic material, set here to 0.

far the most influential variable on dElev/dt (changes in dElev/dt translate directly to changes in marsh lifespan). The next most important variables were TSS, Tamp, lf_r and SubR, which all had similar magnitudes of impact on accretion (Table D3). The least influencial variables on dElev/dt were xo, qs, ks. Given the strength of Gmax on influencing model outcomes, factors that influence productivity (salinity, inundation, mineral input, nutrient availability, plant species, etc…) are very important. The future dynamics of Gmax when influenced by river diversions and climate change are the principle uncertainties of this analysis. Other important variables that may be impacted by river diversions and climate are the labile fraction of below ground biomass, the decomposition rate of organic matter, and the refractory organic matter in suspended sediments (See Rybzyck et al. 2002; Lane et al. 2016 cited in APPENDIX-C). Future changes in geomorphic setting and hydrology will influence the tidal range, salinity and TSS concentrations. These factors should be investigated in future studies.

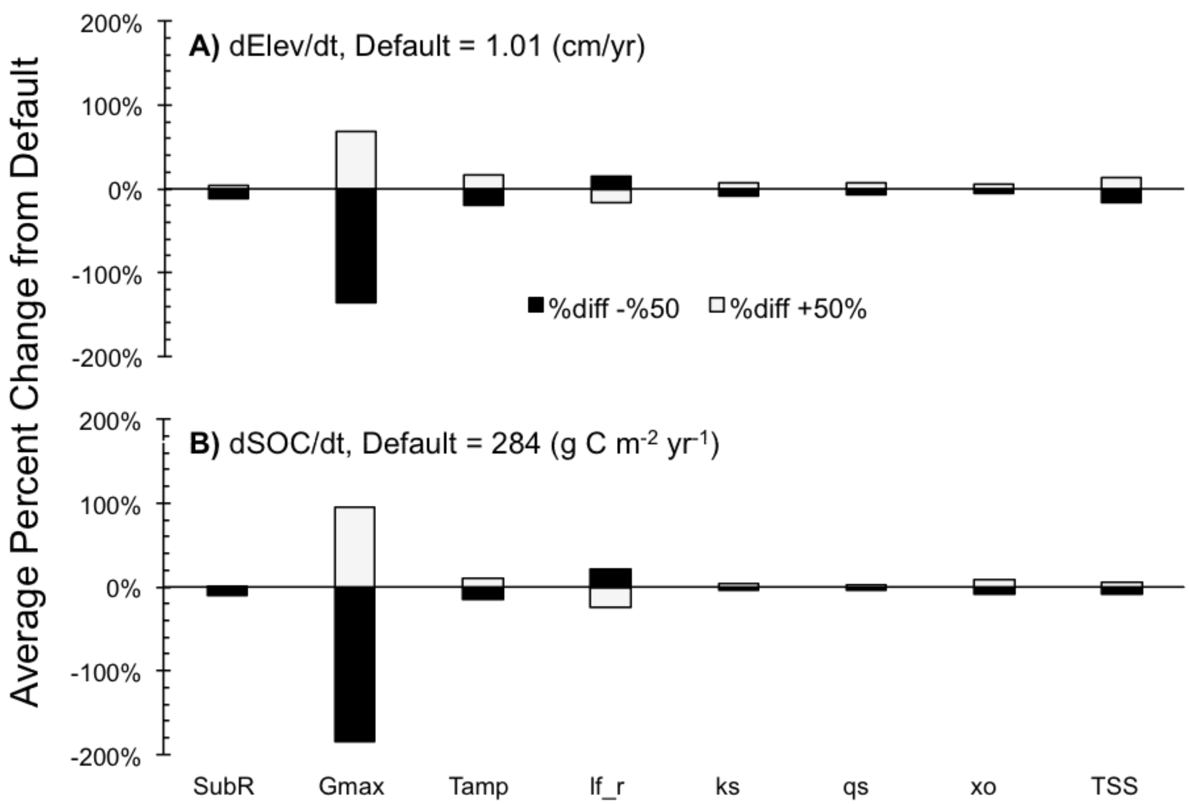

FIGURE D3. Percent change in response variables, (A) long term elevation change (dElev/dt), (B) Soil organic carbon accumulation (dSOC/dt), with a +/- 50% change in a parameter value. 50% increases in parameter values are shown in white, 50% decreases in parameters values are shown in black. The percentages are reported for the mean of model runs with initial TSS of 40, 80, 120, 160 mg/L. Mean is the mean of the default parameter values for the four TSS levels.

TABLE D1. Parameters for Mississippi Delta tidal backish/saline marsh used in WECRM. Date of run (yyymmdd):20170512

Name	Value	Units	Description	Notes & Sources
Initrelev	10 or -50	(cm)	initial relative elevation of marsh in simulation year 1, set to 10 for calibration, and to -50 for MC simulations	WECRM uses 10 yrs of "spin up" time where Relev is set equal to initrelev to allow root volume to stabilize
Tamp	23.4	(cm)	amplitude of tide: 90%WL (high tide) - MWL (median Water Level)	CRMS data, see Table C1
f	312/52	(wk-1)	number of indundations/floodings per time step: louisina has a diurnal tide but is also inlfuenced by seasonal WL fluctuation	Water Level Analysis of CRMS data
Dmax	25	(cm)	amplitude of extreme flooding events: 99%WL (wind tide from storms & fronts) - 90%WL (high tide)	Water Level Analysis of CRMS data
TSS	20-160	(mg/l)	Suspended mineral and refractory organic sediment: average conc. range from 20-40 in Terrebone Bay; 60-90 in Fourleague Bay; 100-200 in Mississippi & Atchafalaya	Perez et al. 2000; Wang 1997; Murray et al. 1993; Day et al 2011; Allison et al. 2012
SubR	0.87	(cm/yr)	Regional subsidence: median subsidence estimate from CRMS sites is 0.87; 25th% is 0.52 and 75% is 1.16	CRMS Table C2; also See CPRA 2012 Appendix E; Shinkle & Dokka 2004
k1	0.085	(g/cm3)	self packing density of organic matter assuming particle density of 1.14	Morris et al. 2016
k2	1.99	(g/cm3)	self packing density of mineral sediment assuming particle density of 2.65	Morris et al. 2016
xo	0.03	(g/g)	fraction of suspended sediments made up of refractory particulate organic matter, assume no labile OM in TSS	see figure 7 in Day et al. 2016
sl	0.3	(cm/cm)	settlement ratio of initial fill height to total settling after 20 years from MC geotechnical survey settlement curves.	Calibrated to match MC settlement curves
pk	2	(yr)	half settling period after hyrdaulic dredging: time at 50% of total settlement	Calibrated to match MC settlement curves
lf_a	0.99	(g/g)	labile fraction of above ground litter	Morris Pers. Com.
lf_r	0.9	(g/g)	labile fraction of root litter	Morris & Calleway in Prep

Name	Value	Units	Description	Notes & Sources
k_ld	4.9E-02	(wk-1)	decay rate of labile organic matter	Morris Pers. Com.
Gmax	2000/52	(g/m2/wk)	annual above ground net primary productivity at RPf of 1 (using Wigert Evans method)	Hopkinson et al. 1978; Nyman et al. 1993, see eqn. C22
export	7.10E-03	(wk-1)	rate of dead and senescent above ground biomass export from marsh system	Nyman et al. 1995 estimate 50%
T_opt	25.8	(deg C)	tempurature at max growth rate (see Tfunc); calibrated *to Sp. alterniflora*	Hopkinson et al. 1978
T_min	11	(deg C)	tempurature at min growth rate (see Tfunc); calibrated to *Sp. alterniflora*	Hopkinson et al. 1978
qs	1/52	(cm/wk)	settling velocity coefficient for suspended sediments under laminar flow condition, calibrated to accretion rates of LA tidal marshes	Morris et al. 2002; CRMS Data, see Table C1 and Figures C2 and C3
ks	7.8/52	(g/g/wk)	efficiency of above ground vegetation (live and dead) biomass as sediment trap, calibrated to accretion rates of LA tidal marshes	Morris et al. 2002; CRMS Data, see Table C1 and Figures C2 and C3
E_{fill}	0-200	(cm)	fill elevation target (cm above WL) of marsh creation and nourishment project.	user specified, see CPRA 2012c
E_{crt}	-10	(cm)	marsh critical elevation, the elevation at which marsh collapse is iminend and renourishment with dredging is triggered	user specified, see Couvillion & Beck 2013; Snedden et al. 2015;
bf	1.5	(-)	loss adjustment factor to account for spillage or pipeline leaks equal to the typical ratio of the borrow volume to the fill volume for an MC project	Variable depending on borrow and fill site characteristics; see Thompson 2007
mf	1.5	(-)	mark up factor for total construction costs as a function of hydraulic dredging costs	CPRA 2012b
DR	0	(-)	binary variable indicating whether a project is dune restoration (DR=1), if DR = 0, the project is either marsh creation/nourishment or beneficial navigation dredging	See APPENDIX B
Ek	4.9	(CY/hp)	efficiency factor of hydraulic dredging = ln(CY/hp),borrow volume divided by horsepower dedidated to dredging set to the mean value for of projects reviewed in this study	See APPENDIX B

TABLE D2. Summary WECRM of wetland system parameter tests. The values in this table summarize the a response variable (accretion, and soil carbon accumulation) for change to a change in a parameter value. Each parameter was run for the default settings, +50% and -50% for TSS concentrationsof 20, 40, 60 and 80 for a total of twelve model runs per parameter. Raw data and parameter values are provided in provided in TABLE D5.

Response variable: Accretion - dElev/dt (cm/year)					
Parameter	Mean[1]	STDEV.S[2]	Mean Diff[3]	Vector[4]	Magnitude[5]
SubR	0.99	0.18	0.16	0.89	0.18
Gmax	0.79	0.94	2.08	2.21	1.19
Tamp	1.01	0.21	0.37	1.74	0.21
lf_r	1.01	0.19	-0.33	-1.70	0.19
ks	1.02	0.14	0.16	1.11	0.14
qs	1.02	0.14	0.14	0.98	0.14
xo	1.02	0.14	0.12	0.87	0.13
TSS	1.01	0.18	0.30	1.67	0.18
Response variable: Soil Carbon Accumulation - dSOC/dt (g C m^2/year)					
Parameter	Mean	STDEV.S	Mean Diff	Vector	Magnitude
SubR	274.64	37.90	31.76	0.84	0.14
Gmax	200.49	350.54	793.64	2.26	1.75
Tamp	279.87	38.60	72.35	1.87	0.14
lf_r	282.34	59.10	-128.16	-2.17	0.21
ks	283.64	21.02	20.94	1.00	0.07
qs	283.84	20.53	17.95	0.87	0.07
xo	283.60	28.78	50.12	1.74	0.10
TSS	281.85	25.40	39.91	1.57	0.09

1 Mean is the mean of all twelve sensitivty tests (default, +50%, -50%)*(TSS 40,80,120,160); **2** STDEV.S is Sample standard deviation of sensitivity tests; **3** Mean Diff is the average difference between +50% and -50% for all four TSS levels; **4** Vector = Mean Diff / STDEV.S gives a standardized estimate of the degree and direction (+/-) that a positive change in the parameter will yield on the response variable; **5** Strength = STDEV.S/Mean a standardized estimate of the magnitude of the effect of a parameters change will yield on the response variable.

TABLE D3. Summary of WECRM wetland system parameter sensitivity tests. Change in responce variable with a +/- 50% change in a parameter. Values represent averages for model concentrations of 20, 40, 60 and 80 for a total of twelve model runs per parameter. Raw data and parameter values are provided in provided in TABLE D5.

Response variable: Accretion - dElev/dt (cm/year)						
Parameter	Default	+50%	-50%	+50% - Default	-50% - Default	% Diff[1]
SubR	1.01975	1.06	0.90	0.04	-0.12	-178%
Gmax	""	1.71	-0.36	0.69	-1.38	-99.7%
Tamp	""	1.19	0.82	0.17	-0.20	-21.9%
lf_r	""	0.85	1.18	-0.17	0.16	-9.4%
ks	""	1.09	0.94	0.08	-0.08	-13.0%
qs	""	1.09	0.95	0.07	-0.07	-11.1%
xo	""	1.08	0.96	0.06	-0.06	-10.1%
TSS	""	1.15	0.85	0.13	-0.17	-26.1%
Response variable: Soil Carbon Accumulation - dSOC/dt (g C m2/year)						
Parameter	Default	+50%	-50%	+50% - Default	-50% - Default	% Diff[1]
SubR	284.3575	285.7	253.9	1.3	-30.4	-2229%
			-			
Gmax	""	555.4	238.3	271.0	-522.6	-92.8%
Tamp	""	313.8	241.5	29.4	-42.9	-45.7%
lf_r	""	217.2	345.4	-67.1	61.0	-9.0%
ks	""	293.8	272.8	9.4	-11.5	-22.9%
qs	""	292.6	274.6	8.2	-9.7	-18.8%
xo	""	308.3	258.2	23.9	-26.2	-9.4%
TSS	""	300.5	260.6	16.2	-23.7	-46.5%

1 % Diff = (ABS(+50% - Default) - ABS(-50% - Default))/(+50% - Default); this metric indicates the level of nonlinearity and the direction of acceleration for a given a parameters change. A value close to zero means that the parameters effect is close to linear. A value much greater than zero indicates that the parameters effect is highly nonlinear and accelerates when a positive change in the parameter is made. A value much less than zero indicates that the parameters effect is highly nonlinear and accelerates when a negative change in the parameter is made.

TABLE D4. Summary of WECRM wetland system parameter sensitivity tests

(A) SubR - Subsidence Rate (cm/yr)							
SubR		TSS (mg/L)	dRel/dt (cm/yr)	dEl/dt (cm/yr)	%change	dSOC/dt (gC/yr)	%change
default	0.87	20	-0.370	0.830	0.00	254.04	0.00
-50%	0.435	20	0.035	0.800	-3.58	249.96	-1.61
50%	1.305	20	-0.942	0.693	-16.54	196.91	-22.49
default	0.87	40	-0.199	1.001	0.00	285.99	0.00
-50%	0.435	40	0.124	0.890	-11.15	256.61	-10.27
50%	1.305	40	-0.597	1.039	3.73	286.70	0.25
default	0.87	60	-0.106	1.094	0.00	296.98	0.00
-50%	0.435	60	0.177	0.942	-13.90	256.00	-13.80
50%	1.305	60	-0.427	1.208	10.36	321.67	8.31
default	0.87	80	-0.046	1.154	0.00	300.42	0.00
-50%	0.435	80	0.212	0.977	-15.27	253.07	-15.76
50%	1.305	80	-0.327	1.308	13.39	337.38	12.30
(B) Gmax - Maximum Net Primary Productivity (g m-2 yr-1)							
Gmax		TSS (mg/L)	dRel/dt (cm/yr)	dEl/dt (cm/yr)	%change	dSOC/dt (gC/yr)	%change
default	38	20	-0.370	0.830	0.00	254.04	0.00
-50%	19	20	-2.164	-0.964	-216.18	-398.01	-256.67
50%	57	20	0.509	1.709	105.91	582.01	129.10
default	38	40	-0.199	1.001	0.00	285.99	0.00
-50%	19	40	-1.688	-0.488	-148.71	-270.35	-194.53
50%	57	40	0.513	1.713	71.12	562.22	96.59
default	38	60	-0.106	1.094	0.00	296.98	0.00
-50%	19	60	-1.327	-0.127	-111.63	-174.31	-158.69
50%	57	60	0.515	1.714	56.69	545.65	83.73
default	38	80	-0.046	1.154	0.00	300.42	0.00
-50%	19	80	-1.078	0.122	-89.43	-110.37	-136.74
50%	57	80	0.515	1.715	48.63	531.63	76.96

(C) Tamp - Tidal Amplitude (1/2 tidal range) (cm)							
Tamp		TSS (mg/L)	dRel/dt (cm/yr)	dEl/dt (cm/yr)	%change	dSOC/dt (gC/yr)	%change
default	23.4	20	-0.370	0.830	0.00	254.04	0.00
-50%	11.7	20	-0.448	0.752	-9.44	239.60	-5.69
50%	35.1	20	-0.308	0.892	7.53	263.12	3.57
default	23.4	40	-0.199	1.001	0.00	285.99	0.00
-50%	11.7	40	-0.366	0.834	-16.74	251.39	-12.10
50%	35.1	40	-0.064	1.136	13.46	308.85	7.99
default	23.4	60	-0.106	1.094	0.00	296.98	0.00
-50%	11.7	60	-0.354	0.846	-22.66	243.19	-18.11
50%	35.1	60	0.098	1.297	18.57	333.93	12.44
default	23.4	80	-0.046	1.154	0.00	300.42	0.00
-50%	11.7	80	-0.359	0.841	-27.08	231.62	-22.90
50%	35.1	80	0.215	1.415	22.68	349.31	16.27

(D) lf_r - labile fraction of below ground biomass							
lf_r		TSS (mg/L)	dRel/dt (cm/yr)	dEl/dt (cm/yr)	%change	dSOC/dt (gC/yr)	%change
default	0.9	20	-0.370	0.830	0.00	254.04	0.00
-50%	0.855	20	-0.164	1.036	24.81	330.50	30.10
50%	0.945	20	-0.607	0.593	-28.51	166.34	-34.53
default	0.9	40	-0.199	1.001	0.00	285.99	0.00
-50%	0.855	40	-0.038	1.162	16.09	348.07	21.71
50%	0.945	40	-0.376	0.824	-17.68	217.79	-23.85
default	0.9	60	-0.106	1.094	0.00	296.98	0.00
-50%	0.855	60	0.032	1.232	12.61	351.94	18.51
50%	0.945	60	-0.254	0.946	-13.51	238.02	-19.85
default	0.9	80	-0.046	1.154	0.00	300.42	0.00
-50%	0.855	80	0.077	1.277	10.72	351.10	16.87
50%	0.945	80	-0.177	1.023	-11.30	246.84	-17.84

(E) ks - retention of sediment from biomass							
ks		TSS (mg/L)	dRel/dt (cm/yr)	dEl/dt (cm/yr)	%change	dSOC/dt (gC/yr)	%change
default	0.15	20	-0.370	0.830	0.00	254.04	0.00
-50%	0.075	20	-0.435	0.765	-7.87	241.36	-4.99
50%	0.225	20	-0.310	0.890	7.21	265.21	4.40
default	0.15	40	-0.199	1.001	0.00	285.99	0.00
-50%	0.075	40	-0.283	0.917	-8.39	273.32	-4.43
50%	0.225	40	-0.124	1.076	7.43	296.37	3.63
default	0.15	60	-0.106	1.094	0.00	296.98	0.00
-50%	0.075	60	-0.198	1.002	-8.47	285.81	-3.76
50%	0.225	60	-0.025	1.175	7.37	305.71	2.94
default	0.15	80	-0.046	1.154	0.00	300.42	0.00
-50%	0.075	80	-0.144	1.056	-8.47	290.76	-3.22
50%	0.225	80	0.038	1.238	7.30	307.73	2.43

(F) qs - fraction of sediment volume at maximum depth captured per indundation							
qs		TSS (mg/L)	dRel/dt (cm/yr)	dEl/dt (cm/yr)	%change	dSOC/dt (gC/yr)	%change
default	0.019	20	-0.370	0.830	0.00	254.04	0.00
-50%	0.01	20	-0.425	0.775	-6.66	243.33	-4.22
50%	0.029	20	-0.319	0.881	6.17	263.63	3.77
default	0.019	40	-0.199	1.001	0.00	285.99	0.00
-50%	0.01	40	-0.270	0.930	-7.08	275.37	-3.71
50%	0.029	40	-0.135	1.065	6.40	294.97	3.14
default	0.019	60	-0.106	1.094	0.00	296.98	0.00
-50%	0.01	60	-0.185	1.015	-7.21	287.56	-3.17
50%	0.029	60	-0.035	1.165	6.45	304.66	2.59
default	0.019	80	-0.046	1.154	0.00	300.42	0.00
-50%	0.01	80	-0.131	1.069	-7.32	292.19	-2.74
50%	0.029	80	0.029	1.229	6.52	306.97	2.18

(G) xo - fraction of refractory organic matter in suspended bay bottom sediment (g/g)							
xo		TSS (mg/L)	dRel/dt (cm/yr)	dEl/dt (cm/yr)	%change	dSOC/dt (gC/yr)	%change
default	0.03	20	-0.370	0.830	0.00	254.04	0.00
-50%	0.015	20	-0.418	0.782	-5.79	235.48	-7.31
50%	0.045	20	-0.325	0.875	5.42	271.46	6.86
default	0.03	40	-0.199	1.001	0.00	285.99	0.00
-50%	0.015	40	-0.260	0.940	-6.14	260.93	-8.76
50%	0.045	40	-0.143	1.057	5.62	308.98	8.04
default	0.03	60	-0.106	1.094	0.00	296.98	0.00
-50%	0.015	60	-0.174	1.026	-6.21	267.93	-9.78
50%	0.045	60	-0.044	1.156	5.62	323.35	8.88
default	0.03	80	-0.046	1.154	0.00	300.42	0.00
-50%	0.015	80	-0.119	1.081	-6.25	268.34	-10.68
50%	0.045	80	0.019	1.218	5.62	329.35	9.63
(H) TSS - Suspended Sediment Concentration (mg/L)							
TSS		TSS (mg/L)	dRel/dt (cm/yr)	dEl/dt (cm/yr)	%change	dSOC/dt (gC/yr)	%change
default	20	20	-0.370	0.830	0.00	254.04	0.00
-50%	10	20	-0.496	0.704	-15.18	229.11	-9.81
50%	30	20	-0.263	0.937	12.89	273.67	7.73
default	40	40	-0.199	1.001	0.00	285.99	0.00
-50%	20	40	-0.364	0.836	-16.46	260.21	-9.01
50%	60	40	-0.067	1.133	13.16	303.82	6.24
default	60	60	-0.106	1.094	0.00	296.98	0.00
-50%	30	60	-0.290	0.910	-16.84	273.58	-7.88
50%	90	60	0.038	1.238	13.10	311.86	5.01
default	80	80	-0.046	1.154	0.00	300.42	0.00
-50%	40	80	-0.243	0.957	-17.07	279.66	-6.91
50%	120	80	0.104	1.304	13.06	312.83	4.13

APPENDIX-F. WECRM OUTPUTS FOR COSTS TO SUSTAIN MARSH

This appendix shows results of changing fill elevation (E_{fill}), on marsh creation costs. E_{fill} was increased from 10 to 100 cm (the maximum fill height allowed by CPRA) at 10 cm increments. The lowest cost outcomes of this analysis are reported in Figure F1, the respective E_{fill} of the lowest cost outcome are given in Figure F2. By altering E_{fill} the cost increases due to energy and sea level rise can be reduced, significantly (compare Figures F1 and F2 with Figure 7 and Figure 8). Higher TSS levels favor lower E_{fill} (Figure F2). Less optimistic scenarios and longer time horizons favor higher E_{fill} (Figure F1).

