

Title Page

Title: Biotic and abiotic factors control the geomorphic characteristics of channel networks in salt marshes

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Running Head: What factors drive the evolution of tidal channel?

Keywords: tidal channel evolution; bio-geomorphology; vegetation; tidal marshes; physical processes

22 **Statement of Significance**

23 Tidal channel networks are typical morphological features of coastal landscapes. A key question
24 is how biotic and abiotic processes control their long-term geomorphic development. This
25 knowledge gap is of theoretical and practical importance. The comprehensive understanding of
26 how these driving forces work would inform on how channel network systems evolve and help
27 forecast the long-term resilience of these landscapes to climate change and human interference.
28 Based on observational research, we found that salt marshes dominated by different grass species
29 do display different channel networks, but this difference seems driven more by physical than
30 biological factors. We developed sample models, which can explain more than 60% of the
31 variability in mean unchanneled path length. Our work contributes significantly to a broader
32 understanding of coastal landscape morphodynamics, and provides insights into future model
33 development and testing of landscape evolution models.

Abstract:

Biotic and abiotic processes control the formation and evolution of tidal channel networks. However, which factor regulates the planimetric geometry of the network remains unclear. Here, we compare the geometric properties of tidal channel networks in fourteen salt marshes along the coasts of the USA and China. Significant difference in the geometric properties of tidal channel networks was found in salt marshes dominated by different vegetation species. Physical parameters better explained these differences, while vegetation parameters had a weaker effect on the network geometry. In particular, mean marsh elevation and tidal range were found to be the best variables to explain the variability in drainage density, mean unchanneled path length and sinuosity (R^2 values range from 0.239 to 0.465), while biotic parameters (i.e., aboveground biomass, stem density, height and diameter) were only significant predictors for one or two of these geometric properties (R^2 values range from 0.005 to 0.312). We used multiple regressions to develop sample models, explaining more than 60% of the variability in mean unchanneled path length. Our findings underline the key role of physical factors in shaping tidal channel networks. We conclude that physical processes are more important than vegetation species in determining the long-term development of tidal channels.

Text:

Introduction

A long-standing challenge in landscape morphodynamics is to elucidate how biotic and abiotic processes drive the development of geomorphic patterns and to predict the long-term dynamics of landforms (Murray et al., 2008; Reinhardt et al., 2010; Corenblit et al., 2011; van Maanen B et al., 2015; Schwarz et al., 2018). Tidal channel networks are typical morphological features of coastal landscapes. They promote exchange of materials (water, sediments, nutrients, biota) between coastal marshes and the open sea, hence maintaining the structure and function of salt marshes (French and Stoddart, 1992; Vandenbruwaene et al., 2012; Kearney and Fagherazzi, 2016; Li et al., 2019). A comprehensive understanding of the initial formation and long-term evolution of channel networks is fundamental to address their response to climate change and human interference (Kearney and Fagherazzi, 2016; Schwarz et al., 2018).

Numerous field surveys, laboratory studies and numerical models have shown that tidal channels typically form because of water flow concentration within small-scale topographic depressions, leading to an increase in flow velocity, and hence erosion and deepening of the initial depressions (Fagherazzi and Furbish 2001; D'Alpaos et al. 2006; Stefanon et al. 2010). This process drives further flow concentration and creates a positive feedback mechanism between erosion and channel formation (Tambroni et al., 2005; Vlaswinkel et al., 2011; Fagherazzi et al., 2012). Other studies have shown that also the presence of vegetation can trigger the formation of dense, efficient tidal channel networks (Temmerman et al., 2007; Vandenbruwaene et al., 2013; Kearney & Fagherazzi, 2016; Schwarz et al., 2018; Taramelli et al., 2018). For example, the establishment of dense pioneer vegetation patches on an initially bare landscape can partially force the water flow around these patches, leading to an increase in flow velocity (Zong & Nepf, 2010),

erosion (Bouma et al., 2007) and, in some cases, channel incision (Temmerman et al., 2007; Schwarz et al., 2014). It is now widely accepted that both biotic and abiotic processes can influence the formation and long-term evolution of tidal channel networks (Temmerman et al., 2007; Fagherazzi et al., 2012; van Maanen et al., 2013; Schwarz et al., 2018). However, the relative importance of these two groups of drivers has never been studied on a global scale.

Previous studies revealed that the formation, deepening and expansion of channel networks are facilitated with high tidal ranges and low water depths (Kirwan and Guntenspergen, 2010; Stefanon et al., 2010; Van Maanen et al., 2013). There is however growing recognition that vegetation-landform interactions play a key role in shaping intertidal landscapes (Fagherazzi et al., 2012; Coco et al., 2013; Vandenbruwaene et al., 2013; Kearney and Fagherazzi, 2016; Schwarz et al., 2018), although some studies suggest that the influence of vegetation is only secondary (Vandenbruwaene and Temmerman, 2012; Li et al., 2019). In general, several numerical model studies have reported enhanced channel formation due to vegetation in early stages of development (D'Alpaos et al., 2007; Temmerman et al., 2007; Tal and Paola, 2010; Schwarz et al., 2014; Bij de Vaate et al., 2020), but they did not consider later stages of channel evolution.

