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Keeping Pace with Relative Sea Level Rise: Marsh Platform Monitoring Shows Minimal Sediment Deficit along the Louisiana Coast

Kelly Marie Sanks
University of Arkansas, Fayetteville

Keeping Pace with Relative Sea Level Rise: Marsh Platform Monitoring Shows Minimal Sediment Deficit along the Louisiana Coast

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Kelly Sanks
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John B. Shaw, Ph.D.
Thesis Director

____
Matt Covington, Ph.D.
Committee Member

____
Jill A. Marshall, Ph.D.
Committee Member

____
Kusum Naithani, Ph.D.
Committee Member

Abstract

Recent reports estimate that the marshes of the Mississippi Delta receive just 30% of the sediment necessary to sustain current land area[1]. An extensive monitoring campaign by the USGS and LCPRA provides direct measurements of sediment accumulation, subsidence rates, and deposit characteristics along the coast over the past 10 years[2], allowing us to directly evaluate this sediment balance. By interpolating bulk density, organic fraction, and vertical accretion rates from 273 sites, a direct measurement of organic and inorganic sediment accumulation can be made. Results show that a total of 82 MT/year of sediment is delivered to the coast. Using a fluvial sediment discharge of 113 MT/yr[1], 52% of the riverine transported sediment is accumulated in the coastal lands of the Mississippi Delta. Assuming an average 9 mm/yr subsidence rate[3] and 3 mm/yr sea-level rise[1], this accumulation results in a 2.7 MT/yr (3.5%) sediment mass surplus. However, there is a 0.014 km^3/yr (5.4%) sediment volume deficit caused by the sediment porosity being too small to fill the accommodation space. About 20 MT/yr inorganic and 6 MT/yr organic sediment initially accumulates in deltaic areas directly nourished by the Mississippi and Atchafalaya rivers, resulting in an initial sediment trapping efficiency of 18%. The remaining sediment must be delivered indirectly to the coast after passing through the ocean, accounting for another 39 MT/yr of inorganic sediment being trapped on coastal marshes. 17 MT/yr organic sediment is produced through marsh plant production. These results suggest that even if current relative sea level rise rates do not change, the gap between accommodation and accumulation is not as dire as previously thought.

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Introduction

Over the last century, the Louisiana coast has lost about 5000 km^2 of land, mainly coastal marshes[4]. Although the rates of loss over the last decade have slowed[5], the Louisiana coast still loses wetlands each year[6]. These marshes are economically and environmentally important regions, as they have high biodiversity, help mitigate the detrimental impacts of storms, help buffer the effects of relative sea level rise (RSLR)[7,8], and provide a source of livelihood for the millions of people who depend on the coast[9]. Consequently, recent government efforts have focused on the restoration and protection of coastal Louisiana[10].

In order to create the most successful restoration and management plans, an accurate estimate of the coastal sediment deficit is needed. A recent analysis of land loss using historical surveys and aerial imagery showed that the rates of wetland loss along the coast have drastically slowed over the last few decades. Current land loss rates are shown to be about 28 km^2/yr, which is significantly smaller than the 83 km^2/yr observed in the 1970's. Some potential reasons for this dramatic decrease in land loss are the lack of major hurricanes within the last 10 years, as well as previous loss of the most vulnerable coastal lands. Further, restoration strategies, such as river diversions, have likely been successful in restoring coastal lands[5].

Wetland loss is due to erosion and lack of sufficient deposition. Sediment is typically eroded from wetlands by the action of major storms. Major storms increase wave action in wetlands, which has been shown to be the primary factor in marsh edge erosion[11]. About 527 km^2 of wetlands were lost during Hurricane Katrina because of this[12]. RSLR combined with anthropogenic alterations to coastal lands have been interpreted to be the major causes of insufficient deposition in coastal Louisiana marshes. Damming and leveeing of the Mississippi River in the 1930's through 1950's changed sediment fluxes and pathways in the delta. Damming of within the Mississippi Basin has caused a slight decrease of sediment since 1980[13]. Levee construction also prevented floods from transporting sediment directly to large swaths of the delta. Since these basins have been cut off from river nourishment, they must receive mineral sediments indirectly from the coast.

Further, increased subsidence rates due to groundwater fluid extraction significantly increased the RSLR rate experienced on the coast[14]. For this reason, land loss on the Mississippi Delta has been linked primarily to a sediment deficit to coastal marshes, where accumulation cannot keep pace with rising relative sea level[1,2,5,15].

The sediment deficit of the Mississippi Delta was recently estimated by Blum and Roberts (2009) to be between 10 and 90 MT/yr (5-30%). This prediction showed that significant drowning of coastal lands by 2100 was inevitable[1]. These predictions were based on various assumptions including a 40% trapping efficiency of riverine delivered suspended sediment (~205 MT [mega tons]/yr by both Mississippi and Atchafalaya Rivers), a sediment density of 1.5 g/cm^3, and subsidence rates ranging from 1-8 mm/yr. However, it involved no direct measurement of accumulation on the delta itself. Organic sediment accumulation was also not taken into account[1]. However, organic production plays an important role in land building, especially in areas where inorganic sediment is not abundant and/or in areas where riverine sedimentation has been abandoned[16].

While sediment mass balances and deficits have been calculated along the Louisiana coast[1], we are lacking a sediment balance and deficit calculated using direct field measurements, primarily due to a deficiency of field data. Here, we will show the first ever estimate of sediment mass and volume balance along the Louisiana coast calculated with direct field measurements.

A novel dataset (CRMS [Coastwide Reference Monitoring System]) compiled by the United States Geological Survey (USGS) and Louisiana's Coastal Protection and Restoration Authority (LCPRA) provides direct measurements of recent sediment accumulation, subsidence rates, and sediment characteristics along the entire Louisiana coast over the past 10 years[2,3]. These data afford the opportunity to directly observe the sediment balance along the coast, as well as the effectiveness of river diversions.

In this study, we use the CRMS data to calculate an independent, field-based estimate of the recent sediment accumulation showing a smaller sediment deficit along the coast than previous estimates. By interpolating dry bulk density (ρ; g/cm^3), fraction organic matter (F_{org}; -), and vertical accretion rates (V_a; cm/yr) across the coast from 273 CRMS sites, we show a new estimate of sediment accumulation, both inorganic and organic. We also show the first field-based estimate of deltaic wetland sediment trapping efficiency by combining sediment accumulation with direct discharge and suspended sediment concentration data from USGS river gauging stations. These estimates are particularly useful for restoration, planning, and management of coastal lands.

Methods

Data Collection

In cooperation with the USGS and LCPRA, Coastwide Reference Monitoring System (CRMS) data shows direct measurements of different coastal marsh characteristics in Louisiana. A coastal marsh, whether fresh or salt, is an area that is flooded daily, typically during high tide[17]. These areas are flat, shallow, subaerial parts of the coastline and can extend hundreds of miles inland. Each CRMS site serves as a 1 km^2 area that can be used for land/water analysis and consists of four feldspar plots that measure accretion rates at each site. Accretion rates are specifically the height (h) of material that accumulates over a certain amount of time (t). The sites also include a

Rod Surface Elevation Table (RSET) that measures surface elevation change, which is influenced by both subsurface processes like shallow compaction and accretion rates. The accretion rate gives change in soil height above the feldspar plot (Δh), the RSET gives the change in surface elevation (Δz), and subsidence (σ) comes from (Δz - Δh)[17]. CRMS monitoring captures vertical accumulation, and also erosion if it is small enough that the feldspar horizon is not destroyed. Lateral erosion, such as at marsh edges, cannot be monitored. Hence, the dataset does not account for subaqueous deposition and/or erosion, marsh edge erosion, or erosion of the marsh interior.

Collection of the CRMS data began in 2006 and has since been measuring surface elevation change and vertical accretion rates at each site. Sediment characteristics were collected in 2006 for 391 sites along the coast, before site establishment. A subset of 273 sites (Figure 1) was selected for interpolation based on methods described in Jankowski (2017)[2]. The subset for vertical accretion rates was chosen based on three parameters: (1) the sites were never re-established because of damage, (2) the sites have at least one continuous vertical accretion record, and (3) the accretion record must be at least 6 years long. A mean of all vertical accretion measurements was calculated to obtain an average vertical accretion rate for each of the 273 sites[2]. For more information on vertical accretion collection methods please refer to the CRMS Standard Operating Procedure Manual[17] or Jankowski (2017)[2].

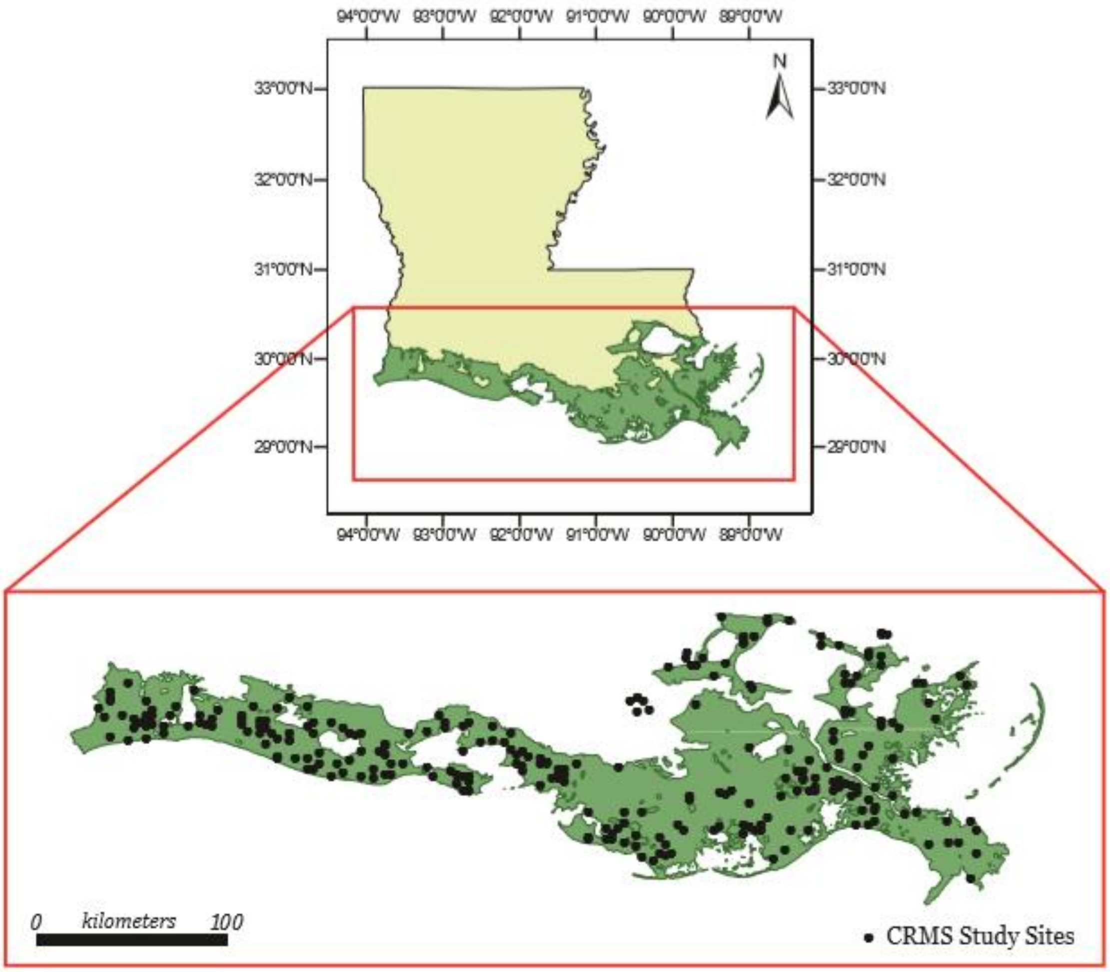

Figure 1: *Red box highlights the study area (Coastal Louisiana). Black dots show the subset of 273 sites CRMS sites used for this study. These sites are all located in coastal Louisiana and display a variety of different environments (i.e. indirectly nourished marsh sites and fluvial-dominated deltaic marsh sites). Each site has at least a 6-year record of accretion rates, as well as data from 24 cm cores, in which bulk density and organic fraction were measured.*

Before accretion plots and surface elevation tables were established, a core from each site was processed and analyzed for dry bulk density and fraction organic matter at different depths, typically 0-24 cm. It is assumed that the average bulk density and organic content of this material is characteristic of the material that accumulates on the surface after site establishment. A mean of fraction organic content (-) and dry bulk density (g/cm^3) was calculated for the 273 sites that had viable vertical accretion records along the coast[17].

CRMS Data

We are interested in using these data for interpolation, so it is imperative to understand what the data show. The data are relatively normal with both the accretion rates and dry bulk densities being slightly right skewed, likely because the variables cannot have values < 0. The median and mean values of all three variables do not differ much (Figure 2).