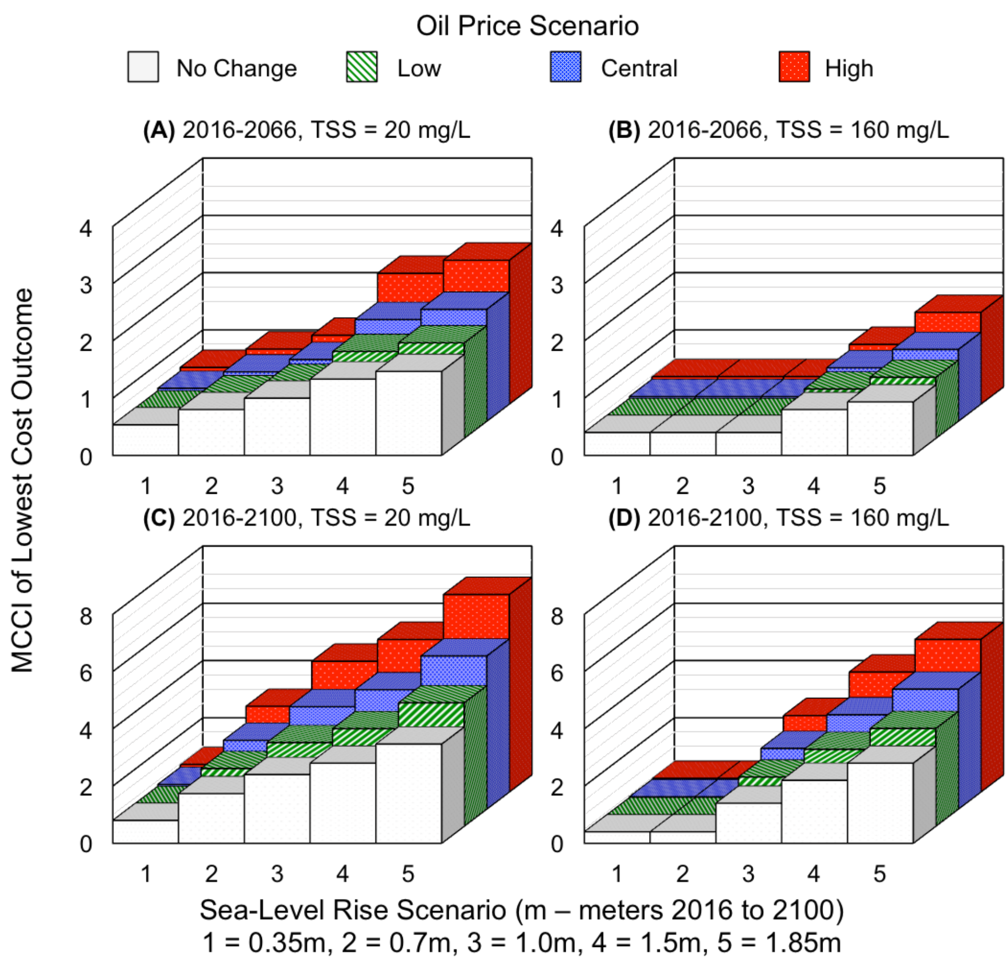

FIGURE F1. Marsh creation cost index (MCCI) for the lowest cost outcome for marsh hydraulic dredging at different fill elevation during a given time interval. Fill elevations given in Figure F2 correspond to the MCCI values shown here. MCCI is the increase in cost above a no change scenario in sea level rise and energy costs, which is equal to \$121,600 ha^{-1}.

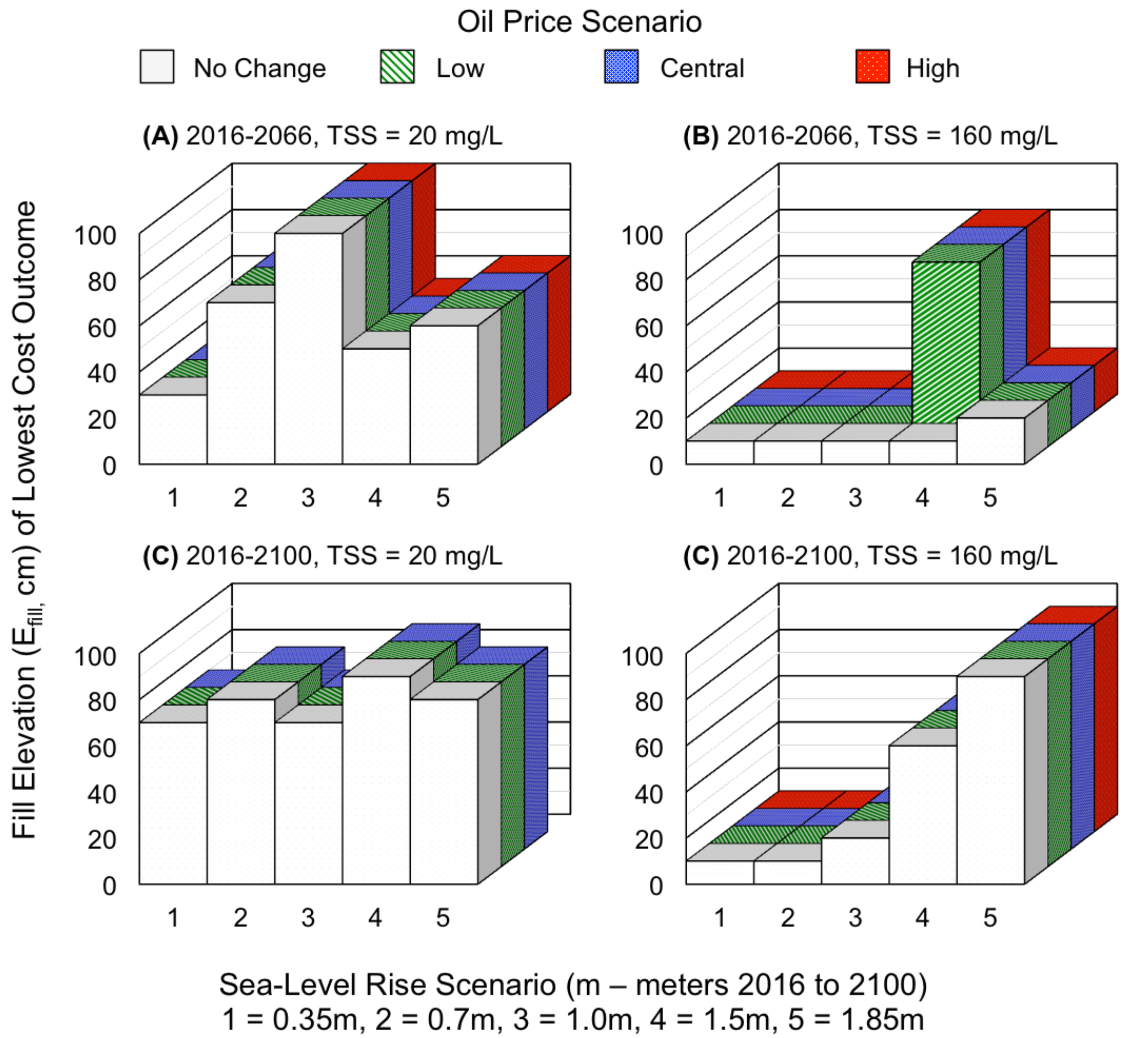

FIGURE F2. Fill elevation (cm) that resulted in the lowest cost outcome for hydraulic dredging to sustain coastal marsh. Fill elevations shown in this figure correspond to the marsh creation costs shown in Figure F1.