It is now widely accepted that the formation and evolution of channel networks result from the interactions between hydrodynamic conditions (e.g. tidal currents, waves, tidal prism), geomorphic characteristics (e.g. elevation, slope, coastal alignment, sediment properties) and vegetation traits (e.g. above- and belowground biomass, stem density, height and diameter) (Fagherazzi and Sun, 2004; Fagherazzi et al., 2012; Schwarz et al. 2018; Li et al., 2019). These factors govern the balance between erosion and deposition and vary across channel network systems. Despite these studies, we still lack an understanding of which biotic and abiotic processes dominate the long-term morphology of salt marshes. This knowledge gap is of theoretical and

practical importance. The comprehensive understanding of how these driving forces work would inform on how channel network systems evolve and potentially help forecast the long-term resilience of these landscapes to disturbances.

Here, we compare geometric properties of channel networks in 14 different salt marshes along the US and Chinese coastlines, each dominated by one typical salt marsh species, with seven different species in total. We first investigate whether different vegetation species lead to different geometrical channel network characteristics. We then examine the relationships between geometrical characteristics of channel networks and various physical and biological parameters to determine the relative importance of biotic and abiotic drivers. Finally, we develop a sample model to predict geometrical characteristics of tidal channel networks from these drivers; the model further tests the relative importance of biotic versus abiotic factors. The results of this work lend insight into future model development of salt marsh evolution.

Methods

Study Sites and data sources

We selected seven plant species dominant in salt marshes along the coasts of the US and China: *Salicornia virginica* Linn., *Spartina alterniflora* Loisel., *Juncus roemerianus* Scheele, *Spartina patens* (Aiton) Muhl., *Carex lyngbyei* Hornem., *Scirpus triqueter* Linn. And *Suaeda salsa* (L.) Pall. For each species, we selected two different sites where it is dominant. For each site, we selected three watersheds (Fig. 1a).

