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Sediment supply explains long-term and large-scale patterns in saltmarsh lateral 1 expansion and erosion 2 Cai J. T. Ladd^{1,2}, Mollie F. Duggan-Edwards¹, Tjeerd J. Bouma³, Jordi F. Pagès⁴, 3 Martin W. Skov¹ 4 5 ¹School of Ocean Sciences, Bangor University, Menai Bridge, LL59 5AB, UK. 6 ²Department of Geography, Swansea University, Swansea, SA2 8PP, UK. ³Department of Estuarine and Delta Systems, Royal Netherlands Institute for Sea Research 7 (NIOZ), Utrecht University, 4400 AC Yerseke, P.O. Box 140, The Netherlands. 8 9 ⁴Centre d'Estudis Avançats de Blanes (CEAB-CSIC), Blanes, 17300, Catalonia (Spain). 10 11 Corresponding author: C. Ladd (c.ladd@bangor.ac.uk) **Key Points:** 12 13 Sea level rise alone does not explain marsh lateral changes over the past 150 years • 14 Sediment flux is by far the strongest indicator of long-term lateral changes in • 15 saltmarsh extent. Small increases in fetch length may boost marsh expansion through stimulating wind-16 • 17 driven sediment transport onto marshes

18 Abstract

19 Salt marshes often undergo rapid changes in lateral extent, the causes of which lack common explanation. We combine hydrological, sedimentological and climatological data with analysis 20 21 of historical maps and photographs to show that long-term patterns of lateral marsh change can 22 be explained by large-scale variation in sediment supply and its wave-driven transport. Over 23 150 years, northern marshes in Great Britain expanded while most southern marshes eroded. 24 The cause for this pattern was a north to south reduction in sediment flux and fetch-driven 25 wave sediment resuspension and transport. Our study provides long-term and large-scale 26 evidence that sediment supply is a critical regulator of lateral marsh dynamics. Current global 27 declines in sediment flux to the coast are likely to diminish the resilience of salt marshes and 28 other sedimentary ecosystems to sea level rise. Managing sediment supply is not common-29 place, but may be critical to mitigating coastal impacts from climate change.

30

31 Plain Language Summary

32 Salt marshes are valuable ecosystems for human societies, and are especially vulnerable to 33 losses caused by human activity and climate change. Little is known about how the size of marshes has changed in response to disturbance over large- and long-term scales. We used 34 35 historical maps and aerial photographs to capture 150 years of change in marsh area extent in 25 estuaries and ~100 marshes across Great Britain. We then related the rates of marsh change 36 37 to existing data on hydrology, biology, climate, sediment supply and other variables, to find out which elements best explained patterns of erosion and expansion for the period between 38 39 1967 and 2016. We found a shift from long-term marsh erosion in the south-east, to long-term 40 marsh expansion in the north-west of Great Britain, and that this pattern was explained by a south-to-north gradient of increasing sediment flux into marshes and wave fetch lengths which 41

- 42 helps transport sediment onto marshes. Our study demonstrates how sediment supply should
- 43 be monitored and managed to preserve saltmarsh extent into the future.
- 44

45 **1 Introduction**

46 The threat of sea level rise has dominated theoretical and empirical saltmarsh research for more 47 than thirty years, from concerns that over 90% of global marshes could drown by 2100 (Crosby et al., 2016; Spencer et al., 2016; Horton et al., 2018; Valiela et al., 2018). Recent results show 48 49 that marshes are adept at keeping pace with sea level rise by growing vertically when sediment 50 is available to settle onto the marsh surface (Kirwan et al., 2016a); an irony, given that fear of 51 marsh loss by drowning has had an overriding influence on conservation policy since the 1970s 52 (Hatvany et al., 2015). Despite the vertical resilience to sea level rise, there are many 53 documented cases from Europe, North America and Asia where marshes have undergone 54 extensive lateral changes in cover, expanding or eroding hundreds of metres in just a few years 55 (Yang et al., 2001; Lotze et al., 2006; Fagherazzi et al., 2013; Gunnell et al., 2013; Leonardi et 56 al., 2016). This study heeds the call to investigate the drivers causing lateral marsh change 57 (Kirwan et al., 2016a; Kirwan et al., 2016b; Schuerch et al., 2018), shifting the current 58 emphasis away from a predominant focus on vertical growth dynamics alone (Mariotti & Fagherazzi, 2010; Kirwan et al., 2016b). The causes for lateral marsh change need to be 59 60 understood if natural coastal protection by marshes is to be effectively managed (Bouma et al., 2014; Kirwan et al., 2016b; Ganju, 2019). 61

62

63 Marsh loss by lateral retreat is thought to be the consequence of wind-wave attack (Mariotti & Fagherazzi, 2010, 2013; Marani et al., 2011; Mariotti & Carr, 2014). Sea level rise and 64 65 increased severity of storm and river flooding collectively act to raise water depths and wave/current scour over tidal flats, thereby increasing the likelihood of initiating lateral marsh 66 erosion (Mariotti & Fagherazzi, 2010; Mariotti & Carr, 2014; Hu et al., 2015b). Previous 67 68 studies have indicated that sediment supply from marine or riverine sources can diminish this 69 erosion risk when the replenishment of sediment is sufficiently large to cause tidal flats to 70 elevate through accretion. For example, marshes in the macrotidal Bay of Fundy, Canada, are 71 resilient to erosion because new sources of sediment from ice rafting are transported to the 72 saltmarsh edge by large-amplitude tides (van Proosdij et al., 2006). In contrast, some marshes 73 in the microtidal Venice Lagoon, Italy, are erosion-prone because of low river sediment supply, 74 as well as limited tide-driven sediment mobilisation and transport (Day et al., 1999; Marani et 75 al., 2007; Fagherazzi et al., 2013). Along sediment-starved coastlines, erosion of adjacent tidal 76 flats can provide a local sediment source for marsh accretion (Schuerch et al., 2019) even if 77 tidal flat loss eventually exposes marshes to long-term lateral erosion (Bouma et al., 2016). Marsh change is also associated with human activity. Land reclamation has reduced the extent 78 79 of marshes globally (Gedan et al., 2009), while the introduction of invasive marsh building plants (Spartina species) has expanded marshes (Ranwell, 1967; Gedan et al., 2009). Large 80 fluctuations in marsh cover have also been linked to changes in hydrology and sediment 81 82 transport driven by coastal development and land-use change (Yang et al., 2001).

83

While numerical models have pioneered the mechanistic understanding of lateral marsh
dynamics (Mariotti & Fagherazzi, 2010; Mariotti & Carr, 2014; Hu et al., 2015a; D'Alpaos &
Marani, 2016; Kirwan et al., 2016b; Schuerch et al., 2018), empirical evidence has lagged
behind and been limited to process-based studies (Feagin et al., 2009; Francalanci et al., 2013),
isolated sites (Chauhan, 2009; Gunnell et al., 2013; McLoughlin et al., 2014) and single

89 explanatory drivers of change (Weston, 2013; Gabler et al., 2017). We aimed to change this

90 situation. Here we ask which key climate, biotic, and anthropogenic drivers best explain long-

- 91 term (150-year), large-scale (across Great Britain) lateral marsh change.
- 92

93 2 Methods

94 2.1 Study sites

95 We measured change in saltmarsh extent for 25 estuaries and embayments located in 6 regions 96 across Great Britain (GB): the Solway, Morecambe and Cardigan regions located along the 97 west coast, in the Irish Sea; and the Wash, Essex-Kent and Solent regions along the east/south-98 east, in the North Sea and English Channel (Figure 1). In total, these estuaries occupied around 99 19,000 ha of salt marsh (~40% of the total marsh area in GB) (Phelan et al., 2011; Haynes, 100 2016). Estuaries were shallow, generally well-mixed with semidiurnal meso- to macro-tidal ranges. Flood-dominance was common along the west coast, the Wash region and many of the 101 102 Essex-Kent regions, whereas in the Solent region, all the estuaries were ebb-dominant (Manning & Whitehouse, 2012). Typical estuary morphology ranged from bar-built to 103 104 embayment/coastal plains (Pye & Blott, 2014). Relative sea level rise (RSLR) generally 105 increases along an axis from the north-west to the south-east due to isostatic adjustment of the 106 British Isles following deglaciation at the end of the Last Glacial Maximum (Bradley et al., 107 2009). Along a similar axis, tidal amplitude and estuary depth generally decrease, and sediment 108 type changes from sand- to silt/clay-dominance (Goudie, 2013). All regions have historically 109 seen some sea wall construction, with extensive stepwise reclamation occurring in the Wash and the Essex-Kent regions (Davidson et al., 1991). Fluvial suspended sediment supply to the 110 111 coastline across the UK has been historically low (Worrall et al., 2013).

112 113

2.2 Change in saltmarsh extent

114 We quantified saltmarsh area for the entirety of each estuary approximately every 30 years between 1846 and 2016 using a combination of Ordnance Survey (OS) maps and aerial 115 116 photographs. OS maps were accessed via the EDINA Digimap Resource Centre. Survey dates 117 of maps were taken from Oliver (2013) and used as timestamps. For the Cardigan regions, aerial photographs were taken from the Royal Commission on Ancient Historical Monuments 118 119 Wales. Photographs were scanned and georeferenced onto OS 1:25,000 rasters in the British 120 National Grid projection. Pixel size corresponded to ca. 0.25×0.25 m in the field. Marsh extent 121 measurements for the Solent and Essex-Kent regions, originally delineated from aerial 122 photographs, were taken from Baily and Pearson (2007) and Cooper et al. (2001) respectively. 123

124 Marsh extent from OS maps and aerial photographs were delineated manually at a scale of 125 1:7,500 by placing vertices along the marsh edge approximately every 5 m. To account for 126 boundary precision of the seaward marsh edge, visual comparisons between our georeferenced images to reference shapefiles (Phelan et al., 2011; Haynes, 2016) was done to ensure accuracy 127 128 of the georeferencing procedure. We also looked for site-specific literature to verify whether 129 observations of significant change in marsh extent could be considered 'real' or were likely 130 caused by differences in map surveyors' interpretation of where the marsh edge lay (see supporting information, Table S1). In the case of the Wash, large areas of marshland were 131 132 reclaimed over the study period. To account for this, we calculated the area of reclaimed land 133 and subtracted it from the marsh extent in the previous map revision. The new value was included as an additional measurement of marsh area between map revisions. See supporting 134 135 information, Text S1, for methods used to calculate an error term for each measure of marsh 136 area.