APPENDIX-H. WECRM FORTRAN CODE

```
!----------------------------------------TITLE PAGE--------------------------------
!Title: WETLAND ENERGY AND CLIMATE RESTORATION MODEL – MISS. DELTA
!PROGRAM AUTHOR: ADRIAN R.H. WIEGMAN, awiegman@gmail.com
!a copy of the fortran 95 project folder can be obtained upon email to the author
!Development Team: Adrian Wiegman, John Day (PI), Jeff Rutherford, Robet R. Lane (co-PI)
!Consulting Contributors: Jim Morris, Eric Roy, John Rybzcyck, Gary Shaffer, G. Paul Kemp
!co-PI'S on GRPf funding:  Christopher D'Elia, David Dismukes, Brian Snyder,
!Ecosystem: Mississippi Delta Tidal Brackish/Saline Marsh
!Objective: Model Wetland Ecosystem Productivity and Elevation in Responce to Sea Level
!         Rise and Subsidence under various restoration scenarios at sites along
!         a longitudinal transect away from a natural levee.
!Components: The model adapts the MEM (Morris et al. 2002; Morris & Calleway 2017) and
                 !sediment cohort models
!          developed by Rybzyck et al. 1998 and Day et al. 1999, Pont et al. 2000
!          Rybzcyk and Cahoon 2002 and adds subroutines for mineral input to
!          wetlands via restoration.
!          In order to capture the effects of restoration obseverd in the literature
!          We modify the functions from the studies above
!          -sediment deposition
!          -primary productivity
!          -soil compaction
!          In addition we add subroutines for restoration costs and ecosystem services
!
!Louisiana State University and the Department of Oceanography & Coastal Science
!Funding Sources:
!Gulf Research Program of the National Academy of Sciences [Award # 2000005991]
!Coastal Sustainability Studio [award # 1512], and the Department of
!Oceanography and Coastal Sciences, both at Louisiana State University (LSU).

!LAST UPDATE: 5-12-2017
!Update/Debug Status
!Running: Yes
!Errors:
!                    None
!Concerns:
!                    None

!-------------------------BUILD LOG---------------------------
!                20170310: 1. Added an extra 100 years to model spin up time model starts in
                 1816
!           2. Checked primary productivity subroutine and carbon accumulation rates
!           3. Elected not to use function that alters productivity as a function of TSS
!                20170311: Added subroutine for sensitivity tests see $ 14
!                    1. Checked the following subroutines:
```

```
!           OBJ 1. Functioning! Saved
!   20170312: 1. Checked the following subroutines:
!           edited TSS values in sedadvec subroutine
!           OBJ 6. Functioning! Saved
!   20170414: FINAL MODEL CALIBRATION
!           Doublechecked MASS BALANCE of Soil cohorts
!           changed state equations in SOILCOHORT
!           doubled checked modified relhydrop and sedadvec
!           ran simulations with same parameters as MEMv5.41
!                 SOILCOHORT: sediment transfer rate
!                 primprod_md: all state equations rates and functions
!                 initialize: biological, and sediment deposition parameters: GOOD
!                 relhydrop: ptind
!                 sedadvec: Sfunc
!   20170417: Added Compaction Subroutine
!   20170420: Debugged Comaction Subroutine/ Recalibrated
!          FINAL CHECK THROUGH
           !Double checked that each OBJ is running smoothly and saved new outputs
!          OBJ 1: WORKING, NO ERRORS; Calibrated Initial Elevations for restoration
!          OBJ 2: WORKING, NO ERRORS
!          OBJ 3: WORKING, NO ERRORS
!          OBJ 4: WORKING, NO ERRORS
!          OBJ 5: WORKING, NO ERRORS
!          OBJ 6: WORKING, NO ERRORS
!   20170510: Updated function for dredging price and added organic sediment to TSS
!          Sediment inputs are now comprised of mineral and organic sediment
!          Function for dreding price is log-linear w/ respect to crude oil
!          Sediment input from MC is correct Efill = 100 yields relev of 100, when pk is 0
!          RE-RAN OBJ 1-6
!   20170512: FINAL CHANGES TO MODEL
!          CLEANED COMMENTS
!          ALL SUBROUTINES CHECKED
!          Found minor bug in Aboveground biomass calculation and fixed it
!          Found minor bug in Compaction and fixed it
!          Made all TSS input 3% refractory organic matter
!          Reduced number of cohorts to 2 to speed up calculation time (no impact on outputs)
!          Doublechecked mass balance and sediment input subroutines.
!          RE-RAN OBJ 1-6

!---------------SUBROUTINES-------------------
!$ 1 WORKFILES - Opens Working/Output Files
!$ 2 INPUTFILES - Opens/Reads Input Files
!$ 3 INITIALIZE - Initialize Model With Parameters
!$ y OUTHEADERS - Writes Headers to Output Files
!$ 4 DOCUMENTATION - Writes a Documentation File
!$ 5 SUB_SEARISE - Sea-Level Rise Scenarios
```

```
!$ 6 SUB_RESTSCNR - Restoration Scenario Algorithms
!$ 7 SUB_RELHYDROP - Water Level Relative Elevation & Indundation
!$ 8 SUB_SEDADV - Sediment depostion
!$ 9 SUB_PRIMPROD_MD - Marsh Primary Production
!$ 10 SUB_SOILRESET - Reset Soil Stock Counting Variables
!$ 11 SOILCOHORT - Soil Organic Dynamics and Depth Integration
!$ 12 CARBONSTOCK - Calculate Carbon Stock
!$ 13 COSTBENEFIT - Calculates Cost Benfit & Creates Output Files
!$ 14 SENSITIVITY - Sensitivity Tests on Model Parameters

!--------------- NAVIGATION-----------------------------
!Jump to lines and subroutines using [cntrl+G]
!Search for appendix n using [cntrl+F] "***"
!Search for program segment n such as call statments using "@ n"
!Search for Do loop n using "# n"
!Search for Call Statement/Subroutine n using "$ n"
!Search for Instruction n using "` n"

! ---------------OBJECTIVES-------------------
!THIS PROGRAM MODELS MARSH ELEVATION AND RESTORATION COSTS
!UNDER FUTURE ENERGY, SEA LEVEL RISE, AND MANAGEMENT SCENARIOS
!THE PROGRAM EXECUTES THE FOLLOWING OBJECTIVES
!
!OBJ = 1: HINDCAST - SIMULATE MARSH ELEVATION
!               1816 - 2016 with varying TSS (40, 80, 120, 160) and Subsidence
!OBJ = 2: Test the influence changing the fill height on marsh lifespan from 1cm to 150cm with
                  varying TSS and SLR
!       Produce graphs of marsh life span (SLR) verses fill height, for TSS level 1 to 4
!       Produce graphs of benefit:cost (SLR) verses fill height, for TSS level 1 to 4
!OBJ = 3: Test the influence of pushing back the date of restoration on marsh lifespan
!
!       Produce graph of marsh life span (SLR) and date of restoration, for TSS levels 1 to 4
!OBJ = 4: SIMULATE THE EFFECT ON MARSH LIFE SPAN OF PUSHING BACK THE
                  Date of Diversion Completion
!              (river influence is proxied with TSS) by 1 Year increments
!OBJ = 5: SIMULATE MARSH RESTORATION FROM 2016 to 2066 and to 2100
!        Starting an open bay ~-50 cm
!        A failing marsh  ~-10cm
!        in a bay with SLR and TSS
!OBJ = 6: SENSITIVITY TEST
!        Simulate marsh with 0.21 mm/yr eustatic SLR and after 100 years
!        simulate the following changes and report percentage % change
!        in elevation after 10 years from default parameters
!        SENSIT = 1 SubR: Subsidence Rate
!        SENSIT = 2 Gmax: max NPP rate
!        SENSIT = 3 Tamp: Tidal Range
```

```
!       SENSIT = 4 k_l: surface labile decomposition rate
!       SENSIT = 5 lf_r: labile fraction of root & rhyzomes
!       SENSIT = 6 ks: capture of sediment from biomass
!       SENSIT = 7 qs: capture of sediment during indundation
!       SENSIT = 8 xo: fraction of organic matter in suspended sediment
!       SENSIT = 9 TSS: suspended suspended sediment concentration

!-------------------EXECUTION INSTRUCTIONS-------------------
!Before running a simulation:
!         1. Jump to "$ 3" INITIALIZE, check parameter values
!         2. Jump to "@ 4",
!                  a. Set program ecosystem
!                  b. Set program restoration type
!                  c. Set program objective

!---------------------------------------------MAIN PROGRAM---------------------------------------------
PROGRAM WECRM_MARSH
WINAPP
IMPLICIT NONE
 !____________________________________________________________________
  !@ 1 DECLARE VARIABLES [specification]

  !date_and_time stamp variables
  CHARACTER(8)  :: date
  CHARACTER(10) :: time
  CHARACTER(5)  :: zone
  INTEGER,DIMENSION(8) :: values
  !SCENARIO AND DO LOOP VARIABLES
  INTEGER::
              YEAR,WEEK,SLR,ENERGY,n,nstat,nmax,Basin,dummy,dum2,count,inputfile,T
              rans,Restore,ECOS,River,sens,&
  SAL,dvtest,dum,Figure,Sentest,SENSIT,OBJ,dum1,dum2,dum3,MCY,RDY,nMC,PnMC
  INTEGER,PARAMETER:: steps = 52, ntrans = 11, yrs=600,nSL=5,nEn=5,nST=9,nFigs=9
  CHARACTER  (LEN=3):: h1(3),a(1),c
  CHARACTER  (LEN=11):: KimInput(nTRans)
  CHARACTER (LEN=22):: YearOut(nSL,nST,nTrans),TimeOut(nSL,nST,nTrans),&
  SoilOut(nSL,nST,nTrans)
  CHARACTER (LEN=20):: FigureA(nFigs,nSL,nST,nTrans)
  CHARACTER (LEN=20):: FigureB(nFigs,nST,nTrans)
  CHARACTER (LEN=20):: FigureC(nFigs,nTrans)
  CHARACTER (LEN=20):: FigureD(nFigs,nSL,nST)
  CHARACTER (LEN=20):: FigureE(nFigs,nST),FigureF(nFigs,nSL)
  CHARACTER (LEN=100):: Ecosystem,Mgmt
  REAL
              ::Y,Yr,Ymc(100),w,dSL,Init_Elev,Flood,Tamp,WL,RWL,Elev,TEMP,Gmax,W,L
              ,R,V,RPf,w_i,dW,dL,dV,dR,&
```

```
mrt,Leaflit,RootLit,FAVlit,r_g,s,v_func,vmax,vK,T_func,T_opt,T_min,Y,rk,S_in,&

                dQ,dB,dM,dP,k_l,k_ld,aL,aR,lf_v,lf_a,lf_r,k_r,k_rd,Sfunc,Relev,pk,sl,xo,acf,dcf,
                Cfunc,PSmin,PSmax,T_height,drt,SubR,&

                RHW,MHW,RHT,MHT,MLW,LMAX,ERHW,D,dD,TSS,MC,Flood,Hfill(100),S
                TLG,Ffreq,Initrelev,Sacc,mcacc,WkOp,&
mck,Efill,Ecrt,rfunc,pdm=2.65,pdo=1.14,OM2OC=0.42,MCin,ptind,Dmax,ks,qs,&
R2S,tr_ag,tr_bg,leaflitd,leaflitg,T_org_cm,T_m_cm,T_ps_cm,T_SOC,&

                PT_org_cm,PT_m_cm,PT_ps_cm,dT_org_cm,dT_m_cm,dT_ps_cm,PT_Height,d
                T_Height,T_mass,PT_mass,&

                T_SOC,dT_SOC,PT_SOC,AGOC,dAGOC,PT_AGOC,dTOC,TOC,T_TOC,T_A
                GOC,PT_TOC,dT_mass,Tfunc,rL,oilP(yrs,4),&
export,t1,t2,x(20,3),dt,dy(10,20),py(10,20),dydt(10,20),&
T_Org,T_M
REAL,DIMENSION (20000) ::rt,Z,Q,B,M,P,g,PS,Org_cm,M_cm,P_cm,PS_cm,height,&
&rt_in,BD,pctRt,pctOrg,Org,mass,Depth,rDepth
REAL,DIMENSION (yrs,nTrans):: RD
REAL,DIMENSION (nTrans):: Initelev
WRITE (c,900) ','
900 FORMAT (A1) !____________________________________________________________

!______________________________________________________________________
!@ 2 OPEN FILES [execution]
!$ 1
CALL WORKFILES (SLR,Energy,Dvtest,Sens,Sentest,Year,TRANS,&
NTRANS,nSL,nST,Figure,nFigs,&
KimInput,YearOut,TimeOut,SoilOut,&
FigureA,FigureB,FigureC,FigureD,FigureE,FigureF)
!Working Files for Inputs,Dump,Figures,Tables
!See ` A - INSTRUCTIONS FOR OPENING/WRITING TO WORK FILES
!Document your output files as you create to them in $1
!See $ 1 - WORKFILES
!(Search for "` A" or "$ 1") !________________________________________________

!______________________________________________________________________
!@ 3 MAIN PROGRAM
!subprograms...
!----------------------------------------------------------------------------------------
!@ 4 SELECT ECOSYSTEM, RESTORATION, SPATIAL DIMENSION, and OBJECTIVE
!User Input Section
PRINT*, "SELECT ECOSYSTEM and RESTORATION STRATEGY"
!what is the ecosystem???
ECOS = 1
```

```
IF (ECOS.EQ.1) WRITE (Ecosystem,*)"Mississippi Delta - Terrebonne/Barataria
            Backish/Saline"
IF (ECOS.EQ.2) WRITE (Ecosystem,*)"Mississippi Delta - Mid Barataria
            Oligohaline/Intermediate"
IF (ECOS.EQ.3) WRITE (Ecosystem,*)"Mississippu Delta - West Ponchartrain Maurepas
            Oligohaline"
IF (ECOS.EQ.4) WRITE (Ecosystem,*)"Ebro Delta - Impounded Oligohaline/Brackish
            Marsh"
IF (ECOS.EQ.5) WRITE (Ecosystem,*)"Ebro Delta - Saline Marsh"
!what is the management regime
RESTORE = 4
IF (Restore.EQ.1) WRITE (Mgmt,*)"No Action"
IF (Restore.EQ.2) WRITE (Mgmt,*)"River Diversion"
IF (Restore.EQ.3) WRITE (Mgmt,*)"Hydrologic Restoration"
IF (Restore.EQ.4) WRITE (Mgmt,*)"Marsh Creation"
IF (Restore.EQ.5) WRITE (Mgmt,*)"MC & RD"

!SET MODELING OBJECTIVE
DO OBJ = 1,1
dum3 = 0  !Calculate MC benefits
dum2 = 0  !ANNUAL SIMULATIONS ONGOING
dum1 = 1  !Initialize
Yr = 0
CALL COSTBENEFIT
            (dum1,dum2,dum3,SENS,RIVER,SLR,OBJ,Year,Yr,RDY,MCY,Relev,V,R,TOC
            ,T_SOC,nMC,Efill,Hfill,Ecrt)
dum1 = 0
PRINT*, ECOSYSTEM
PRINT*, Mgmt
!START NECESSASY LOOPS

!LOOP FOR SENSITVITY TESTS
SENSIT = 0
SENSITLOOP:&
DO
  SENSIT = SENSIT + 1
  IF (OBJ.NE.6.AND.SENSIT.GT.1) EXIT
  IF (OBJ.EQ.6.AND.SENSIT.GT.9) EXIT

!# 1 DO SLR AND RIVER
DO SLR = 1,5
  !IF (OBJ.EQ.1.AND.SLR.EQ.5) EXIT
  IF (OBJ.EQ.6.AND.SLR.EQ.2) EXIT
DO RIVER = 1,4
  !IF (OBJ.EQ.6.AND.RIVER.EQ.2) EXIT
!# 2 DO Trans
```

```
CALL INPUTFILES (Yrs,nTrans,Energy,SLR,Year,Trans,n,OilP,Initelev,RD)
Trans = 1
Sentest = 1
!# 2 DO Sens (Multiplier for sensitivity tests)
SENS = 0
SENSLOOP:&
DO
  IF(OBJ.EQ.1)THEN
    SENS = SENS + 1
    IF(SENS.GT.1)EXIT
  ELSE IF(OBJ.GE.2.AND.OBJ.LE.4)THEN
    SENS = SENS + 1
    IF (SENS.GT.100) EXIT
  ELSE IF(OBJ.EQ.5)THEN
    SENS=SENS + 5
    IF (SENS.GT.100) EXIT
  ELSE IF(OBJ.EQ.6)THEN
    SENS=SENS+1
    IF (SENS.GT.3) EXIT
  END IF

  IF (SLR.EQ.1.AND.OBJ.EQ.5) THEN
    dum1 = 3 !INITIALIZE COSTS
    PRINT*, OBJ,SLR,dum1
    CALL COSTBENEFIT
                (dum1,dum2,dum3,SENS,RIVER,SLR,OBJ,Year,Yr,RDY,MCY,Relev,V,R,TOC
                ,T_SOC,nMC,Efill,Hfill,Ecrt)
    dum1 = 0
  END IF
!INITIALIZE PROGRAM FOR EACH OF THE ABOVE LOOPS
!$ 2 CALL INITIALIZE
CALL INITIALIZE (&
Yrs,ntrans,&
Ecos,Restore,sentest,Dvtest,Energy,SLR,Year,Trans,&
OilP,&
n,Q,B,P,rt,M,PS,Org_cm,PS_cm,M_cm,P_cm,height,depth,mass,&
T_org_cm,T_M_cm,T_ps_cm,T_height,T_mass,T_SOC,T_TOC,T_Org,T_M,&

                Tamp,TSS,SubR,V,W,D,R,R2S,PSmin,PSmax,rootlit,leaflit,rk,sl,xo,pk,lf_r,lf_a,
                w_i,T_opt,T_min,&
Initelev,RD,qs,ks,k_r,k_rd,k_l,k_ld,Dmax,S_in,MC,MCin,mck,Ecrt,&
WKop,Hfill,Ffreq,Initrelev,Relev,Elev,WL,Efill,Flood,export,Gmax)

MCY = 100 !Marsh Creation Year
Efill = 50 !Target fill elevation cm above MWL
RDY = 100 !River Diversion Year
```

```
IF (OBJ.EQ.2.OR.OBJ.EQ.5) EFill = 2*Sens !Fill height of marsh creation
IF (OBJ.EQ.3) MCY  = 99+1*Sens !Year Marsh Creatio is initiated
IF (OBJ.EQ.4) RDY  = 99+1*Sens !Year diversion is installed
Print*, "OBJ",OBJ,"SLR",SLR,"RIVER",RIVER,"Efill",Efill,"MCY",MCY,"RDY",RDY

!$ 13 CALL COSTBENEFIT INITIALIZE OIL PRICES
IF (Sentest.EQ.1) THEN
  dum2 = 0
  dum1 = 2
  Print*, OBJ,SLR,RIVER,SENS,dum1
  CALL COSTBENEFIT
              (dum1,dum2,dum3,SENS,RIVER,SLR,OBJ,Year,Yr,RDY,MCY,Relev,V,R,TOC
              ,T_SOC,nMC,Efill,Hfill,Ecrt)
  dum1 = 0
  Sentest = Sentest + 1
END IF
nMC = 0 !Set number of marsh creation efforts to zero
!$ 3 CALL OUTHEADER
!ERROR WITH HEADERS CAUSED BY INFINITE DO LOOP?
CALL OUTHEADERS (c,Ecosystem,Mgmt,SLR,sentest,TRANS,TSS,River)
PRINT*, "CALLING OUTHEADERS",SLR*RIVER
!USER INPUT REQUIRED Set Scenario Parameters
!USER INPUT REQUIRED Set Sensitivity Parameters
!USER INPUT REQUIRED Set Restoration Parameters

PRINT*, INITrelev, "INITRELEV (CM)"

   !$ 4 CALL DOCUMENTATION
   IF(OBJ.EQ.1.AND.SLR.EQ.1.AND.RIVER.EQ.1.AND.SENS.EQ.1)CALL
              DOCUMENTATION (&
   Ecosystem,Mgmt,c,&
   Tamp,TSS,SubR,V,W,D,R,PSmin,PSmax,rootlit,rk,sl,xo,pk,lf_r,lf_a,w_i,T_opt,T_min,&

              Initelev,OilP,RD,qs,ks,Dmax,S_in,MC,mck,Ecrt,WKop,Hfill,Ffreq,Initrelev,Elev,
              WL,Efill,Flood)



              !~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
              ~~~~~~~~~~~
!@ 5 START WETLAND SIMULATION LOOPS