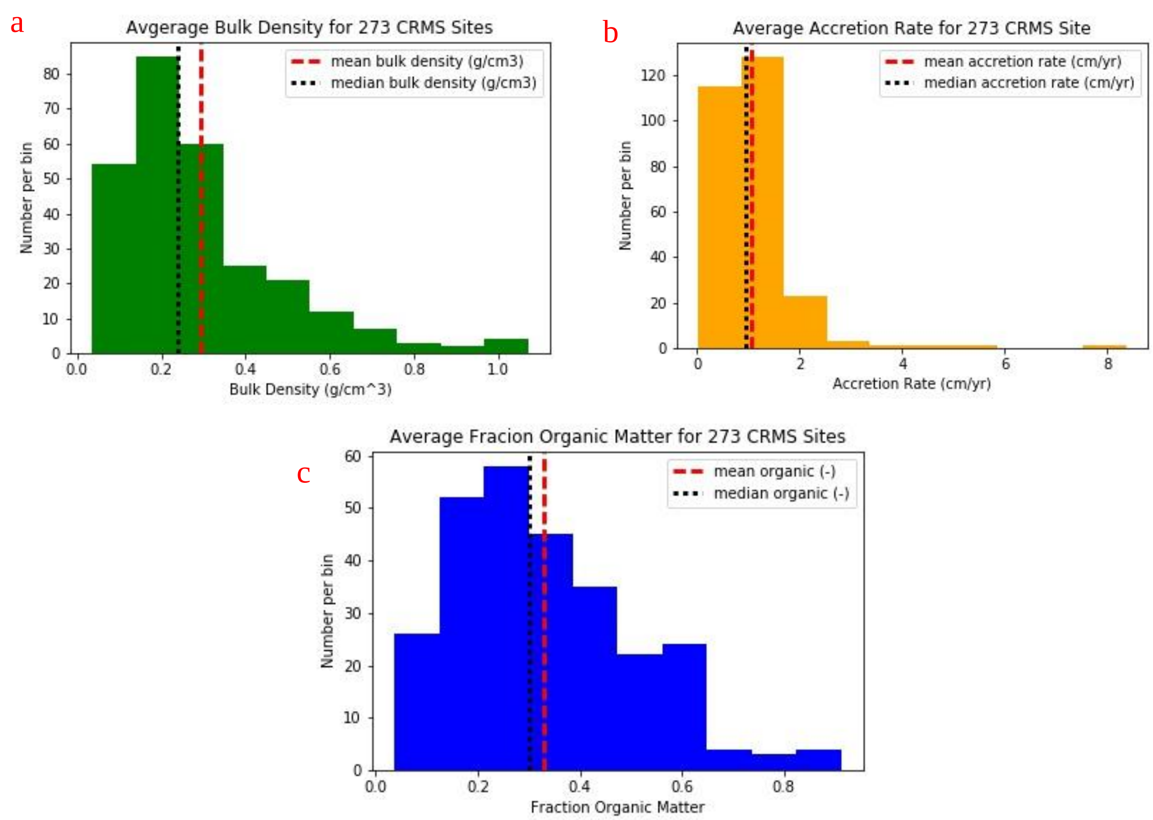

Figure 2: *(a) Histogram of the distribution of the dry bulk densities from the 273 CRMS sites, which are an average of the dry bulk densities from 0-24 cm depth at each site. The average dry bulk density of the 273 sites is 0.29 g/cm^3 and the median is 0.24 g/cm^3. (b) Histogram of the distribution of the accretion rates from the 273 CRMS sites. The average and median accretion rates are 1.1 and 0.95 cm/yr, respectively. (c) Histogram of the distribution of the fraction organic matter at each of the 273 CRMS sites. The data points are an average of the fraction organic matter from 0-24 cm depth. The average fraction organic matter is 0.33 and the median is 0.30.*

Further, the variables are all somewhat correlated. However, dry bulk density (g/cm^3) and organic content (-) are very strongly correlated, as can be seen from an r^2 value of 0.87 and a very low p-value. These numbers indicate that there is a strong negative relationship between the two variables, and as bulk density increases, organic fraction decreases (Figure 3c). However, there is only a small, relatively weak relationship between organic fraction and accretion rates, as well as bulk density and accretion rates (Figure 3a and 3b).

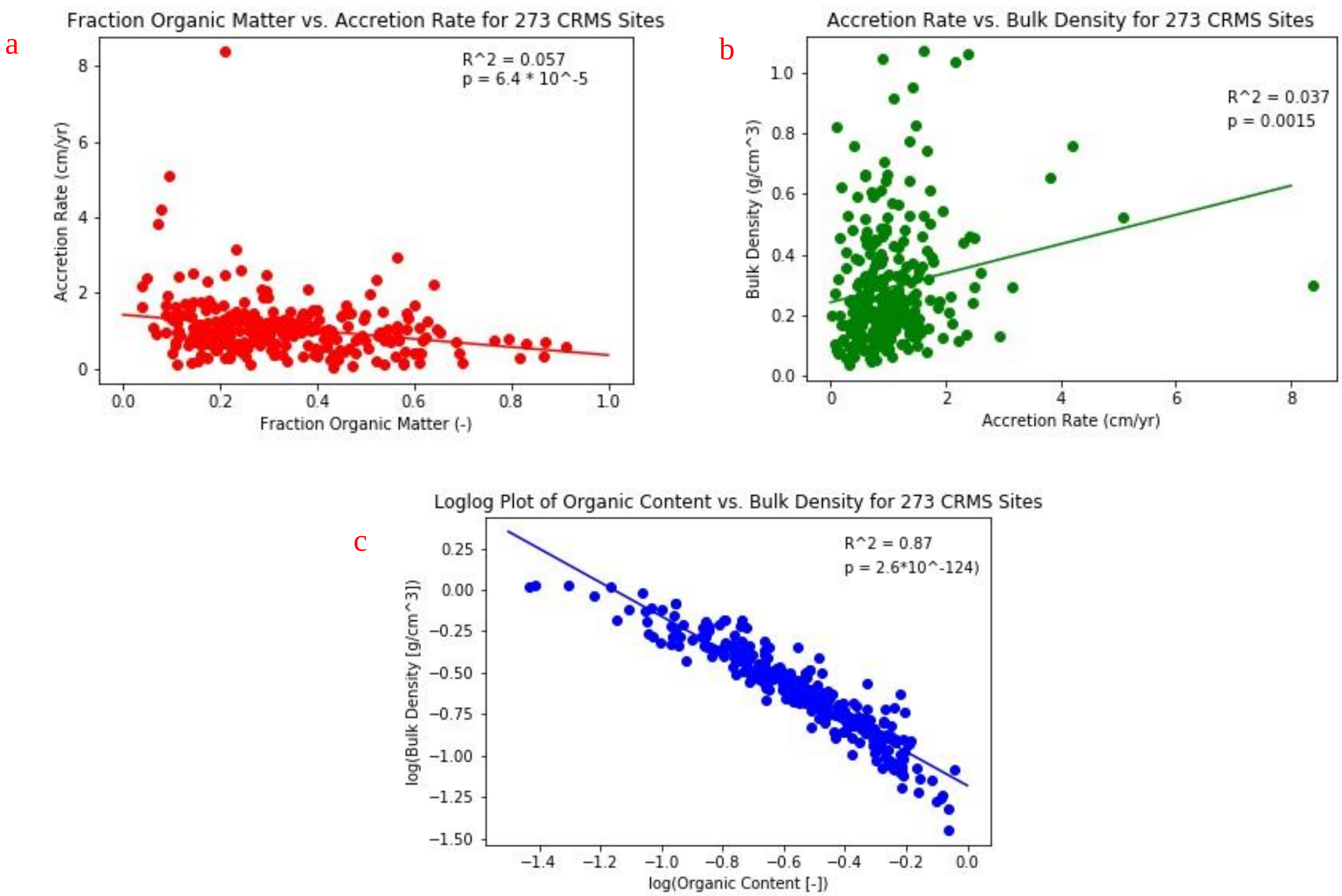

Figure 3: *(a) Weak negative relationship between fraction organic matter (-) and accretion rates (cm/yr). Typically, as accretion rates increase, the fraction organic matter decreases. (b) Weak positive relationship between accretion rate and bulk density (g/cm^3). Typically, as bulk density increases, accretion rates increase as well. (c) Strong negative relationship between organic content (-) and bulk density (g/cm^3). As bulk density decreases, organic content increases.*

Since the variables are correlated, we will take this into account during interpolation and error propagation. In order to do so, we will use the calculated covariance numbers (σ) (Table 1).

Table 1: *Calculated covariance numbers to show correlation of variable pairs, which are used in error propagation calculation.*

Variable Pair	**Covariance Number**
$\sigma_{\rho Forg}$ (bulk density-fraction organic)	-0.02732
$\sigma_{\rho Va}$ (bulk density-vertical accretion)	0.02955
σ_{ForgVa} (fraction organic-vertical accretion)	-0.03294

Interpolation

We use universal kriging to interpolate maps of vertical accretion (V_a; cm/yr), dry bulk density (ρ; g/cm^3), and fraction organic matter (F_{org}; -). Universal kriging is often used in geostatistics to model spatial data because it does not smooth out the data during interpolation. Further, universal kriging on a trend surface model allows us to remove any trends in the data that may bias interpolation. The interpolation was performed using a 1 km^2 grid covering the extent of the Louisiana coast. We show end results for two methods of interpolation (Table 1).

The automap package in R was used to run an ordinary kriging simulation on the data points. Ordinary kriging shows that the data exhibit a linear spatial trend. In order to remove the trend, a trend surface model was created for each variable. Please refer to the automap R manual[18] for information on how to use the automap package.

The gstat package in R was used to create a trend surface model, which was then used to perform universal kriging using the krige function in the R software package. Please refer to the gstat R manual[19] for information on how to use the krige function. When fitting a model to the semivariogram, there are four different choices: Exponential, Spherical, Gaussian, and Matern. All of these models fit the semivariogram data fairly well, so the interpolation model was run using each of these choices (Table 2).

Table 2: *Estimated sediment accumulation (Mton/yr) to the Louisiana Coast (right column) using different interpolation methods and semivariogram models.*

Method	**Total Estimated Sediment Accumulation (MT/yr)**
Ordinary Kriging	75.2
Universal Kriging- Exponential Variogram	81.7
Universal Kriging- Spherical Variogram	79.1
Universal Kriging- Gaussian Variogram	81.2
Universal Kriging- Matern Variogram	81.7

Since the choice of the variogram model did not significantly alter the results of the interpolation, the exponential model was chosen to perform universal kriging individually on all three variables- V_a, ρ, and F_{org}. (Figure 4). See Supplementary Information (Appendix B) for entire code.

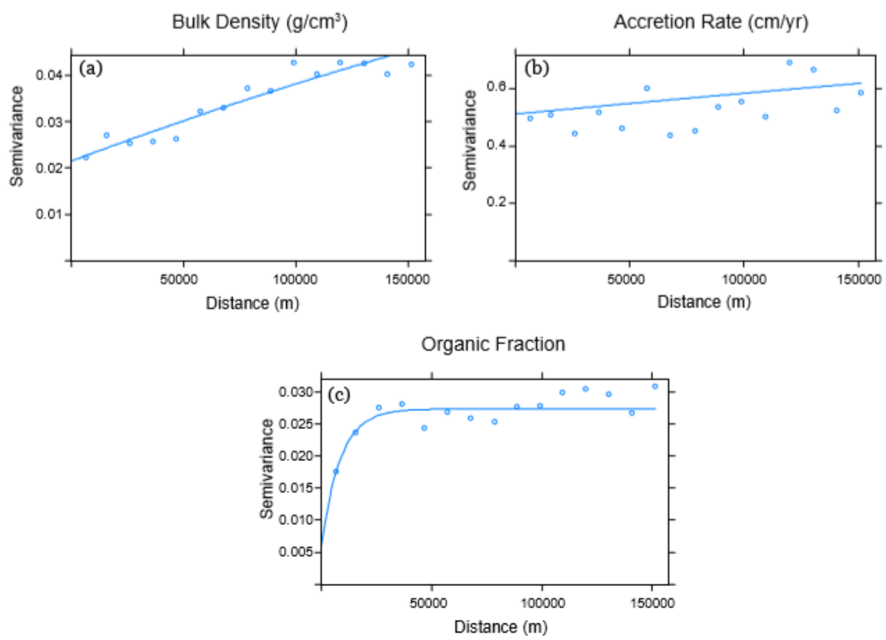

Figure 4: *The experimental variogram and the fitted exponential models for (a) bulk density (g/cm*^{3}*) (b) accretion rates (cm/yr) and (c) fraction organic matter. These models were used for interpolation of the variables.*

The kriging prediction maps were then masked and cropped to include only data that falls within study area (Figure 1) using a recent land area polygon[3] of coastal Louisiana created using ArcGIS. The shapefile used to mask the interpolation was chosen specifically because it excludes cities, rivers, areas of high elevation, and levees[3]. It is also the most recent known land/water polygon for the coast, so areas that have already drowned are presumably removed. Depending on total current land area, the choice of shape file may alter the trapping efficiency prediction for the coast.

For secondary analysis, directly nourished areas of the coast were compared to areas that are indirectly nourished. Directly nourished areas refer to areas of the coast that receive direct riverine input, whereas indirectly nourished areas do not have a source of significant direct riverine sedimentation, and must therefore receive any sediment either from elsewhere in the marsh, shallow bays, or the continental shelf. Thus, the shapefile used for this mask excludes both the Atchafalaya River Basin and the Mississippi River Basin, as these are the main areas receiving direct riverine sediment. The Mississippi River drains 40% of the entire United States, so smaller rivers along the coast are assumed to have negligible sediment loads in comparison. Further, a recent study aimed at constraining the sediment budget to the Louisiana Coast also excluded the smaller rivers from their analysis, presumably for this same reason[20].

The masked rasters (one map for each variable for total sediment accumulation and one map for each variable for indirectly nourished areas) were then multiplied together using raster math from the raster package in R. The data, including interpolated data and error for each grid square, was then extracted as a csv file (Appendix B).