138 A linear rate of saltmarsh change per year was calculated for each estuary and used as the 139 response variable in statistical modelling. Due to the highly non-linear change of marsh extent 140 in the Wash region, an average rate of marsh change was calculated following each reclamation 141 phase. See supporting information, Table S2, for the rates of marsh change, and the dates over which this rate was taken. We also contrasted observed rates of lateral marsh change with 142 143 published empirical measurements of vertical accretion on the nearby marsh surface. All 144 accretion rates were measured in the low-marsh zone using Caesium radio-isotope dating, 145 Sediment Elevation Tables or Marker Horizons (see references in Table 1). See supporting 146 information, Table S2, for dates over which accretion rates were measured.

147 148

2.3 Predictor variables of lateral marsh change

For each estuary, we collated data on key hydrological, sedimentological and climatological 149 variables known to structure saltmarsh extent within estuaries. Annual net sediment flux per 150 151 unit area of marsh was calculated by using the ratio of vegetated and unvegetated surfaces within each estuarine marsh complex (UVVR), which has been shown to be a proxy for 152 153 external sediment supply (Ganju et al., 2017). See supporting information, Text S2, for information on how net sediment flux was calculated and validated. Estimated bedload 154 sediment flux volume (in or out of the estuary) were taken from HR Wallingford (2002), Brown 155 156 and Davies (2010), Halcrow (2010), and NFDC (2017). Due to differences in the precision of 157 modelled bedload sediment flux estimates between studies, all values were rounded to their nearest 10th value, representing a magnitude flux either into (positive) or out (negative) at the 158 159 estuary mouth. Long-term tide gauge records were used to calculate the rate of RSLR for each 160 estuary. Trends of RSLR are linear rates calculated from monthly-averaged records with a 161 minimum 30-year timespan (NOAA, 2019). Where nearby tide gauges were unavailable, we took the average RSLR rate from two nearest equidistant stations. Admiralty Tide Tables were 162 163 used to determine the mean tidal range of each estuary, taken from Manning and Whitehouse (2012). Frequency of storm events were calculated using daily averaged wind speed data from 164 the UK Met Office Integrated Data Archive System (Met Office, 2012). Stations were selected 165 based on their proximity to each estuary. The temporal range for each station varied 166 considerably, although at most limited to between 1957 and 2016. As a consequence, some 167 stations nearby had low number of samples and were rejected for further analysis. The final 168 169 representation of stations was limited to one per region, and storm events recorded by that station were assumed to be representative of all estuaries for the respective region. Prior to 170 171 analysis, wind speed data was screened for quality and completeness (see Watson et al. (2015) 172 for method). Frequency of storm events were then estimated from annual datasets as a count above an absolute threshold of 23 ms⁻¹ ('strong gale' on the Beaufort scale), and rate of change 173 174 in number of events per year was used in the statistical analysis. Prevailing wind directions 175 within 10-degree compass bearing intervals of each station were also used to calculate fetch 176 length of each estuary (the distance over which wave-generating winds blow). The Waves Toolbox for ArcGIS 10.1 (Rohweder et al., 2012) with an 'SPM-Restricted' method was used 177 178 to calculate fetch length every 200 m along the seaward marsh edge of each estuary (using a 179 national marsh shapefile taken from Phelan et al. (2011) and Haynes (2016)). The median fetch 180 lengths for each estuary were recorded. Rate change in river flood frequency events were 181 calculated using number of Peaks-Over-Threshold per water year data provided by the National River Flow Archive (Robson and Reed, 1999). Predictor variables, and the timescale over 182 which they were measured, are noted in supporting information, Table S2. Dates of Spartina 183 184 townsendii and Spartina anglica (henceforth Spartina spp). Colonisation (Figure 2; grey 185 shading) were taken from Goodman et al. (1959), Hubbard and Stebbings (1967), and Harwood and Scott (1999). Information on significant infrastructure projects (Figure 2; arrows) were 186

187 taken from Kestner (1962), Marshall (1962), and Burd (1992) for the Solway, Wash and Essex-

- 188 Kent regions.
- 189
- 190 2.4 Statistical treatment

191 All statistical analyses were implemented in R. Predictor variables were checked for outliers, 192 and log- or cube-transformed to meet assumptions of normality and equal variance. Predictor variables were also checked for collinearity, and dropped if Variance Inflation Factors 193 194 exceeded 3 (Zuur et al., 2009). To identify groupings across our study sites, we used pairwise 195 Euclidean distances between all 25 estuaries and found 6 clearly defined regions (Figure 1). 196 We then used region as a random variable to test for spatial autocorrelation, but did not find a 197 significant effect. A Stepwise Linear Regression model was therefore used to select the 198 minimal adequate model. See supporting information, Text S3, for details on the full statistical 199 analysis used.

200

201 **4 Results and Discussion**

202 Our analysis of marsh extent change revealed a stronger tendency for seaward lateral marsh 203 expansion than for marsh erosion. Five of the six regions increased in marsh cover by 29% to 204 158% between 1846 and 2016 (Figures 2a-e and 2h) and marshes overall expanded by 11%. 205 South-east Britain was the only region to consistently lose marsh cover (Figures 2f and 2g). 206 The largest lateral expansion occurred in the south, where Solent marshes had grown 307% by 207 the 1970s before declining to their current levels; 29% greater than in 1868 (Figures 2d and 208 2h). The north-eastern Wash region lost large areas of salt marsh on four occasions due to land 209 reclamation (Figure 2e; arrows), however new marshes always expanded laterally on the 210 seaward side of walls, leading to a 52% overall increase in marsh area.

211

212 Effects of *Spartina* colonisation on long-term marsh change appeared to be limited. In estuaries 213 where marsh areal extent had been increasing, trends of marsh expansion generally preceded 214 the arrival of invasive Spartina (Figures 2a-c; grey shading), with the exception of the Solent 215 region (Figures 2d and 2h; grey shading), where Spartina invasion has been substantial (Hubbard, 1965). Causes for erosion post-1970 in the Solent are unclear (Baily & Pearson, 216 217 2007), however studies have reported marsh loss through lateral marsh erosion which indicates 218 losses may be related to dynamics at the salt marsh- tidal flat interface (Johnson, 2000). In the 219 Essex-Kent region, eroding marshes saw a prolonged period of little marsh change between 220 1900 and 1970 during which Spartina was first recorded and several sea walls were breached 221 by storms (Figures 2f and 2g; grey bars and white arrows). Overall, coastal works also had little effect on long-term marsh change. In the Wash and Solway regions, marshes expanded 222 223 despite losses through reclamation (Figure 2e; black arrows) and canalisation (Figure 2a; grey 224 arrows) respectively. The prevailing hydrological and sedimentological environment appeared 225 to be conducive to achieving a new dynamic equilibrium in marsh extent (Kestner, 1975). Both 226 the effects of the introduction of *Spartina* and coastal works appear to have only temporarily 227 offset a long-term trend of marsh decline. We therefore conclude that long-term patterns of 228 marsh lateral change were not driven by direct human impact alone.

229

We next considered which key drivers were responsible for lateral marsh change for the periodbetween 1967 and 2016. Results from a Stepwise Linear Regression model showed that

sediment flux per unit area and median fetch length in combination best explained (62% of

- variation) the rate of marsh lateral change in estuaries across Great Britain (Table S3). Marshes
- shifted from eroding to expanding when sediment flux and fetch length concurrently increased

(Figure 3). Bedload sediment flux was retained in the best fit model, but was not significant(Table S3).

237

238 From a range of key hydrological, sedimentological and climatological variables known to 239 influence lateral marsh dynamics, we find that sediment supply plays a crucial role in 240 explaining large-scale, long-term trends of lateral marsh change (Figure 3a). Whilst increases 241 in fetch length are typically associated with marsh loss rather than expansion (Callaghan et al., 242 2010), the relatively sheltered meso- to macro-tidal estuaries in our study had small fetch 243 lengths (averaging 1.2 km) compared to the ~10 km threshold fetch lengths needed to trigger 244 runaway marsh erosion along microtidal U.S. coastlines (Mariotti & Fagherazzi, 2013). Since 245 wave action is also responsible for sediment resuspension and transport (Green & Coco, 2014), 246 it is likely that moderate increases in fetch length enhances sediment transport to the coast, 247 thereby facilitating marsh accretion (Figure 3b) as observed along other macro-tidal coastlines (Pringle, 1995; van de Groot et al., 2011). Across Great Britain, marshes with larger wave fetch 248 lengths also tended to have longer foreshore widths (Taylor et al., 2002). The presence of a 249 250 wide foreshore can attenuate incoming waves, reducing the potential for marsh edge erosion (Bouma et al., 2014 and references therein). Additional field-based measurements would be 251 252 required to ascertain whether a shift from marsh erosion to expansion across Great Britain is 253 primarily influenced by increased wave-driven sediment transport to the coast, or greater wave-254 protection from wider foreshores. Nevertheless, our results provide empirical support for large-255 scale and long-term shifts in the lateral extent of marshes driven by sediment supply and 256 transport, in agreement with numerical models (Mariotti & Fagherazzi, 2010).