!# 5 DO YEAR
   Year = 0
   Y = 1916.0
   IF (OBJ.GT.1.AND.OBJ.LT.6)THEN
     Year = 90
```

```
      Y = 2006.0
    END IF

    YEARLOOP:&
    DO
      YEAR = YEAR + 1
      Y = Y + 1
      IF (OBJ.EQ.1.AND.YEAR.GT.300) EXIT YEARLOOP
! SENSITIVITY TESTS
      IF (OBJ.EQ.6) THEN
        IF(SLR.EQ.2) EXIT YEARLOOP
        IF(YEAR.GT.100) EXIT YEARLOOP
        IF (Year.EQ.20)THEN
          dummy = 1
          Call SENSITIVITY& !Do sensitivity analysis on key variables
         (dummy,SENSIT,SENS,RIVER,Y,TSS,Elev,WL,Relev,S_in,&
         dT_height,T_SOC,dT_SOC,T_Org_cm,T_mass,T_height,&
         SubR,Gmax,Tamp,k_l,xo,export,pk,t1,t2,dt,x,&
         dy,py,dydt)
        END IF
        IF (YEAR.EQ.30)THEN
          dummy = 2
          Call SENSITIVITY& !Do sensitivity analysis on key variables
          (dummy,SENSIT,SENS,RIVER,Y,TSS,Elev,WL,Relev,S_in,&
         dT_height,T_SOC,dT_SOC,T_Org_cm,T_mass,T_height,&
         SubR,Gmax,Tamp,k_l,xo,export,pk,t1,t2,dt,x,&
         dy,py,dydt)
        END IF !YEAR
      END IF !OBJ
      IF (OBJ.EQ.5.AND.YEAR.GT.300) EXIT YEARLOOP
      IF (OBJ.LT.5.AND.YEAR.GT.500) EXIT YEARLOOP
      IF (OBJ.GE.2.AND.OBJ.LE.4.AND.YEAR.GT.100) THEN
        IF (nMC.GT.2) EXIT
      END IF

  !$ 5 Sea Level Rise
      CALL SUB_SEARISE(YEAR,dSL,WL,T_Height,SubR,MCY,OBJ)
      !PRINT *, SLR, Trans, Efill, YEAR

  !# 6 DO week
      count = 0 !Count for relev logic
      w = 0
      WEEKLOOP:&
      DO week = 1,steps
        w = w + 1.0
        Yr =  Y+(w-1)/52.0
```

```
      !IF (Week.Eq.30)Print*,Yr
!$ 7 Relative elevation and hydroperiod
      CALL COMPACTION (Yr,Week,Ymc,MCY,nMC,STLG,sl,pk,acf,Hfill)
      CALL SUB_RELHYDROP
              (Week,Yr,Ecos,Elev,T_height,Initrelev,RWL,WL,MHW,MLW,&
         Tamp,ERHW,Relev,ptind,Dmax,Lmax,MHT,RHT,SubR,steps,STLG)
!$ x CLIMATE
      TEMP = 8*(-COS(6.283*(week-3)/steps))+20
!$ 9 Primary Production
      SELECT CASE (ECOS)
      CASE (1)
      CALL SUB_PRIMPROD_MD (week,Steps,ECOS,Gmax,RPf,RELEV,r2s,&
      rfunc,tr_bg,tr_ag,rootlit,leaflit,V,W,D,R,s,rk,aL,rL,TEMP,Tfunc,&
      T_opt,T_min,lf_a,TSS,export,ptind)
      END SELECT
      !IF (MC.EQ.1)PRINT*,"MC=1 Calling Sedadv..."
 !$ 5 Restoraion Scenario
    CALL SUB_RESTSCNR
              (YEAR,yrs,Restore,RD,MC,RDY,MCY,TSS,RIVER,Trans,Ntrans)
    PnMC = nMC !previous number of marsh creation efforts
    !MARSH CREATION LOGIC
    IF (MC.EQ.1)THEN
     count = count + 1
     IF (count.EQ.1) nMC = nMC+1!Number of marsh creation efforts
     IF (count.GT.1) MC = 0 !checking to see if MC happens twice in a year
     Hfill(nMC) = Efill - Relev !SET FILL HEIGHT
     Ymc(nMC) = Yr
    END IF
    !$ 13 Caclulate MC project Life and ESV Benefits
    IF (OBJ.GT.1.AND.nMC.GT.PnMC) THEN
     PRINT*,Year, SENS, Week, nMC, "Calling $ 13 COSTBENEFIT", "relev", RELEV
     dum3 = 1!Calculate MC cost/benefits
     CALL COSTBENEFIT
              (dum1,dum2,dum3,SENS,RIVER,SLR,OBJ,Year,Yr,RDY,MCY,Relev,V,R,TOC
              ,T_SOC,nMC,Efill,Hfill,Ecrt)
     dum3 = 0
     IF (OBJ.GT.2.AND.OBJ.LT.5.AND.nMC.GT.1) THEN
       PRINT*, "count gt 1 EXITING WEEKLOOP"
       EXIT WEEKLOOP
     END IF
    END IF

    IF (OBJ.GT.2.AND.nMC.EQ.1.AND.YEAR.EQ.499)THEN
    dum3 = 1 !Calculate MC cost/benefits
    PRINT*,Y,"nMC",nMC,"Calling $ 13 COSTBENEFIT"
```

```
    CALL COSTBENEFIT
              (dum1,dum2,dum3,SENS,RIVER,SLR,OBJ,Year,Yr,RDY,MCY,Relev,V,R,TOC
              ,T_SOC,nMC,Efill,Hfill,Ecrt)
    dum3 = 0
    EXIT WEEKLOOP
    END IF

    IF (OBJ.GT.2.AND.nMC.EQ.0.AND.YEAR.EQ.499)THEN
    dum3 = 2 !Calculate MC cost/benefits
    PRINT*,Y,"nMC",nMC,"Calling $ 13 COSTBENEFIT"
    CALL COSTBENEFIT
              (dum1,dum2,dum3,SENS,RIVER,SLR,OBJ,Year,Yr,RDY,MCY,Relev,V,R,TOC
              ,T_SOC,nMC,Efill,Hfill,Ecrt)
    dum3 = 0
    EXIT WEEKLOOP
    END IF

!$ 8 Sediment depostion
      CALL SUB_SEDADV
              (ECOS,Y,RDY,MCY,nMC,Sacc,TSS,Sfunc,qs,ks,V,ptind,RHW,Dmax,steps,&

              S_in,MC,Relev,Flood,Hfill,Efill,Ffreq,mck,MCin,RD,week,YEAR,TRANS,pdm,
              Wkop,count)
      !IF (MC.EQ.1)PRINT*,"MCin",MCin," g cm-2"
      !IF (nMC.EQ.2) PRINT*,"Hfill =", HFill(2)
      CALL SUB_SOILRESET (week,T_height,T_mass,T_org_cm,T_m_cm,T_ps_cm,&

              T_SOC,PT_org_cm,PT_m_cm,PT_ps_cm,PT_Height,PT_mass,PT_SOC,PT_AG
              OC,PT_TOC,&
      T_TOC,T_AGOC,T_ORG)
!# 7 DO n
      n = 0
      COHORTLOOP:&
      DO
        n = n +1
!$ 10 Soil dynamics
        CALL SOILCOHORT&
        (n,nmax,nstat,Week,Year,Trans,Relev,RWL,Leaflit,RootLit,FAVlit,&
        r_g,s,rk,S_in,MCin,MC,WkOp,pdm,pdo,OM2OC,R2S,&
        dQ,dB,dM,dP,k_l,k_ld,aL,aR,lf_v,lf_a,lf_r,k_r,k_rd,pk,sl,xo,acf,&

              dcf,Cfunc,PSmin,PSmax,T_height,drt,T_org_cm,T_m_cm,T_ps_cm,PT_SOC,T_
              SOC,&

              PT_org_cm,PT_m_cm,PT_ps_cm,dT_org_cm,dT_m_cm,dT_ps_cm,PT_Height,d
              T_Height,&
```

```
            T_mass,mass,PT_mass,Tfunc,rL,rt,Z,Q,B,M,P,g,PS,Org_cm,M_cm,P_cm,PS_cm
            ,height,&
        rt_in,BD,pctRt,pctOrg,Org,Depth,rDepth,RD,T_Org,T_M)
        IF (WEEK.LT.2)THEN
          SELECT CASE (YEAR)
            CASE (2:20)
            CASE (21:50)
            CASE (51:98)
            CASE (105:500)
            CASE DEFAULT
            IF
              (OBJ.EQ.1.OR.OBJ.EQ.6)WRITE(100000+10000*3+SLR*1000+100*RIVER+T
              RANS,971)&
            Trans,c,Sens,c,Yr,c,n,c,Depth(n),c,rDepth(n),c,BD(n),c,pctOrg(n)
            971 FORMAT (I2,A1,I3,A1,F8.3,A1,I2,4(A1,F16.8))
          END SELECT
        END IF
        IF (n.EQ.nmax) EXIT COHORTLOOP
      END DO COHORTLOOP
!# 7  END DO N
      !WRITE DATA AT WEEKLY INTERVAL FOR ALL YEARS NOT IN SELECTED
            INTERVALS
      SELECT CASE (YEAR)
        CASE (:200)
      IF (OBJ.LE.2) THEN
      WRITE(20000+SLR*1000+100*River+TRANS,961)&
      Yr,c,Relev,c,V,c,D,c,R,c,T_mass,c,BD(1),c,pctOrg(1)
      IF (OBJ.LE.2.OR.OBJ.EQ.6)
            WRITE(100000+10000*2+SLR*1000+100*RIVER+TRANS,962)&
      Trans,c,Sens,c,Yr,c,Elev,c,WL,c,Relev,c,V,c,D,c,R,c,S_in,c,BD(1),c,pctOrg(1)
      END IF
        CASE DEFAULT
      END SELECT !n
      961 FORMAT (F8.3,7(A1,F16.8))
      962 FORMAT (I2,A1,I3,A1,F8.3,9(A1,F16.8))
      !FIGURE = 1
      !WRITE(FigureA(FIGURE,SLR,sentest,Trans),*) YEAR + week/STEPS ,c, RELEV
      !FIGURE = 2
      !WRITE(FigureA(FIGURE,SLR,sentest,Trans),*) YEAR + week/STEPS ,c, T_SOC
      !FIGURE = 3
      !WRITE(FigureA(FIGURE,SLR,sentest,Trans),*) YEAR + week/STEPS ,c, V

            IF(MOD(YEAR,10).EQ.0.AND.WEEK.EQ.1)PRINT*,Yr,Relev,V,D,dT_SOC*1
            0000,dT_Height
    END DO WEEKLOOP
```

```
    IF(YEAR.EQ.99)PRINT*,Yr,Relev,V,D,T_mass/T_Height,T_Org_cm*pdo/T_mass
    IF(YEAR.EQ.100)PRINT*," end hindcast     ***     begin forecast"

!# 6 END DO week
    CALL
        CARBONSTOCK(PdO,V,W,T_SOC,dT_SOC,PT_SOC,AGOC,dAGOC,PT_AG
        OC,dTOC,TOC,PT_TOC,OM2OC,&
    T_height,T_mass,T_Org,T_M,T_org_cm,T_m_cm,T_ps_cm,&
    PT_org_cm,PT_m_cm,PT_ps_cm,PT_Height,PT_mass,&
    dT_height,dT_mass,dT_org_cm,dT_m_cm,dT_ps_cm)
    !IF (Efill.EQ.1)PRINT*,"CALLING CARBONSTOCK"

!$ WRITE OUTPUT FILES ON ANNUAL STEP
    !IF(MOD(YEAR,5).EQ.0)PRINT*,Y,Relev,V,D,pctorg(10),BD(10)
    !WRITE(10000+SLR*1000+100*RIVER+TRANS,981)&
    !IF (OBJ.EQ.1.OR.OBJ.EQ.6) THEN
    WRITE(100000+10000*1+SLR*1000+100*RIVER+TRANS,981)&
    Y-1916,c,Elev,c,WL,c,Relev,c,V,c,D,c,R,c,&
    S_in*52*10000+MCin*10000,&!mineral input g m-2 yr-1
    c,dT_height,&!total accretion rate of soil column inputs to n=1 adjusted for
        decay/compaction
    c,T_SOC*10000,c,dT_SOC*10000,&!soil organic carbon stock, g C m-2, and delta soil
        organic carbon g C m-2 yr
    c,T_Org_cm*0.085/T_mass,&!average percent organic matter of the entire soil column %
    c,T_mass/T_Height!average bulk density of the entire soil column

    981 FORMAT (F8.3,12(A1,F16.8))
   ! END IF
  END DO YEARLOOP
!# 5 END DO YEAR
!@ 5 END WETLAND UNIT SIMULATION

        !~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
        ~~~~~~~~~~~~~~
!# 4 END DO Sens
END DO SENSLOOP!SENS
!# 3 END DO RIVER SLR
END DO !SLR
END DO !RIVER
END DO SENSITLOOP !SENSIT
CLOSE (10000+SLR*1000+100*River+TRANS)
CLOSE (20000+SLR*1000+100*River+TRANS)
CLOSE (30000+SLR*1000+100*River+TRANS)
!CLOSE FILES
IF(OBJ.GT.1.AND.OBJ.LT.6) THEN
dum2 = 1
```

```
  PRINT*,dum1,"MCY", MCY
  CALL COSTBENEFIT
                (dum1,dum2,dum3,SENS,RIVER,SLR,OBJ,Year,Yr,RDY,MCY,Relev,V,R,TOC
                ,T_SOC,nMC,Efill,Hfill,Ecrt)
  END IF
  END DO !OBJ
PRINT*, "END MAIN PROGRAM"
!---------------------------------------- END OF MAIN PROGRAM--------------------------------------
CONTAINS
!----------------------------------------------SUBROUTINES----------------------------------------------

!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
!$ 14 SENSITIVITY TESTS
SUBROUTINE SENSITIVITY&
        (dummy,SENSIT,SENS,RIVER,Y,TSS,Elev,WL,Relev,S_in,&
         dT_height,T_SOC,dT_SOC,T_Org_cm,T_mass,T_height,&
         SubR,Gmax,Tamp,k_l,xo,export,pk,t1,t2,dt,x,&
         dy,py,dydt)
         !INTEGER, INTENT (INOUT):: SENSIT,SENS,dummy,RIVER
INTEGER, INTENT(IN):: SENS,SENSIT,RIVER,dummy
REAL, INTENT (INOUT)::Y,TSS,Elev,WL,Relev,S_in,dT_height,&
T_SOC,dT_SOC,T_Org_cm,T_mass,T_height,SubR,Gmax,Tamp,k_l,xo,&
export,pk
INTEGER,PARAMETER :: nv=10,ns=20,nd=2
REAL, DIMENSION (nv,ns,nd)::y1 !State variable y1 for v1 = 1...n
REAL, DIMENSION (nv,ns), INTENT(INOUT) ::dy,py,dydt
!dy - change in y1 from d1 = 1 to d1 = 2
!py - percent change in state variable y1...n from baseline, s = 1
!dydt - change in y1 divided by change in time
INTEGER::v1,s1,d1,r1,s2
REAL,INTENT(INOUT)::t1,t2,dt,x(ns,3) !change in time from d1 = 1 to d1 = 2 (years)
REAL :: mult
Character (len=8) :: aa,bb
s1=SENSIT
s2=SENS
d1=dummy
r1=RIVER
WRITE(bb,*)"null"

PRINT*, "ENTERED SENSITIVTTY SUBROUTINE, Calculatig Y vars..."
!SET VALUES FOR ECOSYTEM RESPONSE VARIABLES
DO v1 = 1,nv !do variable from 1 to n
 IF (v1.EQ.1)y1(v1,s2,d1) = Elev
 IF (v1.EQ.2)y1(v1,s2,d1) = Relev
 IF (v1.EQ.3)y1(v1,s2,d1) = T_height
 IF (v1.EQ.4)y1(v1,s2,d1) = T_SOC*10000 !soil organic carbon stock, g C m-2
```

```
 IF (v1.EQ.5)y1(v1,s2,d1) = T_Org_cm*pdo !total mass of organic matter
 IF (v1.EQ.6)y1(v1,s2,d1) = T_m_cm*pdm !total mass of mineral matter
 IF (v1.EQ.7)y1(v1,s2,d1) = T_mass !total soil colum mass
 IF (v1.EQ.8)y1(v1,s2,d1) = T_height !total soil colum height
 IF (v1.EQ.9)y1(v1,s2,d1) = T_mass/T_height !Bulk Density (g cm-3)
 IF (v1.EQ.10)y1(v1,s2,d1) = T_Org_cm*pdo/T_mass !percent organic matter
END DO

IF(s2.EQ.1) THEN
 WRITE(aa,*)"default"
 mult = 0
ELSE IF(s2.EQ.2) THEN
 WRITE(aa,*)"-50%"
 mult = -0.5
ELSE IF(s2.EQ.3) THEN
 WRITE(aa,*) "+50%"
 mult = 0.5
END IF

IF(d1.EQ.1)THEN !ALTER
 PRINT*,"dummy variable equals 1 modify x varibles"
 t1=Y !set time1 equal to year
 PRINT*,"Time 1 is", Y
 IF (s1.EQ.1) THEN
  SubR = SubR*(1+mult) !Changes Subsidence -50%, 0%, +50%
  PRINT*, "(A) SubR - Subsidence Rate (cm/yr)", SubR
  IF(r1.EQ.1.AND.s2.EQ.1)WRITE(17,*)"(A) SubR - Subsidence Rate (cm/yr)"
  x(s1,s2) = SubR
  WRITE (bb,*) "SubR"
 ELSE IF (s1.EQ.2) THEN
  Gmax = Gmax*(1+mult) !etc...
  PRINT*, "(B) Gmax - Maximum Net Primary Productivity (g m-2 yr-1)"
  IF(r1.EQ.1.AND.s2.EQ.1)WRITE(17,*)"(B) Gmax - Maximum Net Primary Productivity (g
            m-2 yr-1)"
  x(s1,s2) = Gmax
  WRITE (bb,*) "Gmax"
 ELSE IF (s1.EQ.3) THEN
  Tamp = Tamp*(1+mult)
  PRINT*, "(C) Tamp - Tidal Range (cm)"
  IF(r1.EQ.1.AND.s2.EQ.1)WRITE(17,*)"(C) Tamp - Tidal Range (cm)"
  x(s1,s2) = Tamp
  WRITE (bb,*) "Tamp"
 ELSE IF (s1.EQ.4) THEN
  k_l = k_l*(1+mult)
  PRINT*, "(D) k_l - decay rate of surface labile organic matter (wk-1)"
```

```
  IF(r1.EQ.1.AND.s2.EQ.1)WRITE(17,*)"(D) k_l - decay rate of surface labile organic matter
                (wk-1)"
  x(s1,s2) = k_l
  WRITE (bb,*) "k_l"
 ELSE IF (s1.EQ.5) THEN
  lf_r = lf_r*(1+mult/10)
  PRINT*, "(E) lf_r - labile fraction of below ground biomass"
  IF(r1.EQ.1.AND.s2.EQ.1)WRITE(17,*)"(E) lf_r - labile fraction of below ground biomass"
  x(s1,s2) = lf_r
  WRITE (bb,*) "lf_r"
 ELSE IF (s1.EQ.6) THEN
  ks = ks*(1+mult)
  PRINT*, "(F) ks - additional capture/retention of sediment from biomass"
  IF(r1.EQ.1.AND.s2.EQ.1)WRITE(17,*) "(F) ks - retention of sediment from biomass"
  x(s1,s2) = ks
  WRITE (bb,*) "ks"
 ELSE IF (s1.EQ.7) THEN
  qs = qs*(1+mult)
  PRINT*, "(G) qs - fraction of sediment volume at maximum depth captured per indundation"
  IF(r1.EQ.1.AND.s2.EQ.1)WRITE(17,*)"(G) qs - fraction of sediment volume at maximum
                depth captured per indundation"
  x(s1,s2) = qs
  WRITE (bb,*) "qs"
 ELSE IF (s1.EQ.8) THEN
  xo = xo*(1+mult)
  PRINT*, "(H) xo - fraction of organic matter in suspended bay bottom sediment (g/g)"
  IF(r1.EQ.1.AND.s2.EQ.1)WRITE(17,*)"(H) xo - fraction of organic matter in suspended bay
                bottom sediment (g/g)"
  x(s1,s2) = xo
  WRITE (bb,*) "xo"
 ELSE IF (s1.EQ.9) THEN
  TSS = TSS*(1+mult)!Changes -50%, 0%, +50%
  PRINT*, "(I) TSS - Suspended Sediment Concentration (mg/L)", TSS
  IF(r1.EQ.1.AND.s2.EQ.1)WRITE(17,*)"(I) TSS - Suspended Sediment Concentration
                (mg/L)"
  x(s1,s2) = TSS
  WRITE (bb,*) "TSS"
 END IF

 PRINT*, bb,",, TSS (mg/L), dRel/dt (cm/yr), dEl/dt (cm/yr), %change, dSOC/dt (cm/yr),
                %change"
  IF(r1.EQ.1.AND.s2.EQ.1)WRITE(17,*) bb,",, TSS (mg/L), dRel/dt (cm/yr), dEl/dt (cm/yr),
                %change, dSOC/dt (cm/yr), %change"
END IF
IF(d1.EQ.2) THEN
 t2=Y
```

```
  dt = t2-t1
  DO v1 = 1,nv
    dy(v1,s2)  = y1(v1,s2,d1) - y1(v1,s2,1)
    dydt(v1,s2)= dy(v1,s2)/dt
    py(v1,s2)  = 100*(dydt(v1,s2) - dydt(v1,1))/dydt(v1,1) !percent change in dydt
  END DO
  PRINT*,aa,x(s1,s2),',',TSS,',',dydt(2,s2),',',dydt(1,s2),',',py(1,s2),',',dydt(4,s2),',',py(4,s2)

        WRITE(17,951)aa,',',x(s1,s2),',',TSS,',',dydt(2,s2),',',dydt(1,s2),',',py(1,s2),',',dydt(
        4,s2),',',py(4,s2)
  951 FORMAT (A8,A1,F8.3,A1,F4.0,10(A1,F10.4))
END IF
   RETURN
END SUBROUTINE SENSITIVITY
!-----------------------------------------------------------------------

!-----------------------------------------------------------------------
!$ 13 CALCULATE COST AND BENEFITS OF MARSH CREATION AND PRINT OUTPUT
        FILES
SUBROUTINE COSTBENEFIT
        (dum1,dum2,dum3,SENS,RIVER,SLR,OBJ,Year,Yr,RDY,MCY,Relev,V,R,TOC
        ,T_SOC,nMC,Efill,Hfill,Ecrt)
!VARIABLES FROM THE MAIN PROGRAM
INTEGER, INTENT (INOUT)::
        SENS,SLR,OBJ,RIVER,dum1,dum2,dum3,Year,RDY,MCY,nMC
REAL, INTENT (INOUT):: Yr,Relev,V,R,TOC,T_SOC,Efill,Hfill,Ecrt
!INTERNAL VARIABLES FOR MARSH CREATION COSTS BENEFITS AND OUTPUT
        FILES
CHARACTER(8)  :: date
CHARACTER(10) :: time,met,slname
CHARACTER(5)  :: zone,b
INTEGER,DIMENSION(8) :: values
INTEGER :: nOBJ=5,nSL=5,nRV=5,nMetrics=5,nSEN=5
CHARACTER (LEN=23):: SENSTable(6,6,6)
CHARACTER (LEN=23):: CostTable(200,6,6)
INTEGER :: numMC,ENERGY,METRIC,SEN
REAL::&
VB,P_d,C_mc,CRD,MCYr,OilP(500,4),&
RDp,MCp,MCmp,MCp_lcl,MCp_ucl,&
MCLife(6,200,6,6),&
RBC_cm(6,200,6,6,6),RBC_dl(6,200,6,6,6),mRBC_dl(6,200,6,6,6),mRBC_cm(6,200,6,6,6),&
TOTMCP_66(6,200,6,6,6),TOTMCP_100(6,200,6,6,6),&
TOTMCCseq_66(6,200,6,6,6),TOTMCCseq_100(6,200,6,6,6),&
TOTMCCem_66 (6,200,6,6,6),TOTMCCem_100(6,200,6,6,6),&
MCCI2066(6,200,6,6,6),MCCI2100(6,200,6,6,6),&
RCI2066(6,200,6,6,6),RCI2100(6,200,6,6,6)
```

```
!--------------------------------------------------------------
!INITIALIZE
SEN = 0
IF (dum1.EQ.1) THEN
!TIME STAMP OF MODEL RUN
call date_and_time(date,time,zone,values)
        print*, 'yyyymmdd',"_",'hhmmss.ttt',"_",'UTC zone'
        print*,date,time,zone