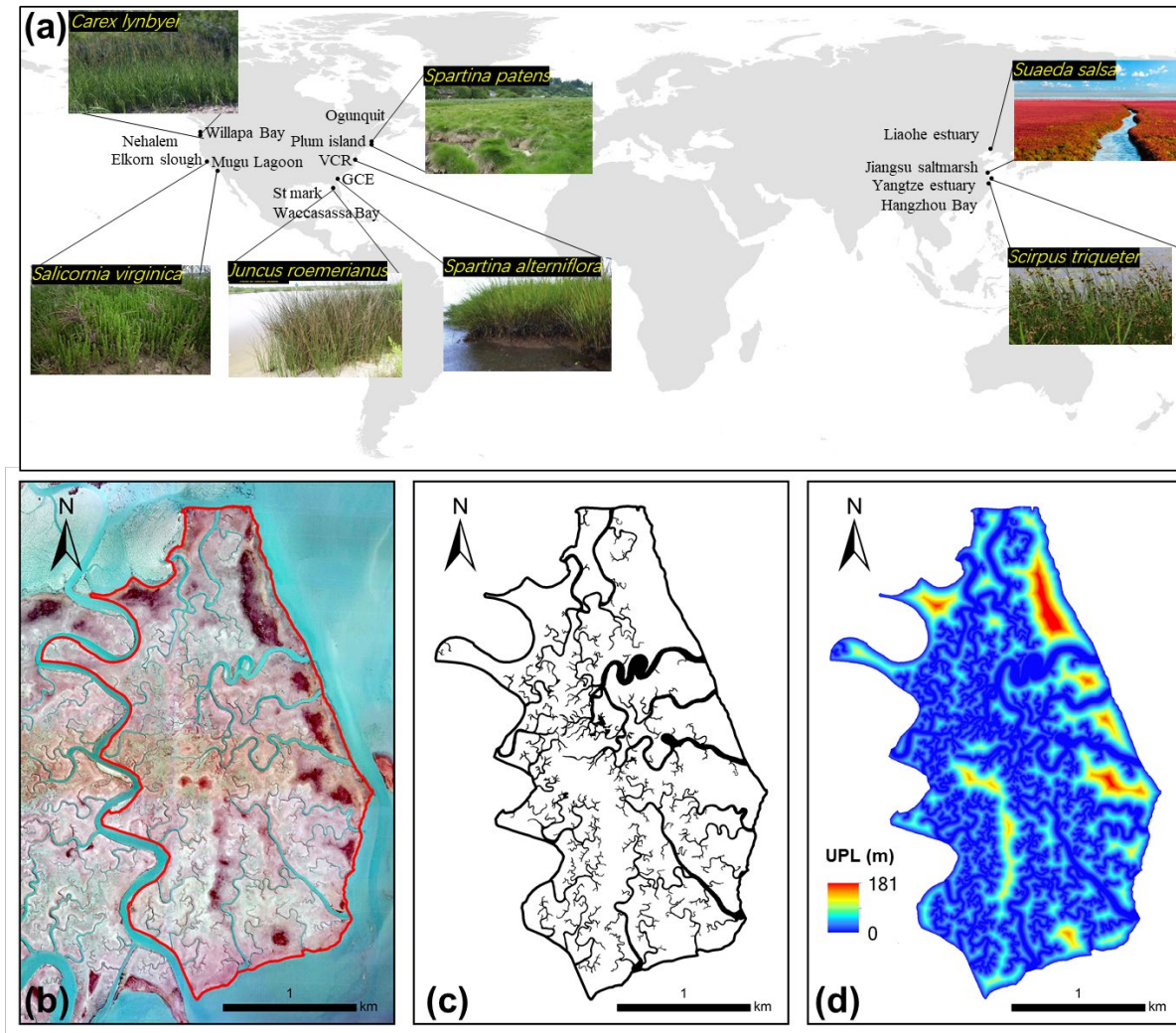


Fig 1. Map of study sites (a), and example of satellite imagery (b), channel network (c) and unchanneled path length (d) of a *Spartina alterniflora* marsh in the Virginia Coast Reserve, USA. For the maps of the other study sites see [Fig. S1](#).

We collected different biotic and abiotic parameters characterizing the different sites. Due to scarcity of elevation data in China, the collection of elevation data and hydroperiod is limited to the US sites. Tidal data (i.e., tidal range, mean sea level and astronomical tide water levels) were obtained from the Center for Operational Oceanographic Products and Services (CO-OPS) (<https://tidesandcurrents.noaa.gov/>). For each site, we used the data from the closest station (Fig.

2b; Table S1). The distance between the marsh watersheds and the corresponding tidal stations range from 1 to 50 km, with an average distance of about 13 km (Table S2). Elevation data for the study area were provided by a digital elevation model (DEM) from the US Geologic Survey's National Elevation Dataset (NED) (<http://nationalmap.gov/elevation.html>) (Fig. S2), which was used in other geomorphic studies (e.g. Ganju et al., 2017; Daly et al., 2017). NED is a seamless raster format dataset, which was developed by merging diverse source datasets, such as high-quality LiDAR data, USGS DEM collection, SRTM (Shuttle Radar Topography Mission) and other sources (U.S. Geological Survey, 2017). The horizontal resolution is 1/9 arc-second (i.e., about 3 m for our sites). The vertical accuracy varies spatially because of the different sources, with an estimated error of 20-30 cm (Gesch et al., 2014; Amante, 2018). The vertical error can increase in dense vegetation areas where LiDAR signals do not easily detect the ground beneath the vegetation canopy. For example, Rosso et al. (2006) measured a vertical error of about 20-30 cm in *Spartina* marshes of the San Francisco Bay, California, USA. Elevation data were expressed relative to local mean sea level by accounting for the difference between the North American Vertical Datum of 1988 (NAVD 88; reference datum used in NED) and the observed mean sea level at the closest CO-OPS station (Table S1). In this study, we used the mean value of elevation of each watershed for our analysis, thus there are six elevation data for each vegetation species (Fig. 2a; Fig. S2). We also calculated the mean overmarsh hydroperiod as the total inundated time during which astronomical tide water levels are above the mean marsh elevation for one lunar month (i.e., 29.5 days) (Fig. S3).