257

258 Global declines in sediment supply to the coast could lead to large-scale marsh loss through 259 lateral erosion, as observed along the eastern U.S. coast (Weston, 2013). A spatial shift over 260 the 1967-2013 period, from marsh complexes with a positive sediment flux to marshes that have been exporting sediment (Figure 3a) implies there might have been differences in 261 sediment availability across Great Britain. There is no evidence that fluvial suspended sediment 262 flux to the UK coast has changed since 1974 (Worrall et al., 2013) and there is also no 263 indication that marine sediment sources have depleted over the past 50 years (HR Wallingford, 264 265 2002; Halcrow, 2010; NFDC, 2017). Intertidal flats, which can provide a local sediment source for marsh accretion (Mariotti & Carr, 2014; Schuerch et al., 2019), have reduced in size across 266 GB since 1843 (Taylor et al., 2004; Pontee, 2011). More severe reductions in tidal flat widths 267 along south and eastern England (Taylor et al., 2004) may have impaired their capacity to 268 269 supply marshes with enough sediment to keep pace with sea level rise, exposing the marsh 270 edge to long-term lateral erosion (Figure 2d and 2f-h). Estuaries with a greater capacity for sediment remobilisation and transport by wave action (Figure 3b) may have allowed marshes 271 272 to continue to expand at the expense of tidal flat erosion (Figure 2a-c and 2e). Without increases in sediment supply to the coast, trends of lateral marsh erosion are likely to continue (Figure 273 274 2d and 2f-h) and may reverse trends of marsh expansion currently observed in the northern 275 regions of Great Britain (Figure 2a-c and 2e).

276

277 Given that studies of marsh stability have tended to focus on whether or not vertical growth is 278 equal to or greater than local sea level rise (Crosby et al., 2016; Kirwan et al., 2016a; Spencer 279 et al., 2016; Horton et al., 2018; Schuerch et al., 2018; Valiela et al., 2018), we also compared 280 our rates of lateral marsh change with the rates of vertical marsh accretion (references within 281 Table 1) versus RSLR for each region. We found that all marshes had a positive accretion 282 balance (Table 1). Marshes can erode at their flanks, but still accrete with RSLR, because 283 lateral erosion provides a sediment source for vertical accretion (Mariotti & Carr, 2014). 284 Coupled lateral and vertical marsh dynamics may therefore better predict saltmarsh resilience

285 than comparing marsh vertical growth against RSLR alone (Mariotti & Carr, 2014; Gonneea 286 et al., 2019; Kirwan et al. 2016a; Kirwan et al. 2016b).

287

288 Schemes involving managed realignment of the coastline with engineering solutions to control sediment supply and tidal inundation can be used to build large-scale and long-term marsh 289 290 resilience in historically eroding systems including San Francisco Bay, U.S.A. (Stralberg et al., 291 2011), and the Scheldt estuary, Netherlands (Vandenbruwaene et al., 2011). Despite such large 292 investments into the restoration of saltmarsh flood protection, the monitoring of short-term 293 sediment dynamics at the marsh edges (Bouma et al., 2016) and profile changes of tidal flats 294 (Taylor et al., 2004; Pontee, 2011; Murray et al., 2014) is rarely done. This hampers the ability 295 to predict whether marsh restoration schemes are likely to succeed or fail. Having shed light 296 on the key drivers of long-term saltmarsh lateral change, researchers should now capitalise on 297 advances in satellite remote sensing (Dorji et al., 2016) and novel and cheap instruments to 298 quantify the short-term sediment dynamics at the coast (Hu et al., 2015c) to evaluate coastal 299 resilience against human- and environment-induced change at a global scale. The evidence 300 presented here contributes to an emerging emphasis on investigating the causes for spatial 301 shifts in coastal systems, including mudflats (Murray et al., 2014), seagrass beds (Suykerbuyk 302 et al., 2015) and mangroves (Gabler et al., 2017). Though important, a shift away from a focus 303 on sea level rise alone to consider also the influences of other anthropogenic and macroclimatic

304 drivers of coastline change should be a priority.

305

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- 320

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689	
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692 693	Table 1. Rates of lateral and vertical marsh change per region. Mean \pm S.E values per region for marsh lateral expansion rates, and the rate of marsh vertical accretion, minus the rate of relative sea level rise,

to give the 'accretion balance'. Measures of vertical marsh accretion rates were unavailable for the
 Morecambe region.

Decion	Lateral expansion	Accretion balance
Region	$(ha yr^{-1})$	(mm yr ⁻¹)
Solway	0.88 ± 1.17	15.41 ± 14.53 (Marshall, 1962)
Morecambe	2.94 ± 0.37	n.a.
Cardigan	2.31 ± 1.37	8.25 ± 4.06 (Kestner, 1975)
Wash	1.27 ± 0.00	46.17 ± 26.87 (Shi, 1993)
Essex-Kent	-6.42 ± 3.55	3.20 ± 3.56 (Cundy & Croudace, 1996)
Solent	-3.59 ± 1.65	2.91 ± 0.84 (van der Wal & Pye, 2004)



Figure 1. Estuaries examined within each region. A total of 25 estuaries separted into 6 regions 700 across Great Britain.





703 Figure 2. Change in estuarine-scale marsh extent across Great Britain. Regional- (blue line) and 704 estuarine-scale (orange line) change in areal extent of salt marshes between 1856 and 2016 from 705 photographs (filled circles) or maps (hollow circles). Arrows indicate occurrences of embankment 706 (solid arrow), canalisation (grey arrow) or collapse of sea walls after storms (hollow arrow). Grey 707 shading indicates Spartina spp. Colonisation in each region. Vertical error bars indicate 95% confidence 708 intervals in marsh area extent. Horizontal lines indicate the dates over which surveys of marsh extent 709 were carried out. Essex-Kent and Solent regions have been subdivided for ease of presentation. 710 Regional-scale marsh change (blue line) only includes marsh extent measures for all estuary in a given 711 region and year. Marsh change in Southampton estuary (panel d: dashed line) was excluded from the 712 regional-scale marsh change line due to paucity of contiguous cover in saltmarsh extent across multiple 713 years. 714



Figure 3. Relationships of estuarine-scale lateral marsh change with two significant predictor variables

717 identified from a best-fit linear regression model on data for 1967 to 2016 (n = 22): **a** sediment flux per 718 unit area and **b** median fetch length. Data points represent distribution of standardised partial residuals.

719 Solid lines represent model-fit though the data, bounded by 95% confidence intervals (solid grey

solution of each plot denote deciles of the distribution of each predictor

721 value.

722

	AGU PUBLICATIONS
724	
725	Geophysical Research Letters
726	Supporting Information for
727 728	Sediment supply explains long-term and large-scale patterns in saltmarsh lateral expansion and erosion
729	Cai J. T. Ladd ^{1,2} , Mollie F. Duggan-Edwards ¹ , Tjeerd J. Bouma ³ , Jordi F. Pagès ⁴ , Martin W. Skov ¹
730 731 732 733 734	 ¹School of Ocean Sciences, Bangor University, Menai Bridge, LL59 5AB, UK. ²Department of Geography, Swansea University, Swansea, SA2 8PP, UK. ³Department of Estuarine and Delta Systems, Royal Netherlands Institute for Sea Research (NIOZ), Utrecht University, 4400 AC Yerseke, P.O. Box 140, The Netherlands. ⁴Centre d'Estudis Avançats de Blanes (CEAB-CSIC), Blanes, 17300, Catalonia (Spain).
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737	
738 739	Contents of this file
740	Tables S1 to S3
741	Text S1 to S3
742	
743	
744	Introduction
745	The following supporting information contains details on how error resulting from digitising
746	saltmarsh extent across Great Britain was calculated (Text S1), how net sediment fluxes values
747	across marsh complexes were calculated and validated from the unvegetated/vegetated ratio (Text
748	S2), and a report on the full statistical treatment applied to our data (Text S3). Tables S1 to S3
749	provide further details on literature that corroborates marsh extent change detected from the GIS
750	study, the variables used to explain change in marsh extent, and the results of a Stepwise Linear
751	Regression model used to identify which key variables explain marsh change respectively.
752	