!SET RESTORATION COSTS
READ (16,*) ((OilP(Year,ENERGY),ENERGY = 2,4),YEAR = 94,184)
REWIND (16)
DO YEAR = 94,184
   OilP(Year,1) = 55
END DO
DO YEAR = 185,500
  DO ENERGY = 1,4
    IF (ENERGY.EQ.1) THEN
      OilP(Year,Energy) = 55
    ELSE
      OilP(Year,Energy) = OilP(184,Energy)
    END IF !ENERGY
  END DO
END DO
RETURN

END IF

IF (dum1.EQ.2) THEN!First SENS test in river and SLR loops
  !CREATE OUTPUT FILES
  !Sensitivity Tests for Created Marsh Lifespan and Cost Benefit
  IF (OBJ.GE.2.AND.OBJ.LE.4.AND.SLR.EQ.1)THEN
    DO METRIC = 1,5
          WRITE (SENSTable(OBJ,RIVER,METRIC),905)
                        "1SensTab",OBJ,"_RV",RIVER,"_MT",METRIC,".csv"
          OPEN  (400000+10000*OBJ+1000+RIVER*100+10*METRIC,&
          File=SENSTable(OBJ,RIVER,METRIC), STATUS="UNKNOWN")
    END DO
  END IF
  RETURN
END IF

!Total Costs of Restoring Marsh From 2016 - 2066 and 2100
!Outputs are cost(SLR,ENERGY) for SLR 1,5 and Energy 1,4
IF (dum1.EQ.3) THEN
  IF (MOD(SENS,5).EQ.0.AND.OBJ.EQ.5.AND.SLR.EQ.1) THEN
```

```
  DO METRIC = 1,6
    PRINT*, "OPENING FILE #", 500000+10000*METRIC+1000*RIVER+SENS
    WRITE (CostTable(SENS,RIVER,METRIC),906)
              "1CostMt",METRIC,"_RV",RIVER,"_Sn",Sens,".csv"
    !A7,I1,A3,I1,A3,I3,A4
    OPEN
              (500000+10000*METRIC+1000*RIVER+SENS,File=CostTable(SENS,RIVER,
              METRIC), STATUS="UNKNOWN")
  END DO
 END IF
 RETURN
END IF
905 FORMAT (A9,I1,A3,I1,A3,I1,A4)
906 FORMAT (A7,I1,A3,I1,A3,I3,A4)


IF(dum2.EQ.0.AND.dum3.EQ.2)THEN !IF MARSH CREATION IS NOT TRIGGERED
!MAIN PROGRAM IN PROGRESS CACLULATE COSTS AND BENEFITS OF MARSH
              CREATION
!Caclulate Marsh Creation Costs
DO ENERGY = 1,4
 !MARSH CREATION COST SUBROUTINE
              ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
  !PRINT*,"SENS",SENS,"  Efill",Efill,"   RELEV", RELEV
  !NO FILL IS DEPOSITED VB IS EQUAL TO ZERO
  VB  = 0 !Volume Borrow area or Dredge Cut per sqaure meter of marsh (m^3/m^2)
  CRD  = 0.47 !$47,000/ha * 1ha/10,000m2 net benefit after 50 years
  !P_d  = 0.036*oilP(YEAR,Energy) + 1.621  !unit price of dredging (2010$/m^3)as a function
              of the price of crude oil (2010$/bbl)
  P_d = exp(0.449+0.470*LOG(oilP(Year,Energy))+0.528*0-0.204*4.9) !:] 20170510
  !P_d = exp(bo+b1*LOG(oilP(Year,Energy))+b2*DR-b3*Ek)
  !where: oilP is oil price $/bbl, DR is an indicator for dune restoration, and Ek is the Log_e of
              VB

  MCp  = P_d*VB*1.5 !Total cost of MC per m^2 including mobilization costs, contingency and
              risk

  MCp_lcl = P_d*VB*1.5*0.75 !lower confidence limit for MC assuming error of 25%
  MCp_ucl = P_d*VB*1.5*1.25 !lower confidence limit for MC assuming error of 25%
  MCmp = 1.5*(Efill)/100 * P_d * 1.5 !marginal price of dredging over MSL
  IF (RIVER.EQ.1)  RDp  = 0
  IF (RIVER.GT.1)  RDp  = 4.7 !$47,000 dollars per ha of land benefited after 50 years CPRA
              2012 Appendix A2

              !^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
              ^^^^^^^^^^^^^^^^^
```

```
!^^^^^^^^^^ CALCULATE MARSH LIFESPAND AND COST BENEFIT^^^^^^^^^^^^^^
IF (OBJ.GE.2.AND.OBJ.LE.4) THEN
  PRINT*, "y energy obj:",Y,ENERGY,OBJ,"  relev:",Relev
  MCLife (OBJ,SENS,River,SLR) = 999
  PRINT*, "MCLIFE", MCLife (OBJ,SENS,River,SLR)
  P_d  = 0.036*oilP(MCY,Energy) + 1.621  !unit price of dredging (2010$/m^3)as a function
                of the price of crude oil (2010$/bbl)
  !P_d  = 0.013*oilP(MCY,Energy) + 0.81  !+50 percent
  !P_d  = 0.049*oilP(MCY,Energy) + 2.431 !-50 percent
  MCp  = P_d*VB*1.5
  MCmp = 0 !marginal price of dredging over MSL
  IF(OBJ.EQ.3)PRINT*, "nMC", nMC,"SENS", SENS!,"MCLIFE",
                MCLife(OBJ,SENS,RIVER,SLR)
  RBC_dl  (OBJ,SENS,RIVER,ENERGY,SLR) = -999
  RBC_cm  (OBJ,SENS,RIVER,ENERGY,SLR) = -999!benefit:cost
  mRBC_dl (OBJ,SENS,RIVER,ENERGY,SLR) = -999!marginal benefit:cost
  mRBC_cm (OBJ,SENS,RIVER,ENERGY,SLR) = -999!marginal benefit:cost
  !OBJECTIVE 1 DUMP
  PRINT*, Year - MCY,',',RBC_cm(OBJ,SENS,RIVER,ENERGY,SLR)! &
  !&',',MCLife(OBJ,RIVER,SLR,SENS),',',MCp,&
  !&
                ',',RBC_dl(OBJ,SENS,RIVER,ENERGY,SLR),',',RBC_cm(OBJ,SENS,RIVER,E
                NERGY,SLR)
END IF !OBJ 2 - 4 Completed^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

!INITIALIZE COST SUMMARY VARIABLES
IF (YEAR.EQ.100)THEN
   TOTMCP_66 (OBJ,SENS,RIVER,ENERGY,SLR)= 0
   TOTMCP_100(OBJ,SENS,RIVER,ENERGY,SLR)= 0
   TOTMCCseq_66 (OBJ,SENS,RIVER,ENERGY,SLR)= 0
   TOTMCCseq_100(OBJ,SENS,RIVER,ENERGY,SLR)= 0
   TOTMCCem_66 (OBJ,SENS,RIVER,ENERGY,SLR)= 0
   TOTMCCem_100(OBJ,SENS,RIVER,ENERGY,SLR)= 0
END IF !YEAR

!^^^^^^^^^^^^^^^^^^^^^^^^^^^^^OBJ 5 Caclulate Total Costs^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
IF (OBJ.EQ.5) THEN
   IF (Year.LT.150) TotMCp_66 (OBJ,SENS,RIVER,ENERGY,SLR)=
                TotMCp_66(OBJ,SENS,RIVER,ENERGY,SLR)+ MCp
   PRINT*, "Hfill",Hfill,"(cm)  ENERGY",ENERGY,"    MCP $/m2", MCp
      !TOTMCCseq_66 (SENS,RIVER,ENERGY,SLR)=
                TOTMCCseq_66(SENS,RIVER,ENERGY,SLR) + T_SOC
      !Baseline TOTMCP_66(5,50,1,1,1) = $12.16/m2
      !Baseline TOTMCP_100(5,50,1,1,1) = $12.16/m2
```

```
    IF (Year.LT.184) TotMCp_100 (OBJ,SENS,RIVER,ENERGY,SLR)=
              TotMCp_100(OBJ,SENS,RIVER,ENERGY,SLR)+ MCp
    IF (YEAR.LT.150) THEN
      MCCI2066(OBJ,SENS,RIVER,ENERGY,SLR)=
              TOTMCP_66(OBJ,SENS,RIVER,ENERGY,SLR)/12.16
      RCI2066(OBJ,SENS,RIVER,ENERGY,SLR) =
              MCCI2066(OBJ,SENS,RIVER,ENERGY,SLR)+RDp
    END IF  !Marsh Creation Costs Pl
       !IF (YEAR.EQ.150) PRINT*, "YEAR is
              150!",MCCI2066(OBJ,SENS,RIVER,ENERGY,SLR)
    IF (YEAR.LT.184) THEN
     MCCI2100(OBJ,SENS,RIVER,ENERGY,SLR)=
              TOTMCP_100(OBJ,SENS,RIVER,ENERGY,SLR)/12.16
     RCI2100(OBJ,SENS,RIVER,ENERGY,SLR) =
              MCCI2100(OBJ,SENS,RIVER,ENERGY,SLR)+RDp
    END IF!Marsh Creation Costs Plus River Diversion Costs

   END IF !OBJ = 5 Completed^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

  END DO !ENERGY
  RETURN
END IF
!-----------------------------------------------------------------------
IF(dum2.EQ.0.AND.dum3.EQ.1)THEN
!MAIN PROGRAM IN PROGRESS CACLULATE COSTS AND BENEFITS OF MARSH
              CREATION
!Caclulate Marsh Creation Costs
DO ENERGY = 1,4

   !MARSH CREATION COST SUBROUTINE ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
   VB  = 1.5*(Hfill)/100 !Volume Borrow area or Dredge Cut per sqaure meter of marsh
              (m^3/m^2)
   CRD  = 0.47 !$47,000/ha * 1ha/10,000m2 net benefit after 50 years
   !P_d  = 0.036*oilP(YEAR,Energy) + 1.621  !unit price of dredging (2010$/m^3)as a function
              of the price of crude oil (2010$/bbl)
   P_d = exp(0.449+0.470*LOG(oilP(Year,Energy))+0.528*0-0.204*4.9) !:] 20170510
   !P_d = exp(bo+b1*LOG(oilP(Year,Energy))+b2*DR-b3*Ek)
   !where: oilP is oil price $/bbl, DR is an indicator for dune restoration,
   !and Ek is the Log_e of VB divide by dredge HP capacity
   MCp  = P_d*VB*1.5 !Total cost of MC per m^2 including mobilization costs, contingency and
              risk
   MCp_lcl = P_d*VB*1.5*0.75 !lower confidence limit for MC assuming error of 25%
   MCp_ucl = P_d*VB*1.5*1.25 !lower confidence limit for MC assuming error of 25%
   MCmp = 1.5*(Efill)/100 * P_d * 1.5 !marginal price of dredging over MSL
   IF (RIVER.EQ.1)  RDp  = 0
```

```
IF (RIVER.GT.1)  RDp  = 4.7 !$47,000 dollars per ha of land benefited after 50 years CPRA
              2012 Appendix A2

              !^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
              ^^^^^^^^^^^^^

!^^^^^^^^^^^^^^^CALCULATE MARSH LIFESPAND AND COST BENEFIT^^^^^^^^^^^^
IF (OBJ.GE.2.AND.OBJ.LE.4) THEN
  PRINT*, "y energy obj:",Y,ENERGY,OBJ,"  relev:",Relev
  MCLife (OBJ,SENS,River,SLR) = Yr - (MCY + 1916)
  PRINT*, "MCLIFE", MCLife (OBJ,SENS,River,SLR)
  P_d  = 0.036*oilP(MCY,Energy) + 1.621  !unit price of dredging (2010$/m^3)as a function
              of the price of crude oil (2010$/bbl)
  !P_d  = 0.013*oilP(MCY,Energy) + 0.81  !+50 percent
  !P_d  = 0.049*oilP(MCY,Energy) + 2.431 !-50 percent
  MCp  = P_d*VB*1.5
  MCmp = 1.5*(Efill)/100 * P_d * 1.5 !marginal price of dredging over MSL
  IF(OBJ.EQ.3)PRINT*, "nMC", nMC,"SENS", SENS!,"MCLIFE",
              MCLife(OBJ,SENS,RIVER,SLR)
  RBC_dl  (OBJ,SENS,RIVER,ENERGY,SLR) = MCLife(OBJ,SENS,River,SLR)/
              MCp!benefit:cost
  RBC_cm  (OBJ,SENS,RIVER,ENERGY,SLR) =
              MCLife(OBJ,SENS,River,SLR)/(Hfill)!benefit:cost
  mRBC_dl (OBJ,SENS,RIVER,ENERGY,SLR) =
              MCLife(OBJ,SENS,River,SLR)/MCmp!marginal benefit:cost
  mRBC_cm (OBJ,SENS,RIVER,ENERGY,SLR) = MCLife(OBJ,SENS,River,SLR)/(Efill)
              !marginal benefit:cost
  !OBJECTIVE 1 DUMP
  PRINT*, Year - MCY,',',Hfill,',',RBC_cm(OBJ,SENS,RIVER,ENERGY,SLR)
END IF !OBJ 2 - 4 Completed^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

!INITIALIZE COST SUMMARY VARIABLES
IF (YEAR.EQ.100)THEN
   TOTMCP_66 (OBJ,SENS,RIVER,ENERGY,SLR)= 0
   TOTMCP_100(OBJ,SENS,RIVER,ENERGY,SLR)= 0
   TOTMCCseq_66 (OBJ,SENS,RIVER,ENERGY,SLR)= 0
   TOTMCCseq_100(OBJ,SENS,RIVER,ENERGY,SLR)= 0
   TOTMCCem_66 (OBJ,SENS,RIVER,ENERGY,SLR)= 0
   TOTMCCem_100(OBJ,SENS,RIVER,ENERGY,SLR)= 0
END IF !YEAR

!^^^^^^^^^^^^^^^^^^^^^^^^^^OBJ 5 Caclulate Total Costs^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
IF (OBJ.EQ.5) THEN
   IF (Year.LT.150) TotMCp_66 (OBJ,SENS,RIVER,ENERGY,SLR)=
              TotMCp_66(OBJ,SENS,RIVER,ENERGY,SLR)+ MCp
   PRINT*, "Hfill",Hfill,"(cm)  ENERGY",ENERGY,"    MCP $/m2", MCp
```

```
      !Baseline TOTMCP_66(5,50,1,1,1) = $12.16/m2
      !Baseline TOTMCP_100(5,50,1,1,1) = $12.16/m2
    IF (Year.LT.184) TotMCp_100 (OBJ,SENS,RIVER,ENERGY,SLR)=
                TotMCp_100(OBJ,SENS,RIVER,ENERGY,SLR)+ MCp
    IF (YEAR.LT.150) THEN
      MCCI2066(OBJ,SENS,RIVER,ENERGY,SLR)=
                TOTMCP_66(OBJ,SENS,RIVER,ENERGY,SLR)/12.16
      RCI2066(OBJ,SENS,RIVER,ENERGY,SLR) =
                MCCI2066(OBJ,SENS,RIVER,ENERGY,SLR)+RDp
    END IF  !Marsh Creation Costs Pl
    IF (YEAR.LT.184) THEN
     MCCI2100(OBJ,SENS,RIVER,ENERGY,SLR)=
                TOTMCP_100(OBJ,SENS,RIVER,ENERGY,SLR)/12.16
     RCI2100(OBJ,SENS,RIVER,ENERGY,SLR) =
                MCCI2100(OBJ,SENS,RIVER,ENERGY,SLR)+RDp
    END IF!Marsh Creation Costs Plus River Diversion Costs

   END IF
   !OBJ = 5 Completed^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

  END DO !ENERGY
  RETURN
END IF !dum2------------------------------------------------------------------------

!----------------------------MAIN PROGRAM COMPLETE---------------------------------------------
IF (dum2.EQ.1) THEN

  !WRITE OUTPUT FILES FOR OBJECTIVES 2 - 5
  PRINT*, "OBJECTIVES COMPLETE PRINT OUTPUTS!!!"
  PRINT*, "WRITING OUTPUTS FOR OBJ:",OBJ
   IF (OBJ.GE.2.AND.OBJ.LT.5) THEN
    ENERGY = 3 !no change $55/bl
    DO METRIC = 1,5
    DO RIVER = 1,4
      IF (RIVER.EQ.1) WRITE(slname,*)"20"
      IF (RIVER.EQ.2) WRITE(slname,*)"40"
      IF (RIVER.EQ.3) WRITE(slname,*)"80"
      IF (RIVER.EQ.4) WRITE(slname,*)"160"
      call date_and_time(date,time,zone,values)
      Sen = 0
     DO SENS = 1,100!
       Sen = Sen + 1!1
       call date_and_time(date,time,zone,values)
       IF (OBJ.EQ.2) THEN
         Efill = 2*SENS !Efill height of marsh creation
         IF (SEN.EQ.1)THEN
```

```
 !WRITE(400000+10000*OBJ+SLR*1000+100+10*METRIC,*)&
 !"     Efill          20              80              160             320",&
 WRITE(400000+10000*OBJ+1000+RIVER*100+10*METRIC,*)&
 "Efill,0.35,0.7,1.0,1.5,1.85,",&
 "TSS ",slname,c,date
 END IF
 PRINT*,Efill,"Efill MClife", MCLife (OBJ,SENS,RIVER,1),&
 MCLife (OBJ,SENS,RIVER,2),MCLife
         (OBJ,SENS,RIVER,3),MCLife(OBJ,SENS,RIVER,4),MCLife(OBJ,SENS,RIVE
         R,5)
 IF (METRIC.EQ.1)WRITE(400000+10000*OBJ+1000+RIVER*100+10*METRIC,*)&
   Efill,c,MClife(OBJ,SENS,RIVER,1),c,&
   MClife(OBJ,SENS,RIVER,2),c,&
   MClife(OBJ,SENS,RIVER,3),c,&
   MClife(OBJ,SENS,RIVER,4),c,&
   MClife(OBJ,SENS,RIVER,5)!,c,"MCLife"
 IF (METRIC.EQ.2)WRITE(400000+10000*OBJ+1000+RIVER*100+10*METRIC,*)&
   Efill,c,RBC_cm(OBJ,SENS,RIVER,ENERGY,1),c,&
   RBC_cm(OBJ,SENS,RIVER,ENERGY,2),c,&
   RBC_cm(OBJ,SENS,RIVER,ENERGY,3),c,&
   RBC_cm(OBJ,SENS,RIVER,ENERGY,4),c,&
   RBC_cm(OBJ,SENS,RIVER,ENERGY,5)!,c,"RBC_cm"
 IF (METRIC.EQ.3)WRITE(400000+10000*OBJ+1000+RIVER*100+10*METRIC,*)&
   Efill,c,RBC_dl(OBJ,SENS,RIVER,ENERGY,1),c,&
   RBC_dl(OBJ,SENS,RIVER,ENERGY,2),c,&
   RBC_dl(OBJ,SENS,RIVER,ENERGY,3),c,&
   RBC_dl(OBJ,SENS,RIVER,ENERGY,4),c,&
   RBC_dl(OBJ,SENS,RIVER,ENERGY,5)!,c,"RBC_dl"
 IF (METRIC.EQ.4)WRITE(400000+10000*OBJ+1000+RIVER*100+10*METRIC,*)&
   Efill,c,mRBC_cm(OBJ,SENS,RIVER,ENERGY,1),c,&
   mRBC_cm(OBJ,SENS,RIVER,ENERGY,2),c,&
   mRBC_cm(OBJ,SENS,RIVER,ENERGY,3),c,&
   mRBC_cm(OBJ,SENS,RIVER,ENERGY,4),c,&
   mRBC_cm(OBJ,SENS,RIVER,ENERGY,5)!,c,"mRBC_cm"
 IF (METRIC.EQ.5)WRITE(400000+10000*OBJ+1000+RIVER*100+10*METRIC,*)&
   Efill,c,mRBC_dl(OBJ,SENS,RIVER,ENERGY,1),c,&
   mRBC_dl(OBJ,SENS,RIVER,ENERGY,2),c,&
   mRBC_dl(OBJ,SENS,RIVER,ENERGY,3),c,&
   mRBC_dl(OBJ,SENS,RIVER,ENERGY,4),c,&
   mRBC_dl(OBJ,SENS,RIVER,ENERGY,5)!,c,"mRBC_dl"
ELSE IF (OBJ.EQ.3) THEN
! TEST THE INFLUENCE OF THE DATE OF MARSH CREATION PROJECT
 IF (SEN.EQ.1)THEN
 WRITE(400000+10000*OBJ+1000+RIVER*100+10*METRIC,*)&
 "MCY,0.35,0.7,1.0,1.5,1.85,",&
 "TSS ",slname,c,date
```

```
  END IF
  MCY  = 99+1*Sens !Year Marsh Creatio is initiated
  IF (METRIC.EQ.1)WRITE(400000+10000*OBJ+1000+RIVER*100+10*METRIC,*)&
    MCY + 1916,c,MClife(OBJ,SENS,RIVER,1),c,&
    MClife(OBJ,SENS,RIVER,2),c,&
    MClife(OBJ,SENS,RIVER,3),c,&
    MClife(OBJ,SENS,RIVER,4),c,&
    MClife(OBJ,SENS,RIVER,5)!,c,"MCLife"
  IF (METRIC.EQ.2)WRITE(400000+10000*OBJ+1000+RIVER*100+10*METRIC,*)&
    MCY + 1916,c,RBC_cm(OBJ,SENS,RIVER,ENERGY,1),c,&
    RBC_cm(OBJ,SENS,RIVER,ENERGY,2),c,&
    RBC_cm(OBJ,SENS,RIVER,ENERGY,3),c,&
    RBC_cm(OBJ,SENS,RIVER,ENERGY,4),c,&
    RBC_cm(OBJ,SENS,RIVER,ENERGY,5)!,c,"RBC_cm"
  IF (METRIC.EQ.3)WRITE(400000+10000*OBJ+1000+RIVER*100+10*METRIC,*)&
    MCY + 1916,c,RBC_dl(OBJ,SENS,RIVER,ENERGY,1),c,&
    RBC_dl(OBJ,SENS,RIVER,ENERGY,2),c,&
    RBC_dl(OBJ,SENS,RIVER,ENERGY,3),c,&
    RBC_dl(OBJ,SENS,RIVER,ENERGY,4),c,&
    RBC_dl(OBJ,SENS,RIVER,ENERGY,5)!,c,"RBC_dl"
  IF (METRIC.EQ.4)WRITE(400000+10000*OBJ+1000+RIVER*100+10*METRIC,*)&
    MCY + 1916,c,mRBC_cm(OBJ,SENS,RIVER,ENERGY,1),c,&
    mRBC_cm(OBJ,SENS,RIVER,ENERGY,2),c,&
    mRBC_cm(OBJ,SENS,RIVER,ENERGY,3),c,&
    mRBC_cm(OBJ,SENS,RIVER,ENERGY,4),c,&
    mRBC_cm(OBJ,SENS,RIVER,ENERGY,5)!,c,"mRBC_cm"
  IF (METRIC.EQ.5)WRITE(400000+10000*OBJ+1000+RIVER*100+10*METRIC,*)&
    MCY + 1916,c,mRBC_dl(OBJ,SENS,RIVER,ENERGY,1),c,&
    mRBC_dl(OBJ,SENS,RIVER,ENERGY,2),c,&
    mRBC_dl(OBJ,SENS,RIVER,ENERGY,3),c,&
    mRBC_dl(OBJ,SENS,RIVER,ENERGY,4),c,&
    mRBC_dl(OBJ,SENS,RIVER,ENERGY,5)!,c,"mRBC_dl"
! TEST THE INFLUENCE OF DATE OF RIVER DIVERSION COMPLETION
ELSE IF (OBJ.EQ.4) THEN
  IF (SEN.EQ.1)THEN
  !WRITE(400000+10000*OBJ+SLR*1000+100+10*METRIC,*)&
  WRITE(400000+10000*OBJ+1000+RIVER*100+10*METRIC,*)&
 "RDY,0.35,0.7,1.0,1.5,1.85,",&
  "TSS ",slname,c,date
  END IF
  RDY  = 99+1*Sens !Year diversion is installed
  IF (METRIC.EQ.1)WRITE(400000+10000*OBJ+1000+RIVER*100+10*METRIC,*)&
    RDY + 1916,c,MClife(OBJ,SENS,RIVER,1),c,&
    MClife(OBJ,SENS,RIVER,2),c,&
    MClife(OBJ,SENS,RIVER,3),c,&
    MClife(OBJ,SENS,RIVER,4),c,&
```

```
        MClife(OBJ,SENS,RIVER,5)!"MCLife"
      IF (METRIC.EQ.2)WRITE(400000+10000*OBJ+1000+RIVER*100+10*METRIC,*)&
        RDY + 1916,c,RBC_cm(OBJ,SENS,RIVER,ENERGY,1),c,&
        RBC_cm(OBJ,SENS,RIVER,ENERGY,2),c,&
        RBC_cm(OBJ,SENS,RIVER,ENERGY,3),c,&