Sediment Mass Accumulation

Sediment mass accumulation rates for the entire coast were calculated to directly compare estimates from Blum and Roberts (2009) of sediment accumulation and sediment deficit along the Louisiana coast. In order to calculate an estimate for total (inorganic plus organic) sediment mass accumulated along the coast (m_T), the following equation was used:

$$m_T = A_i \sum_{i€A} \rho_i V_{a_i}$$

Where m_T is the total rate of sediment mass accumulation in Mississippi Delta marshes (MT/yr), V_{a_i} is vertical accretion rate in cm/yr at an individual pixel or grid cell (i) within the Mississippi River Delta Marsh area (~21918 km^2 –size of shapefile), and ρ_i is dry bulk density in g/cm^3 at an individual pixel. A_i is the area of one individual pixel (10^{10} cm^2 or 1 km^2). The same methods were applied to calculate an organic sediment load, except the following equation was used:

$$m_{org} = A_i \sum_{i€A} \rho_i V_{a_i} F_{org_i}$$

where m_{org} is the total mass organic sediment accumulation rate (MT/yr) and F_{org_i} is fraction organic matter at an individual pixel (-). Total inorganic sediment mass accumulation rate $m_{I;}$ MT/yr) was then calculated using:

$$m_I = m_T - m_{org}$$

Further analysis was conducted to differentiate between areas fed by the Mississippi and Atchafalaya Rivers (directly nourished) and the rest of the coast, which is assumed to be indirectly nourished. The same analysis was then conducted on the second shapefile excluding the Mississippi River and Atchafalaya Basins; though, the new inorganic and organic sediment mass accumulation rates are assumed to be areas of indirect nourishment (m_O). These numbers were then subtracted from total inorganic and organic sediment mass accumulation rates to determine a sediment mass accumulation rate (m_R) of areas that are directly nourished.

Error for the sediment mass accumulation was propagated using the standard deviation of V_a, and ρ, as well as F_{org} for organic sediment accumulation. We also considered spatial autocorrelation, but we found it to be negligible because the range of the semivariogram was 10 km and the entire coast spans about 400 km. The error was calculated as follows:

$$\delta_{m_{org}} = \sqrt{\sum_{i \in A} \left(A_i \sqrt{(\rho_i^2 \delta_{\rho_i}^2) + (V_{a_i}^2 \delta_{V_{a_i}}^2) + ({F_{org}}_i^2 \delta_{F_{org_i}}^2) + 2(\rho_i V_{a_i} \sigma_{\rho_i V_{a_i}} + \rho_i F_{org_i} \sigma_{\rho_i F_{org_i}} + {F_{org}}_i V_{a_i} \sigma_{F_{org_i} V_{a_i}}} \right)^2}$$

Where $\delta_{m_{org}}$ is the total interpolation error (MT/yr) for sediment organic mass accumulation along the coast, δ_{ρ_i} is the estimated standard deviation of dry bulk density for each pixel (g/cm^3), $\delta_{V_{a_i}}$ is the estimated standard deviation of vertical accretion rate for each pixel (cm/yr), and $\delta_{F_{org_i}}$ is the estimated standard deviation of fraction organic matter (-) for each pixel. Note that ${F_{org}}_i^2 \delta_{F_{org_i}}^2$ is only used when calculating the organic sediment mass accumulation error. Associated covariance terms using F_{org} are also only considered when calculating organic sediment mass error. A_i is 10^{10} cm^2, which is the area of each pixel. σ is the covariance number between two variables (Table 1).

Sediment Volume Accumulation

Total sediment volume accumulation estimates were calculated since volume of sediment is what fills the accommodation space created by RSLR. In order to calculate an estimate for total (inorganic plus organic) sediment volume accumulated along the coast (V_T), the following equation was used:

$$V_T = \sum_{i€pix} V_{a_i} A_i$$

Where m_{T_i} is the total mass at pixel *i* (g/cm^{2}yr) and V_T is the total volume of sediment accumulated along the entire coast in km^3/yr. For volume of organic sediment accumulated along the coast (V_{org}; km^3/yr), F_{org_i} is multiplied in as well, which is the fraction organic matter at pixel i (-):

$$V_{org} = \sum_{i€pix} V_{a_i} A_i F_{org_i}$$

The total inorganic volume accumulation rate (V_I; km^3/yr) is calculated as follows:

$$V_I = V_T - V_{org}$$

The error $\left(\delta_v; \frac{\text{km}^3}{\text{yr}}\right)$ associated with the total sediment volume accumulation is:

$$\delta_v = \sqrt{\sum_{i€A} \left(A_i V_T \sqrt{\left(\frac{\delta_{V_{a_i}}}{V_{a_i}}\right)^2} \right)^2}$$

Where δ_v is the error on the sediment mass accumulation rate (MT/yr).

Trapping Efficiency

To compare m_T to total sediment discharge of both the Mississippi River and Atchafalaya Rivers from the 2006-2016, the same time period covered by the accretion measurements, a combined sediment discharge from the rivers was calculated. Trapezoidal integration, which assumes linear change from one measurement to the next, of direct USGS measurements for suspended sediment concentrations (C_{SS}) * discharge (Q_w) over the 10 years allowed us to calculate an estimate of the amount of sediment delivered to the coast each year (Q_s). The Mississippi River at Baton Rouge, LA (USGS Station: 07374000) has a record of C_{ss} from the 1970's to 2016. The Atchafalaya River at Melville, LA (USGS Station: 07381495) has a record of C_{ss} from 1979-2016. The integration gives a total sediment load of 113 MT/yr over the 10-year period (Figure 5). This is significantly smaller than the 205 MT/yr sediment load calculated by Blum and Roberts (2009)[1] for the period following damming (~1970-2009) using the Mississippi River at Tarbert Landing, MS (USGS Station: 07295100), and the Atchafalaya River at Simmesport, LA (USGS Station: 07381490).

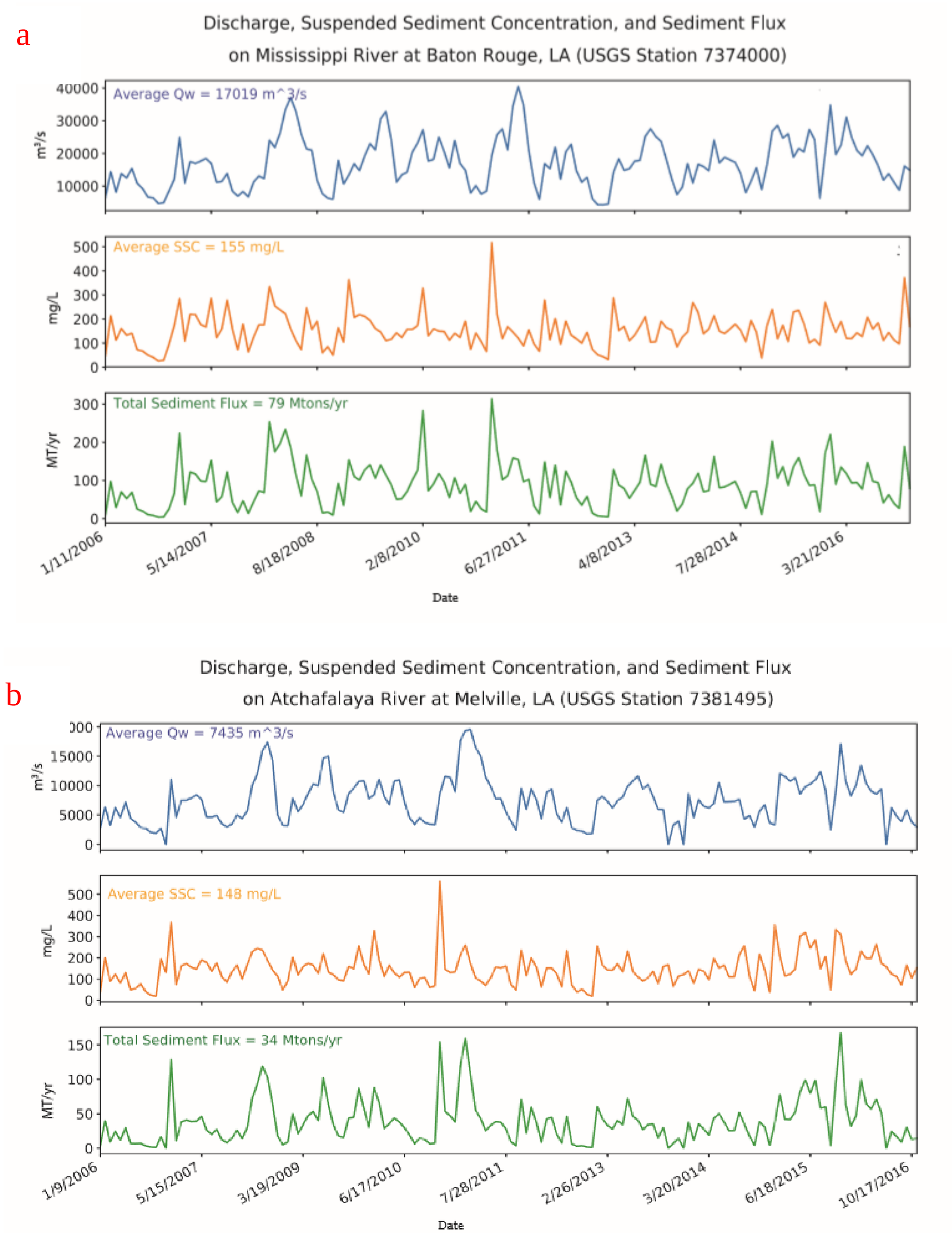

Figure 5: *Discharge (blue- m^3/s) and suspended sediment concentration (orange- mg/L) data gathered from the USGS for the two main rivers, The Mississippi River (a) and the Atchafalaya River (b) that feed the Louisiana coast. Integrating discharge and suspended sediment concentration over the 10-year study period gives the sediment flux (green- MT/yr) over that period. The total sediment flux for both rivers combined is 113 MT/yr, which is used to calculate the trapping efficiency along the coast.*

By determining the annual suspended sediment load to the coast over the past 10 years, a trapping efficiency can be directly calculated using the equation:

$$F_{trap} = \frac{m_T}{Q_s}$$

Where F_{trap} is total trapping efficiency (-), m_T is total sediment mass accumulation rate along the coast (MT/yr), and Q_s is combined river sediment load (MT/yr). m_T can be exchanged with m_R to get an initial trapping efficiency for directly nourished parts of the coast. For the trapping efficiency of indirectly nourished areas, we exchange m_T with m_O.

The error of the trapping efficiency is only affected by the error on the total sediment mass accumulation rate, since we do not have an estimate of error on the sediment discharge from the rivers. The error is calculated as follows:

$$\delta_{trap} = \sqrt{\left(\frac{\delta_{m_T}}{m_T}\right)^2} F_{trap}$$

Where $\delta_{trap}$is the estimated error on the trapping efficiency (-).

Sediment Deficit

Finally, a sediment deficit to the coast can be calculated by determining the amount of accommodation space created along the coast each year using the average Louisiana coastal subsidence rate[3] and average SLR rate. The coastal subsidence rate used is 9 mm/yr based on the geostatistical analysis of CRMS data to produce estimates of subsidence at the sediment surface[3]. Eustatic SLR has been shown to be 3 mm/yr[21]. This results in a 12 mm/yr or 1.2 cm/yr RSLR rate. In order to have a total net loss of 0 cm^2 of land, then:

$$m_N = A_i \sum_{i \in A} \rho_i R_{slr_i}$$

where m_N is mass of sediment needed (MT/yr) to fill the accommodation space created by RSLR each year. R_{slr_i} is relative sea level rise rate at each pixel (cm/yr), and A_i and is total land area of each pixel along the coast (cm^2). R_{slr_i} is assumed to be a constant 1.2 cm/yr.

The total error on the mass needed (MT/yr) is calculated as follows:

$$\delta_{m_N} = \sqrt{\left(\sum_{i \in A} A_i \sqrt{\left(\frac{\delta_{\rho_i}}{\rho_i}\right)^2 + \left(\frac{\delta_{R_{slr_i}}}{R_{slr_i}}\right)^2}\right)^2}$$

Where δ_{m_N} is the total error on the sediment mass needed (MT/yr) and $\delta_{R_{slr_i}}$ is the error on the relative sea level rise rate, which is a constant 0.1 cm/yr[3].

This mass is then compared to the total mass of sediment trapped on the coast each year. Sediment mass deficit is given by:

$$m_D = m_N - m_T$$

where m_D is the sediment mass deficit in MT/yr. If negative, then there is a sediment mass surplus. The error on the total sediment mass deficit ($\delta_{m_D}; MT/yr$) is given by:

$$\delta_{m_D} = \sqrt{(\delta_{m_N})^2 + (\delta_{m_T})^2}$$

A fraction mass sediment deficit is given by:

$$F_{m_D} = \left(\frac{m_D}{m_N}\right)$$

where F_{m_D} is the sediment deficit or surplus (-). The error on the fraction mass sediment deficit ($\delta_{F_{m_D}};\ -$) is given by:

$$\delta_{F_{m_D}} = \sqrt{\left(\frac{\delta_{m_D}}{m_D}\right)^2 + \left(\frac{\delta_{m_N}}{m_N}\right)^2}\, F_{m_D}$$

Similarly, the sediment volume deficit and fraction volume deficit can also be calculated. The volume of sediment needed to fill the accommodation space created each year is given by:

$$V_N = R_{slr} A$$

where A is the area of the entire shape file (cm^2) and R_{slr} is the constant relative sea level rise rate of 1.2 cm/yr. V_N is the volume of sediment needed to fill the accommodation space in (km^3/yr). The error associated on the volume needed is only dependent on the error of the relative sea level rise rate, which is 0.1 cm/yr for each pixel. The error on the volume of sediment needed is given by:

$$\delta V_N = \sqrt{\left(\frac{\delta_{R_{slr}}}{R_{slr}}\right)^2} V_N$$

This volume is then compared to the total volume of sediment trapped on the coast each year. Sediment volume deficit is then given by:

$$V_D = V_N - V_T$$

where V_D is the sediment volume deficit in km^3/yr. If negative, then there is a sediment volume surplus. The error on the volume deficit ($\delta_{V_D}; km^3/yr$) is given by:

$$\delta_{V_D} = \sqrt{\left(\delta_{V_N}\right)^2 + \left(\delta_{V_T}\right)^2}$$

A fraction volume sediment deficit is given by:

$$F_{V_D} = \left(\frac{V_D}{V_N}\right)$$

where F_{V_D} (-) is the fraction volume sediment deficit (+) or surplus (-). The associated error ($\delta_{F_{V_D}}; -$) is given by:

$$\delta_{F_{V_D}} = \sqrt{\left(\frac{\delta_{V_D}}{V_D}\right)^2 + \left(\frac{\delta_{V_N}}{V_N}\right)^2} F_{V_D}$$

Results

Sediment Accumulation

Between 2006 and 2016, our geostatistical analysis estimates that about 82 ± 1.3 MT/yr of sediment is trapped in the marshes of the Mississippi Delta. Of this 82 MT/yr of sediment, 59 ± 1.9 MT/yr was inorganic sediment and 23 ± 1.3 MT/yr was organic.