Region	Area of rapid change	Description and reference
Solway	Rapid expansion and erosion phases of all major marshes in each estuary	OS maps record the expansion and erosion of these larger marshes throughout the Solway region, with a net increase in marsh extent. A study by Marshall (1962) reaches a similar conclusion from interpreting maps (1856-1864) and aerial photographs (1946). Marshall (1962) also investigated aspects of saltmarsh morphology (accretion rates, areas of erosion and expansion and channel configuration) to corroborate their findings and conclude that there is close agreement between phases of expansion and erosion observed in the field and change recorded from maps. Rapid expansion of Caerlaverock is also described by Bridson (1980) from maps dating back to 1654, in agreement with Marshall (1962). Firth et al. (2000) and CCO (2011) describe the rapid expansion and erosion of different parts of Rockcliffe marsh (Inner Solway) and the marshes in Moricambe Bay since 1776 and 1864 from literature searches and site visits, which we observe in the OS maps.
Morecambe	Rapid erosion and expansion phases in all estuaries	OS maps record the overall expansion of marshes throughout the Morecambe Bay region, with individual marshes undergoing extensive erosion and accretion phases. Of the most drastic change, phases of erosion in Silverdale marsh have been documented by Pringle (1995) from repeat transect measurements between 1983 and 1992, which is out of phase with marsh expansion at Grange-over-Sands on the opposite side of the estuary, described in field surveys by Gray (1972). All estuaries in Morecambe Bay region are considered dynamic and have experienced rapid changes in saltmarsh extent determined from site visits, historical records and modelling data (CH2M HILL, 2013a, 2013b, 2013c; Dixon-Gough, 2006). These observations support marsh change observed in OS maps.
Cardigan	Rapid expansion of marshes in the outer estuary	rapid rates of expansion around the 1950s. Field sketches made by Yapp (1917) include detailed vegetation surveys of the Dyfi estuary in the mid 1910s which show a similar extent of saltmarshes to the OS maps. Rapid expansion of the marshes in the outer estuary in the late 1940s is documented by Chater & Jones (1957) from site surveys. Both studies are in agreement with observations of marsh change from OS maps.
Wash	Rapid expansion following reclamation	OS maps document the step-wise loss of marshlands to reclamation, followed by phases of new marsh growth in front of seawalls throughout the Wash embayment. Kestner (1962) reconstructed past area cover of salt marsh extent for the Wash by knowing the dates when seawalls were constructed. Kestner (1975) later described the mechanism by which sediment deposits in front of the sea wall, allowing marshes to rapidly colonise and expand. These phases of reclamation and new marsh growth are in agreement with marsh change determined from OS maps.
Essex-Kent	Gradual erosion across all estuaries, with some areas of rapid marsh expansion	OS maps record the gradual erosion of marshes across Essex-Kent, with small areas of rapid expansion of erosion subject to embankment/deembankment. Burd (1992) report in detail the numerous areas of embankment and deembankment from history books, parish and estate records, property deeds, maps and historical surveys from the 17 th century onwards. Areas of reclaimed and deembanked marshland is reported by Wolters et al. (2005). Burd (1992) also report that the government at the time were aware of marsh erosion and more frequent flooding due to land subsidence and rising sea levels. Kirby (2013) and Spearman et al. (2014) also document marsh decline from historical maps and illustrations in the northern and southern parts of the region respectively.
Solent	Rapid expansion across all estuaries	OS maps record the expansion of marshes across the Solent region. Baily & Inkpen (2013) account for the rapid expansion because of the colonisation and spread of the pioneer-marsh hybrid <i>Spartina townsendii</i> , and later, fertile allotetraploid species <i>Spartina anglica</i> , onto tidal flats across the region. Baily & Inkpen (2013) support this argument by referring to a number of articles published during this period that document the nature and spread of <i>Spartina spp</i> . across the region. Baily & Inkpen (2013) did find issues with the accuracy of maps compared to aerial photographs, however much of the error was due to not knowing the date a map was surveyed (only when it was published) when comparing to an aerial photograph, and revision errors where marshes were copied over to successive map editions thus not representing the true marsh extent of that year. Both error terms were accounted for in our study and described in Text S1.

Table S1. Literature searched to determine whether marsh change from maps can be considered

755 'real'.

	Lateral expansion	Vertical accretion (mm yr ⁻¹) ±	Relative sea level rise	Net sediment flux	Suspended sediment conc.
	(ha yr-1)	S.D.	(mm yr-1)	(kg m ⁻² yr ⁻¹)	(mg l ⁻¹)
				(2006-2009)	(2000)
Solway	(1970-2016)	(1961)	(1960-2015)		
Outer Solway	0.14	21.43 ± 10.56	2.28 ± 0.65	0.313	404.22
Upper Solway	2.22	11.79 ± 18.12	2.28 ± 0.65	0.302	404.22
Moricambe	0.27	25.40 ± 0.00	2.28 ± 0.65	0.281	404.22
Morecambe	(1967-2010)		(1960-2015)		
Duddon	2.84	NA	2.34 ± 0.68	0.211	291.49
Leven	3.35	NA	2.34 ± 0.68	0.173	313.42
Kent	2.62	NA	2.34 ± 0.68	0.251	313.42
Cardigan	(1969-2013)		(1938-2016)		
Glaslyn-Dwyryd	1.56	NA	2.27 ± 0.30	0.212	89.37
Mawddach	1.48	NA	2.27 ± 0.30	0.155	NA
Dyfi	3.89	10.29 ± 4.06 (1988-1989)	2.27 ± 0.30	0.239	111.03
Wash	(1972-2016)		(1955-2016)		
Wash	1.27	48.00 ± 26.87 (1956-1962)	1.83 ± 0.38	0.257	295.97
Essex-Kent	(1973-1998)		(1933-2016)		
Orwell	-1.85	NA	1.89 ± 0.27	-0.003	64.46
Stour	-6.39	NA	1.89 ± 0.27	-0.017	64.46
Hamford	-9.98	NA	1.89 ± 0.27	-0.517	59.51
Colne	-3.81	NA	1.89 ± 0.27	0.059	78.69
Blackwater	-7.99	4.84 ± 5.00 (1963-1998)	1.22 ± 0.19	-0.200	122.68
Crouch	-6.50	6.70 ± 0.00 (1897-1994)	1.22 ± 0.19	-0.011	106.40
Thames	-3.93	3.93 ± 1.38 (1963-1998)	1.22 ± 0.19	-0.060	NA
Medway	-13.22	4.05 ± 2.05 (1989)	1.22 ± 0.19	-0.031	86.05
Swale	-4.11	NA	1.22 ± 0.19	0.026	NA
Solent	(1971-2001)		(1961-2016)		
Lymington	-4.86	5.2 ± 0.00 (1893-1995)	1.62 ± 0.46	-0.134	42.54
Beaulieu	-2.44	3.3 ± 0.00 (1893-1995)	1.62 ± 0.46	-0.224	54.12
Southampton	-4.31	4.8 ± 0.14 (1870-1995)	1.62 ± 0.46	-0.093	102.87
Portsmouth	-2.72	NA	1.62 ± 0.46	-1.509	83.39
Langstone	-1.45	1.5 ± 0.00 (1907-1995)	1.62 ± 0.46	-0.643	79.57
Chichester	-5.77	NA	1.62 ± 0.46	-0.590	78.56

Table S2. Site characteristics for all 25 estuaries divided into 6 regions. Parentheses indicate the timescales over which rates were measured, or in which empirical data was used to derive values. These dates are representative of either the entire Great Britain, a whole region, or a specific estuary.

	Bedload sediment flux	Wind storm frequency	River flood frequency	Median fetch length	Tidal range
	(m³ yr-1)	(n yr ⁻¹)	(n yr ⁻¹)	(m)	(m)
				(2006-2009)	(2006-2009)
Solway	(2010)	(1961-2008)			
Outer Solway	10,000,000	0.02	1.34 (1979-2014)	3,120	5.92
Upper Solway	100,000	0.02	-1.36 (1963-2014)	2,520	5.92
Moricambe	0	0.02	0.00	1,880	5.92
Morecambe	(2010)	(1957-2015)			
Duddon	10,000	0.01	0.79 (1968-2014)	1,000	6.12
Leven	1,000,000	-0.15	0.44 (1939-2014)	1,440	6.36
Kent	10,000,000	-0.15	0.28 (1968-2014)	3,960	6.36
Cardigan	(2010)	(1957-2015)			
Glaslyn-Dwyryd	NA	0.09	0.34 (1961-2014)	520	3.04
Mawddach	NA	0.09	NA	1,040	2.94
Dyfi	-1,000,000	0.09	0.02 (1962-2013)	1,360	2.90
Wash	(2002)	(1969-2015)			
Wash	10,000,000	-0.01	0.04 (1939-1996)	2,840	4.42
Essex-Kent	(2002)	(1957-2015)			
Orwell	10,000	0.04	0.11 (1964-1996)	400	2.64
Stour	10,000	0.04	-0.13 (1928-1992)	600	2.64
Hamford	1,000	0.04	0.00	560	2.64
Colne	10,000	0.04	0.07 (1959-2014)	720	3.24
Blackwater	10,000	0.04	0.10 (1932-1968)	520	3.48
Crouch	1,000,000	-0.50	0.21 (1976-2014)	560	3.76
Thames	-1,000,000	-0.50	0.27 (1883-2014)	600	5.00
Medway	100,000	-0.13	-0.02 (1956-2014)	600	4.08
Swale	10,000	-0.13	0.00	760	3.90
Solent	(1998)	(1957-2015)			
Lymington	0	0.06	0.57 (1960-2014)	1,440	1.56
Beaulieu	0	0.06	NA	240	2.26
Southampton	10,000	0.06	0.05 (1972-2014)	440	2.72
Portsmouth	1,000	0.06	0.26 (1951-2014)	680	2.82
Langstone	1,000	0.06	0.11 (1979-2014)	1,680	2.98
Chichester	1,000	0.06	0.04 (1967-2014)	1,120	2.98

Table S2. Continued.

	Model variables	Estimate	SE	<i>t</i> -Value	P value	<i>R</i> ²
	Best model fit (AIC = 116.79, F = 9.9	5, df = 3, 18, P <	0.001***, R ²	= 0.62)		
	Net sediment flux (kg m ⁻² yr ⁻¹)	3.547	1.332	2.662	0.016*	0.48
	Median fetch length (km)	3.549	1.323	2.682	0.015*	0.46
	Bedload sediment flux (m ³ yr ⁻¹)	-0.014	0.010	-1.495	0.152 n.s.	0.06
757	<i>P</i> < 0.05*, <i>P</i> < 0.01**, <i>P</i> < 0.001***, n.s. =	<i>P</i> > 0.05.				
758 759	Table S3. Predictor variables explained models (Stepwise Linear Regression	aining lateral sa on) for 25 estua	altmarsh cha aries across (nge (1967-20 Great Britain.	16) identified b	y best fit
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761						

762 **Text S1.** Estimating error in saltmarsh area cover.