        RBC_cm(OBJ,SENS,RIVER,ENERGY,4),c,&
        RBC_cm(OBJ,SENS,RIVER,ENERGY,5)!,c,"RBC_cm"
      IF (METRIC.EQ.3)WRITE(400000+10000*OBJ+1000+RIVER*100+10*METRIC,*)&
        RDY + 1916,c,RBC_dl(OBJ,SENS,RIVER,ENERGY,1),c,&
        RBC_dl(OBJ,SENS,RIVER,ENERGY,2),c,&
        RBC_dl(OBJ,SENS,RIVER,ENERGY,3),c,&
        RBC_dl(OBJ,SENS,RIVER,ENERGY,4),c,&
        RBC_dl(OBJ,SENS,RIVER,ENERGY,5)!,c,"RBC_dl"
      IF (METRIC.EQ.4)WRITE(400000+10000*OBJ+1000+RIVER*100+10*METRIC,*)&
        RDY + 1916,c,mRBC_cm(OBJ,SENS,RIVER,ENERGY,1),c,&
        mRBC_cm(OBJ,SENS,RIVER,ENERGY,2),c,&
        mRBC_cm(OBJ,SENS,RIVER,ENERGY,3),c,&
        mRBC_cm(OBJ,SENS,RIVER,ENERGY,4),c,&
        mRBC_cm(OBJ,SENS,RIVER,ENERGY,5)!,c,"mRBC_cm"
      IF (METRIC.EQ.5)WRITE(400000+10000*OBJ+1000+RIVER*100+10*METRIC,*)&
        RDY + 1916,c,mRBC_dl(OBJ,SENS,RIVER,ENERGY,1),c,&
        mRBC_dl(OBJ,SENS,RIVER,ENERGY,2),c,&
        mRBC_dl(OBJ,SENS,RIVER,ENERGY,3),c,&
        mRBC_dl(OBJ,SENS,RIVER,ENERGY,4),c,&
        mRBC_dl(OBJ,SENS,RIVER,ENERGY,5)!,c,"mRBC_dl"
     END IF !OBJ
    END DO !SENS
    CLOSE (400000+10000*OBJ+SLR*1000+100+10*METRIC)
   END DO !RIVER
   END DO !METRIC
  END IF !OBJ
  IF (OBJ.EQ.5) THEN
   call date_and_time(date,time,zone,values)
   DO RIVER = 1,4
    DO SENS = 5,100,5
     !IF (OBJ.EQ.4) RDY  = 99+1*Sens
     Efill = SENS*2
     IF (RIVER.EQ.1) RDp = 0
     IF (RIVER.GT.1) RDp = 4.7
     PRINT*, "RDp", RDp
     DO METRIC = 1,6
      IF (METRIC.EQ.1) WRITE(Met,*)"TMCP2066"
      IF (METRIC.EQ.2) WRITE(Met,*)"MCCI2066"
      IF (METRIC.EQ.3) WRITE(Met,*)"TMCP2100"
      IF (METRIC.EQ.4) WRITE(Met,*)"MCCI2100"
      IF (METRIC.EQ.5) WRITE(Met,*)"RCI2066"
```

```
 IF (METRIC.EQ.6) WRITE(Met,*)"RCI2100"
 !IF (OBJ.EQ.4) WRITE(500000+10000*METRIC+1000*RIVER+SENS,*)&
 !Met," RDY",RDY," ",date
 WRITE(500000+10000*METRIC+1000*RIVER+SENS,*)&
 Met,",Efill,",Efill,",cm,",date
 WRITE(500000+10000*METRIC+1000*RIVER+SENS,*)&
 "SLR,$55/bbl,Low,Central,High"
END DO
DO METRIC = 1,6
DO SLR = 1,5
 IF (SLR.EQ.1) WRITE(slname,*)"0.35"
 IF (SLR.EQ.2) WRITE(slname,*)"0.7"
 IF (SLR.EQ.3) WRITE(slname,*)"1.0"
 IF (SLR.EQ.4) WRITE(slname,*)"1.5"
 IF (SLR.EQ.5) WRITE(slname,*)"1.85"
 PRINT*,"CONGRATULATIONS YOUR MODEL RUN HAS COMPLETED WITH
        NO ERRORS!!!!!"
 PRINT*,SENS,slname,(TOTMCP_66(OBJ,SENS,RIVER,ENERGY,SLR),ENERGY =
        1,4)
 IF (METRIC.EQ.1)WRITE(500000+10000*METRIC+1000*RIVER+SENS,*)&

        slname,c,TOTMCP_66(OBJ,SENS,RIVER,1,SLR),c,TOTMCP_66(OBJ,SENS,R
        IVER,2,SLR),c,&
  TOTMCP_66(OBJ,SENS,RIVER,3,SLR),c,TOTMCP_66(OBJ,SENS,RIVER,4,SLR)
 IF (METRIC.EQ.2)WRITE(500000+10000*METRIC+1000*RIVER+SENS,*)&

        slname,c,MCCI2066(OBJ,SENS,RIVER,1,SLR),c,MCCI2066(OBJ,SENS,RIVE
        R,2,SLR),c,&
  MCCI2066(OBJ,SENS,RIVER,3,SLR),c,MCCI2066(OBJ,SENS,RIVER,4,SLR)
 IF (METRIC.EQ.3)WRITE(500000+10000*METRIC+1000*RIVER+SENS,*)&

        slname,c,TOTMCP_100(OBJ,SENS,RIVER,1,SLR),c,TOTMCP_100(OBJ,SENS
        ,RIVER,2,SLR),c,&
  TOTMCP_100(OBJ,SENS,RIVER,3,SLR),c,TOTMCP_100(OBJ,SENS,RIVER,4,SLR)
 IF (METRIC.EQ.4)WRITE(500000+10000*METRIC+1000*RIVER+SENS,*)&

        slname,c,MCCI2100(OBJ,SENS,RIVER,1,SLR),c,MCCI2100(OBJ,SENS,RIVE
        R,2,SLR),c,&
  MCCI2100(OBJ,SENS,RIVER,3,SLR),c,MCCI2100(OBJ,SENS,RIVER,4,SLR)
 IF (METRIC.EQ.5)WRITE(500000+10000*METRIC+1000*RIVER+SENS,*)&
  slname,(RCI2066(OBJ,SENS,RIVER,ENERGY,SLR),ENERGY = 1,4)
 IF (METRIC.EQ.6)WRITE(500000+10000*METRIC+1000*RIVER+SENS,*)&
  slname,(RCI2100(OBJ,SENS,RIVER,ENERGY,SLR),ENERGY = 1,4)
END DO !SLR
!CLOSE(500000+10000*METRIC+1000*RIVER+SENS)
END DO !METRIC
```

```
      END DO !SENS
     END DO !RIVER
   END IF !OBJ 5
   904 FORMAT (I1,4(F16.8))
   RETURN
END IF
!-----------------------------------------------------------------------
END SUBROUTINE COSTBENEFIT
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
!$ 12 CARBON
SUBROUTINE
                  CARBONSTOCK(PdO,V,W,T_SOC,dT_SOC,PT_SOC,AGOC,dAGOC,PT_AG
                  OC,dTOC,TOC,PT_TOC,OM2OC,&
       T_height,T_mass,T_Org,T_M,T_org_cm,T_m_cm,T_ps_cm,&
       PT_org_cm,PT_m_cm,PT_ps_cm,PT_Height,PT_mass,&
       dT_height,dT_mass,dT_org_cm,dT_m_cm,dT_ps_cm)
REAL, INTENT (INOUT)::
                  PdO,V,W,T_SOC,dT_SOC,PT_SOC,AGOC,dAGOC,PT_AGOC,dTOC,TOC,PT
                  _TOC,OM2OC,&
T_height,T_Org,T_M,T_mass,T_org_cm,T_m_cm,T_ps_cm,&
PT_org_cm,PT_m_cm,PT_ps_cm,PT_Height,PT_mass,&
dT_height,dT_mass,dT_org_cm,dT_m_cm,dT_ps_cm
    T_SOC = T_Org*OM2OC !Total soil organic carbon
    dT_SOC = T_SOC - PT_SOC
    AGOC = (W+D+V)*OM2OC !above ground organic carbon
    dAGOC = AGOC - PT_AGOC
    TOC = T_SOC + AGOC
    dTOC = TOC - PT_TOC

    dT_org_cm = T_org_cm - PT_org_cm
    dT_m_cm   = T_m_cm - PT_m_cm
    dT_ps_cm  = T_ps_cm - PT_ps_cm
    dT_Height  = T_height - PT_height
    dT_mass = T_mass - PT_mass
    RETURN
END SUBROUTINE CARBONSTOCK
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
!$ 11 Soil Dynamics Subroutine
SUBROUTINE SOILCOHORT&
           (n,nmax,nstat,Week,Year,Trans,Relev,RWL,Leaflit,RootLit,FAVlit,&
            r_g,s,rk,S_in,MCin,MC,WkOp,pdm,pdo,OM2OC,R2S,&
            dQ,dB,dM,dP,k_l,k_ld,aL,aR,lf_v,lf_a,lf_r,k_r,k_rd,pk,sl,xo,acf,&
```

```
            dcf,Cfunc,PSmin,PSmax,T_height,drt,T_org_cm,T_m_cm,T_ps_cm,PT_SOC,T_
            SOC,&

            PT_org_cm,PT_m_cm,PT_ps_cm,dT_org_cm,dT_m_cm,dT_ps_cm,PT_Height,d
            T_Height,&

            T_mass,mass,PT_mass,Tfunc,rL,rt,Z,Q,B,M,P,g,PS,Org_cm,M_cm,P_cm,PS_cm
            ,height,&
      rt_in,BD,pctRt,pctOrg,Org,Depth,rDepth,RD,T_Org,T_M)
 INTEGER,INTENT (INOUT):: nmax,nstat
 INTEGER,INTENT (IN)::YEAR,n,TRANS,week
 REAL, INTENT (IN) ::Relev,RWL,Leaflit,RootLit,FAVlit,r_g,s,rk,S_in,MC,MCin,&
 WkOp,pdm,pdo,OM2OC,R2S
 REAL,INTENT(INOUT)::dQ,dB,dM,dP,k_l,k_ld,aL,aR,lf_v,lf_a,lf_r,k_r,k_rd,pk,sl,xo,acf,&
 dcf,Cfunc,PSmin,PSmax,T_height,drt,T_org_cm,T_m_cm,T_ps_cm,PT_SOC,T_SOC,&
 PT_org_cm,PT_m_cm,PT_ps_cm,dT_org_cm,dT_m_cm,dT_ps_cm,PT_Height,dT_Height,&
 T_mass,T_Org,T_M,PT_mass,Tfunc,rL
 REAL,DIMENSION (500,11), INTENT (IN):: RD
 REAL,DIMENSION (20000)::rt,Z,Q,B,M,P,g,PS,Org_cm,M_cm,PS_cm,P_cm,height,&
 &rt_in,BD,pctRt,pctOrg,Org,mass,Depth,rDepth
 REAL::PSo,PSm,k1,k2,zz,BDo,BDm

            !''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
            ''''''''''''''''''''''''''''''''''
!CALCULATE CHANGES IN SOIL COHORTS, With Mass Balance :) 20170413
!''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
!LABILE ORGANIC MATTER IN COHORTS
IF (n.EQ.1)THEN
  dQ = aL+rt(n)*rootlit*lf_r-Q(n)*k_l
ELSE
  dQ = rt(n)*rootlit*lf_r-Q(n)*k_l
END IF
Q(n) = Q(n)+dQ
!Q(n)- labile organic matter in cohort g cm-2
!dQ - change in refractory organic matter in cohort per unit week
!a - above ground labile litter to surface cohort (g.d.w cm-2 week-1)
!lf_a - labile fraction of above ground biomass = 0.3
!r(n) - root litter inputs to cohort n(g.d.w. cm-2 week-1)
!lf_r - labile fraction of root litter
!Z_l(n-1) - transfer rate of labile matter from overlying cohort
!Q(n-1) - labile organic matter in overlying cohort, (g.d.w. cm-2)
!k_l - (0.028 week-1) decomposition rate of labile OM
!Z_l(n)- transfer rate of labile matter to underlying cohort
!''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
```

```
!''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
!REFRACTORY ORGANIC MATTER IN COHORT
 IF (n.EQ.1)THEN
     dB = aR+S_in*xo+rt(n)*rootlit*(1-lf_r)-B(n)*k_r
 ELSE
     dB = rt(n)*rootlit*(1-lf_r)-B(n)*k_r
 END IF
 B(n) = B(n)+dB
!B(n)- refractory organic matter in cohort g cm-2
!dB - change in refractory organic matter in cohort per unit week
!aR - above ground refractory litter to surface cohort (g.d.w cm-2 week-1)
!lf_a - labile fraction of above ground biomass = 0.3 (unitless)
!rt(n) - root litter inputs to cohort n(g.d.w. cm-2 week-1)
!lf_r - labile fraction of root litter
!B(n-1) - refractory OM in overlying cohort, (g.d.w. cm-2)
!k_r - (week-1) decomposition rate of refractory OM
!IF (week.EQ.1.AND.n.EQ.1)PRINT*, "rt(n)",rt(n)*rootlit," dB",dB," dQ",dQ
!''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

!''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
!TOTAL ORGANIC MATTER IN COHORT
Org(n) = Q(n)+B(n)+rt(n)
!''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

!''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
!MINERAL MATTER IN COHORT
IF (n.EQ.1) THEN
  dM = S_in*(1-xo)
ELSE
  dM = 0
END IF
M(n)= M(n)+dM
!M(n)- mineral matter in cohort g cm-2
!S_in - sedimentation (g cm-2 week-1)from TSS or marsh creation
!xo - the fraction of organic matter in deposited sediment, equal to 0.2, see INITIALIZE


           !''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
           ''''''''''''''''''''''''''''''''

!SUM UP COHORT MINERAL AND INORGANIC MASS CONTRIBUTIONS
!''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
!PREVENT DIVISION BY ZERO
IF(M(n).LE.10.0**(-8))   m(n)  = 10.0**(-8)
IF(Org(n).LE.10.0**(-8)) Q(n)  = 10.0**(-8)
IF(Rt(n).LE.10.0**(-8))  Rt(n) = 10.0**(-8)
```

```
!Calculate Mass
mass(n) = Org(n) + M(n)
pctOrg(n) = (Org(n))/mass(n)
pctRt(n)  = (rt(n))/mass(n)
T_Org = T_Org + Org(n)
T_M = T_M + M(n)
T_mass = T_mass + mass(n)
!""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""
!""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""

!""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""
!CALCULATE HEIGHT OF COHORTS
!MEM v5.41 Assumes No Compaction mineral and organic matter are discrete packages
!Bulk Density of Mineral Organic Matter With Zero Loading
k1=0.085 !g/cm3 Self Packing Density of Organic Matter Morris et al. 2016
k2=1.99  !g/cm3 Self Packing Density of Mineral Matter Morris et al. 2016
M_cm(n)= M(n)/k2
Org_cm(n) = (Q(n)+B(n)+rt(n))/k1 !Assumes incompressible organic matter.
!Org_cm(n) - hieght of mineral matter in cohort n
!M_cm - hieght of mineral matter in cohort (g cm-2 / g cm-3)
!OM2OC = 2.22 - converts carbon content to dry wieght
!PDo = 1.14 - particle density of organic matter g cm-3 (DeLaune et al 1983)
height(n) = Org_cm(n)+M_cm(n)
!height(n) - hieght (cm) of sediment cohort
IF (n.EQ.1) Depth(n) = 0
IF (n.GT.1) Depth(n) = Height (n-1)+ Depth(n-1) !Depth at Upper edge of soil cohort
rDepth(n) = Relev - Depth(n) + Height(1) !Depth relative to water level
IF(height(n).LE.10**(-8)) height(n) = 10**(-8)
IF(mass(n).eq.0)PRINT*,Year,Week,n,"COHORT MASS EQUALS ZERO" !cohorts MASS
        EQUALS ZERO
IF(height(n).eq.0)PRINT*,Year,Week,n,"COHORT HEIGHT EQUALS
        ZERO",height(n),mass(n) !cohorts MASS EQUALS ZERO

BD(n) = mass(n)/height(n) !Bulk density
!ideal mixing model from Morris et al. 2016:
!BD(n) = 1/((LOI/k1+(1-LOI)/k2)) bulk density mixing model from Morris et al 2016
!where: LOI is loss on ignition (g/g) or %org/100, k1 is the BD when LOI=1, k2 is the BD
        when LOI = 2

!SUM HEIGHT IN COHORTS
!IF(n.EQ.18) PRINT*, "T_mass",T_mass
T_height = T_height + height(n) !cm
T_Org_cm = T_Org_cm + Org_cm(n)
T_M_cm = T_M_cm + M_cm(n)
T_PS_cm = T_PS_cm + PS_cm(n)
!""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""
```

```
!""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""
!Root Allocation In Cohorts (Rybzcyk & Cahoon 2002)
rt(n) = (s/10000)*(EXP((-rk)*T_height)-EXP((-rk)*depth(n)))/(-rk)
!""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""

		!"""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""
		""""""""""""""""""""

		!________________________________________________________________________
		_____________
		!Write Cohort State Variables to dump file
IF(week.EQ.1.OR.week.EQ.52)THEN
IF(Year.EQ.1.OR.Year.EQ.50.OR.Year.EQ.100.OR.Year.EQ.125.OR.Year.EQ.150) THEN

		WRITE(30000+1000*SLR+100*sentest+TRANS,971)Year+1916,',',n,',',depth(n),
		',',rdepth(n),',',Height(n),',',Rt(n),&
',',Q(n),',',Org(n),',',M(n),',',Org_cm(n),',',M_cm(n),',',PS_cm(n),',',BD(n),',', pctOrg(n),',',&
dQ,',',dB,',',dM,',',aR,',',aL,',',rootlit
END IF
END IF
971 FORMAT (I4,A1,I2,21(A1,F16.8))

		!________________________________________________________________________
		_____________


		!"""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""
		""""""""""""""""""""
!TRANSFER OF MATTER BETWEEN COHORTS
!"""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""
!Transfer rate of material between cohorts
!Exponential decay of transfer with depth to give best resolultion
nmax = 2 !18
Z(n)=0.1-0.1*n/(10+n)
!This function for mass transfer gives proper resolution with depth at 18 cohorts
!It is not nessecary to simulate 18 soil cohorts
!nmax can be reduced to decrease calculation time

!CALCULATE TRANSFER OF MATTER
!"""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""""
IF (n.GT.1.AND.WEEK.EQ.1) THEN
  !LABILE ORGANIC MATTER
  Q(n) = Q(n)+Z(n-1)*Q(n-1)
  Q(n-1) = Q(n-1)-Z(n-1)*Q(n-1)
```

```
    !REFRACTORY ORGANIC MATTER
    B(n) = B(n)+Z(n-1)*B(n-1)
    B(n-1) = B(n-1)-Z(n-1)*B(n-1)

    !MINERAL MATTER
    M(n) = M(n)+Z(n-1)*M(n-1)
    M(n-1) = M(n-1)-Z(n-1)*M(n-1)
  END IF
  !Mass is balanced using these equations :) 201740134
  !This caclulation must be done after cohort production decay and sediment advection
  !''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
  !''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
  RETURN
END SUBROUTINE SOILCOHORT
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
!$ 10 Reset Soil Variables
SUBROUTINE SUB_SOILRESET (week,T_height,T_mass,T_org_cm,T_m_cm,T_ps_cm,&
T_SOC,PT_org_cm,PT_m_cm,PT_ps_cm,PT_Height,PT_mass,PT_SOC,PT_AGOC,PT_TOC,
                &
T_TOC,T_AGOC,T_ORG)
INTEGER, INTENT (IN):: week
REAL, INTENT (INOUT):: T_height,T_mass,T_org_cm,T_m_cm,T_ps_cm,&
T_SOC,PT_org_cm,PT_m_cm,PT_ps_cm,PT_Height,PT_mass,PT_SOC,PT_AGOC,PT_TOC,
                &
T_TOC,T_AGOC,T_ORG
  ! at week 1 Store Cohort Total Data from Previous Year
 IF (week.EQ.1) THEN
   PT_org_cm  = T_org_cm
   PT_m_cm  = T_m_cm
   PT_ps_cm  = T_ps_cm
   PT_Height = T_height
   PT_mass = T_mass
   PT_SOC = T_SOC
   PT_AGOC = T_AGOC
   PT_TOC = T_TOC
  END IF
  !Reset T_height to zero
  T_height = 0
  T_mass   = 0
  T_Org    = 0
  T_M      = 0
  T_org_cm = 0
  T_m_cm   = 0
  T_ps_cm  = 0
```

```
   T_SOC = 0
   RETURN
END SUBROUTINE SUB_SOILRESET
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
!$ 9 Primary Production
SUBROUTINE SUB_PRIMPROD_MD (week,Steps,ECOS,Gmax,RPf,RELEV,r2s,&
rfunc,tr_bg,tr_ag,rootlit,leaflit,V,W,D,R,s,rk,aL,rL,TEMP,Tfunc,&
T_opt,T_min,lf_a,TSS,export,ptind)
  INTEGER, INTENT (IN):: week,Steps,ECOS
  REAL, INTENT(IN)::ptind
  REAL, INTENT (INOUT):: Gmax,RPf,RELEV,r2s,rfunc,tr_bg,tr_ag,&
  rootlit,leaflit,V,W,D,R,s,rk,aL,rL,TEMP,Tfunc,T_opt,T_min,lf_a,TSS,export
  REAL::Mort,RGMax,Hfunc,rtlit
  !THE FOLLOWING SUBROUTINE IS ADAPTED FROM Rybczyk et al. 2002 AND Morris
        et al. 2002
  !MISSISSIPPI DELTA MARSH PRODUCTIVITY - SALINE/BRACKISH MARSH

  !MAXIMUM WEEKLY NET PRIMARY PRODUCTIVITY
  RGMax = Gmax !RGmax is a variable for Gmax used/modified in this subroutine only
  !g dw/m2/year * if reported in C multiply by 0.45 (g C/g dw)

  !SCENARIO DIVERSION INCREASES PRIMARY PRODUCTIVITY
  !RGMax = 1600+ 1600*(TSS/(3+TSS))  !Snedden et al. 2015; Roberts et al. 2015; DeLaune et
        al. 2016

  !MODIFY PRODUCTIVITY IF MARSH CREATION OCCURS
  IF (MC.EQ.1) THEN
  !the marsh dies all above ground biomass is littered
    RGmax = 0.01
    Mort = 0.99
    !mort - LEAF SENESENCE, the rate of TRANSITION FROM LIVE TO DEAD ABOVE
        GROUND BIOMASS
    Leaflit = 0.99
  END IF !Producivity modification

  IF (week.LE.38) THEN
    Mort = 0.06 !Calibrated to fit Hopkinson et al. 1978 for S. Alterniflora live and dead biomass
  ELSE