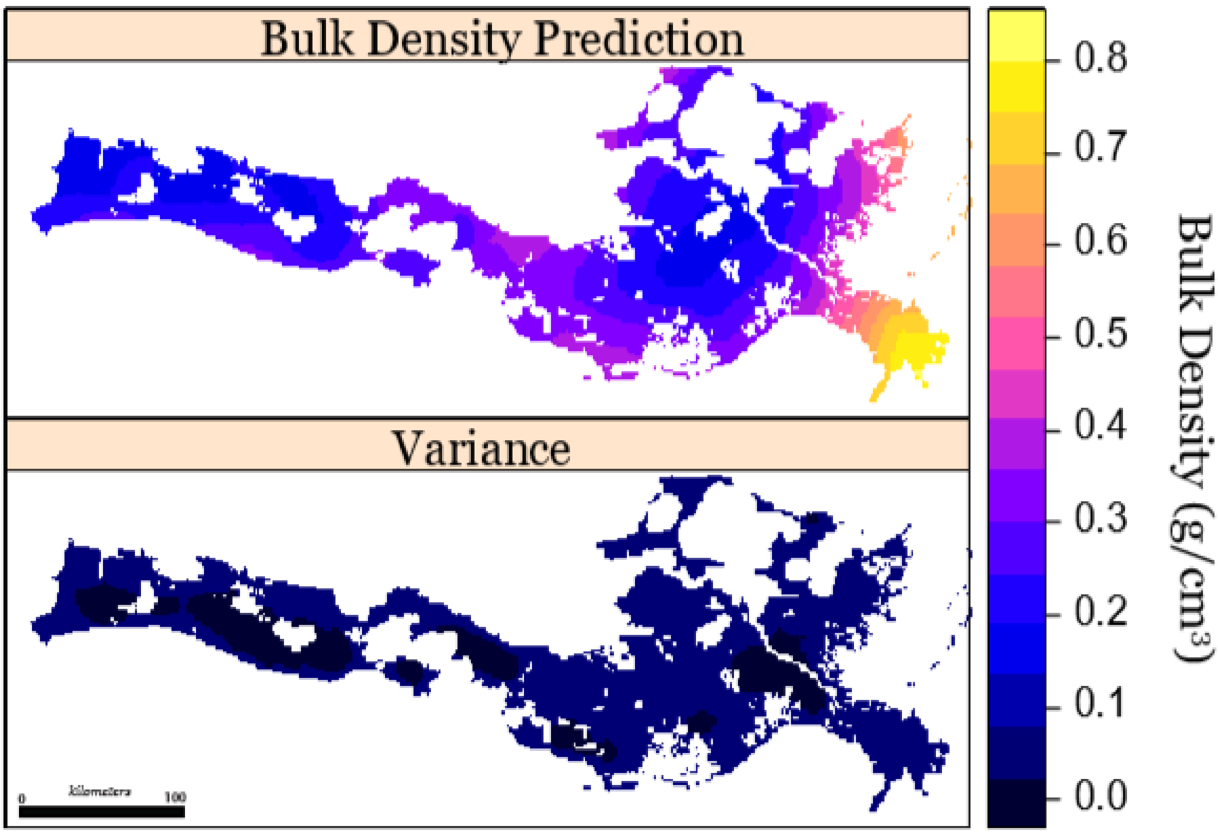

Figure 6: *The interpolated dry bulk density (g/cm^3) and associated variance across the entire study area. The 24 cm cores taken before establishment of platforms were used to gather bulk densities. We assume the average bulk density of the 24 cm core is representative of accumulated sediment in the 10 years following. Average bulk densities vary and tend to be higher where riverine sedimentation dominates (i.e. 'bird's foot').*

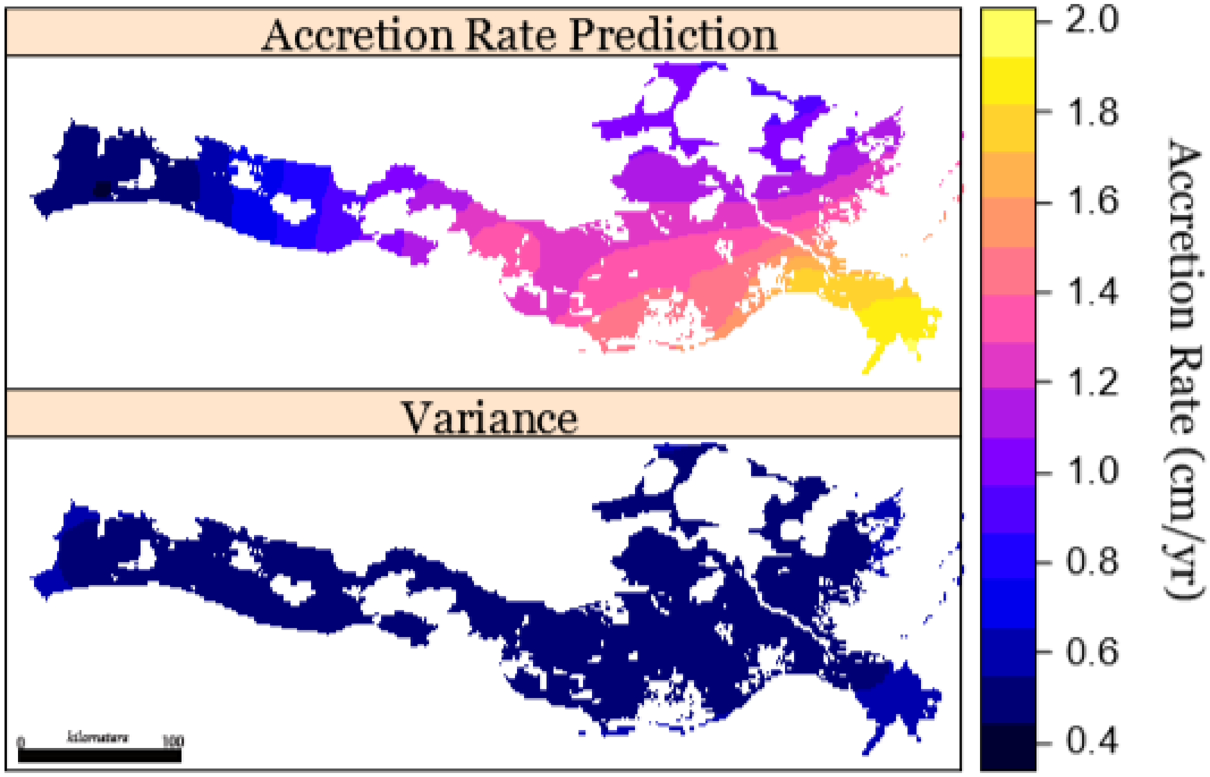

Figure 7: *The interpolated accretion rates (cm/yr) and associated variance across the entire study area. The 10-year average accretion rates for each of the 273 sites was used for interpolation with a 1 km^2 grid. Generally, the average accretion rate across the coast is about 1.1 cm/yr.*

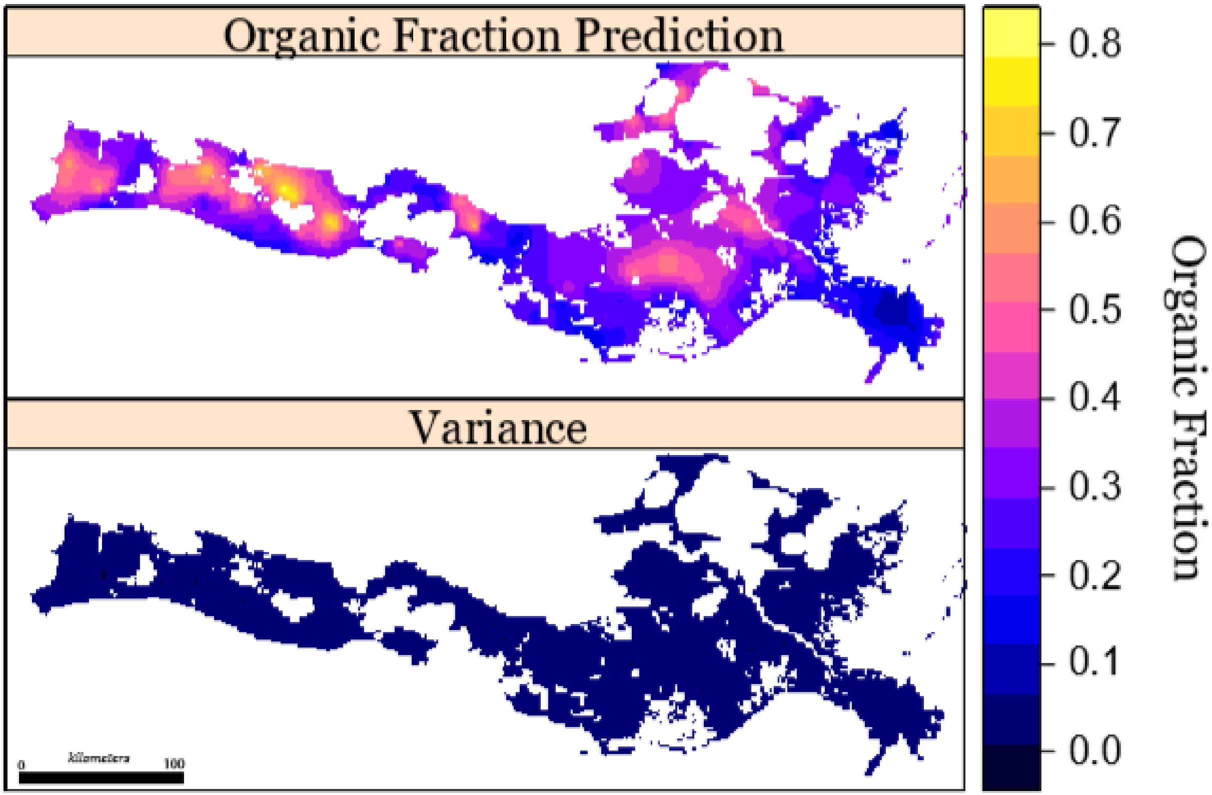

Figure 8: *This shows the interpolated organic fraction and associated variance across the entire study area. The 24 cm cores taken before establishment of platforms were used to measure organic fraction. We assume the average organic fraction of the 24 cm core is representative of accumulated sediment in the 10 years following. Average organic fractions vary and tend to be lower where riverine sedimentation dominates.*

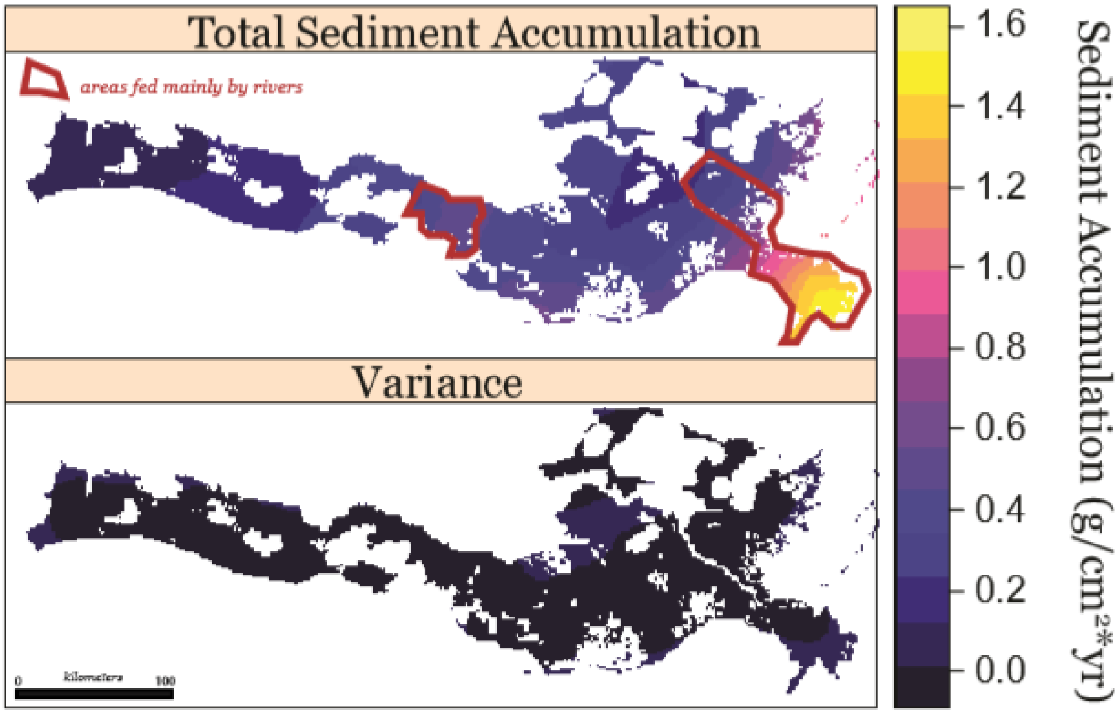

Figure 9: *The total sediment accumulation along the coast (g/cm^{2}yr) is calculated by multiplying the rasters of interpolated dry bulk density (fig. 6) and accretion rates (fig 7.). The top figure shows the rates along the coast and the red areas highlight the areas that are fed by the two main rivers (left box- Atchafalaya River, right box- Mississippi River). These areas tend to have higher accumulation rates than the rest of the coast. The bottom figure shows the associated variance of the accumulation rates.*

When the Mississippi Delta marshes are separated into regions with direct fluvial nourishment and regions with only indirect nourishment, we find that directly nourished regions accumulate 20 ± 2.4 MT/yr inorganic and 6 ± 1.7 MT/yr organic sediment. Compared to the combined load of the Mississippi and Atchafalaya Rivers (113 MT/yr), this is a trapping efficiency of 18%. Indirectly nourished areas accumulate the remaining 39 ± 1.6 MT/yr, of which 17 ± 1.1 MT/yr is organic. If the fluvial input to the Gulf of Mexico is 69 MT/yr (fluvial discharge minus inorganic accumulation in directly nourished areas), then the indirectly nourished areas trap about 32% of this.