763 764 We calculated change in the areal extent of salt marshes across Great Britain using maps and aerial 765 photographs. Analysis was done in ArcGIS 10.1. In order to quantify an error term associated with 766 these measurements, we calculated the Root Mean Squared Error (RMSE) which describes the 767 average deviation of observed points from their true positions (Wernette et al., 2017). Four 768 independent RMSE sources are associated with geographical data: displacement of the basemap, to 769 which historical maps and aerial photographs are referenced, from its 'true' location on the Earth's 770 surface (RMSE_B); distortions in historical maps and aerial photographs that introduce error when 771 georeferencing to a basemap (RMSE_g); interpreter error when digitising the salt marsh at a given 772 scale (RMSE_i), and; errors introduced by the cartographer when presenting spatial data on a map 773 (not relevant for aerial photographs) (RMSE_M). Because each error source is independent, they can 774 be added for a total error estimate. To determine distances, in metres, below which 95% of the 775 positional errors in delineated salt marsh edges are expected to fall, FGDC (1998) recommend the 776 added RMSE values are multiplied by 1.7308 in order to calculate RMSE₉₅, given as:

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778

779

$$RMSE_{95} = 1.7308 \left(\sqrt{(RMSE_B^2 + RMSE_G^2 + RMSE_I^2 + RMSE_M^2)} \right)$$

780 Maps produced between 1842 and 1952 (Six-inch County Series Edition) the Ordnance Survey (OS), 781 the national mapping agency of the UK, were produced using ground surveys. Demarcating the 782 seaward limit of the salt marsh accurately is dependent on the cartographer's capacity to survey 783 difficult-to-reach or dangerous areas, and distinguish the edge of the marsh which is often 'fuzzy' 784 (due to patchy growth of plants) (Baily & Collier, 2010; Baily, 2011; Baily & Inkpen, 2013). OS 785 standards on the quality and accuracy of saltmarsh surveying were not stringent (Baily & Inkpen, 786 2013) therefore the marsh edge is sometimes represented as a stamped symbol without a clearly 787 defined margin (Baily & Inkpen, 2013). OS maps produced after 1952 (National Series Edition maps) 788 were compiled using a combination of ground surveys and aerial photographs. Delineating the 789 marsh edge from aerial photographs accurately depends on surveyor capacity to correctly 790 distinguish plants from other features (such as macroalgae patches) as well as the quality of the 791 aerial image. There is no specific guidance set by the OS on demarcating the marsh edge from aerial 792 photographs (OS, pers. comm., 2018). Baily and Inkpen (2013) assessed how successful OS ground-793 surveys were at determining the marsh edge by comparing maps with aerial photographs captured 794 near the map publication date. Where maps were surveyed at similar times to when images were 795 taken, both media were in close agreement. 796

A value for the positional error of digitised marsh edge (map or photo) from the true position
(RMSE_i) was not given by Baily and Inkpen (2013). To calculate RMSE_i, we selected an example marsh
boundary (a 5 km section saltmarsh edge in the Wash) to digitise at very high resolution (vertice
placed every metre) at high magnification to capture the 'true' marsh edge from an OS map.

Resolution of the map was then scaled to 1:7500, and the marsh edge was digitised once again to
capture the 'interpreted' marsh edge. Distance from the 'interpreted' line to the 'true' line was
calculated every 20 metres along perpendicular lines from the 'true' line. This is the same procedure
used when assessing interpreter error for maps and aerial photographs. RMSE₁ is given as:

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$$RMSE_I = \sqrt{\left(\frac{\sum d^2}{n}\right)}$$

807 808 Where:

d is the distance between the 'true' and 'interpreted' marsh edge *n* is the number of distance measurements.

An additional error term, associated with maps produced from ground surveys only, is the interpretation of the surveyor of where the marsh edge lies which is then reproduced on a map as a line or stamp (RMSE_M). Given that marsh edges from maps and photos have been shown to be in

815 close agreement (Baily & Inkpen, 2013), RMSE_M, is assumed to be of the same magnitude as RMSE_I: 816

817 818

$RMSE_M = RMSE_I$

819Both RMSE_M and RMSE_I should be included for estimates of marsh extent taken from maps that have820drawn from ground surveys.

821

822 RMSE_G in maps and aerial photographs can arise during and after the survey. For maps, inaccuracies 823 arise when noting positions from traditional trigonometry surveys or modern Geographical 824 Positioning Systems. After publication, historical maps can distort over time through shrinkage and 825 stretching before digitisation occurred. For aerial photographs, tilt, pitch and yaw of the aeroplane 826 will affect the angle at which images were taken. Unevenness of the topography being captured will 827 also cause distortions to the image. After acquisition, both the original film and reprints can distort 828 over time once produced. These issues reduce the accuracy of features on maps and aerial 829 photographs once images are georeferenced. Georeferencing distortion can be calculated by the 830 distance from which the source deviates from a reference position (Jongepier et al., 2016) as 831 follows: 832

833
$$RMSE_G = \sqrt{\frac{(\sum V_{xy}^2)}{n-2}}$$

834

835 Where *n* is the number of points and V_{xy_r} is a displacement vector made up of vector distances v_x and 836 v_y (in metres) between the distorted points and the reference positions. Both V_x and V_y are 837 calculated as follows:

 $V_{xy} = \sqrt{\left(v_x^2 + v_y^2\right)}$

- 838
- 839

840

RMSE_G was calculated for all maps and photographs to OS 1:2500 basemaps as reference, using
MapAnalyst (Jenny & Hurni, 2011). 12 well-distributed control points were identified in both the
source and OS 1:2500 maps and the RMSE_G between them was calculated using a Helmert
transformation (Jongepier et al., 2016). Measurements of marsh extent for the Essex-Kent and
Solent regions were taken from Cooper et al. (2001) and Baily & Pearson (2007). Cooper et al. (2001)
does not report RMSE_G for their survey, however Baily and Pearson (2007) report a precision value

847 of between \pm 3 and 5 m. An average RMSE_G of 4 metres was taken for their survey and applied to 848 Essex-Kent and Cardigan Bay regions where aerial photography was used to delineate marsh extent.

849

850 The OS 1:2500 maps used as a reference for measuring distortions in older maps and aerial 851 photographs in this study are themselves subject to some positional error between the 'real life' 852 position and that recorded on the map known as RMSE_B. For the OS 1:2500, RMSE_B of 1.1 metres has 853 been calculated (HMLR, 2016). RMSE₉₅ is a linear measure (units in metres). In order to express 854 RMSE₉₅ for areal measures, we constructed a buffer area around the inner and outer circumference 855 of each marsh where the width was RMSE₉₅ calculated for each source (Wernette et al., 2017). The 856 buffer area indicates the minimum and maximum size of the marsh to provide an error term for 857 each extent measurement, representing a 95% confidence interval. Calculating a buffer area was not 858 possible for values taken from Cooper et al. (2001) and Baily and Pearson (2007), and no error term 859 is reported by these authors. A marsh buffer area was therefore estimated for each study. The 860 buffer area was estimated by resampling marsh extent from aerial photographs of Cardigan Bay, but 861 at the image scales used by Cooper et al. (2001) and Baily and Pearson (2007) (1:5,000 and 1:10,000 862 respectively). RMSE₉₅ was recalculated, then the percentage difference in area extent between 863 delineated marsh extent and maximum/minimum area buffers were calculated for each scale. Marsh 864 extent was found to vary by ±18.4 and ±20.0% at scales of 1:5,000 and 1:10,000 respectively. These 865 error margins were applied to the values of marsh extent taken from Cooper et al. (2001) and Baily 866 and Pearson (2007) as the RMSE₉₅ error term. The final error term for marsh area extent can be 867 considered conservative, because accuracy in delineating the marsh edge in many cases will be 868 much higher. For example, where the back of the marsh is bounded by a clearly-defined seawall that 869 can be mapped to a high degree of accuracy.

870

871 After the OS produced first edition maps (County and National Series), revisions were soon needed 872 to keep maps up-to-date in a rapidly developing landscape. However, revisions did not always 873 include complete re-surveys of an area. Revisions tended to be made only for areas heavily used by 874 people, whilst less important features were simply copied over from the previous edition known as 875 'partial-revisions' (Baily & Inkpen, 2013). Salt marshes were not always resurveyed during map 876 revisions, and when revisions occurred, the specific area that had been revised was not always 877 recorded (Baily, 2011). In our study, revision error was accounted for by comparing map revisions 878 against first editions of each marsh in each estuary. On the assumption that the marsh boundary is 879 likely to change during a ~30 year period, marshes that had near-identical boundaries in both first 880 and revised editions were considered copied, so areal extent was not calculated.

881

882 All RMSE values are contained within the attributes table of the marsh extent change GIS layer 883 accessible via the Environmental Information Data Centre repository (DOI: 10.5285/03b62fd0-41e2-884 4355-9a06-1697117f0717).

- 885
- 886

887 Text S2. Calculating and validating net sediment flux.

888

889 Sediment supply is a key predictor of long-term marsh stability (e.g. Kirwan et al., 2016), yet 890 empirical measurements of sediment flux across marshes are sparse (Ganju et al., 2015). Recent 891 work has shown that the ratio of unvegetated surfaces such as tidal channels, saltpans and marsh 892 edges (sites of sediment erosion) to vegetated marsh areas (sites of sediment accretion) can act as a 893 proxy for external sediment supply (Ganju et al., 2017). We calculated the UVVR values for all 894 marshes in our study and used regression fits from (Ganju et al., 2017) to derive measures of net 895 sediment flux. We also validated the flux rates against estimated measues of suspended sediment 896 concentration for UK estuaries.

