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Supporting Information for

Coastal Marsh Degradation into Ponds Induces Irreversible Elevation Loss Relative to Sea Level in a Microtidal System

Lennert Schepers[1,2], Patrick Brennand[3], Matthew L. Kirwan[4], Glenn R. Guntenspergen[3] and Stijn Temmerman[1]

[1]Ecosystem Management Research Group, University of Antwerp, Wilrijk, Belgium.

[2]Flanders Marine Institute (VLIZ), InnovOcean Site, Ostend, Belgium.

[3]Patuxent Wildlife Research Center, U.S. Geological Survey, Laurel, Maryland, USA.

[4]Department of Physical Sciences, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, USA.

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Introduction

This supplementary information gives more details on the marsh loss patterns in the study area (Figure S1-S2), a general overview of the elevation measurements (Table S1), and more information and detailed results of the statistical analyses that we mention in the main paper (Text S1, Figures S3-S4, Tables S2- S3).

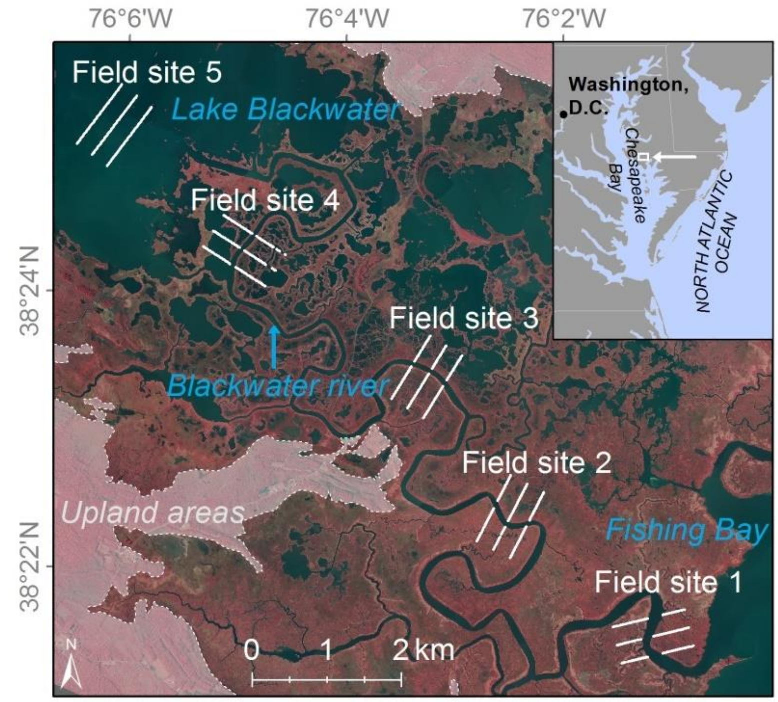

Figure S1. Aerial image of the Blackwater Marshes. From lower right corner to upper left corner of the image (i.e. in upstream direction along the Blackwater River) marshes are changing from high marsh vegetation cover (reddish color) close to the Fishing Bay (SE-corner) to increasing open water areas (dark color) in upstream direction, and ultimately to Lake Blackwater (NW-corner). White lines indicate GPS measurement points. White shaded areas with dashed outlines are no marshes but upland areas. Inset: Location of the Blackwater marshes along the Chesapeake Bay (white rectangle).