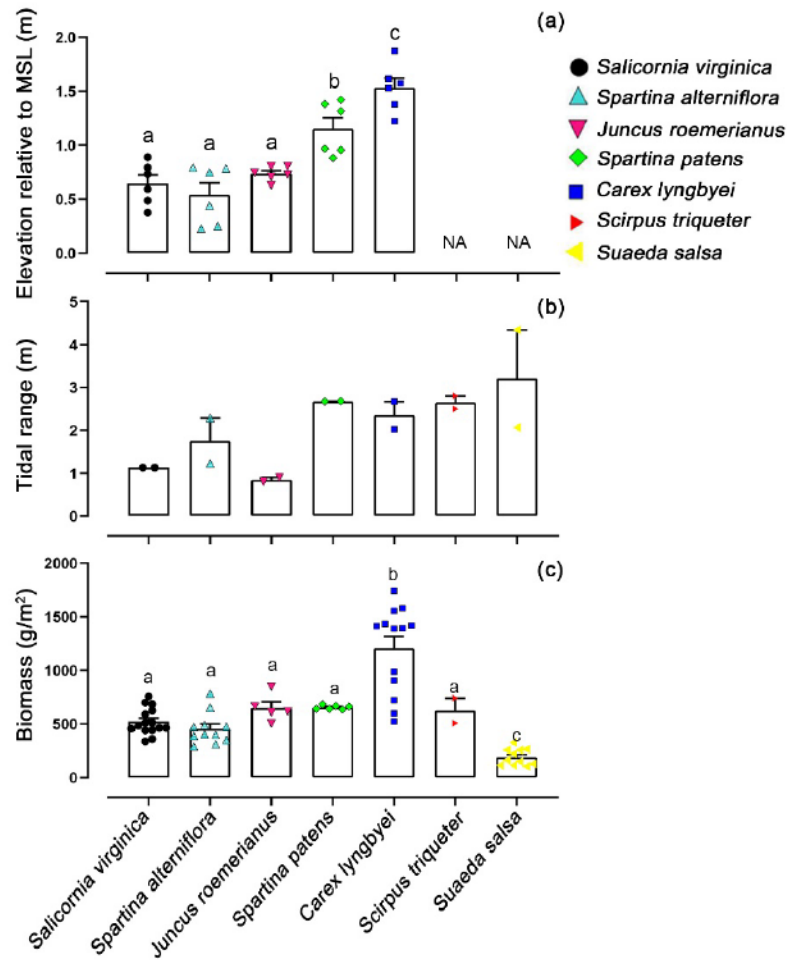


Fig. 2. Elevation relative to mean sea level (a), tidal range (b) and aboveground biomass (c) for the saltmarshes studied here and aggregated per vegetation species. Error bars represent the standard error. Means with the same letter do not differ significantly from each other ($P \leq 0.05$, LSD, ANOVA). NA indicates data unavailability. Individual jitter points denote individual values for each species.

We also collected measurements of plant traits characteristic for each considered species (i.e., aboveground biomass, stem density, diameter and height) by reviewing the literature and using datasets of the LTER Network Data Portal (<https://portal.lternet.edu/nis/home.jsp>). Following the method used by Kirwan et al. (2009) to minimize variability associated with comparing vegetation

parameters derived from different methodologies, we only included measurements performed at the end of the growing season (July-September) and in their native populations. We also excluded measurements located near a channel to focus on measurements from relatively homogenous topographic and hydrologic environments. For *Spartina alterniflora*, we only included measurements of their short form, which typically occupies the expansive marsh interior. In general, we collected those biotic parameters from marshes close to our study areas. If not available, we used data in the same state or in neighboring states (Table S3). At the end, for each parameter, we used the average value from the collected data of a given species (Fig. 2c; Table S4).

Geometric Properties of Channel Networks

For each site in the USA and China, we selected three watersheds and manually extracted tidal channel networks from Google Earth satellite imagery (Table S1 for corresponding dates). Channels were identified based on tuning the image's brightness (Fagherazzi et al. 1999). To exclude uncertainties in the visual interpretation, all images were down-sampled to 1-meter pixel resolution and those parts of the channel networks with channel width less than 1 m were neglected (Liu et al., 2020). Then we calculated six parameters that quantify geometric properties of tidal channel networks and the surrounding marshes. The drainage density is calculated as the ratio between the total channel length and the watershed area (Marani et al., 2003). The mean unchanneled path length (UPL) is calculated as the average shortest distance between any location on the vegetated platforms and the nearest channel edge (Tucker et al., 2001, Marani et al. 2003). The geometric efficiency is the Hortonian length divided by the mean UPL, which gives an indication of how efficiently a channel network can distribute sediments to the marsh platforms (Marani et al. 2003; Kearney and Fagherazzi, 2016). The Hortonian length is defined as the inverse

of drainage density (Kearney and Fagherazzi, 2016). The sinuosity is calculated as the ratio between the length of a channel along its centerline and the straight-line distance from start to end (Kearney and Fagherazzi, 2016). As each channel has its own sinuosity, we take here the average value over all channels to quantify the sinuosity at the watershed scale, excluding channels with a width lower than 1 m or a length lower than 100 m. Finally, the unvegetated-vegetated marsh ratio (UVVR) is calculated as the area of channels and ponds divided by area of the vegetated marsh (Ganju et al., 2017).

Statistical Analyses

Statistical differences in elevation relative to mean sea level and aboveground biomass between the different vegetation species were assessed using a one-way ANOVA and LSD tests. Statistical differences in geometric properties of channel networks between the different vegetation species were also assessed using a one-way ANOVA and LSD tests. To investigate the relative importance of each abiotic and biotic parameters to explain the observed variability in channel networks, simple linear regressions were used. Shapiro-Wilk normality tests were conducted to evaluate the normality of the different explanatory variables (Table S5). Hydroperiod, aboveground biomass and stem density were log-transformed prior to the analysis as they were deviating from a normal distribution. Furthermore, we used dummy variable regression models (with vegetation species as dummy variables and *Salicornia virginica* as the reference species) to check whether the influence of biotic parameters was already embedded in the abiotic parameters (tidal range and mean marsh elevation).