Table 3: Sediment accumulation, sediment deficit, and trapping efficiency summary table. *From 2006-2016, about 82 Mton of sediment accumulated along the coast each year. Current land area is about 22,000 km^2. Assuming a relative sea level rise rate of 1.2 cm/yr, there was about a 3 Mton/yr sediment mass surplus (or 3.5% mass surplus) along the Louisiana Coast. However, there was a sediment volume deficit of about 0.014 km^3/yr (or about 5.4%). The breakdown between directly nourished areas and indirectly nourished areas and the relative mass and volume surplus/deficit for these areas are also shown. Negative sediment surplus numbers are indicative of a sediment deficit.*

	Inorganic (Mton/yr)	**Organic (Mton/yr)**	**Total (Mton/yr)**
Sediment Mass Accumulation	59 ± 1.9	23 ± 1.3	82 ± 1.3
Directly Nourished Mass Accumulation	20 ± 2.4	6 ± 1.7	26 ± 1.7
Indirectly Nourished Mass Accumulation	39 ± 1.6	17 ± 1.1	56 ± 1.1
	Inorganic (km^3/yr)	**Organic (km^3/yr)**	**Total (km^3/yr)**
Sediment Volume Accumulation	0.172 ± 0.276	0.077 ± 0.203	0.249 ± 0.187
Directly Nourished Volume Accumulation	0.041 ± 0.356	0.013 ± 0.261	0.054 ± 0.242
Indirectly Nourished Volume Accumulation	0.131 ± 0.224	0.064 ± 0.164	0.195 ± 0.153

Total Area

Sediment Mass Needed to Sustain Land Area	**79 ± 0.94 Mton/yr**	**Sediment Volume Needed to Sustain Land Area**	**0.263 ± 0.022 km^3/yr**
Sediment Mass Surplus	2.7 ± 1.6 Mton/yr	**Sediment Volume Surplus**	-0.014 ± 0.19 km^3/yr
Percent Sediment Mass Surplus	3.5 ± 2.1%	**Percent Volume Surplus**	-5.4 ± 8.3%
Trapping Efficiency	52 ± 1.6 %		

Directly Nourished Area

Sediment Mass Needed to Sustain Land Area	**20 ± 1.3 Mton/yr**	**Sediment Volume Needed to Sustain Land Area**	**0.049 ± 0.004 km^3/yr km^3/yr**
Sediment Mass Surplus	5.3 ± 2.2 Mton/yr	Sediment Volume Surplus	0.0051 ± 0.15 km^3/yr
Percent Sediment Mass Surplus	26.5 ± 10.9%	Percent Volume Surplus	10.4 ± 500%
Trapping Efficiency	18 ± 2.2 %		

Table 3: Sediment accumulation, sediment deficit, and trapping efficiency summary table-Cont'd.

Indirectly Nourished Area

	Inorganic (Mton/yr)	**Organic (Mton/yr)**	**Total (Mton/yr)**
Sediment Mass Needed to Sustain Land Area	59 ± 0.88 Mton/yr	Sediment Volume Needed to Sustain Land Area	0.21 ± 0.018 km^3/yr
Sediment Mass Surplus	-2.6 ± 1.4 Mton/yr	Sediment Volume Surplus	-0.019 ± 0.15 km^3/yr
Percent Sediment Mass Surplus	-4.4 ± 2.4%	Percent Volume Surplus	-9.0 ± 72 %
Trapping Efficiency	41± 1.7%		

Trapping Efficiency

The combined fluvial (MR and AR) sediment discharge from 2006-2016 was about 113 Mton/yr. Since the areas directly nourished by the rivers trapped about 20 MT of inorganic sediment per year, the directly nourished areas of sediment accumulation account for about 18% initial trapping efficiency on the delta top. The remaining 39 MT of inorganic sediment that accumulates in marshes each year is assumed to be delivered indirectly to the marshes, being delivered to the coast through tides or storms (continental shelf) or from somewhere else on the marsh platform. This sedimentation produces a total coastal marsh trapping efficiency of 52%.

Sediment Deficit

Sediment Deficits can be estimated by (a) comparing accumulation volume to accommodation volume generated by relative sea level rise over the marsh area, or by (b) comparing mass accumulation to the estimated mass required to fill the accommodation volume. Working volumetrically, the average accretion rate along the coast is 1.1 cm/yr. Since the predicted RSLR rate in Louisiana is 1.2 cm/yr throughout the study area, it is evident that there is not enough volume of sediment accumulating along the coast. In order to halt land loss completely, 0.26 ± 0.022 km^3/yr of sediment needs to be accumulated along the coast each year (land area ~ 22,000 km^2). This results in a 0.014 ± 0.19 km^3/yr sediment volume deficit or about 5.4% sediment volume deficit.

However, comparing mass accumulation to mass needed, it becomes evident that there is a small surplus. The total mass needed is about 78.9 MT/yr and about 81.7 MT accumulated each year. This results in a mass surplus of about 2.7 MT/yr or 3.5% mass surplus along the coast, which supports the recent insight that land loss is finally beginning to slow along the coast.

Further analysis provides insight into differences between directly nourished and indirectly nourished wetlands. In the directly nourished areas, there is a volume and mass surplus (Table 2). These areas trap about 5 MT (~26.5%) more sediment than they need each year, and the accumulation results in a surplus volume of 0.0051 km^3 (~10%) each year.

However, the indirectly nourished wetlands, which tend to receive less inorganic sediment more organic sediment, do not thrive like the directly nourished areas do. These areas have about a 2.6 MT/yr sediment mass deficit, which is about a 4.4% deficit. Furthermore, they have about a 0.019 km^3/yr volume deficit, which is about an 8.9% volume deficit.

Discussion

A New Estimate of Sediment Deficit

The CRMS dataset provides the data needed to calculate the first large-scale, field-based estimate of sediment accumulation along the Louisiana coast over the past decade. We show that between 2006 and 2016, there is about enough sediment mass and volume accumulating in coastal marshes counteract relative sea level rise and sustain the land area.

These results contrast with the previous studies of sediment deficit along the coast by Blum and Roberts (2009). The difference in estimates is due to differences in subsidence rates bulk density, as well as the neglect of the organic fraction. The subsidence rates calculated using the

CRMS data by Nienhuis (2017) show subsidence rates higher than the 1-8 mm/yr used by Blum and Roberts (2009). Therefore, the relative sea level rise of 12 mm/yr used in this study is higher than the relative sea level rise rate used by Blum and Roberts (2009), which ranged from 4 mm/yr - 12 mm/yr. Even with the higher RSLR rate, and subsequently more accommodation space to fill, we still show a smaller sediment deficit.

The shallow cores at the CRMS stations had mean and maximum dry bulk densities of coastal marsh sediment of about 0.2 and 0.8 g/cm^3, respectively. These densities indicate marsh sediment porosities between 70-90%, assuming that the mineral sediment had a density of 2.65 g/cm^3. In contrast, Blum and Roberts (2009) assumed a dry bulk density of 1.5 g/cm^3, which corresponds to a 45% porosity. Thus, the dry bulk densities directly measured along the coast are much smaller because the sediment has more porosity than previously assumed. This is likely the main reason for the difference in sediment deficit estimations.

Subsidence on the Mississippi Delta is primarily due to shallow sediment compaction[22], meaning that bulk density and subsidence rates are highly coupled properties that both vary with depth. In order to accurately calculate the mass flux due to subsidence, one must know the subsidence rate and the bulk density at a given depth. The CRMS data is particularly valuable because it provides measurements of subsidence and bulk density at the same horizon (the sediment surface). Therefore, the high subsidence rates at the sediment surface are offset by the small bulk densities found at the same locations.

Finally, Blum and Roberts (2009), neglected organic accumulation in the deposit completely for simplicity. Although inorganic sediment accounts for most of the sediment accumulation along the coast, organic sediment production by coastal marsh plants accounts for about 28% of all sediment mass accumulation. Because the highly organic rich marsh sediment tends to have lower bulk densities than inorganic sediment, it also has more pore space. Therefore, organic rich deposits (high fraction organic matter) take up more space than deposits with lower amounts of organic matter (i.e. have more volume). The volume of organic sediment accounts for 29% of the total volume of sediment accumulated. If we neglect organic accumulation, our results suggest that the small sediment mass surplus would turn into a significant mass deficit of 20 MT/yr (25%), in line with previous estimates. Thus, the mass and/or volume of the organic deposits should not be neglected when calculating sediment deficits in coastal marshes.

While there is enough mass of sediment being trapped along the coast every year to theoretically fill the accommodation space (3.5% mass surplus), because of sediment properties, enough volume does not accumulate each year. The volume depends on the accretion rates, which are impacted by the amount of sediment entering the marsh platform, as well as the porosity the sediment is deposited with. If the sediment was deposited with more porosity (i.e. had lower bulk density), then there would potentially be enough volume to fill the accommodation space created. Although there is not enough volume to fill the accommodation space, there is only a 5.4% volume sediment deficit. This sediment volume deficit could be mitigated in the future with sediment diversions that would promote deposition of the 30% of Mississippi River sediment that currently does not reach marshes.

Most of the marshes in the western portion of the coast (Chenier Plain) are indirectly nourished, as there is no major river feeding this portion of the coast. When dividing up the land area into directly nourished vs. indirectly nourished areas, it becomes evident that the directly nourished areas have enough sediment (mass and volume) to keep pace with the RSLR rates they are experiencing; however, the indirectly nourished areas experience a 9% sediment volume deficit. Thus, these areas cannot keep pace with RSLR, even with the higher organic contribution observed in these areas. While they do not keep pace with RSLR, the sediment deficit is not as large as previously thought. However, these areas should be the focus of future restoration plans.

On top of the different assumptions, the smaller total sediment deficit may also be in part due to additional land loss from the time of the last sediment deficit study[1]. Further, these new estimates of the Mississippi River sediment accumulation and deficit characterized deposition over about 22,000 km^2 of marsh. The size of the shapefile used to conduct the study may alter results slightly, though our shapefile is representative of coastal marshlands, as it spans the entire area of known CRMS sites.

A Field Based Estimate of Trapping Efficiency

By calculating a sediment budget in deltaic coastal marshes using the Mississippi and Atchafalaya River discharge and suspended sediment concentrations, we show that the coast traps about 52% of the inorganic sediment being delivered. Our calculated trapping efficiency is slightly greater than the 40% trapping efficiency assumed in Blum and Roberts (2009)[1]. This higher trapping efficiency is likely seen because over the 10-year period of our study the sediment supplies of the Mississippi and Atchafalaya rivers (113 MT/yr) were significantly smaller than the values used by Blum and Roberts, 2009 (205 MT/yr). The reduced sediment discharge is potentially due to natural variability of fluvial sediment transport or may be a part of the trend of reduced sediment transport since 1970[23]. If river sediment discharges were the 205 MT/yr used by Blum and Roberts (2009)[1], than the trapping efficiency would be about 40%.

The loss of delta marsh in the 20th century has been attributed to several causes, but the separation of the river from marsh reducing sediment supply is among the primary causes[24]. Just 18% of the inorganic sediment is trapped in areas that are directly nourished, while 41% of the sediment transported indirectly to coastal marshes is trapped. The difference in trapping efficiency is highly affected by the amount of sediment entering the two systems. The directly nourished areas receive the entire riverine sediment input and the marshes receive only the sediment input not trapped in the directly nourished areas. Although coastal marshes that do not receive direct sediment have higher trapping efficiencies than areas with direct sediment input, they do not trap enough sediment to sustain their current land area.

Limitations of this study

The CRMS network of sites were designed to monitor sedimentary accumulation on marsh platforms. This study quantifies the sediment balance in these areas. However, there are also several types of erosion and deposition which are not characterized in this study, including marsh edge erosion and subaqueous deposition. However, we estimate these processes have only a minor effect on the overall delta mass balance.