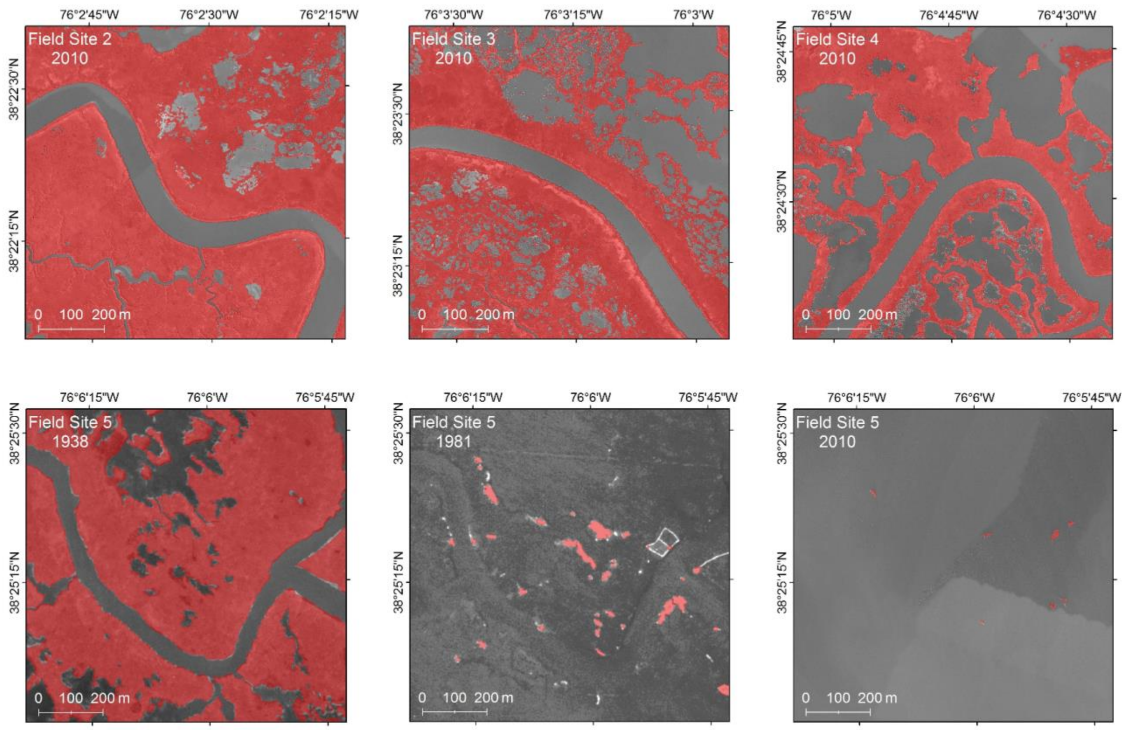

Figure S2. The spatial patterns of marsh loss in the Blackwater Marshes. Top row: spatial pattern of marsh loss at field site 2, 3 and 4 with increasing marsh loss (see location on Figure S1). Bottom row: also at field site 5 (Lake Blackwater), extensive marshes existed in the 1930s, but are now completely lost. Greyscale aerial images with marshes in red. For more information on the spatio-temporal patterns of marsh loss in this study area, see (Schepers et al., 2017).

Table S1. Number of regular transect points, mean elevation relative to local mean sea level (MSL, in m) and mean inundation time (in %) for marsh and pond points. Different letters in between brackets indicate significant differences between field sites (pairwise Wilcoxon Rank Sum Test with Bonferroni correction, α= 0.05).

	number of points (n)		% pond points	Mean Elevation (m rel. to MSL)		Mean Inundation Time (%)		Mean Fetch Length (m)
Pond(P)/ Marsh(M)	P	M		P	M	P	M	P
Field site 1	5	222	2.2	-0.09 (a)	0.24 (A)	60.4 (a)	21.4 (A)	4.23 (a)
Field site 2	22	243	8.3	-0.41 (bc)	0.01 (B)	97.8 (b)	46.9 (B)	68.3 (b)
Field site 3	111	164	40.4	-0.39 (b)	-0.01 (C)	98.3 (b)	53.6 (C)	60.5 (b)
Field site 4	140	114	55.1	-0.52 (c)	-0.03 (C)	99.6 (c)	63.0 (D)	281 (c)
Field site 5	300	0	100	-0.96 (d)	/	100.0 (d)	/	2398 (d)

Text S1. Details and results of the statistical analyses

Linear Regression analyses

All statistics were performed in R, version 3.2.2 (R Core Team, 2017). To test which environmental variables significantly influence the soil elevation, we fitted a linear regression model to explain the elevation of the vegetated marsh platform using 916 marsh elevation points (regular transects and additional measurements at the pond edges). The four calculated variables ((1) downstream river length to the river mouth, (2) the Euclidean distance to the Blackwater River, (3) distance to secondary channels that are directly connected with the Blackwater River and (4) distance to inner marsh ponds) were not correlated. The Pearson's r was lower than 0.45 and the variance inflation factors (VIF, a measure for collinearity) was lower than 1.5 for all variables, hence we started the model selection with all four variables.

A second model was fitted to explain the pond bottom elevations. 692 pond points from regular transects and additional measurements at the pond edges were used, but points at Lake Blackwater that were located at the position of the former channel of the Blackwater River (as defined on old aerial images of 1938) were omitted. The nearest marsh distance data were log-transformed to obtain a linear relationship (Figure 3 in main paper, left), needed in the linear regression model. The mean fetch length was highly correlated with the log-transform of distance to the nearest marsh (Pearson's r: 0.86) and with the minimum width of the connecting channel (Pearson's r: 0.89), so we left the mean fetch length out of the analyses to avoid collinearity. The minimum width of the connecting channel was also highly correlated to the log-transformed distance to the nearest marsh (Pearson's r: 0.89), but the variance inflation factors (VIF, a measure for collinearity) were < 7 and the scatterplot revealed no relationship. Therefore, we started the model with five variables, (1) downstream river length to the river mouth, (2) the (log) distance to the nearest marsh, (3) minimum width and (4) length of connecting channel and (5) the minimum pond age.