We used a Stepwise Multiple Linear Regression to develop sample models that can predict geometric properties of channel networks with a combination of the abiotic and biotic parameters

that we have collected. Using a forward selection, the stepwise regression starts with no variable and adds new variables one by one. The independent variable with the largest correlation with regards to the dependent variable is the first selected, then the variable with the second largest correlation, and so on (Schwingshackl et al., 2018). During this process, every coefficient of the parameter in the equation must reach the level of significance $p < 0.05$. Variables were also disregarded if they would cause the tolerance of another variable already in the regression model to drop below the tolerance criterion, specified as the probability of $F > 0.1$ (Yang 2012). To validate the different regression models, we compared predicted and observed geometric properties of channel networks. We computed the variance inflation factor (VIF), a diagnostic tool to assess multicollinearity in the models, which exists when the independent variables are highly correlated with each other. The VIF is computed post-analysis and measures how much the variance of the estimated regression coefficients is inflated compared to conditions when the independent variables are uncorrelated (Drobot and James, 2002). Neter et al. (1990) suggested that a collinearity exists amongst the parameters when $VIF > 10$. Results in Table 3 indicate that no collinearity exists among independent variables in our multivariate regression models. All analyses were conducted with SPSS 25.0 for Windows.

Due to scarcity of elevation data in China, some analyses were limited to the US sites. Statistical differences in aboveground biomass and geometric properties of channel networks between the different vegetation species were assessed in all sites and associated vegetation species in the US and China (Fig. 2 c and 3). However, the analyses of statistical differences in elevation relative to mean sea level between the different vegetation species was limited to the US sites (Fig. 2a). Furthermore, linear regressions and Shapiro-Wilk normality tests were also limited to the US sites and associated vegetation species (Fig. 4, 5, 6 and S4; Tables 1, 2, 3 and S5).

Results

Variability in Channel Network Geometry

In general, most geometric properties of tidal channel networks vary considerably among marshes dominated by different vegetation species (Fig. 3), with the exception of geometric efficiency (for which there is no significant difference among the different species, $F=1.532$, $P=0.197$, Fig. 3d). For the other parameters, we can distinguish two groups: *Salicornia virginica*, *Spartina alterniflora* and *Juncus roemerianus* on the one hand, and *Carex lynbyei*, *Scirpus triqueter* and *Suaeda salsa* on the other hand. Indeed, our results indicate that the first group presents significantly higher drainage density (Fig. 3a), lower mean UPL (Fig. 3b), higher sinuosity (Fig. 3e) and higher UVVR (Fig. 3c) than the second group. Moreover, *S. patens* has significantly higher mean UPL than *S. virginica* and *S. alterniflora* (Fig. 3b), and higher sinuosity than *C. lynbyei*, *S. triqueter* and *S. salsa* (Fig. 3e). *J. roemerianus* also has significantly higher sinuosity than *S. virginica* and *S. patens* (Fig. 3e). *S. virginica* has significantly higher UVVR than *S. alterniflora* and *S. patens*, while *Suaeda salsa* marshes have the lowest UVVR among these vegetation species (Fig. 3c).

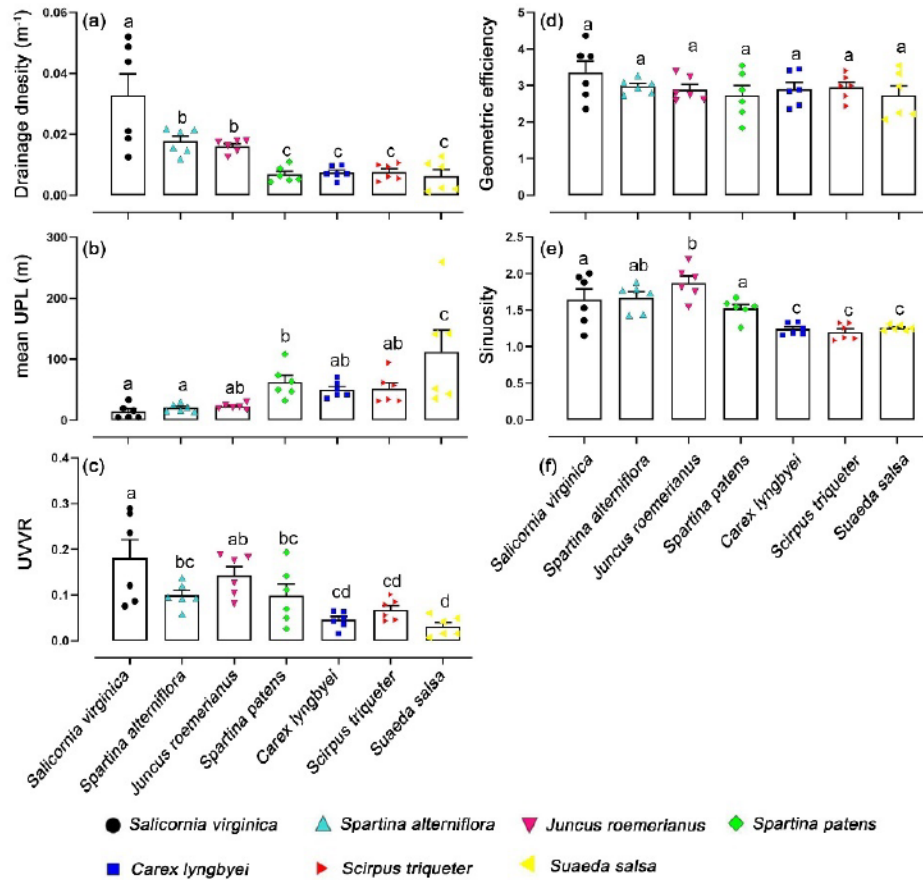


Fig. 3. Drainage density (a), mean UPL (b), UVVR (c), geometric efficiency (d) and sinuosity (e) for various saltmarshes dominated by different vegetation species. Error bars represent standard error. Means with same letter do not differ significantly from each other ($P > 0.05$, LSD, ANOVA). Individual jitter points represent individual values.