Marsh edge erosion at the edges of ponds, and result in lateral changes in marsh extent. CRMS stations measure vertical accretion change to marsh platforms and are not designed to measure any lateral erosion to marsh edges. However, marsh edge erosion likely did not play a large role during our study period, as marsh edge erosion generally happens due to large breaking waves, typical of hurricanes. Over 34 years, there has only been 250 km^2 of marsh erosion attributed directly to marsh edge erosion[25]. If the thickness of this marsh erosion is 2 m[26] and the average bulk density of marsh sediment is 0.3 g/cm^3, then this results in about 4 MT/yr of marsh edge erosion over the 34-year period. Marsh sediment that experiences gradual threats, like RSLR, is generally able to handle these stresses and marsh edge erosion is not a factor in these scenarios[11]. During the 10-year study period, there were two minor hurricanes along the Louisiana coast, Hurricane Gustav and Hurricane Ike. Hurricane Gustav is shown to have caused only about 0.9% of land loss along the coast; however, recovery of marshlands has been shown to be slowly erasing the loss caused by this hurricane[27]. Hurricane Ike was also a category 2 storm but mostly impacted Texas, so we assume the effects of this storm are similar to the effects of Ike, and the coast is likely recovering from this storm as well. The effects are much less severe than the land loss of some 500 km^2 caused by Hurricane Katrina, which occurred before deployment of CRMS stations, so erosion along marsh edges is assumed to not significantly alter our results.

The CRMS sites also do not measure delta front deposition, which is significant in parts of the 'birds foot' of the Mississippi Delta, as well as the Wax Lake and Atchafalaya Deltas in Atchafalaya Bay. There has been about 3 m of sediment deposited over about 100 km^2 on the Wax Lake Delta since 1970. Assuming a bulk density of 0.65 g/cm^3 (average of bulk density of core 0-24 cm depth at CRMS station 0479- Wax Lake Delta), this results in about 4 MT/yr of sediment since formation. The deposition on the Atchafalaya Delta and the 'birds foot' part of the Mississippi River Delta is assumed to be of the same order of magnitude, so these three areas combined account for around an extra 12 MT of sediment mass accumulation along the coast each year.

When monitoring marsh accretion, it is important to monitor marsh top erosion as well, so as to not bias mass balance estimations[28]. In most cases, accumulation time series at CRMS sites showed short periods of erosion within the long-term depositional signal. Hence, we consider the deposition rates to be characteristic of decadal scale marsh stability. However, we do not rule out the possibility that some CRMS sites were neglected because erosion over the same time scale did not allow an accumulation record to persist. We assume that this erosion is counter-balanced by deposition in the subaqueous delta regions. Therefore, excluding erosion and deposition should not significantly alter our results.

Implications for coastal restoration

Recent management plans have been aimed at increasing the sediment supply in order to decrease the loss of lands along the coast. Direct nourishment of wetlands, typically due to riverine sediment input, allows coastal lands to keep pace with RSLR[24]. Indirect nourishment of marshes, areas that do not have a significant source of riverine input, depend on both inorganic and organic contributions to sustain the land area[29]. While this helps wetlands keep pace with RSLR, if rates of RSLR are too high, wetlands may still drown[8]. The western portion (the Chenier Plain) of the coast has the highest subsidence rates[3], as well as the lowest accretion rates[2], so this should be the target area for future restoration strategies.

The Atchafalaya Basin is currently keeping pace with RSLR, which shows the promise for rerouting of riverine sediment to other part of the coast. While river diversions may be a good management strategy to increase sediment supply to areas not currently keeping pace with RSLR, other restoration strategies should be explored too, as the western portion of the coast, and other areas not receiving direct sediment input, are not as doomed as previously thought.

Since the trapping efficiency is only about 50%, management strategies should focus on ways of trapping more of this sediment along the coast. Because of this trapping efficiency and the low volume deficit, it is evident that there is not a sediment deficit in the sediment budget, which gives hope for restoring and protecting these lands.

The sediment deficit measurements presented here are based of a dataset gathered over a decade that was remarkable in several ways. 1) few hurricanes. 2) low river sed discharge. The likely do not represent the sediment of previous decades, were large areas of marsh were drowned. The behavior of deltas is very timescale dependent. Hence, we reason that measurements from the next decade may bear some resemblance to the ones presented here. However, they should not be used as a predictive tool for longer timescales.

Conclusion

There is enough sediment transported to the coast to halt land loss along the Louisiana Coast. The small sediment volume deficit observed along the coast is due to the low marsh bulk density measured at the marsh surface and significant accumulation rates of organic material. The deficit is due, in part, to the trapping efficiency of these coastal wetlands. Half of all the sediment delivered by the rivers is trapped in the wetlands. Further, wetlands are also great producers of organic sediment, which enhances their ability to keep pace with RSLR. Even though the RSLR rate along the Louisiana Coast is among the highest in the U.S., the wetlands are doing a significantly better job at keeping pace with RSLR than previously thought.

The directly nourished areas have a significant sediment surplus in terms of mass and volume and are accreting at rates higher than RSLR. However, the areas that are indirectly nourished and not fed by a major river are more susceptible to degradation caused by RSLR. Although a sediment deficit is observed in the indirectly nourished areas, surprisingly, they are not as sediment starved as previously thought. Even though they are not nourished directly by a river, they manage to trap almost enough sediment to keep pace with a 1.2 cm/yr RSLR. However, these areas should be of primary focus in future restoration and management plans. Future projections of increased sea level rise rates, as well as spatially distributed subsidence rates can shed even more light on the vulnerability of different regions along the coast.

Overall, since there is enough sediment to sustain the land area, future management should focus on increasing the deltaic and coastal sediment trapping efficiency, as well as rerouting more inorganic sediment to areas that cannot currently keep pace with RSLR.

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Appendix A- Variables

$\rho_i - sediment\ density\ at\ pixel\ i\ (\frac{g}{cm^3})$

$V_{a_i} - vertical\ accretion\ rate\ at\ pixel\ i\ (\frac{cm}{yr})$

$F_{org_i} - fraction\ organic\ matter\ at\ pixel\ i\ (-)$

$A_i - area\ of\ one\ pixel - \ 1\ km^2$

$m_T - total\ sediment\ mass\ (\frac{MT}{y})$

$m_{org} - total\ organic\ sediment\ mass\ (\frac{MT}{yr})$

$m_I - total\ inorganic\ sediment\ mass\ (\frac{MT}{yr})$

$\delta_{\rho_i} - standard\ deviation\ of\ bulk\ density\ at\ pixel\ i\ (\frac{g}{cm^3})$

$\delta_{V_{a_i}} - standard\ deviation\ of\ vertical\ accretion\ rate\ at\ pixel\ i\ (\frac{cm}{yr})$

$\delta_{F_{org_i}} - standard\ deviation\ of\ fraction\ organic\ matter\ at\ pixel\ i\ (-)$

$\sigma_{\rho_i V_{a_i}} - covariance\ between\ bulk\ density\ and\ vertical\ accretion\ rate\ at\ pixel\ i$

$\sigma_{\rho_i F_{org_i}} - covariance\ between\ bulk\ density\ and\ fraction\ organic\ matter\ at\ pixel\ i$

$\sigma_{F_{org_i} V_{a_i}}$
$- covariance\ between\ fraction\ organic\ matter\ and\ vertical\ accretion\ rate\ at\ pixel\ i$

$\delta_m - the\ error\ on\ the\ total\ sediment\ mass\ accumulated\ (\frac{MT}{yr})$

$V_T - total\ volume\ accumulation\ rate\ (\frac{km^3}{yr})$

$V_{org} - organic\ volume\ deficit\ rate\ (\frac{km^3}{yr})$

$V_I - inorganic\ volume\ deficit\ rate\ (\frac{km^3}{yr})$

$\delta_v - error\ of\ the\ total\ sediment\ volume\ accumulation\ rate\ (\frac{km^3}{yr})$

$Q_s - riverine\ sediment\ discharge\ (\frac{MT}{yr})$

$F_{trap} - trapping\ efficiency\ (-)$

$\delta_{trap} - error\ of\ trapping\ efficiency\ (-)$

$R_{slr_i} - relative\ sea\ level\ rise\ rate\ at\ pixel\ i\ (\frac{cm}{yr})$

$\delta_{R_{slr_i}} - error\ of\ relative\ sea\ level\ rise\ rate\ at\ pixel\ i\ (0.1\frac{cm}{yr})$

$m_N - total\ sediment\ mass\ needed\ to\ sustain\ land\ area\ (\frac{MT}{yr})$

$\delta_{m_N} - error\ of\ sediment\ mass\ needed\ to\ sustain\ land\ area\ (\frac{MT}{yr})$

$m_D - sediment\ mass\ deficit\ (\frac{MT}{yr})$

$\delta_{m_D} - error\ of\ sediment\ mass\ deficit\ (\frac{MT}{yr})$

$F_{m_D} - fraction\ mass\ deficit\ (-)$

$\delta_{F_{m_D}} - error\ of\ fraction\ mass\ deficit\ (-)$

$V_N - sediment\ volume\ needed\ to\ sustain\ current\ land\ area\ (\frac{km^3}{yr})$

$\delta_{V_N} - error\ of\ sediment\ volume\ needed\ to\ sustain\ current\ land\ area\ (\frac{km^3}{yr})$

$V_D - sediment\ volume\ deficit\ (\frac{km^3}{yr})$

$\delta_{V_D} - error\ of\ sediment\ volume\ deficit\ (\frac{km^3}{yr})$

$F_{V_D} - fraction\ volume\ deficit\ (-)$

$$\delta_{F_{V_D}} - error\ of\ fraction\ volume\ deficit\ (-)$$

Appendix B- Interpolation Code

CRMS Universal Kriging- Sediment Accumulation along the Louisiana Coast

Introduction

```
#Read Shape Polygon

coast <- readOGR("C:/Users/kmsanks/Documents/Research/Kriging/UKrig","Vegetation")

## Warning in ogrInfo(dsn = dsn, layer = layer, encoding = encoding, use_iconv
## = use_iconv, : ogrInfo: C:/Users/kmsanks/Documents/Research/Kriging/UKrig/
## Vegetation.dbf not found

## OGR data source with driver: ESRI Shapefile
## Source: "C:/Users/kmsanks/Documents/Research/Kriging/UKrig", layer: "Vegetation"
## with 86 features
## It has 0 fields

#Project into UTM Zone 15N
LC <- spTransform(coast, CRS("+proj=utm +north +zone=15 +datum=WGS84"))

#Read in the Spatial Data
Delta_Data <- read.csv(file="CRMS_Data.csv", header=TRUE, sep=",")
#Summary of data
head(Delta_Data)

##   Site Longitude Latitude Accretion     BulkD OrganicContent   XCoord
## 1  174  -89.7630  29.3963      8.37 0.2983333     0.20818889 814159.1
## 2  302  -90.9170  29.1478      5.08 0.5227778     0.09387222 702618.9
## 3  156  -89.1667  29.1639      4.20 0.7588889     0.07860000 872918.8
## 4  479  -91.4480  29.5269      3.81 0.6533333     0.07109444 650398.9
## 5  272  -89.6980  29.4180      3.17 0.2911111     0.23337778 820407.0
## 6  386  -90.3543  29.4325      2.93 0.1300000     0.56469444 756663.8
##    YCoord      mult
## 1 3256252 2.4970500
## 2 3226158 2.6557111
## 3 3232234 3.1873333
## 4 3267363 2.4892000
## 5 3258835 0.9228222
## 6 3258818 0.3809000

#Convert this basic data frame into a spatial points data frame
coordinates(Delta_Data) = ~XCoord + YCoord #UTM vs. lat/long which are in degrees N

#Plot the CRMS points on the land polygon
plot(LC, main="273 CRMS Stations on Coast Polygon")
plot(Delta_Data, pch=20, add=TRUE)
```

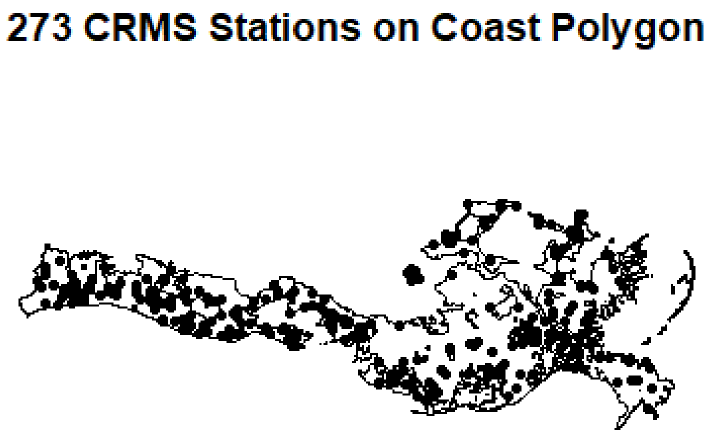

Figure 1: The 273 CRMS Stations used for interpolation are shown on the Louisiana coastal land polygon used to mask the interpolation.