The spatial auto-correlation that was present in our data was modelled by an exponential correlation structure for both analyses. This correlation structure had produced the lowest Akaike Information Criterion (AIC, a measure for the goodness of fit and model complexity) values among a wide range of possible correlation structures. We started with a full model including all the variables, and performed a backward model selection by subsequently removing the least significant variable of likelihood ratio tests (a test to assess differences in model performance between including and excluding a variable), until only significant variables (α: 0.05) were present in the model. The models were fitted and validated following the procedures in (Zuur et al., 2009).

Decreasing marsh elevation

Marsh elevation decreases along the marsh loss gradient and with increasing distance from the Blackwater River, reflecting gradients in tidal range and sediment availability. The intact marshes (site 1) are highest and have a mean surface elevation of 0.24 m (Figure 1 in main paper). More degraded areas (site 2-4) have lower marsh elevations, with site 4 having a mean elevation of only -0.03 m (Figure 1, Table S1). Lower marsh elevations along the marsh loss gradient might be partly explained by smaller tidal ranges (Figure 1), which limit the elevation range that marshes can occupy ranges (Kirwan & Guntenspergen, 2010). Additionally, with increasing marsh loss, the elevations of remaining marshes also become lower relative to the tidal frame (Figure 1), as reflected by an increase in mean inundation duration of the marshes from less than 25% at the intact marsh site (field site 1) to more than 60% at the most degraded site (field site 4, Table S1).

Decreasing marsh elevations in our system likely reflect decreasing sediment availability along the marsh loss gradient, where the most degraded marshes receive little external sediment, and experience a net export of sediment out of the system during frequent northwestern storms (Ganju et al., 2013, 2015; Stevenson et al., 1985). In contrast, the most intact marshes receive sediment from an external source (i.e. Fishing Bay) (Ganju et al., 2013), and may additionally receive sediment exported from the rapidly eroding marshes.

Our statistical model indicates that lower marsh elevations were also related to larger distances from the river (Table S2). This micro-topography is widely observed in other tidal marshes , where it originates from lower sediment deposition rates with larger distances from channels and marsh edges (Christiansen et al., 2000; Friedrichs & Perry, 2001; Moskalski & Sommerfield, 2012; Temmerman et al., 2003).

Table S2. Output table of the final model explaining marsh elevation. Note that distance to (i) secondary channels and (ii) ponds were not significant variables (α: 0.05) and omitted from the regression model

Term	Value	p-value
intercept	0.40	<0.001
Downstream river length to mouth	-0.000013	<0.001
Distance to river	-0.00017	0.02

Ponds deepen by connecting to tidal system

For explanation, see main article.

Table S3. Output table of the final model explaining pond depth. Note that (i) downstream distance to mouth, (ii) length of connecting channel and (iii) the minimum pond age were not significant variables (α: 0.05) and omitted from the regression model

Term	Value	p-value
intercept	-0.007	0.84
Log(Distance to nearest marsh)	-0.061	<0.001
Minimum width of connection	-0.010	<0.001

Random Forest analysis

We performed a Random Forest analysis (Breiman, 2001), which is a robust, non-parametric statistical method that requires no distributional or functional assumptions of variables to the response variable. The technique uses 1000 individual regression trees to quantify the relationship between the environmental variables and the pond depth/marsh elevation. The outcome is a ranking of the most important environmental variables that determine the pond depth/marsh elevation. This is measured with the variance importance and the minimal depth of the variable. The variance importance gives the difference between the prediction error when the variable is noised up by randomly permuting its values, and the prediction error under the observed values. The Minimal depth considers how soon the variable is used for the first time in each decision tree, the sooner (lower depth value) the more important this variable is. This depth is averaged over all trees in the forest.

As input variables we used all environmental variables, including the mean fetch length that we omitted in the linear regression analysis. The coordinates were also included to account for the spatial autocorrelation.