Drivers of Channel Network Geometry

Overall, abiotic parameters (tidal range, mean marsh elevation and hydroperiod) better explain the geometrical characteristics of the channel network, while biotic parameters (aboveground biomass, stem density, height and diameter) had a much weaker effect on channel network properties (Fig. 4, 5 and S4; Table 1). This suggests that significant differences of geometric

properties of tidal channel networks among marshes dominated by different vegetation species (Fig. 3) are more likely to be attributed to abiotic parameters, rather than biotic parameters. Mean marsh elevation was the best single variable explaining (negatively) variability in drainage density and sinuosity (R^2 values of 0.304 and 0.465, respectively), with tidal range the second-best predictor (negatively) (R^2 values of 0.239 and 0.362, respectively) (Fig. 4). Tidal range was the best single variable explaining (positively) variability in mean UPL ($R^2 = 0.398$) and explaining (negatively) variability in UVVR ($R^2 = 0.233$), with mean marsh elevation the second-best predictor (R^2 values of 0.346, 0.347 and 0.225, respectively) (Fig. 4). The hydroperiod also significantly explained (positively) variability in drainage density (R^2 values of 0.149), but showed insignificant relationships with mean UPL, sinuosity and UVVR (p values of 0.024, 0.109 and 0.095, respectively) (Fig. S4). None of the considered biotic and abiotic parameters were able to explain a significant part of the variability in geometric efficiency (Table 1).

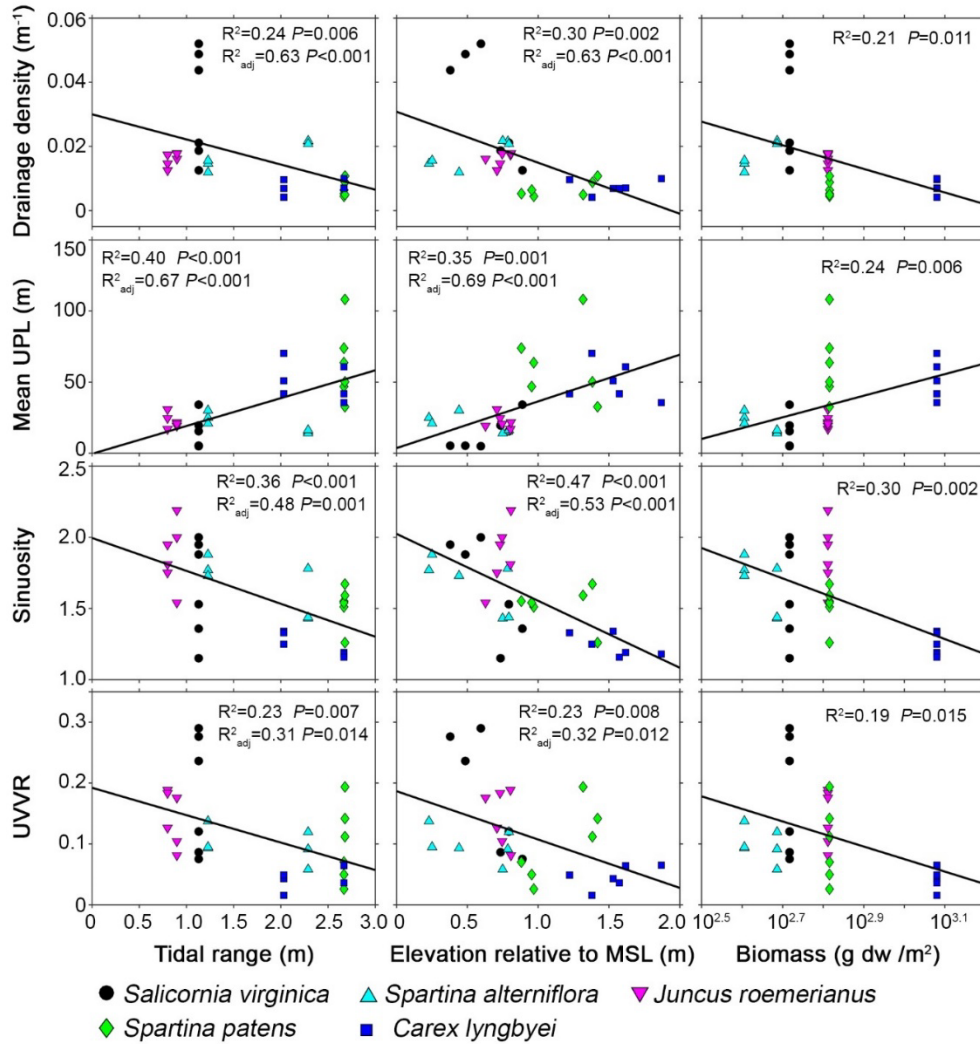


Fig. 4. Channel network properties as a function of tidal range, elevation, and aboveground biomass. R^2_{adj} is the adjusted R-Square of the regression. Vegetation types are also included as dummy variables. The units of biomass read “grams of dry weight per square meters”.