- 898 We used a combined Great Britain-wide saltmarsh extent shapefile (collated by the UK Environment 899 Agency [EA] and the Scottish National Heritage [SNH]) to calculate the UVVR for each estuary. Both 900 the EA and SNH shapefiles represent the vegetated portions of marshes across Great Britain and 901 distinguish vegetated marshes from tidal channels and salt pans. The EA captured colour aerial 902 images with 10 cm resolution for the UK coastline between 2006 and 2009. Images were 903 georeferenced with root mean square error ranging from 10 cm to 1 m. Marsh delineation was done 904 manually, and digitally using various feature-identification techniques. Creeks less than 1.5 m wide 905 and marshes less than 5m² were overlooked. In cases where there was low confidence in mapping 906 results, site visits were made to ground-truth the digitised marsh surface (Phelan et al., 2011). The 907 SNH mapped salt marshes larger than 3 ha from colour aerial photographs captured between 2003 908 and 2009 at a 1:4,000 scale across the Scottish coastline. All creeks, salt pans, and other marsh 909 features were mapped when above the mapping resolution. Marsh edges were compared to field 910 surveys to ensure accuracy (Haynes, 2016).
- 911
- 912 In a GIS, we used both saltmarsh extent shapefiles to calculate the area of vegetated portions for
- 913 each marsh complex within our target estuary. We then applied a workflow of ArcGIS 10.1 tools to
- 914 outline the overall marsh complex, thereby effectively separating tidal channel and salt pan features
- 915 from the vegetated marsh surface. The original shapefile was then subtracted from this 'boundary'
- 916 layer to calculate the area of unvegetated portions within the marsh complex (e.g. Figure S1). UVVR
- 917 was then calculated (A_{UV}/A_V) for all 25 estuaries. We then regressed the values of UVVR and net
- 918 sediment flux reported in Ganju et al. (2017) to give us an equation for predicting net sediment flux
- 919 (y = -0.855 ln x +0.330). We fitted the values of UVVR calculated for each marsh complex in our study
- 920 into the regression equation to derive measures of net sediment flux.
- 921 922



Figure S1. Example of how vegetated and unvegetated portions of a marsh are identified for the 925 Blackwater estuary, south-east Great Britain. Unvegetated areas are shown in blue, vegetated 926 surfaces are shown in green. Saltmarsh extent was taken from the UK Environment Agency, and the 927 marsh boundary was determined using a series of polygon processing tools in ArcGIS 10.1. Imagery 928 from the ArcGIS World Imagery Basemap.

- 930 To validate our use of sediment flux estimated from UVVR as a predictor of lateral marsh change, we
- 931 correlated sediment flux values against an estimated measure of estuarine maximum static time-
- 932 and depth-averaged fine cohesive suspended sediment concentration (SSC_E) (Manning &
- Whitehouse, 2012). SSC_E is indicative of sediment supply, and has been shown to broadly represent
 real conditions in validation studies (Prandle et al., 2005, see Figure 4). We used a Pearson
- 935 real conditions in validation studies (Francie et al., 2005, see Figure 4). We used a real soli
 935 correlation to find that SSC and sediment flux were significantly positively correlated (R = 0.68, p
- 936 <0.001) (Figure S2). We therefore consider our use of net sediment flux a suitable indicator of
- 937 external sediment supply. SSC_E values for each estuary are shown in Table S2.



- Figure S2. Pearson correlation between sediment flux and estimated suspended sediment
 concentration (R = 0.68, p < 0.001).
- 941

- 942
- 943 **Text S3.** Data analysis and model selection.
- In this section, we present the statistical analysis used to determine which
 environmental drivers best describe rate of saltmarsh change across Great Britain.
 All statistical analyses are carried out using the 'R' software package. The data used
 in the statistical analysis is accessible via the Environmental Information Data Centre
 repository (DOI: 10.5285/03b62fd0-41e2-4355-9a06-1697117f0717).
- 951Prior to selecting a statistical model, we tested the necessary assumptions of each952statistical model. We begin by loading the dataset, graphics package ggplot2, and953some additional functions held in the additional_functions.R file:

```
954 library(ggplot2)
```

```
955 source("/Users/Home/Code/additional_functions.R")
```

```
956 marshes<-read.csv("/Users/Home/Data/PredictorVariables.csv",header=T)
```

957 There are 4 cases in the dataset where data on river flood frequency change and
958 bedload sediment flux were unavailable of a given estuary. We therefore subset the
959 dataset by removing NAs:

```
960 marshes_RM<-marshes[complete.cases(marshes),]
```

961Using the subset dataset without NAs (marshes_RM), we begin our data exploration962by investigating how each predictor variable relates to rate of saltmarsh change. To

963 make this easier, we create a new object containing the response and predictor 964 variables only:

```
965
      library(dplyr)
966
      library(tidyr)
967
      marshcheck<-marshes_RM[-c(1:3)]</pre>
968
969
970
      marshcheck %>%
971
        gather(-LateralRateChange,key="var",value="value") %>%
972
        ggplot(aes(x=value,y=LateralRateChange))+
973
        geom point(shape=1)+
974
        facet_wrap(~var,scales="free_x")+
975
        theme bw()
```



976

977 It appears that increases in fetch distance, sediment flux per unit area in/out of the
978 marsh, relative sea level rise rate, and tidal range, may all be associated with shifts
979 from marsh erosion to expansion. The other predictor variables do not appear to
980 have a relationship with lateral marsh change.
981 We used Cleveland dotplots to identify any extreme outliers in our dataset. Outliers

we used Cleveland dotplots to identify any extreme outliers in our dataset. Outliers
 may have a significant impact on the results. The data is organised along the y-axis
 only by row name (i.e. the order in which it was entered into the dataframe):

```
984 par(mfrow=c(2,2))
```

985

986 **lapply**(X=c("StormFreq", "FloodFreq", "TidalRange", "BedloadFlux", "MedianFetch

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```
987 ","RSLR","NetSedFlux"), FUN=function(s)
988 dotchart(sample(marshcheck[, s]), xlab=s,ylab="Row number"))
```



- 991 Large variation from the centre of data clusters suggests the presence of outliers.
- 992 StormFreq, FLoodFreq, BedLoadFlux, and NetSedFlux however none appears to
- be unprecedented. These are not unprecedented amounts, but may affect our
- model results. We will consider their effect when testing the final modelassumptions.
- 996 To check whether the response variable has a normal distribution, we build a 997 boxplot, and scale the y axis to make their ranges comparable:

998 boxplot(scale(marshes_RM\$LateralRateChange), 999 xlab="LateralRateChange")



LateralRateChange

1000	
1001	<pre>shapiro.test(marshes_RM\$LateralRateChange)</pre>
1002 1003 1004 1005 1006	<pre>## ## Shapiro-Wilk normality test ## ## data: marshes_RM\$LateralRateChange ## W = 0.96174, p-value = 0.5253</pre>
1007 1008	There is no evidence of skew. We next consider the distribution of all predictor variables:

1009 **boxplot**(scale(marshes_RM[,5:11]))



1011There is some evidence of skew in the predictor variables, notably for StormFreq,1012BedLoadFLux, MedianFetch, and RSLR. Some of these are likely influenced by1013outliers in the data. Transformations using log- and cube-root- (capable of1014transforming both negative and positive values. See the Math.cbrt function in the1015additional_functions.R file) may produce more normal populations suitable for1016parametric modelling. We apply the transformations and add these to our

1017 dataframe:

```
1018 marshes_RM$StormFreq_cbrt<-Math.cbrt(marshes_RM$StormFreq)
```

- 1019 marshes_RM\$BedloadFlux_cbrt<-Math.cbrt(marshes_RM\$BedloadFlux)
- 1020 marshes_RM\$MedianFetch_log<-log(marshes_RM\$MedianFetch)
- 1021 marshes_RM\$RSLR_log<-log(marshes_RM\$RSLR)
- 1022 marshes_RM\$NetSedFlux_cbrt<-Math.cbrt(marshes_RM\$NetSedFlux)
- 1023 We next inspect the distribution of the transformed predictor variables:
- 1024 boxplot(scale(marshes_RM[,12:16]))



1026 The transformed predictor variables now have a more symmetric distribution. We 1027 consider the distribution of our data suitable for parametric modelling. 1028 Prior to using a parametric model to determine which suite of variables best explains 1029 rate of saltmarsh areal extent change, we need to check for high collinearity 1030 between predictor variables, and reduce it if necessary. We can examine the 1031 Variance Inflation Factor associated with each predictor variable (see *corvif* 1032 function in additional functions. R file) to assess how much variance of an 1033 estimated regression coefficient increases if variables are correlated. Values over 3 1034 are a cause for concern (Zuur et al., 2009):

```
1035 corvif(marshes_RM[,c("StormFreq_cbrt","FloodFreq","TidalRange","BedloadFlu
1036 x_cbrt","MedianFetch_log","RSLR_log","NetSedFlux_cbrt")])
```

```
1037 ## Correlations of the variables
```

1038

StormFreq cbrt FloodFreq TidalRange BedloadFlux cbrt

1057	ππ		Storm req_cort	1 10001 i Eq	Truaritange	Deuroaul rux_col c
1040	##	StormFreq_cbrt	1.00000000	-0.06642290	-0.4471729	-0.2730783
1041	##	FloodFreq	-0.06642290	1.00000000	0.1015293	0.2630995
1042	##	TidalRange	-0.44717292	0.10152926	1.0000000	0.4555946
1043	##	<pre>BedloadFlux_cbrt</pre>	-0.27307833	0.26309947	0.4555946	1.000000
1044	##	MedianFetch_log	-0.01892536	0.07428223	0.5719886	0.5589768
1045	##	RSLR_log	0.41207815	0.06286752	0.4446737	0.2756686
1046	##	NetSedFlux_cbrt	-0.21050716	0.02345964	0.7079982	0.4041456
1047	##		MedianFetch_log	RSLR_log	NetSedFlux_	cbrt
1048	##	StormFreq_cbrt	-0.01892536	0.41207815	-0.2105	0716
1049	##	FloodFreq	0.07428223	0.06286752	0.0234	5964
1050	##	TidalRange	0.57198855	0.44467372	0.7079	9815