Data

```
LA.Spatial <- read.csv("CRMS_Data.csv", header = T)
head(LA.Spatial)

##   Site Longitude Latitude Accretion     BulkD OrganicContent   XCoord
## 1  174  -89.7630  29.3963      8.37 0.2983333     0.20818889 814159.1
## 2  302  -90.9170  29.1478      5.08 0.5227778     0.09387222 702618.9
## 3  156  -89.1667  29.1639      4.20 0.7588889     0.07860000 872918.8
## 4  479  -91.4480  29.5269      3.81 0.6533333     0.07109444 650398.9
## 5  272  -89.6980  29.4180      3.17 0.2911111     0.23337778 820407.0
## 6  386  -90.3543  29.4325      2.93 0.1300000     0.56469444 756663.8
##    YCoord      mult
## 1 3256252 2.4970500
## 2 3226158 2.6557111
## 3 3232234 3.1873333
## 4 3267363 2.4892000
## 5 3258835 0.9228222
## 6 3258818 0.3809000

LA.data <- as.data.frame(LA.Spatial)
#Create a geodata frame for bulk density
#Use geoR to convert data into geodata
bulkd.geodata <- as.geodata(LA.Spatial, coords.col=7:8, data.col=5)
coordinates(LA.Spatial) <- ~XCoord + YCoord
```

Bulk Density

Trend Surface Model

```
tsm <- lm(BulkD ~ I(XCoord^2) + I(XCoord*YCoord), data=LA.Spatial)
summary(tsm)
```

```
##
## Call:
## lm(formula = BulkD ~ I(XCoord^2) + I(XCoord * YCoord), data = LA.Spatial)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -0.25635 -0.12552 -0.04349  0.07607  0.79096
##
## Coefficients:
##                     Estimate Std. Error t value Pr(>|t|)
## (Intercept)        7.316e-01  2.987e-01   2.450   0.0149 *
## I(XCoord^2)        1.821e-12  7.185e-13   2.534   0.0118 *
## I(XCoord * YCoord) -5.837e-13  2.860e-13  -2.041   0.0423 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.1867 on 270 degrees of freedom
## Multiple R-squared:  0.1099, Adjusted R-squared:  0.1034
## F-statistic: 16.68 on 2 and 270 DF,  p-value: 1.483e-07
```

```
x.range <- as.integer(c(400000.0, 910000.0))
y.range <- as.integer(c(3195000.0, 3370000.0))
grd <- expand.grid(x=seq(from=x.range[1], to=x.range[2], by=1000), y=seq(from=y.range[1], t
o=y.range[2], by=1000))
coordinates(grd) <- ~x + y
gridded(grd) <- TRUE
ras <- raster(grd)
LA.grd <- as(ras, "SpatialGrid")
LA.df <- data.frame(LA.grd)
names(LA.df) <- c("XCoord", "YCoord")
LA.grd$tsm.p <- predict(tsm, LA.df)
spplot(LA.grd, zcol="tsm.p", scales=list(draw=T),   main="BulK Density Estimates from Trend
Surface Mo
```

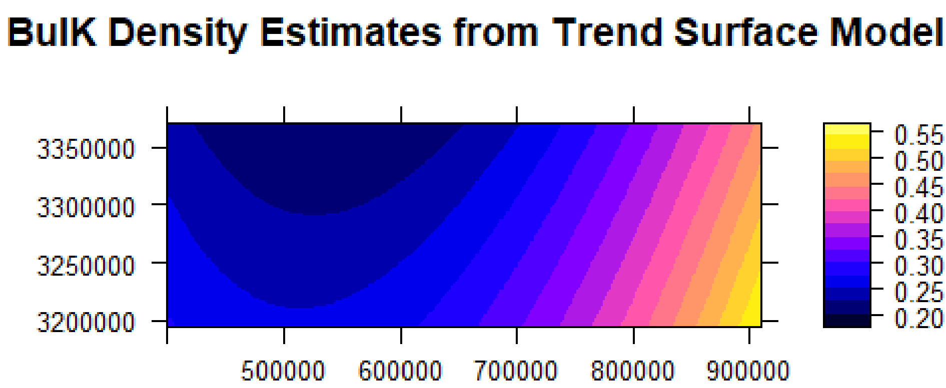

Figure 2: Bulk density estimates (g/cm^3) shown along the interpolation grid using the trend surface model.

```
tsm.BD.v <- variogram(resid(tsm) ~1, LA.Spatial)
tsm.BD.mod <- fit.variogram(tsm.BD.v, vgm(0.045, "Exp", 150000, 0.02))
plot(tsm.BD.v, model=tsm.BD.mod, main="Bulk Density TSM Residuals")
```

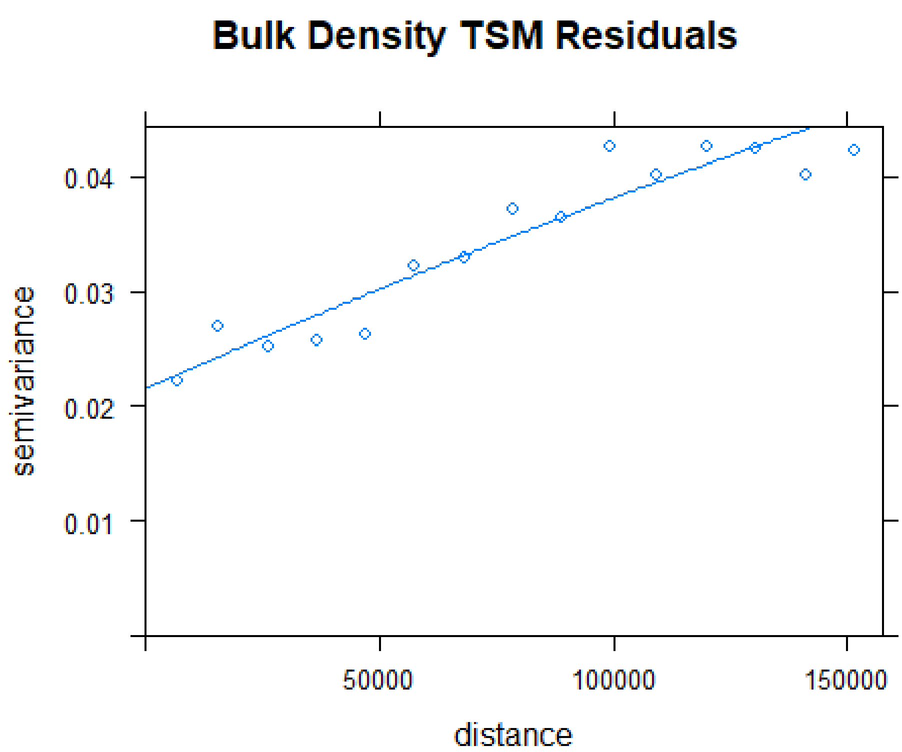

Figure 3: Semivariogram created from trend surface model bulk density residuals (g/cm^3).

Results

```
#Min Bulk D with Spherical Distance Weights and Spatial Trend
LA.grd$XCoord <- LA.df$XCoord
LA.grd$YCoord <- LA.df$YCoord
#LA.grd$ELEV_M <- countries_grd$Alt
bd.uk <- krige(BulkD~1, locations=LA.Spatial, LA.grd, model=tsm.BD.mod)
## [using ordinary kriging]

bd.uk <- brick(bd.uk)
bd.uk <- mask(bd.uk, LC)
names(bd.uk) <- c('Bulk Density Prediction', 'Variance')
spplot(bd.uk, xlim=c(400000,900000))#,scales=list(draw=T))
```

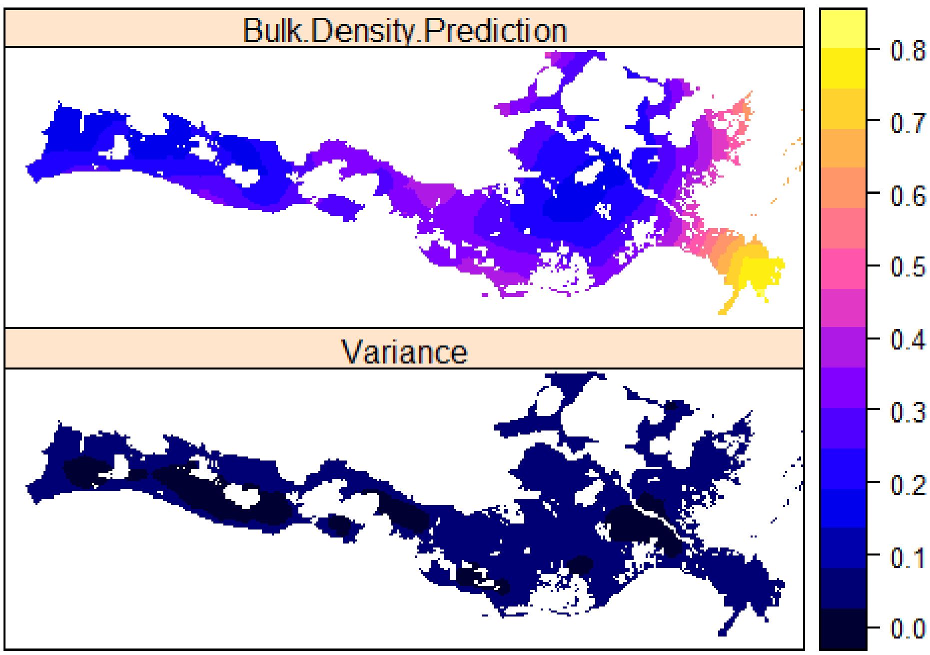

Figure 4: The masked interpolation of bulk density (g/cm^3) and associated variance.

Accretion

Trend Surface Model

```
tsm_acc <- lm(Accretion ~ I(XCoord^2) + I(XCoord*YCoord), data=LA.Spatial)
summary(tsm_acc)

##
## Call:
## lm(formula = Accretion ~ I(XCoord^2) + I(XCoord * YCoord), data = LA.Spatial)
```

```
##
## Residuals:
##     Min      1Q  Median      3Q     Max
## -1.0822 -0.3794 -0.0921  0.2138  6.8888
##
## Coefficients:
##                      Estimate Std. Error t value Pr(>|t|)
## (Intercept)         1.433e+00  1.157e+00   1.239    0.216
## I(XCoord^2)         4.721e-12  2.783e-12   1.696    0.091 .
## I(XCoord * YCoord) -1.162e-12  1.108e-12  -1.049    0.295
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.7233 on 270 degrees of freedom
## Multiple R-squared:  0.1567, Adjusted R-squared:  0.1504
## F-statistic: 25.08 on 2 and 270 DF,  p-value: 1.025e-10
```

```
x.range <- as.integer(c(400000.0, 910000.0))
y.range <- as.integer(c(3195000.0, 3370000.0))
grd <- expand.grid(x=seq(from=x.range[1], to=x.range[2], by=1000), y=seq(from=y.range[1], t
o=y.range[2], by=1000))
coordinates(grd) <- ~x + y
gridded(grd) <- TRUE
ras <- raster(grd)
LA.grd <- as(ras, "SpatialGrid")
LA.df <- data.frame(LA.grd)
names(LA.df) <- c("XCoord", "YCoord")
LA.grd$tsm.p <- predict(tsm_acc, LA.df)
spplot(LA.grd, zcol="tsm.p", scales=list(draw=T),
       main="Accretion Estimates from Trend Surface Model")
```

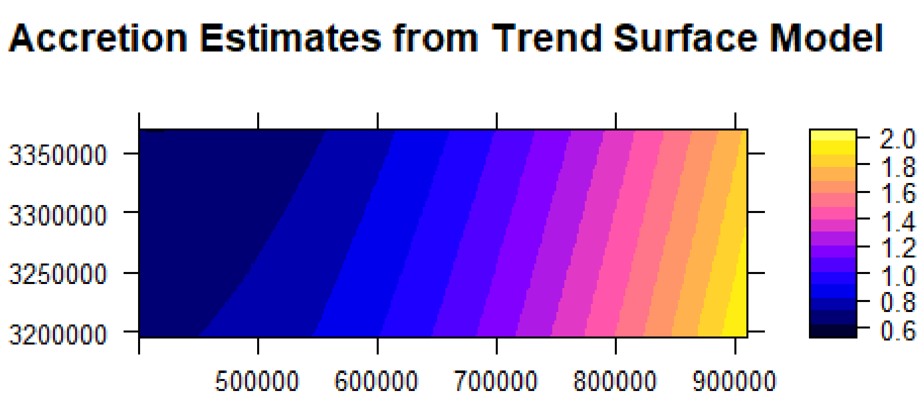

Figure 5: Accretion rate estimates (cm/yr) shown along the interpolation grid using the trend surface model.

```
tsm.acc.v <- variogram(resid(tsm_acc) ~1, LA.Spatial)
tsm.acc.mod <- fit.variogram(tsm.acc.v, vgm(NA, "Exp", NA, NA))

## Warning in fit.variogram(tsm.acc.v, vgm(NA, "Exp", NA, NA)): No convergence
## after 200 iterations: try different initial values?

plot(tsm.acc.v, model=tsm.acc.mod, main="Accretion TSM Residuals")
```

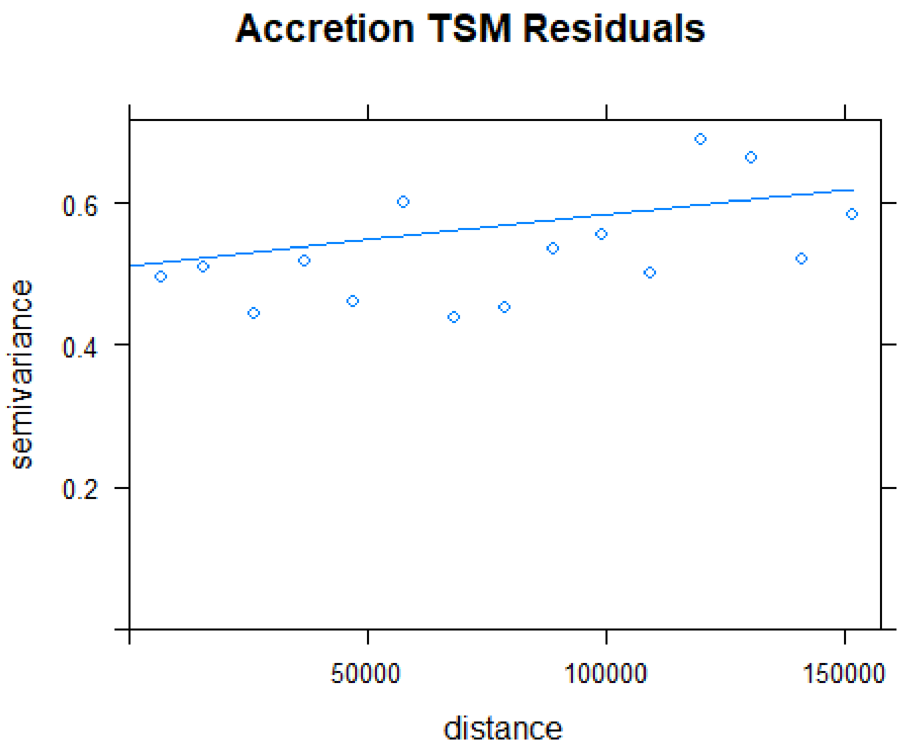

Figure 6: Semivariogram created from trend surface model accretion rate residuals (cm/yr).