Although abiotic parameters are better predictors of channel network geometry, biotic parameters do explain a significant part of their variability (Table 1). For example, the aboveground biomass is a significant predictor for all variables (except for geometric efficiency) and the best biotic predictor for sinuosity and UVVR (R^2 values of 0.344 and 0.193, respectively) (Fig. 4; Table 1). The other biotic parameters were significant predictors for only one or two

geometric properties, with stem density the best biotic predictor for the mean UPL ($R^2 = 0.244$) and stem height for drainage density ($R^2 = 0.216$) (Fig. 5; Table 1).

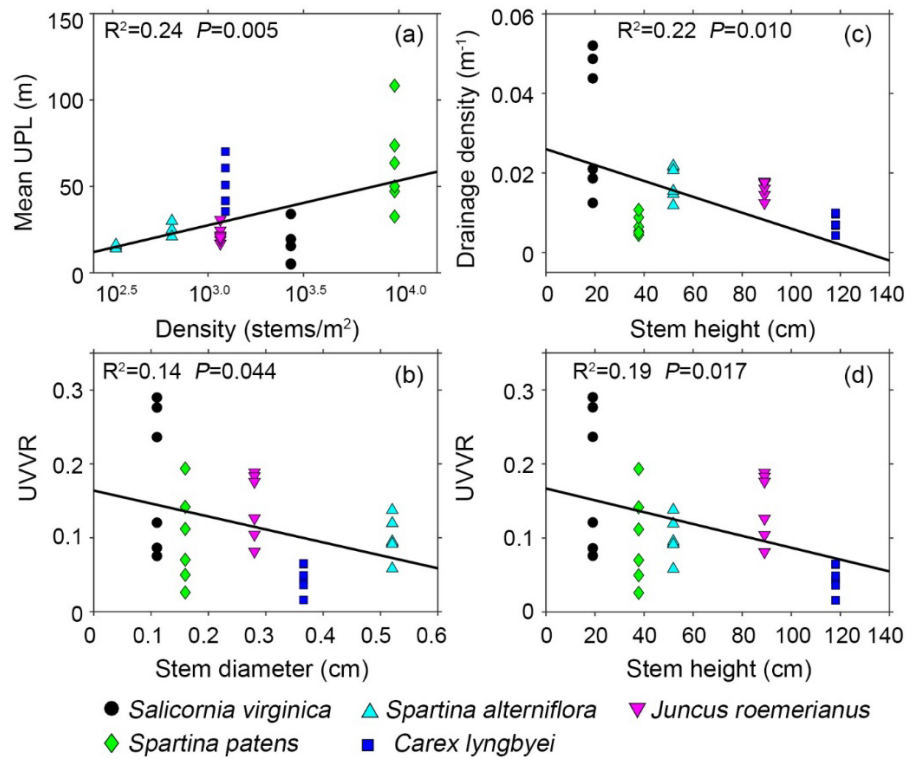


Fig. 5. Channel network properties as a function of vegetation stem density, height and diameter.

In Figure 4, a general linear model with vegetation species as dummy variables confirmed that vegetation species had a significant impact on channel network patterns, as the adjusted R^2 values were higher than the linear model without dummy variables (Fig. 4). This indicates that the linear regression model included vegetation species better explained the variability of geometric properties of tidal channel networks. The abiotic variables measured were correlated with biotic factors (biomass, density, stem diameter, stem height) (Table S6). In particular, tidal range was significantly correlated with stem diameter. Elevation and hydroperiod were strongly correlated with aboveground biomass and stem height (Table S6). Therefore, we suggest that the geometrical

characteristics of the channel network are the result of bio-geomorphic feedbacks between abiotic parameters (tidal range, mean marsh elevation and hydroperiod) and vegetation characteristics (biomass, density, stem diameter, stem height).

Table 1. Logistic regression relationships between channel network properties and drivers. Sign shows sign of regression coefficient, where ‘ $\square$ ’ and ‘ $\square$ ’ indicate that the abiotic and biotic parameters positively or negatively explained the channel properties, respectively. R^2 in bold indicates statistically significant ($p < 0.05$). Hydroperiod, biomass and density were log transformed.