    Mort = 0.19 !Calibrated to fit Hopkinson et al. 1978 for S. Alterniflora live and dead biomass
  END IF

  !PRIMARY PRODUCTIVITY OF MARSH RELATIVE TO ELEVATION
  RPf = 0.5+4*(ptind-0.05)-5.5*(ptind-0.05)**2
  !RPf - relative productivity factor (unitless ranges from 0-2)
```

```
IF (RPf.LT.0)THEN !MARSH VEGETATIVE COLLAPSE (Day et al. 2011)
  RPf = 0
  MORT = 1
  Leaflit = 1
  Rootlit = 1
END IF

!TEMPURATURE AND GROWTH RATE FUNCTION
T_func = TEMP*(1/(T_opt-T_min))*(T_min/(T_opt-T_min))
!calibrated to hopkinson et al. 1978

!MARSH VEGETATION BIOMASS STATE EQUATIONS
dV = RGmax*RPf*T_func-V*mort
!dV - change in above ground live stem biomass (g dw m-2)
!RGmax - maximum growth rate(g dw m-2 wk-1) at optimal relev/ptind for growth
!RPf - a factor (0-1) to adjust production as a function of relev/ptind

!ABOVE GROUND LITTER
!Labile Litter
aL = (D*Leaflit*lf_a)/10000
!Refractory Litter
aR = (D*Leaflit*(1-lf_a))/10000

D = D + V*Mort - D*Leaflit - D*Export
V = V + dV
!V - Marsh Live Vegetation Standing Crop (g dw m-2)
!D - Dead Marsh Vegetation Standing Crop (g dw m-2)
!V from Hopkinson et al 1978
!T_func - tempurature limitation function
!Leaflit - litter rate of V to Dead

!ROOT BIOMASS
r_g = R2S*RGmax*RPf
!r_g - weekly root/rhizome growth (g dw m-2 wk-1)
!R2S - ratio of below ground productivity to above ground productivity
!RGmax - maximum growth rate(g dw m-2 wk-1) at optimal relev/ptind for growth
!RPf - a factor (0-1) to adjust production as a function of relev/ptind

rtlit = rootlit
R = R - R*rtlit !
dR = r_g
R = R + dR
s = R/((-1)/(-rk)) !root biomass at surface cohort (Rybzcyk & Cahoon 2002)
!R - is live root biomass(g dw m-2)
!r_g - root growth g dw m^2 week-1
```

```
  !rootLit - (f_4) root litter rate (week-1)
  !s - weight of roots at sediment surface
  !rk - root depth distribution constant of 0.8

   RETURN
END SUBROUTINE SUB_PRIMPROD_MD
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
!$ 8 Sediment Deposition
SUBROUTINE SUB_SEDADV (ECOS,Y,RDY,MCY,nMC,Sacc,TSS,Sfunc,&
                    qs,ks,V,ptind,RHW,Dmax,steps,&
                    S_in,MC,Relev,Flood,Hfill,Efill,Ffreq,&
                    mck,MCin,RD,week,YEAR,TRANS,pdm,Wkop,count)

INTEGER, INTENT (IN):: Week,YEAR,TRANS,Ecos,steps,MCY,RDY,nMC,count
REAL, INTENT (INOUT):: Y,Sacc,TSS,Sfunc,qs,ks,V,ptind,RHW,Dmax,&
S_in,MC,Relev,Flood,Hfill(100),Ffreq,Efill,mck,MCin,pdm,Wkop
REAL,DIMENSION (500,11):: RD

  !Change suspended sediment based on objective and level of river influence
  IF (OBJ.EQ.1.OR.OBJ.EQ.6.AND.SENSIT.NE.9) THEN
     TSS = 20 + 20*(RIVER-1)
   ELSE IF(SENSIT.EQ.9)THEN
     IF (YEAR.LT.20) TSS = 20 + 20*(RIVER-1)
   ELSE
     TSS = 20
  END IF
  IF(OBJ.GE.2.AND.OBJ.LE.5.AND.YEAR.GE.RDY)THEN
    IF (River.EQ.1) TSS = 20      !Isolated Interior      (Lowest)
    IF (River.EQ.2) TSS = 40      !Coastal Bay/Bayou      (Low)
    IF (River.EQ.3) TSS = 80      !Deltaic Bay Farfield   (High)
    IF (River.EQ.4) TSS = 160     !Deltaic Throughput     (Highest)
  END IF

  !SUSPENDED SEDIMENT ADVECTION/DEPOSITION
  IF (ECOS.LE.3)then
    !MEM v5.41 with vegetation trapping added
    Sfunc = (TSS/10000*(qs+ks*(V+D)/10000)*ptind*(RHW+Dmax)/2)*6
    !Sediment input due to indundation (g cm-3 wk-1)
    !MEM v5.41 without vegetation trapping feedback
    !Sfunc = (TSS/10000*qs*ptind*(RHW+Dmax)/2)*7
    !Sfunc = m*(qs+k*Bs)*w*z/2*f
    !where TSS is total suspended sediment, qs is the settling velocity of particles,
    !ks is the particle trapping coefficient, V is above ground live biomass, D is above ground
                    dead biomass
```

```
  !RHW is relative high water (90% WL), Dmax is differenc between maximum (99% WL)
        flooding depth and RHW.
  !ptind is the percent indundation of the marsh see SUB_RELHYDROP
  ! the term D^2/T  (D- being flooding depth, and T being tidal range) has been replaced with
  ! a percent inundation function that was fit to tidal marsh in louisiana at CRMS sites.
  !Dmax is the maximum water level 99%, Dmax is used so that deposition still occurs even
  !if a marsh is above 90% WL, which is 23 cm, marshes with high TSS will sit at or above 90%
        WL
  !while marshes with low TSS will sit below
  !ks and qs were calibrated to CRMS data
  !equation modified from Morris et al. 2012 Assesment of carbon sequestration potential in
        coastal wetlands
END IF

IF (ECOS.EQ.4.OR.RESTORE.EQ.3)then
  Sfunc = (TSS/10000)*Ffreq*(Flood)/4
END IF
IF (ECOS.EQ.5)then
  Sfunc = (TSS/10000*(qs+ks*(V+D)/10000)*ptind*(RHW+Dmax))*6/2
END IF

S_in = Sfunc !Sediment input (g cm-3 wk-1)
MCin = 0

!SEDIMENT INPUT FROM DREDING (MARSH CREATION, MC)
IF (MC.EQ.1) THEN !IF MC has been triggered
  IF (count.EQ.1)THEN !And this is the first dredging event of the year
    MCin = mck*Hfill(nMC)!add sediment mass equal to the fill height
    !MCin - dredged sediment input (g cm-3)
    !mck - bulk density of dredged sediment
    !     (equal to 1.18 at 3% organic matter), see initialize
    !Hfill - fill height of the nth marsh creation effort
    S_in = MCin !No tidal input only dredged sediment input
  ELSE
  Hfill(nMC) = 0
  MCin = 0
  END IF
  PRINT*, "&^#@&$^#@%R$#@ MARSH CREATION INPUT!!!!",&
  MCin, "(g cm-3)  ", Hfill(nMC), "(cm)"
END IF

!SEDIMENT INPUT FROM A RIVER DIVERSION
!(if a diversion is being modeled explicitly)
IF
        (YEAR.GE.RDY.AND.YEAR.LE.200.AND.RD(YEAR,TRANS).GT.0.AND.we
        ek.LE.Wkop) THEN
```

```
    Sfunc = RD(Year,TRANS)*100*pdm*(1 - 0.6)/Wkop
    !RD (cm) accretion from diversion is read in from an external file
    S_in = Sfunc
  END IF

  !Tally up annual accreation from sediment deposition
  IF(week.EQ.1)Sacc = 0
  Sacc = Sacc + S_in/mck
  !IF(week.EQ.52.AND.RIVER.EQ.1.AND.SENS.EQ.1) PRINT*, Year," rhw",RHW, "
          relev",relev, " %ind",ptind,  " Sacc",Sacc
  RETURN
END SUBROUTINE SUB_SEDADV
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
!$ COMPACTION/SETTLING OF SUBSURFACE SOILS DUE TO DREDGING
          OVERBURDON
SUBROUTINE COMPACTION (Yr,Week,Ymc,MCY,nMC,STLG,sl,pk,acf,Hfill)
INTEGER, INTENT (IN):: Week,MCY,nMC
REAL, INTENT(INOUT):: Yr,STLG,sl,pk,Hfill(100),acf,Ymc(100)
INTEGER :: n,mcyr(100)
  STLG = 0

  IF (nMC.EQ.0) RETURN !IF MARSH CREATION HAS NOT OCCURED RETURN TO
          MAIN PROGRAM

  DO n = 1,nMC !CALCULATE SETTLEMENT FOR EACH DREDGING EVENT (nMC)
   !PRINT*,Yr,n,"Hfill",Hfill(n)
    acf = Hfill(n)*sl*(Yr-Ymc(n))/(pk+(Yr-Ymc(n))) !This function is working properly :}
          20170512
    !autocompaction function - michaelis mentin
    !Hfill - total height of fill
    !pk - compaction constant, years until half of total compaction has occured
    !sl - settling ratio, amount of settling as a fraction of fill height
    !Typically ranges between 0.1 (10% compation) and 0.6 (60% compaction) in the Miss. Delt.
    !This depending on the amount of fill and the characteristics of fill and subsurface sediments
    !Based on settlement curves from geotechinal surveys in marsh creation design reports
    STLG = STLG + acf
    !Sum up total settling for each addition of dredged sediment
  END DO
END SUBROUTINE
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
!$ 7 Relative Elevation and Hydroperiod
```

```
SUBROUTINE SUB_RELHYDROP
                    (Week,Yr,Ecos,Elev,T_height,Initrelev,RWL,WL,MHW,MLW,&
              Tamp,ERHW,Relev,ptind,Dmax,Lmax,MHT,RHT,SubR,steps,STLG)
INTEGER, INTENT (IN):: Week,Ecos,steps
REAL, INTENT (INOUT):: Yr,Elev,T_height,Initrelev,RWL,WL,MHW,MLW,&
Tamp,ERHW,Relev,ptind,Dmax,Lmax,MHT,RHT,SubR,STLG
REAL             :: Y,w,ULE

  !START Water Level & Elevation Subroutine
  !10 Years of "spin up" time to ensure stable below ground biomass
  IF (YEAR.LT.10)WL   = T_Height
  IF (OBJ.GT.1.AND.OBJ.LT.6.AND.YEAR.LT.100) WL = T_Height

  !RELATIVE WATER LEVEL weekly SLR + Subsidence
  WL   = WL + Subr/52 + dSL/52!

  ![INSERT A FUNCTION FOR WEEKLY WATER LEVEL VARIATION HERE]

  !MARSH ELEVATION
  Elev = T_Height + Initrelev - STLG

  !METRICS FOR RELATIVE ELEVATION AND Tamp
  Relev  = Elev - WL !Elevation Relative to Water Level
  RWL = WL - Elev !Depth Relative to Water Level
  MHW = WL + Tamp !Mean High Water and Elev [This could change weekly]
  RHW = WL + Tamp - Elev !Flooding Depth During Mean High Water
  ERHW = -RHW !Elevation Relative Mean High Water

  !PROPORTION OF TIME INUNDATED
  ptind = 1/(1+exp(1.137*2/Tamp*(Relev-2))) !working properly :) 20170512
  !ptind = 1/(1+exp(ki*kii/Tamp*(Relev-kii))
  !ki and kii are fitted parameters
  !Tamp is tidal amplitude in cm
  !calibrated to CRMS data
  !logistic function for percent inundation as a
  !function of tidal range and relative elavation

  !UNITLESS ELEVATION (PROXY FOR PERCENT INUNDATION from MEM v5.41)
  !ULE = (Tamp-Relev)/(Tamp*2) !ULE - Unitless Elevation see Morris & Callaway 2017
  !ptind = ULE
  !IF(ptind.GE.1)ptind=1
  !IF(ptind.LE.0)ptind=0
  !In this mississippi delta double the Tamp amplitude for ULE esimation
  !99%WL - MWL is roughly double the 90%WL - MWL
  !90%WL and MWL are available from CRMS, 90%WL - MWL is used in
  !place of mean astrinomical tidal amplitude, 99%WL must be estimated
```

```
  !with one year of  hourly data using a water level program or spreadsheet software
  !contact: adrian.wiegman@gmail.com (cc: awiegman@uvm.edu) for details on WL
                     calculations
      RETURN
END SUBROUTINE SUB_RELHYDROP
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
!$ 6 RESTORATION SCenario
SUBROUTINE SUB_RESTSCNR
                     (YEAR,yrs,Restore,RD,MC,RDY,MCY,TSS,RIVER,Trans,Ntrans)
INTEGER, INTENT (IN):: YEAR,yrs,RIVER,TRANS,nTrans,Restore,MCY,RDY
REAL, INTENT (INOUT):: MC,TSS
REAL,DIMENSION (yrs,nTrans), INTENT (INOUT):: RD
  IF (YEAR.GE.MCY) THEN
    SELECT CASE (Restore)
    CASE (1)!No Restoration
    MC = 0
    RD(Year,Trans) = 0
    CASE (2)!River Influence Only
    MC = 0
    CASE (3)!Hydrologic Restoration Only
    MC = 0
    RD(Year,Trans) = 0
    CASE (4)!MC Only
    IF (RELEV.LE.Ecrt)MC = 1
    IF (RELEV.GT.Ecrt)MC = 0
    RD(Year,Trans) = 0
    CASE (5)!MC + River Influence
    IF (RELEV.LE.Ecrt)MC = 1
    IF (RELEV.GT.Ecrt)MC = 0
    CASE DEFAULT
    MC = 0
    RD (YEAR,Trans) = 0
    TSS = TSS
    END SELECT
  END IF
  RETURN
END SUBROUTINE SUB_RESTSCNR
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
!$ 5 Sea Level Rise & Subsidence (Relative Sea Level Rise, RSLR)
SUBROUTINE SUB_SEARISE(YEAR,dSL,WL,T_Height,SubR,MCY,OBJ)
INTEGER, INTENT (IN):: YEAR,MCY,OBJ
REAL, INTENT (INOUT):: dSL,WL,T_Height,SubR
```

```
REAL            :: Y
Y = YEAR
IF (OBJ.EQ.3) THEN
  Y = YEAR + MCY - 100
END IF

!IF (YEAR.LT.14) dSL = (0.0006)*100
!IF (YEAR.GE.14.AND.YEAR.LT.76) dSL = (0.0014)*100
!IF (YEAR.GE.76.AND.YEAR.LT.100) dSL = (0.0033)*100
IF (YEAR.LT.100) dSL = 0.2 !cm/yr
IF (OBJ.NE.6.AND.YEAR.LT.100) SubR = 0.8
IF (YEAR.GE.100.AND.SLR.EQ.1) dSL = (0.0035)*100
IF (YEAR.GE.100.AND.SLR.EQ.2) dSL = (0.000161*(Y-100)+0.0035)*100
IF (YEAR.GE.100.AND.SLR.EQ.3) dSL = (0.000290*(Y-100)+0.0035)*100
IF (YEAR.GE.100.AND.SLR.EQ.4) dSL = (0.000409*(Y-100)+0.0035)*100
IF (YEAR.GE.100.AND.SLR.EQ.5) dSL = (0.000517*(Y-100)+0.0035)*100

IF(OBJ.EQ.6) THEN !Current rates of RSLR
  dSL = 0.33!cm/yr
  !with dSL = 0.33 RSLR = 1.2 cm/yr
  !this is the current average across CRMS sites
  !reported by Janowski et al. 2017
END IF
  !MODEL CALIBRATION USING HINDCAST OF GRAND ISLE
  !USE SEA LEVEL AND INFERRED SUBSIDENCE DATA FROM
  !Kolker et al. 2011 Geophysical Reseach Letters
  !ESLR
  !SUBSIDENCE
  !rate of eustatic sea level rise is from Pensacola,FL
  !IF(Year.LT.100) dSL=(0.0021)*100 !cm/yr
  !SELECT CASE (YEAR)
  !  CASE (:142)!Prior to 1959
  !  SubR = 3.16/10
  !  CASE (143:158)!b.w 1959 and 1974
  !  SubR = 12.64/10 !cm/yr
  !  CASE (159:175)!b.w 1975 and 1991
  !  SubR = 8.59/10 !cm/yr
  !  CASE (176:190)!b.w 1992 and 2006
  !  SubR = 1.04/10 !cm/yr
  !  CASE (191:)
  !  SubR = 6.0/10 !cm/yr
  !  CASE DEFAULT
  !  SubR = 6.0/10 !cm/yr
  !END SELECT

!PRINT*, Year, "dsl", dSL*100
```

```
!IF (Year.EQ.99) WL = dSL*100 + T_Height + Subr + Initelev(trans)*100
!SHOULD SUBSIDENCE BE TAKEN FROM ELEVATION OR ADDED TO SEA LEVEL?
RETURN
END SUBROUTINE SUB_SEARISE
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
SUBROUTINE INPUTFILES (Yrs,nTrans,Energy,SLR,Year,Trans,n,OilP,Initelev,RD)

  INTEGER, INTENT (In) ::Yrs,nTrans
  INTEGER, INTENT (INOUT) ::Energy,SLR,Year,Trans,n
  REAL, INTENT (OUT) :: OilP(500,4)
  REAL,DIMENSION (nTrans):: Initelev
  REAL,DIMENSION (yrs,nTrans):: RD
  !READ OIL PRICE INPUT---------------------------------------------------
  READ (16,*) ((OilP(Year,ENERGY),ENERGY = 2,4),YEAR = 94,184)
  REWIND (16)
  DO YEAR = 185,500
    DO ENERGY = 1,4
    IF (ENERGY.EQ.1) THEN
      OilP(Year,Energy) = 50
    ELSE
      OilP(Year,Energy) = OilP(184,Energy)
    END IF
    END DO
  END DO
  !-----------------------------------------------------------------------
  !READ DIVERSION INPUT FILES
  !IF (RESTORE.EQ.1.OR.RESTORE.EQ.5) THEN
  !PRINT*,"READING RIVER SEDIMENT KIM FILE_SLR", SLR
  !READ (40+sentest,*) Wkop, Discharge
  READ (40+SLR,*) (Initelev(Trans),Trans = 1,11)
  READ (40+SLR,*) ((RD(YEAR,Trans),Trans = 1,11), YEAR = 100,150)
  REWIND (40+SLR)
  DO Year = 100,150
     DO Trans = 1, 11
        IF (RD(YEAR,Trans).LT.0) RD(YEAR,TRANS) = 0.00
     END DO
  END DO !Year
  DO YEAR = 151,500
    DO Trans = 1, 11
    RD(YEAR,Trans)=0
    END DO
  END DO
  !END IF
  !-----------------------------------------------------------------------
```

```
   RETURN
END SUBROUTINE INPUTFILES
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
!$ 2
SUBROUTINE INITIALIZE (&
   Yrs,ntrans,&
   Ecos,Restore,sentest,Dvtest,Energy,SLR,Year,Trans,&
   OilP,&
   n,Q,B,P,rt,M,PS,Org_cm,PS_cm,M_cm,P_cm,height,depth,mass,&
   T_org_cm,T_M_cm,T_ps_cm,T_height,T_mass,T_SOC,T_TOC,T_Org,T_M,&

                  Tamp,TSS,SubR,V,W,D,R,R2S,PSmin,PSmax,rootlit,leaflit,rk,sl,xo,pk,lf_r,lf_a,
                  w_i,T_opt,T_min,&
   Initelev,RD,qs,ks,k_r,k_rd,k_l,k_ld,Dmax,S_in,MC,MCin,mck,Ecrt,&
   WKop,Hprd,Ffreq,Initrelev,Relev,Elev,WL,Efill,Flood,export,Gmax)

   INTEGER, INTENT (In) ::Yrs,nTrans
   INTEGER, INTENT (INOUT) ::Ecos,Restore,sentest,Dvtest,Energy,SLR,Year,Trans,n
   REAL, INTENT (OUT) ::
                  OilP(500,4),T_org_cm,T_M_cm,T_ps_cm,T_height,T_mass,T_SOC,T_TOC,&
   Tamp,TSS,SubR,V,W,D,R,R2S,PSmin,PSmax,rootlit,rk,sl,xo,pk,lf_r,lf_a,w_i,T_opt,T_min,&

                  qs,ks,k_r,k_rd,k_l,k_ld,Dmax,S_in,MC,mck,Ecrt,WKop,Flood,Hprd,Ffreq,Initrel
                  ev,relev,Elev,WL,Efill,&
   export,gmax,leaflit,MCin,T_Org,T_M
   REAL, INTENT (OUT),DIMENSION (20000) ::
                  P,P_cm,Q,B,rt,M,PS,Org_cm,PS_cm,M_cm,height,depth,mass
   REAL,DIMENSION (nTrans):: Initelev
   REAL,DIMENSION (yrs,nTrans):: RD

   !INITIALIZE PARAMETERS FOR BRACKISH MD WETLANDS-------------------------
   IF (ECOS.EQ.1) THEN !MD - Brackish/Saline Ter/Bar
     !BIOGEOPHYSICAL PARAMETERS
     Relev = 0
     Initrelev = 10
     IF (OBJ.GT.1.AND.OBJ.LT.6)Initrelev = -50
     Tamp    = 23.4    !90%WL (Mean High Tamp) - 50%WL (Mean Water Level)
     TSS     = 20.0    !Mean Suspended sediment concentration in terrebone bay! assume 90
                  annual mean TSS in Fourleague bay
     Dmax    = 25      !average difference in inundation depth (cm) b.w. 99% WL (storms &
                  fronts)  90% WL (MHT)
                  !to and 90% water level (mean high Tamp) calculated from CRMS stations
     SubR    = 0.87    !Median Subsidence Rate cm/yr from Selected CRMS Sites
                  !25th% is 0.52 and 75% is 1.16 cm/yr
```