Results

```
#Min Bulk D with Spherical Distance Weights and Spatial Trend
LA.grd$XCoord <- LA.df$XCoord
LA.grd$YCoord <- LA.df$YCoord
#LA.grd$ELEV_M <- countries_grd$Alt
acc.uk <- krige(Accretion~1, locations=LA.Spatial, LA.grd, model=tsm.acc.mod)

## [using ordinary kriging]

acc.uk <- brick(acc.uk)
acc.uk <- mask(acc.uk, LC)
names(acc.uk) <- c('Accretion Prediction', 'Variance')
spplot(acc.uk, xlim=c(400000,900000))#,scales=list(draw=T))
```

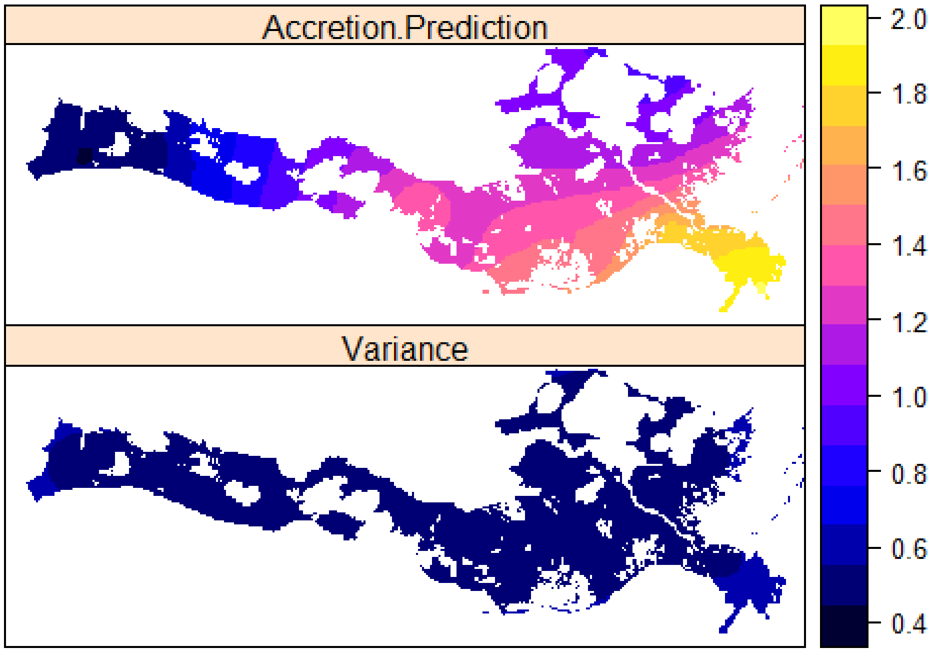

Figure 7: The masked interpolation of accretion rates (cm/yr) and associated variance.

Organic Fraction

Trend Surface Model

```
tsm_org <- lm(OrganicContent ~ I(XCoord^2) + I(XCoord*YCoord), data=LA.Spatial)
summary(tsm_org)

##
## Call:
## lm(formula = OrganicContent ~ I(XCoord^2) + I(XCoord * YCoord),
##     data = LA.Spatial)
##
## Residuals:
##     Min      1Q  Median      3Q     Max
## -0.2953 -0.1194 -0.0286  0.1092  0.5108
##
## Coefficients:
##                      Estimate Std. Error t value Pr(>|t|)
## (Intercept)         1.204e-02  2.627e-01   0.046   0.9635
## I(XCoord^2)        -1.541e-12  6.321e-13  -2.438   0.0154 *
## I(XCoord * YCoord)  4.701e-13  2.516e-13   1.868   0.0628 .
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
##
## Residual standard error: 0.1643 on 270 degrees of freedom
## Multiple R-squared:  0.1349, Adjusted R-squared:  0.1285
## F-statistic: 21.05 on 2 and 270 DF,  p-value: 3.208e-09
```

```
x.range <- as.integer(c(400000.0, 910000.0))
y.range <- as.integer(c(3195000.0, 3370000.0))
grd <- expand.grid(x=seq(from=x.range[1], to=x.range[2], by=1000), y=seq(from=y.range[1], t
o=y.range[2], by=1000))
coordinates(grd) <- ~x + y
gridded(grd) <- TRUE
ras <- raster(grd)
LA.grd <- as(ras, "SpatialGrid")
LA.df <- data.frame(LA.grd)
names(LA.df) <- c("XCoord", "YCoord")
LA.grd$tsm.p <- predict(tsm_org, LA.df)
spplot(LA.grd, zcol="tsm.p", scales=list(draw=T),
    main="Organic Fraction Estimates from Trend Surface Model")
```

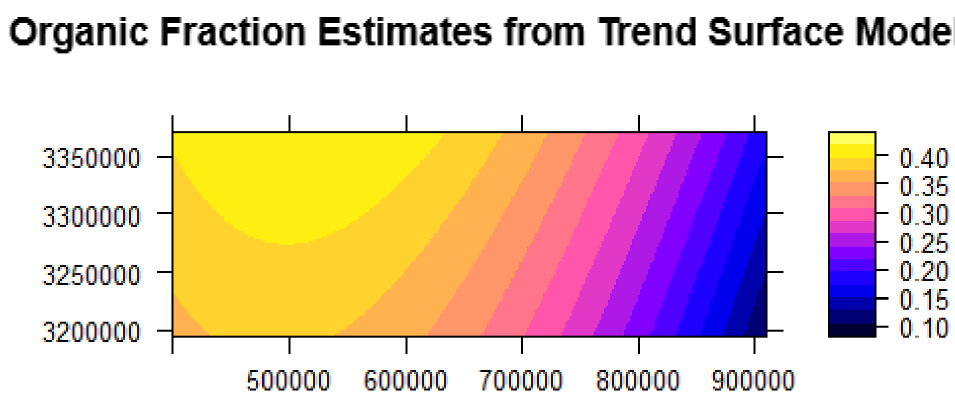

Figure 8: Organic fraction estimates (-) shown along the interpolation grid using the trend surface model.

```
tsm.org.v <- variogram(resid(tsm_org) ~1, LA.Spatial)
tsm.org.mod <- fit.variogram(tsm.org.v, vgm(NA, "Exp", NA, NA))
plot(tsm.org.v, model=tsm.org.mod, main="Organic Fraction TSM Residuals")
```

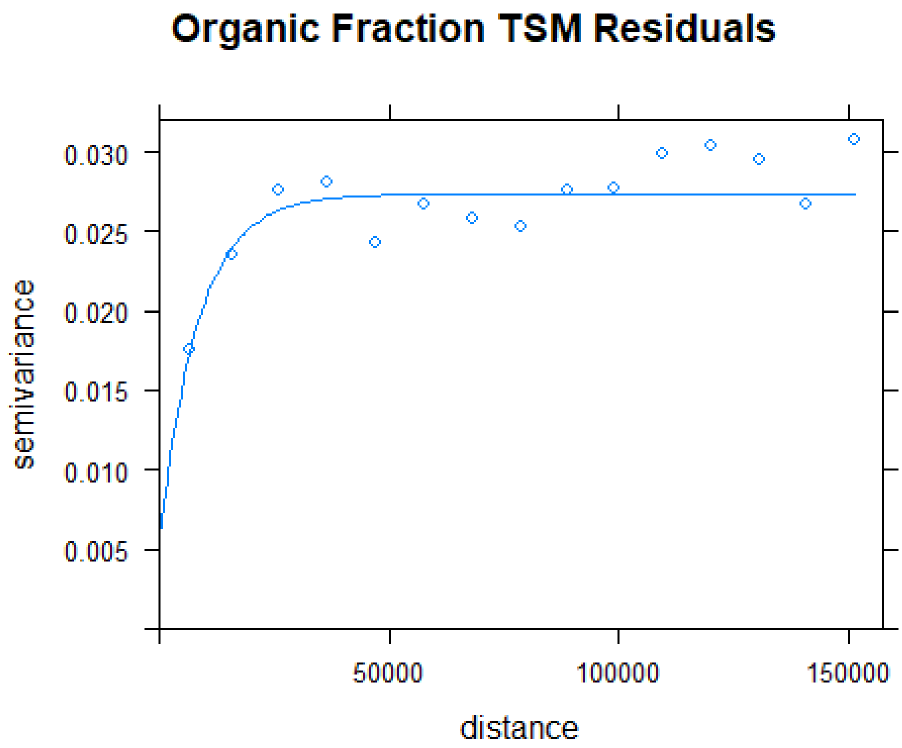

Figure 9: Semivariogram created from trend surface model organic fraction residuals (-).

Results

```
#Min Organic with Exponential Distance Weights and Spatial Trend
LA.grd$XCoord <- LA.df$XCoord
LA.grd$YCoord <- LA.df$YCoord
org.uk <- krige(OrganicContent~1, locations=LA.Spatial, LA.grd, model=tsm.org.mod)

## [using ordinary kriging]

org.uk <- brick(org.uk)
org.uk <- mask(org.uk, LC)
names(org.uk) <- c('Organic Fraction Prediction', 'Variance')
spplot(org.uk, xlim=c(400000,900000))#,scales=list(draw=T))
```

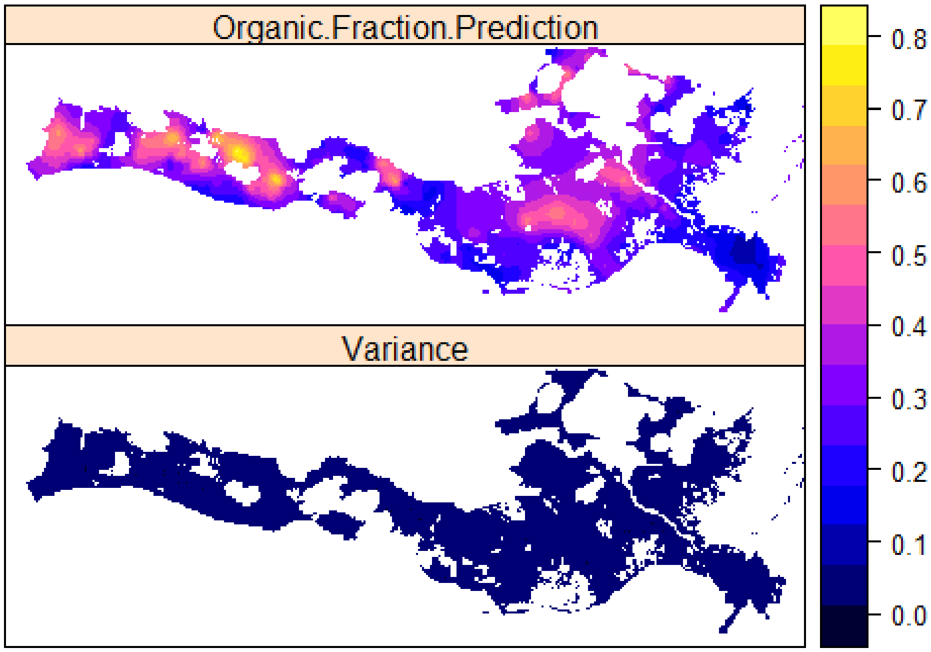

Figure 10: The masked interpolation of organinc fraction (-) and associated variance.

```
#Create raster
writeRaster(bd.uk, filename="bulkdensityuk.tif", format="GTiff", overwrite=TRUE)
bd.uk.df <- as.data.frame(bd.uk)
write.csv(bd.uk.df, "bd_var_df")
bd.raster <- raster("bulkdensityuk.tif")
#plot(bd.raster, main = "Interpolated Organic Fraction across Coast",xlab = "UTM 15 N Longit
ude (m)", ylab = "UTM 15 N Latitude (m)")
bd.df <- as.data.frame(bd.raster)
write.csv(bd.df, "uk_bd_df")

#Create raster
writeRaster(acc.uk, filename="accuk.tif", format="GTiff", overwrite=TRUE)
acc.uk.df <- as.data.frame(acc.uk)
write.csv(acc.uk.df, "acc_var_df")
acc.raster <- raster("accuk.tif")
#plot(acc.raster, main = "Interpolated Organic Fraction across Coast",xlab = "UTM 15 N Long
itude (m)", ylab = "UTM 15 N Latitude (m)")
acc.df <- as.data.frame(acc.raster)
write.csv(acc.df, "uk_acc_df")

#Create raster
writeRaster(org.uk, filename="organicuk.tif", format="GTiff", overwrite=TRUE)
org.uk.df <- as.data.frame(org.uk)
write.csv(org.uk.df, "org_var_df")
```

```
org.raster <- raster("organicuk.tif")
#plot(bd.raster, main = "Interpolated Organic Fraction across Coast",xlab = "UTM 15 N Longit
ude (m)", ylab = "UTM 15 N Latitude (m)")
org.df <- as.data.frame(org.raster)
write.csv(org.df, "org_bd_df")
```

Cell Stats

```
multiply_raster <- (acc.uk * bd.uk)
g_yr <- multiply_raster * 10^10
cellStats(g_yr, sum)

## Accretion.Prediction           Variance
##         8.167580e+13        2.980449e+12

ton_yr_load <- 8.17*10^13 * 10^-12
ton_yr_load

## [1] 81.7

organic_multiply <- (acc.uk*bd.uk*org.uk)
org_g_yr <- organic_multiply*10^10
cellStats(org_g_yr, sum)

## Accretion.Prediction           Variance
##         2.260570e+13        6.080061e+10

org_ton_yr_load <- 2.26*10^13*10^-12
org_ton_yr_load

## [1] 22.6
```