```
## BedloadFlux_corc
## MedianFetch_log
1051
        ## BedloadFlux_cbrt 0.55897675 0.27566864
                                                                     0.40414564
1052
                                     1.00000000 0.59019663
                                                                      0.58825538
1053
        ## RSLR log
                                     0.59019663 1.00000000
                                                                     0.60255965
1054
                                                                1.00000000
        ## NetSedFlux_cbrt
                                     0.58825538 0.60255965
1055
        ##
1056
        ##
1057
        ## Variance inflation factors
1058
        ## Warning in summary.lm(object): essentially perfect fit: summary may be
1059
        ## unreliable
1060
        ##
                                    GVIF
1061
        ## StormFreq cbrt
                               3.519783
        ## FloodFreq
## TidalRange
1062
                               1.099187
1063
        ## TidalRange
                               3.490519
        ## BedloadFlux cbrt 1.751466
1064
1065
        ## MedianFetch_log 2.334006
1066
        ## RSLR log
                               4.365753
1067
        ## NetSedFlux_cbrt 2.883363
1068
               There is high collinearity caused by RSLR_log (VIF = 4.37). We test whether
1069
               collinearity has dropped to acceptable levels after excluding RSLR Log:
1070
        corvif(marshes RM[,c("StormFreq cbrt","FloodFreq","TidalRange","BedloadFlu
        x cbrt", "MedianFetch log", "NetSedFlux cbrt")])
1071
1072
        ## Correlations of the variables
1073
        ##
1074
        ##
                                                    FloodFreq TidalRange BedloadFlux cbrt
                                StormFreq cbrt
1075
        ## StormFreq_cbrt
                                 1.00000000 -0.06642290 -0.4471729
                                                                                   -0.2730783
        ## FloodFreq
## TidalRange
1076
                                   -0.06642290 1.00000000 0.1015293
                                                                                    0.2630995
1077
                                   -0.44717292 0.10152926 1.0000000
                                                                                    0.4555946

      ## BedloadFlux_cbrt
      -0.27307833
      0.26309947
      0.4555946

      ## MedianFetch_log
      -0.01892536
      0.07428223
      0.5719886

      ## NetSedFlux_cbrt
      -0.21650716
      0.02345064
      0.2700823

1078
                                                                                    1.0000000
1079
                                                                                    0.5589768
1080
        ## NetSedFlux cbrt
                                   -0.21050716 0.02345964 0.7079982
                                                                                     0.4041456
1081
        ##
                              MedianFetch log NetSedFlux cbrt
1082
        ## StormFreq_cbrt
                                -0.01892536
                                                       -0.21050716
1083
        ## FloodFreq
                                     0.07428223
                                                        0.02345964
1084
        ## TidalRange
                                    0.57198855
                                                       0.70799815

        ## BedloadFlux_cbrt
        0.55897675

        ## MedianFetch_log
        1.0000000

        ## NetSedFlux_cbrt
        0.58825538

                                                   0.40414564
0.58825538
1.00000000
1085
1086
1087
1088
        ##
1089
        ##
1090
        ## Variance inflation factors
1091
        ## Warning in summary.lm(object): essentially perfect fit: summary may be
1092
        ## unreliable
1093
        ##
                                    GVIF
1094
        ## StormFreq_cbrt 1.502641
1095
        ## FloodFreq
                                1.093159
1096
        ## TidalRange
                               2.869967
1097
        ## BedloadFlux cbrt 1.739354
1098
        ## MedianFetch log 2.257387
1099
        ## NetSedFlux_cbrt 2.257476
```

- 1100 All VIF scores are below 3, so we therefore proceed with investigating which 1101 predictor variables best explain lateral marsh change using General Linear Models 1102 (GLMs). Before proceeding with model selection, we need to account for any spatial 1103 autocorrelation that might invalidate our model. We use hierarchical clustering to identify groups in our data. 1104 1105 Accounting for spatial autocorrelation can dramatically improve model performance, 1106 and help to avoid biased estimates of Type I error. We will examine whether there 1107 are groupings between our estuaries, based on their pairwise Euclidean distances. If so, this will form a random factor in the model structure. 1108 1109 We start by creating the matrix of Euclidean distances between estuaries: 1110 **library**(gmt) 1111 1112 distance estuary matrix=matrix(NA,length(marshes RM\$Estuary),length(marshe 1113 s RM\$Estuary)) 1114 for(est1 in 1:length(marshes_RM\$Estuary)){ 1115 for(est2 in est1:length(marshes_RM\$Estuary)){ 1116 1117 distance estuary matrix[est1,est2]=geodist(marshes RM\$Latitude[est1],marsh 1118 es RM\$Longitude[est1], marshes RM\$Latitude[est2], marshes RM\$Longitude[est2], units="km") 1119 1120 }} 1121 distance_estuary_matrix=as.dist(t(distance_estuary_matrix)) 1122 full=hclust(distance estuary matrix,method="complete") 1123 We can extract the cophenetic distance between groups to select a value for the 1124 inflection point in intra-estuary group variance and use Elbow plots to validate our 1125 selection. First, we prepare our data: 1126 dist clust<-data.frame(data.frame(unique(as.numeric(cophenetic(full))))[or</pre>
- 1127 der((unique(as.numeric(cophenetic(full)))),decreasing=T),])
- 1128 names(dist_clust)<-"distance"</pre>
- 1129 dist_clust\$group<-seq.int(nrow(dist_clust))</pre>
- 1130 add_zero<-c(0,26)
- 1131 dist_clust<-rbind(dist_clust,add_zero)</pre>
- 1132 Now we can plot the number of groups against distance to form the clusters:

```
1133 ggplot(dist_clust, aes(distance, group))+
```

```
1134 geom_step()+
```

```
1135 geom_vline(xintercept=90,linetype="longdash")+
```

```
1136 xlab("Distance for cluster formation (km)")+
```

1137 ylab("Number of groups")





Number of Clusters

1151

1152 Sum of squares within groups flattens out at 6 groups. This is in agreement with the 1153 previous plot, so we can justify grouping our estuaries into 6 hierarchical clusters.

- 1154 We now cut the hierarchical clustering analysis tree at the 90 inflection point to form
- 1155 our 6 groups and bind as a new column to our dataframe:

```
1156 group=cutree(full, h=90)
```

```
1157 marshes_RM=cbind(marshes_RM,group) # column bind the dataset and the previ
```

- 1158 ously determined grouping
- 1159 marshes_RM\$group<-as.factor(marshes_RM\$group)

1160	If we inspect the dataframe marshes, we see that group identity is the same as the
1161	region in which each estuary occurs. We will now build a linear model and determine
1162	whether inclusion of region as a random factor improves the model.

- 1163 Before selecting an appropriate GLM, we consider whether inclusion of location
- 1164 (represented by *group* from the hierarchical clustering analysis) as a random effect
- 1165 term significantly improves a maximal model fit using a Restricted Maximum
 1166 Likelihood (REML) approach (Zuur et al., 2009).
- 1167 We construct two models, one with a random effect, and one without. Anova tables 1168 can be used to see if there is a significant difference between the models. Since the 1169 model is using REML, we need to adapt the significance level using the L Ratio (Zuur 1170 et al., 2009):

1171 **library**(nlme)

1172

1173 m1<-gls(LateralRateChange

1174 ~ 1 + StormFreq_cbrt+FloodFreq+TidalRange+BedloadFlux_cbrt+MedianF

```
1175
       etch log+NetSedFlux cbrt,
1176
               method = "REML",
1177
               control="optim",
1178
               data=marshes RM)
1179
1180
       m2<-lme(LateralRateChange
1181
               ~ 1 + StormFreq cbrt+FloodFreq+TidalRange+BedloadFlux cbrt+MedianF
1182
       etch_log+NetSedFlux_cbrt,
1183
               random = \sim 1 group,
1184
               method = "REML",
1185
               control="optim"
1186
               data=marshes RM)
1187
1188
       anova(m1,m2)
1189
             Model df
       ##
                            AIC
                                     BIC
                                             logLik
                                                      Test L.Ratio p-value
1190
       ## m1
                 1 8 117.1529 122.8173 -50.57646
1191
       ## m2
                 2
                    9 117.3425 123.7150 -49.67127 1 vs 2 1.810397 0.1785
1192
       0.5*(1-pchisq(1.810397,1))
1193
       ## [1] 0.08923031
1194
             Though close (p=0.089), there is no significant difference between the models. We
1195
             can therefore use the more parsimonious model (m1, without accounting for spatial)
1196
             groups).
1197
             Stepwise Linear Regression can be used to identify which suite of predictor variables
1198
             best explain the response variable, based on whichever models produce the lowest
             AIC scores. We apply a Stepwise Linear Regression to our data, using a forwards-and-
1199
             backwards selection criterion to drop terms based on AIC scores. We switch from
1200
1201
             qLs to Lm to do this:
1202
       m3<-lm(LateralRateChange
1203
              StormFreq_cbrt+FloodFreq+TidalRange+BedloadFlux_cbrt+MedianFetch_
1204
       log+NetSedFlux cbrt,
1205
              data=marshes RM)
1206
1207
       step(m3,direction="both")
1208
       ## Start: AIC=56.25
1209
       ## LateralRateChange ~ StormFreq cbrt + FloodFreq + TidalRange +
1210
       ##
              BedloadFlux_cbrt + MedianFetch_log + NetSedFlux_cbrt
1211
       ##
1212
                              Df Sum of Sq
       ##
                                              RSS
                                                      AIC
1213
       ## - FloodFreq
                              1
                                    4.115 154.22 54.842
1214
       ## - TidalRange
                              1
                                     4.605 154.71 54.911
1215
       ## - StormFreq_cbrt 1
                                     9.586 159.69 55.609
1216
       ## <none>
                                            150.11 56.247
1217
       ## - BedloadFlux_cbrt 1 16.489 166.59 56.539
                               1 37.316 187.42 59.131
1218
       ## - NetSedFlux cbrt
1219
       ## - MedianFetch log
                               1
                                    39.266 189.37 59.359
1220
       ##
1221
       ## Step: AIC=54.84
1222
       ## LateralRateChange ~ StormFreq_cbrt + TidalRange + BedloadFlux_cbrt +
```