The random forest analysis of the marsh elevation (1000 trees) explained 84.99 % of the variance. In decreasing order of importance, the primary predictors of the marsh elevation identified by our random forest model were the north and east coordinates. The distance to the river mouth (which represents the different field sites) was important in explaining variance (Figure S3 top). However, this variable was usually considered late in the regression tree (Figure S3 bottom). This is likely because the coordinates also can make a distinction between the different field sites. Other parameters were less important. In our linear regression analysis the distance to the river was also significant (p= 0.02), but the variance importance in our random forest model was rather low.

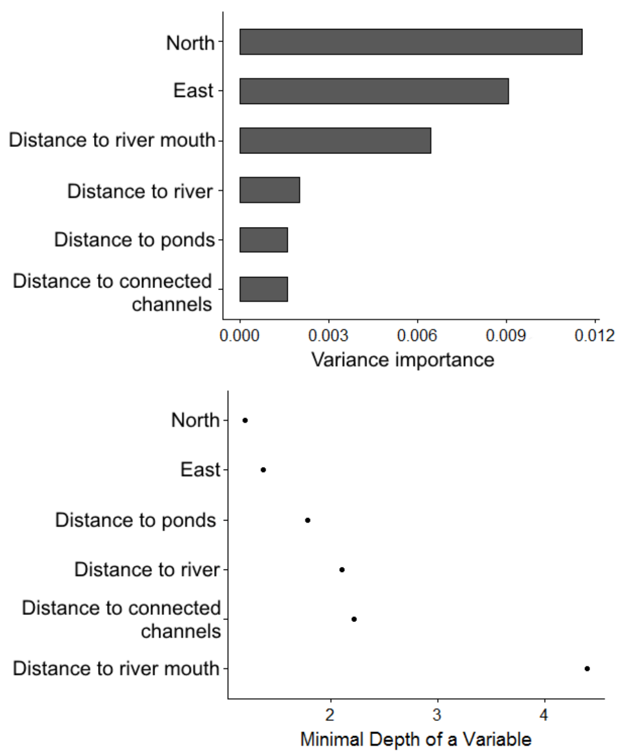

Figure S3. The variance importance (top) and Minimal depth (bottom) of the variables related to marsh elevation.

The random forest analysis of the pond depth (1000 trees) explained 96.66 % of the variance. The mean pond fetch length (~pond size), the minimum width as well as the distance to the nearest marsh were important predictors for the model (Figure S4). The minimum age was not important. This corresponds to our linear regression analysis.

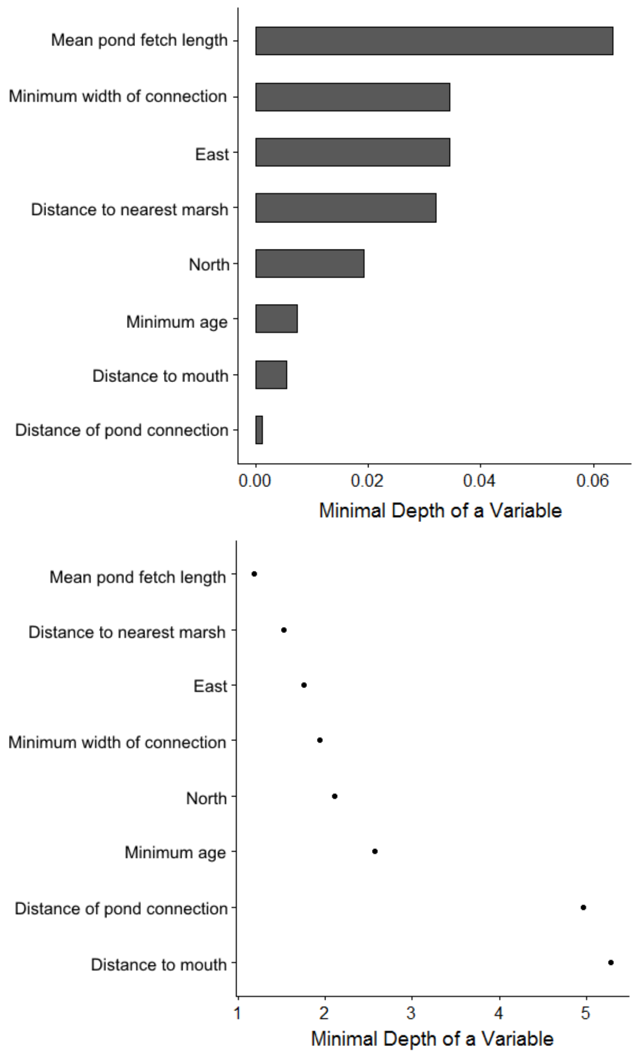

Figure S4. The variance importance (top) and Minimal depth (bottom) of the variables related to pond depth.