! and 0.3-2.9 cm per year in east baratar/birdfoot
!54.0
!acf = 1 - sl*Yr/(pk+Yr)
!sl = (H_f - H_20)/H_f
sl = 0.3 !settlement ratio (unitless b.w. 0-1) of initial fill height to total settling after 20 years from MC geotechnical survey settlement curves.
pk = 2 !half settling period - time at 50% of total settlement calibrated to match MC settlement curves.
Ffreq = 312/52 !times per week
qs = 1.0/52 !sediment capture efficiency the fraction of the sediment mass available during mean high water that is captured by the marsh
!qs is calibrated to accretion rates from crms data See "MEMvsCRMS_Accretion...xlsx"
ks = 7.8/52 !efficiency of vegetation as a sediment trap (g/g) g/m2 sediment per g/m2 of biomass per indundation
export = 0.0071 !portion of dead biomass that is not deposited in the cell based on nyman et al 1993 assume 50% per year
Gmax = 2000/52 !weekly maximum above and belowground productivity when RPf = 1 based on CRMS accretion data and hopkinson et al. 1978 !nyman et al. 1993 (g m-2)
xo = 0.03 !fraction of suspended sediments made of particulate organic matter (Day et al. 2011)
W = 0 !REMOVE
V = 0!200 !Live biomass in January, s. alterniflora !(Hopkinson et al 1978)
D = 0!800 !standing dead biomass, Assume 800 for beginning of year (Hopkinson et al 1978)
R2S = 2 !Root to shoot ratio, Assume ~2:1 shoot:root (Snedden 2015), note: Rybczyk & Cahoon 2002 assume 1:1
R = 0!(V+D)*2*R2S !standing live root biomass
rk = 0.08 !rk - root depth distribution constant ranges from 0.06 - 0.1 OB and BC Rybczyk & Cahoon 2002
leaflit = 0.04 !0.06 Gorwing season/ 0.19 dormant season, variable depending on season calibrated to match hopkinson et al 1978, mean standing biomass at Gmax is ~1600
rootlit = 0.026 !Calibrated to match a 2 to 1 live root & rhyzome to shoot ratio at Gmax of 2*2600 g m-2
lf_r = 0.9 !labile fraction root litter (everything but lignin) Morris & Callaway 2017
lf_a = 0.99 !labile fraction above ground litter (everything but lignin) Morris & Callaway 2017
k_r = 10**(-4) !Decomposition of the true refractory pool, lignin content assumed to be 10%, Morris & Callaway 2017
! (% week-1) solved for annual organic accretion rate at Gmax of 1200 with litter inputs of 4900 (Rybzcyk & Cahoon 2002)
k_l = 0.0098!0.0098!0.09 ! (% week-1) decay rate of surface labile organic matter (Rybzcyk & Cahoon 2002)

```
  k_ld    = 0.0098!0.0098!0.049   ! (% week-1) decay rate of subsurface (deep)labile organic
                matter (Rybzcyk & Cahoon 2002)
  w_i     = 0.09   !REMOVE !w_i - elevation rel high water level for species in Louisiana(Day
                et al 2011)
  T_opt   = 25.8    !Calibrated to fit Hopkinson et al. 1978 for S. Alterniflora live and dead
                biomass
  T_min   = 11 !Calibrated to fit Hopkinson et al. 1978 for S. Alterniflora live and dead
                biomass
  !RESTORATION PARAMETERS
  Wkop    = 6 !weeks of diversion operation
  Efill   = 100 !target fill height (cm) of marsh creation
  Ecrt    = -10 !crit elevation
  Flood   = 30
  mck     = 1/(xo/0.085 + (1-xo)/1.99) !mck - bulk density of MC fill material (g cm-3)
                          !This parameter is used to convert target fill hieght into grams of
                sediment deposited.
                          !assuming 3% organic matter (xo), BD is equal to 1.18(g cm-3)
                          !assuming 2% organic matter (xo), BD is equal to 1.37(g cm-3)
  MC      = 0
  MCin    = 0
END IF
!-----------------------------------------------------------------------
!INITIALIZE SOIL COHORT DATA---------------------------------------------------
!Initial soil profile, height of the soil column, and Carbon Stock
T_height = 0
T_Org_cm = 0
T_M_cm = 0
T_PS_cm = 0
T_SOC = 0
T_mass = 0
T_M =0
T_Org =0
DO n = 1,18
  READ (11,900)Q(n)
  READ (12,900)B(n)
  READ (13,900)M(n)
  READ (14,900)rt(n)
  READ (15,900)PS(n)
  P(n) = 0
  P_cm(n) = P(n)
  Org_cm(n) = (Q(n)+B(n)+rt(n))/pdO
  M_cm(n)= M(n)/pdm
  PS_cm(n) = PS(n)/(1-PS(n))*(M_cm(n)+Org_cm(n))
  height(n) = Org_cm(n)+M_cm(n)+PS_cm(n)
  T_height = T_height+ height(n)
  IF (n.EQ.1) Depth(n) = 0
```

```
   IF (n.GT.1) Depth(n) = Height (n-1)+ Depth(n-1)
   T_Org_cm = T_Org_cm + Org_cm(n)
   T_M_cm = T_M_cm + M_cm(n)
   T_PS_cm = T_PS_cm + PS_cm(n)
   mass(n) = Q(n) + B(n) + M(n) + rt(n)
   T_Org = T_Org + Q(n) + B(n) + rt(n)
   T_M = T_M + M(n)
   T_mass = T_mass + mass(n)
   T_SOC = T_SOC + (Q(n)+ B(n)+Rt(n))*OM2OC
   T_AGOC  = (W+V+D)*OM2OC
   T_TOC   = T_SOC + T_AGOC
   Elev = T_height
   !PRINT*,"T_SOC (g C m-2)", T_SOC*10000
   !Carbon Stock
 !PRINT*, n,"Q=",Q(n),"B=",B(n),"M=",M(n),"rt=",rt(n),
 !PRINT*, n,"org",Org_cm(n),"cm Min",M_cm(n),"cm PS",PS_cm(n),"cm H",height(n)
END DO
DO n = 19,10000
   Q(n)= 0
   B(n)= 0
   M(n)= 0
   rt(n)= 0
   PS(n)= 0
   Org_cm(n) = 0
   M_cm(n)= 0
   PS_cm(n) = 0
   height(n) = 0
   T_height = 0
   Depth(n) = Height (n-1)+ Depth(n-1)
   T_Org_cm = 0
   T_M_cm = 0
   T_PS_cm = 0
   mass(n) = 0
   T_mass = 0
   T_SOC = 0
   T_AGOC  = 0
   T_TOC   = 0
   Elev = T_height
   !Carbon Stock
 !PRINT*, n,"Q=",Q(n),"B=",B(n),"M=",M(n),"rt=",rt(n),
 !PRINT*, n,"org",Org_cm(n),"cm Min",M_cm(n),"cm PS",PS_cm(n),"cm H",height(n)
END DO
REWIND  (11)
REWIND  (12)
REWIND  (13)
REWIND  (14)
```

```
  REWIND  (15)
  !-------------------------------------------------------------------
  900 FORMAT (F8.7)
END SUBROUTINE INITIALIZE
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
!$ 1
SUBROUTINE WORKFILES (SLR,Energy,Dvtest,Sens,Sentest,Year,TRANS,&
  NTRANS,nSL,nST,Figure,nFigs,&
  KimInput,YearOut,TimeOut,SoilOut,&
  FigureA,FigureB,FigureC,FigureD,FigureE,FigureF)
  !date_and_time stamp variables
  CHARACTER(8)  :: date
  CHARACTER(10) :: time
  CHARACTER(5)  :: zone,b
  INTEGER,DIMENSION(8) :: values
  !in and out variables
  INTEGER, INTENT(INOUT) :: SLR,Energy,Dvtest,Sens,Sentest,Year,Trans
  INTEGER, INTENT(IN) :: NTRANS,nSL,nST,nFigs
  INTEGER, INTENT(INOUT) :: FIGURE
  CHARACTER  (LEN=11),INTENT(OUT):: KimInput(nTrans)
  CHARACTER (LEN=22),INTENT(OUT)::
                YearOut(nSL,nST,nTrans),TimeOut(nSL,nST,nTrans),&
  SoilOut(nSL,nST,nTrans)
  CHARACTER (LEN=20),INTENT(OUT):: FigureA(nFigs,nSL,nST,nTrans)
  CHARACTER (LEN=20),INTENT(OUT):: FigureB(nFigs,nST,nTrans)
  CHARACTER (LEN=20),INTENT(OUT):: FigureC(nFigs,nTrans)
  CHARACTER (LEN=20),INTENT(OUT):: FigureD(nFigs,nSL,nST)
  CHARACTER (LEN=20),INTENT(OUT):: FigureE(nFigs,nST),FigureF(nFigs,nSL)
  !Initial Sediment Profiles Derived from Averages reported in Rybczyk & Cahoon 2002
  OPEN (11, File="InQ.prn", STATUS="OLD")
  OPEN (12, File="InB.prn", STATUS="OLD")
  OPEN (13, File="InM.prn", STATUS="OLD")
  OPEN (14, File="InR.prn", STATUS="OLD")
  OPEN (15, File="InPS.prn", STATUS="OLD")

  call date_and_time(date,time,zone,values)
     print*, 'yyyymmdd',"_",'hhmmss.ttt',"_",'UTC zone'
     print*,date,time,zone

  !OIL PRICE
  OPEN (16, File="InOilP.prn", STATUS="OLD")
  !OPEN Dump Files for SLR and Sensitivity Scenarios
  OPEN(17, FILE="sndat.csv",status="UNKNOWN")
```

```
DO SLR = 1,5
TRANS = 1
DO RIVER = 1,4!9!9 !Or sentest
   WRITE (KimInput(SLR),900) "kim_SL",SLR,".prn"
   !A6,I1,A3
   !Input files from Kim Model Results
   OPEN (40+SLR, File=Kiminput(SLR), STATUS="OLD")
   DO TRANS = 1,NTrans
      IF (TRANS.EQ.2) EXIT
      !Output files for elev and soil dynamics
      WRITE (YearOut(SLR,RIVER,Trans),901)
                "YearOut_SL",SLR,"_TR",TRANS,"_Rv",RIVER,".csv"
      WRITE (TimeOut(SLR,RIVER,Trans),901)
                "WeekOut_SL",SLR,"_TR",TRANS,"_Rv",RIVER,".csv"
      WRITE (SoilOut(SLR,RIVER,Trans),901)
                "SoilOut_SL",SLR,"_TR",TRANS,"_Rv",RIVER,".csv"
      !A10,I1,A2,I2,A3,I1,A4
      OPEN  (10000+SLR*1000+100*RIVER+TRANS, File=YearOut(SLR,RIVER,Trans),
                STATUS="UNKNOWN")
      OPEN  (20000+SLR*1000+100*RIVER+TRANS, File=TimeOut(SLR,RIVER,Trans),
                STATUS="UNKNOWN")
      OPEN  (30000+SLR*1000+100*RIVER+TRANS, File=SoilOut(SLR,RIVER,Trans),
                STATUS="UNKNOWN")
   END DO !TRANS
END DO !RIVER
END DO !SLR

!FigureA(SLR,River,Trans)
DO TRANS = 1,1
  DO SLR = 1,5!9
    DO RIVER = 1,4
      DO FIGURE = 1,3
        IF(FIGURE.EQ.1) &
          WRITE (FigureA(FIGURE,SLR,RIVER,Trans),907) "yrdat",SLR*10+RIVER,".csv"
        IF(FIGURE.EQ.2) &
          WRITE (FigureA(FIGURE,SLR,RIVER,Trans),907) "wkdat",SLR*10+RIVER,".csv"
        IF(FIGURE.EQ.3) &
           WRITE (FigureA(FIGURE,SLR,RIVER,Trans),907)"scdat",SLR*10+RIVER,".csv"
        !A5,I5,A4
        907 FORMAT (A5,I5,A4)
        OPEN  (100000+10000*Figure+SLR*1000+100*RIVER+TRANS,&
        File=FigureA(FIGURE,SLR,RIVER,Trans), STATUS="UNKNOWN")
      END DO !FIG
    END DO !RIVER
  END DO !SLR
END DO
```

```
  OPEN (21, File="Fill_SLR.txt", STATUS="UNKNOWN")
  OPEN (22, File="Cost_E_SLR.txt", STATUS="UNKNOWN")

  !OUTPUT FILES
  OPEN (23, File="WPrice_Dump.txt", STATUS="UNKNOWN")
  OPEN (24, File="WECRMDocTable.txt", STATUS="UNKNOWN")
  !Figure 1
  !OPEN
  !Figure 2
  !Figure 3
  !Figure3 50 YR RCI
  OPEN (31, File="Figure3_50yrRCI_dat.txt", STATUS="UNKNOWN")
  !Figure4 100 YR RCI
  OPEN (32, File="Figure4_100yrRCI_dat.txt", STATUS="UNKNOWN")
  !Figure3alt 50 YR TotalCost per km2
  OPEN (33, File="Figure3_50yrCostkm2_dat.txt", STATUS="UNKNOWN")
  !Figure4alt 100 YR TotalCost per km2
  OPEN (34, File="Figure4_50yrCostkm2_dat.txt", STATUS="UNKNOWN")
  !Figure5 MClife vs Efill
  OPEN (35, File="Figure5_MClife_Fill.txt", STATUS="UNKNOWN")
  !Figure6 RBC_cm Life/cm added
  OPEN (36, File="Figure6_RBCcm_dat.txt", STATUS="UNKNOWN")
  !Figure7 RBC_cm Life/$ added per m2
  OPEN (37, File="Figure7_RBCdl_dat.txt", STATUS="UNKNOWN")

  900 FORMAT(A6,I1,A4)
  901 FORMAT(A9,I1,A2,I2,A3,I1,A4)
  902 FORMAT(A6,I1,A3,I1,A2,I2,A3,I1,A4)
  903 FORMAT(A6,I1,A3,I2,A3,I1,A4)
  904 FORMAT(A6,I1,A3,I2,A4)
  905 FORMAT(A6,I1,A3,I1,A3,I1,A4)
  906 FORMAT(A6,I1,A3,I1,A4)
  RETURN
END SUBROUTINE WORKFILES

!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
!$ 3 Write output file headers
SUBROUTINE OUTHEADERS (c,Ecosystem,Mgmt,SLR,sentest,TRANS,TSS,River)
  !date_and_time stamp variables
  CHARACTER(8)  :: date
  CHARACTER(10) :: time
  CHARACTER(5)  :: zone
  INTEGER,DIMENSION(8) :: values
  CHARACTER (LEN=3),  INTENT(IN) :: c
  CHARACTER (LEN=50), INTENT(IN) :: Ecosystem,Mgmt
```

```
  INTEGER, INTENT (IN)::sentest,SLR,Trans,River
  REAL, INTENT (IN):: TSS

 !write headers for output files
 !write headers for each sea level scenario and each transect
  PRINT*,"      Year      Relev       V           D           Org(10)      Mass(10)     pctorg(10)"
  PRINT*,"        -          (cm)        (g dw m-2)    (g dw m-2)    (g dw m-2)      (g dw m-2)     (%)
                 "

  !Transect Site Annual Summary Output
  WRITE(10000+SLR*1000+100*Sentest+TRANS,900)&
  'Year',c,'Elev',c,'WL',c,'Relev',c,'V',c,'D',c,'R',c,'S_in',c,&
  'dT_height',c,'T_SOC',c,'dT_SOC'

  !Transect Site week Step Summary Output
  WRITE(20000+SLR*1000+100*Sentest+TRANS,900)&
  "YEAR",c,"Relev",c,"V",c,"D",c,'R',c,"S_in",c,"BD",c,"pctOrg"
  !Transect Site Soil Cohort Output

                 WRITE(30000+SLR*1000+100*Sentest+TRANS,901)"Year",c,"n",c,"depth",c,"r
                 depth",c,"Height",c,"Rt",&
   c,"Q",c,"Org",c,"M",c,"Org_cm",c,"M_cm",c,"PS_cm",c,"BD",c,"pctOrg",c,&
   "cfunc",c,"acf",c,"dcf",c,"dQ",c,"dB",c,"dM",c,"aR",c,"aL",c,"rootlit"

  WRITE(100000+10000*3+SLR*1000+100*RIVER+TRANS,*)&
          "Trans,Sens,Y,n,Depth(n),rDepth(n),BD(n),pctOrg(n)"
  WRITE(100000+10000*2+SLR*1000+100*RIVER+TRANS,*)&
          "Trans,Sens,Yr,Elev,WL,Relev,V,D,R,S_in,BD(1),pctOrg(1)"
  WRITE(100000+10000*1+SLR*1000+100*RIVER+TRANS,*)& !write variable names
          "Y,Elev,WL,Relev,V,D,R,S_in,dT_height,T_SOC,dT_SOC,pctOrg(1&2),BD(1&2)"
  WRITE(100000+10000*1+SLR*1000+100*RIVER+TRANS,*)& !write units
          "Y,(cm),(cm),(cm),(g dw m-2),(g dw m-2),(g dw m-2),(g m-2 yr),(cm/yr),(g C m-2),(g C
                 m-2 yr-1),(%),(g m-3)"

  900 FORMAT (A4,40(A1,A16))
  901 FORMAT (A4,A1,A2,21(A1,A16))
  RETURN
END SUBROUTINE OUTHEADERS
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
!$ 4 Write documentation table
SUBROUTINE DOCUMENTATION(&
    Ecosystem,Mgmt,c,&
    Tamp,TSS,SubR,V,W,D,R,PSmin,PSmax,rootlit,rk,sl,xo,pk,lf_r,lf_a,w_i,T_opt,T_min,&
```

```
                Initelev,OilP,RD,qs,ks,Dmax,S_in,MC,mck,Ecrt,WKop,Hfill,Ffreq,Initrelev,Elev,
                WL,Efill,Flood)
  !date_and_time stamp variables
CHARACTER(8)  :: date
CHARACTER(10) :: time
CHARACTER(5)  :: zone
INTEGER,DIMENSION(8) :: values
CHARACTER  (LEN=3), INTENT(INOUT):: c
CHARACTER (LEN=100), INTENT(INOUT):: Ecosystem,Mgmt
REAL, INTENT (INOUT) ::&
Tamp,TSS,SubR,V,W,D,R,PSmin,PSmax,rootlit,rk,sl,xo,pk,lf_r,lf_a,w_i,T_opt,T_min,&

                Initelev,OilP,RD,qs,ks,Dmax,S_in,MC,mck,Ecrt,WKop,Hfill(100),Ffreq,Initrelev
                ,Elev,WL,Efill,Flood
call date_and_time (date,time,zone,values)
!WRITE DOCUMENTATION TABLE IN CSV FORMAT-------------------------
WRITE (24,*) "Table E1 - WECRM PARAMETER VALUES",
WRITE (24,*) "Date and time of run (yyymmdd_hhmmss.ttt):",date,"_",time
WRITE (24,*) ECOSYSTEM ,": ", MGMT
WRITE (24,*) "Name ",',',"Value",',',"Units",',',"Discription",',',"Notes & Sources"
!-----------------------------------------------------------------------------------------------
WRITE(24,*)"GEOPHYSICAL PARAMETERS"
WRITE(24,*)"Tamp",c,Tamp,c,"(cm)",c,&
"Tidal amplitude: 90%WL (Mean High Tamp) - 50%WL (Mean Water Level)",c,"CRMS data
                see Table E2)"
WRITE(24,*)"Dmax",c,Dmax,c,"(cm)",c,&
"average difference in inundation depth (cm) b.w. 99%WL",&
"(wind Tamp from storms & fronts)& 90%WL (MHT)",c,&
"CRMS data see Table E2"
WRITE(24,*)"TSS",c,TSS,c,"(mg L-1)",c,&
"Mean suspended inorganic sediment concentration; 30 in Terrebone Bay;",&
"80 in Fourleague Bay; 140 in Atch./Wax Lake",c,"Perez 2000; Wang 1997; Murray 1994;
                Day et al 2011"
WRITE(24,*)"SubR",c,SubR,c,"(cm yr-1)",c,&
"Subsidence rate ranges from 0.6 to 1.2 cm/year in terrbonne and atchafalaya bay marshes",&
"and 6-2.0cm per year in east baratar/birdfoot",c,"CPRA 2012 Appendix E; Shinkle & Dokka
                2004"
WRITE(24,*)"pk",c,pk,c,"(g cm-2)",c,&
"half saturation constant of soil compaction; calibrated Oyster Bayou and Bayou Chitique
                marshes",c,&
"Rybczyk & Cahoon 2002; see file /PS_cfunc_calibration_OB_1"
WRITE(24,*)"qs",c,qs,c,"(g cm-2 wk-1)",c,&
"settling velocity coefficient for suspended sediments under laminar flow conditions;",&
"calibrated to accretion rates of LA tidal marshes",c,"Morris et al. 2002; CRMS Data see Table
                E3"
```

```
!------------------------------------------------------------------------------------------
WRITE(24,*)"BIOPHYSICAL PARAMETERS"
WRITE(24,*)"W",c,W,c,"(g m-2)",c,&
"Tree woody biomass; we assume no significant mangrove propagation"
WRITE(24,*)"V",c,V,c,"(g m-2)",c,&
"Live macrophyte shoot biomass (Initial value for January);",&
"calibrated to S. alterniflora/patens dom marshes",c,&
"Hopkinson et al 1978; Rybzyck & Cahoon 2002; Nyman et al 1995"
WRITE(24,*)"D",c,D,c,"(g m-2)",c,&
"Dead standing macrophyte shoot biomass (Initial value for January)",&
"calibrated to S. alterniflora/patens dom marshes",c,&
"Hopkinson et al 1978; Rybzyck & Cahoon 2002; Nyman et al 1995"
WRITE(24,*)"R2S",c,R2S,c,"(g m-2)",c,&
"Ratio of live root to total (live + dead) shoot biomass (Roots/(V+D));",&
"Rybczyk & Cahoon (2002) assume 1:1; Snedden (2015) report 2:1"
WRITE(24,*)"R",c,R,c,"(g m-2)",c,&
"live root biomass",c,&
"Hopkinson et al 1978; Rybczyk & Cahoon 2002; Nyman et al 1995; Snedden et al. 2015"
WRITE(24,*)"rk",c,rk,c,"(g m-2)",c,&
"root depth distribution exponential decay constant ranges from -0.06 to -0.1 at OB and
        BC",c,&
"Rybczyk & Cahoon 2002"
WRITE(24,*)"rootlit",c,rootlit,c,"(g g-1 wk-1)",c,&
"root litter rate = turnover rate - 50% or 1/R2S * weekly NPP / annual NPP (g/g wk-1)",c,&
"Snedden etal. 2015, Rybzcyk & Cahoon 2002"
WRITE(24,*)"lf_r",c,lf_r,c,"(g g-1)",c,&
"labile fraction root litter",c,"Rybzcyk & Cahoon 2002"
WRITE(24,*)"lf_a",c,lf_a,c,"(g g-1)",c,&
"labile fraction above ground litter",c,"Rybzcyk & Cahoon 2002"
WRITE(24,*)"k_r",c,k_r,c,"(g g-1 wk-1)",c,&
"decay rate of surface refractory organic matter (cohort 1)",c,"Rybzcyk & Cahoon 2002"
WRITE(24,*)"k_l",c,k_l,c,"(g g-1 wk-1)",c,&
"decay rate of surface labile organic matter (cohorts 1)",c,"Rybzcyk & Cahoon 2002"
WRITE(24,*)"k_ld",c,k_ld,c,"(g g-1 wk-1)",c,&
"decay rate of subsurface labile organic matter (cohorts 2-18)",c,"Rybzcyk & Cahoon 2002"
WRITE(24,*)"w_i",c,w_i,c,"(g g-1 wk-1)",c,&
"ERWL where max NPP occurs for Sp. alterniflora/patens dominated marsh in LA",c,&
"Rybzcyk & Cahoon 2002"
WRITE(24,*)"T_opt",c,T_opt,c,"(deg C)",c,&
"Tempurature at max growth rate (see Tfunc); calibrated to Sp. alterniflora",c,&
"Day et al. 2002; Hopkinson et al. 1978"
WRITE(24,*)"T_min",c,T_min,c,"(deg C)",c,&
"Tempurature at min growth rate (see Tfunc); calibrated to Sp. alterniflora",c,&
"Day et al. 2002; Hopkinson et al. 1978"
!-----------------------------------------------------------------------------------------
WRITE(24,*)"RESTORATION PARAMETERS"
```

```
  WRITE(24,*)"Wkop",c,Wkop,c,"(weeks)",c,"weeks of diversion operation",c,&
  "see DP2D - Delta Progradation 2D Model"
  WRITE(24,*)"Efill",c,"0 to 100",c,"(cm)",c,&
  "ERWL fill target of marsh creation; maximum 100 cm relative to water level",c,&
  "CPRA 2012 Appendix A1"
  WRITE(24,*)"mck",c,(1-0.249)*pdm,c,"g cm-3","Bulk density of placed fill material(100%
                mineral);",&
  "used as factor to convert target fill elevation to mineral input (g cm-2)",c,&
  "Edwards & Profit 2003; Mendolsohn & Kuhn 2003"
  WRITE(24,*)"Ecrt",c,"-10 to -30",c,"(cm)",c,"critical elevation threshold for marsh
                collapse;",&
  "estimated from liturature and data from LA tidal marshes",c,&
  "Day et al. 2011; Nyman et al 1995; Couvillion & Beck 2012; CRMS data"
  WRITE(24,*)"Flood",c,"10 to 50",c,"(cm)",c,"Flooding depth for hydrologic restoration;"
  WRITE(24,*)"Ffreq",c,"1 to 4",c,"(wk-1)",c,"Flooding frequency for hydrologic restoration;"
  WRITE(24,*)"Hfill",c,"2 to 6",c,"(num yr-1)",c,"Duration of flooding for hydrologic
                restoration;"
  WRITE(24,*)"RD",c,"-",c,"(cm yr-1)",c,"annual accretion from diversion opening"
  WRITE(24,*)"MC",c,"1 or 0",c,"(-)",c,"binary indicator variable,",&
  "if ERWL is less thant Ecrt MC=1 trigger marsh creation"
  !------------------------------------------------------------------------------------------
  WRITE(24,*)"STATE EQUATIONS"
  WRITE(24,*)"FORCING FUNCTIONS"
  RETURN
END SUBROUTINE DOCUMENTATION
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
END PROGRAM
```

VITA

Adrian Wiegman grew up in Croton-on-Hudson, New York, thirty-five miles north of New York City. He spent much of his youth hiking, canoeing, and swimming. This included exploring the Hudson and Croton River Estuaries and vernal pools and streams in the Hudson Valley. Adrian received his bachelors in science at State University of New York, College of Environmental Science and Forestry (ESF), where he majored in environmental studies. Under the advising of Dr. Charles Hall, he concentrated in biological systems applications, which involved trophic energetics research in streams and a capstone project assessing the fuel use of harvest strategies in willow biomass production systems. At ESF Adrian also obtained a minor in renewable energy under the advising of Dr. Timothy Volk, which involved measuring transpiration and belowground production of willow yield trials. He spent a year working as a research associate at Louisiana State University, researching global energy modeling and coastal wetland restoration, before starting his masters. For his Masters degree, Adrian worked on modeling the costs of marsh creation under future scenarios for energy price and sea level rise, under the advising of Drs. John Day and Christopher D'Elia. He will attend the University of Vermont for his PhD, where he will study the life cycle of phosphorus recycling systems in New England watersheds.