```
MedianFetch_log + NetSedFlux_cbrt
1223
        ##
1224
        ##
1225
        ##
                                    Df Sum of Sq
                                                       RSS AIC
1226
        ## - TidalRange
                                    1 5.309 159.53 53.586
        ## - StormFreq_cbrt
                                    1
1227
                                            10.152 164.37 54.244
1228
        ## - BedloadFlux_cbrt 1 13.370 167.59 54.671
1229
                                                     154.22 54.842
        ## <none> 154.22 54.842
## + FloodFreq 1 4.115 150.11 56.247
## - NetSedFlux_cbrt 1 35.490 189.71 57.398
        ## <none>
1230
1231
1232
        ## - MedianFetch log 1 37.604 191.82 57.642
1233
        ##
1234
        ## Step: AIC=53.59
1235
        ## LateralRateChange ~ StormFreq_cbrt + BedloadFlux_cbrt + MedianFetch_log
1236
        +
1237
        ##
                 NetSedFlux cbrt
1238
        ##
1239
        ##
                                     Df Sum of Sq
                                                       RSS
                                                                  ATC
        ## - StormFreq cbrt
1240
                                  1 5.686 165.22 52.357
        ## - BedloadFlux_cbrt 1
1241
                                          12.994 172.52 53.309
1242
       ## <none>
                                                     159.53 53.586

      ## + TidalRange
      1
      5.309
      154.22
      54.842

      ## + FloodFreq
      1
      4.820
      154.71
      54.911

      ## - MedianFetch_log
      1
      52.575
      212.10
      57.853

      ## - NetSedFlux_cbrt
      1
      70.467
      230.00
      59.635

1243
1244
1245
1246
1247
        ##
1248
        ## Step: AIC=52.36
1249
        ## LateralRateChange ~ BedloadFlux_cbrt + MedianFetch_log + NetSedFlux_cbr
1250
        t
1251
        ##
1252
        ##
                                     Df Sum of Sq
                                                        RSS
                                                                  AIC
1253
        ## <none>
                                                     165.22 52.357
1254
        ## - BedloadFlux_cbrt 1 20.510 185.73 52.931
1255
        ## + StormFreq_cbrt 1 5.686 159.53 53.586

      ## + FloodFreq
      1
      4.912
      160.30
      53.693

      ## + TidalRange
      1
      0.843
      164.37
      54.244

      ## - NetSedFlux_cbrt
      1
      65.049
      230.26
      57.660

1256
1257
1258
1259
        ## - MedianFetch log 1 66.010 231.23 57.752
1260
        ##
1261
        ## Call:
1262
        ## lm(formula = LateralRateChange ~ BedloadFlux cbrt + MedianFetch log +
1263
                 NetSedFlux_cbrt, data = marshes_RM)
        ##
1264
        ##
1265
        ## Coefficients:
1266
        ## (Intercept) BedloadFlux cbrt
                                                           MedianFetch log
                                                                                   NetSedFlux cbrt
1267
        ##
                                           -0.01429
                                                                   3.54861
                      -2.12177
                                                                                             3.54688
1268
                The predictor variables that should be retained in the minimal adequate model are
1269
                BedLoadFlux_cbrt, MedianFetch_log, and NetSedFlux_cbrt. We assign the
1270
                predictor variables to a minimal adequate model:
1271
        m4<-lm(LateralRateChange
1272
                 ~ BedloadFlux_cbrt+log(MedianFetch)+NetSedFlux_cbrt,
```

1273 data=marshes RM)

- 1274 We check for heteroscedacity and bias in the model residuals, to check whether 1275 assumption of Heterogeneity of Variance have been violated:
- 1276 **plot**(m4)



Fitted values teralRateChange ~ BedloadFlux_cbrt + log(MedianFetch) + NetSed



Standardized residuals Standardized residuals Coord Co

Theoretical Quantiles teralRateChange ~ BedloadFlux_cbrt + log(MedianFetch) + NetSed





Fitted values teralRateChange ~ BedloadFlux_cbrt + log(MedianFetch) + NetSed



Leverage teralRateChange ~ BedloadFlux_cbrt + log(MedianFetch) + NetSed

1280

1279

- 1281 There are no major issues with the model assumptions. We can now report the 1282 model results. We use anova tables to identify significant factors in our model using
- 1283 'Type I' sums of squares, and consider which terms of the model are significant, the
- 1284 AIC score, and use the *relaimpo* package to calculate relative importance for the
- 1285 linear model using R^2 partitioned by averaging over orders:

1286 library(relaimpo)

1287 anova(m4)

```
1288
      ## Analysis of Variance Table
1289
      ##
1290
      ## Response: LateralRateChange
1291
      ##
                          Df Sum Sq Mean Sq F value
                                                        Pr(>F)
1292
      ## BedloadFlux_cbrt 1 22.987 22.987 2.5044 0.1309427
1293
      ## log(MedianFetch) 1 185.898 185.898 20.2533 0.0002768 ***
1294
      ## NetSedFlux cbrt 1 65.049 65.049 7.0870 0.0158758 *
1295
      ## Residuals
                          18 165.216
                                      9.179
1296
      ## ---
      ## Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
1297
1298
      summary(m4)
1299
      ##
1300
      ## Call:
1301
      ## lm(formula = LateralRateChange ~ BedloadFlux cbrt + log(MedianFetch) +
1302
             NetSedFlux_cbrt, data = marshes_RM)
      ##
1303
      ##
1304
      ## Residuals:
1305
            Min
                      10 Median
      ##
                                      30
                                             Max
1306
      ## -7.5047 -1.5047 -0.3771 1.8486 4.9780
1307
      ##
1308
      ## Coefficients:
1309
      ##
                           Estimate Std. Error t value Pr(>|t|)
1310
      ## (Intercept)
                          -2.121770 0.758995 -2.795 0.0120 *
1311
      ## BedloadFlux_cbrt -0.014293 0.009561 -1.495
                                                         0.1523
1312
      ## log(MedianFetch) 3.548614
                                      1.323257 2.682
                                                         0.0152 *
1313
      ## NetSedFlux cbrt
                           3.546880
                                      1.332338
                                                 2.662
                                                         0.0159 *
1314
      ## ---
      ## Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
1315
1316
      ##
1317
      ## Residual standard error: 3.03 on 18 degrees of freedom
1318
      ## Multiple R-squared: 0.6238, Adjusted R-squared: 0.5611
1319
      ## F-statistic: 9.948 on 3 and 18 DF, p-value: 0.0004326
1320
      AIC(m4)
1321
      ## [1] 116.7899
1322
      calc.relimp(m4,type=c("lmg"),rela=T)
1323
      ## Response variable: LateralRateChange
1324
      ## Total response variance: 20.91194
1325
      ## Analysis based on 22 observations
1326
      ##
1327
      ## 3 Regressors:
1328
      ## BedloadFlux cbrt log(MedianFetch) NetSedFlux cbrt
1329
      ## Proportion of variance explained by model: 62.38%
1330
      ## Metrics are normalized to sum to 100% (rela=TRUE).
1331
      ##
1332
      ## Relative importance metrics:
1333
      ##
1334
      ##
                                 lmg
1335
      ## BedloadFlux_cbrt 0.06176616
1336
      ## log(MedianFetch) 0.45986451
```

```
1337
      ## NetSedFlux_cbrt 0.47836933
1338
      ##
1339
      ## Average coefficients for different model sizes:
1340
      ##
1341
      ##
                                   1X
                                               2Xs
                                                           3Xs
1342
      ## BedloadFlux cbrt 0.01246703 -0.007295296 -0.01429271
1343
      ## log(MedianFetch) 4.44960924 3.960577731
                                                    3.54861396
1344
      ## NetSedFlux_cbrt 5.08045110 4.288503610 3.54687976
```

1345MedianFetch_Log and NetSedFLux_cbrt are both significant terms, whereas1346BedLoadFLux_cbrt is not. The AIC score of the minimal adequate model is 116.79.1347The proportion of variance explained by the model is 62.38%, and of that variance,1348MedianFetch_log and NetSedFlux_cbrt account for nearly half each (46% and 48%1349respectively). Finally, visualise the significant terms of the regression model using the1350visreg package. Marshes shift from a trend of expansion to erosion in response to1351increased fetch length and sediment supply:

```
1352
       library(visreg)
1353
1354
       visreg(m4, "NetSedFlux_cbrt",
1355
              ylim=c(-11,7),
1356
              scale="response",
1357
              partial=T,
1358
              rug=T,
1359
              line=list(col="black"),
              xlab=expression("Sediment flux per unit area, cube-transformed (kg
1360
1361
      m"^-2*" yr"^-1*")"),
1362
              ylab=expression("Lateral marsh change (ha yr"^-1*")"))
```



Sediment flux per unit area, cube-transformed (kg m⁻² yr⁻¹)

```
1364 visreg(m4, "MedianFetch",
1365 ylim=c(-11,7),
1366 scale="response",
1367 partial=T,
1368 rug=T,
1369 line=list(col="black"),
1370 xlab="Median fetch length (km)",
1371 ylab="")
```



Median fetch length (km)

1372

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