Channel properties	Tidal range		Elevation		Hydroperiod		Biomass		Density		Height		Diameter	
	R^2	Sign	R^2	Sign	R^2	Sign	R^2	Sign	R^2	Sign	R^2	Sign	R^2	Sign
Drainage density	0.239	$\square$	0.304	$\square$	0.149	+	0.208	$\square$	0.020	$\square$	0.216	$\square$	0.056	$\square$
Mean UPL	0.398	$\square$	0.347	$\square$	0.024	$\square$	0.237	$\square$	0.244	$\square$	0.046	$\square$	0.013	$\square$
Sinuosity	0.362	$\square$	0.465	$\square$	0.109	+	0.304	$\square$	0.011	$\square$	0.068	$\square$	0.003	$\square$
UVVR	0.233	$\square$	0.225	$\square$	0.095	+	0.193	$\square$	0.012	$\square$	0.188	$\square$	0.137	$\square$
Geometric efficiency	0.037	$\square$	0.109	$\square$	0.014	+	0.018	$\square$	0.007	$\square$	0.034	$\square$	0.012	$\square$

Predicting Channel Networks Geometry

The above analyses indicate that several factors are controlling the geometric properties of channel networks. We therefore used multivariate stepwise linear regression models to confirm the previous results (Tables 2 and 3). Once again, abiotic parameters appeared to be the best predictors, as mean marsh elevation and tidal range were included as predictors for all geometric properties (Table 2). The multivariate models only explain about 30% of the variability in drainage density and UVVR. In the case of drainage density, this seems driven by three outliers for high values of drainage density (Fig. 6). Here the lack of training data might play a role. In the case of UVVR,

however, our results indicate that other processes are probably at play, for example the marsh sediment budgets, and whether a marsh is eroding or accreting (Ganju et al., 2017). The multivariate models explain about 50% of the variability in sinuosity and more than 60% of the variability in mean UPL (Table 2).

Table 2. Multiple regression models with forward selection for channel network properties.

Channel properties	Model (* = $P < 0.05$, ** = $P < 0.01$, *** = $P < 0.001$)	adjusted R^2
Drainage density	0.031*** – 0.016 elevation**	0.304 (F=12.230, RMSE=0.010, $P=0.002$)
Mean UPL	-209.256* + 5.296 tidal range + 58.584 log(density)* + 0.238 height* + 99.753 diameter*	0.615 (F=12.587, RMSE=14.644, $P < 0.001$)
Sinuosity	2.024*** – 0.47 elevation***	0.465 (F=24.327, RMSE=0.2173, $P < 0.001$)
UVVR	0.234*** – 0.041 tidal range** – 0.001 height*	0.337 (F=8.385, RMSE=0.0577, $P = 0.001$)

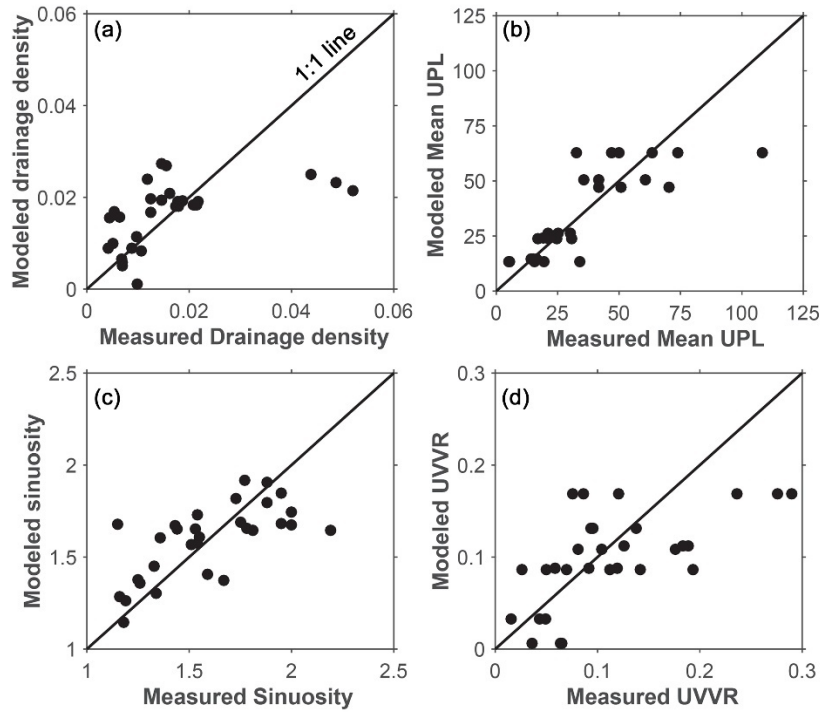


Fig. 6. Comparison between the measured channel network parameters and the corresponding values predicted from the models.

Table 3. Summary of the stepwise multivariate regression models.

Dependent variable	Variables included	Coefficients	t-statistic	p-level	Collinearity Statistics	
					Tolerance	VIF
Drainage density	Intercept	0.031	6.698	<0.001		
	Elevation	-0.016	-3.497	0.002	1.000	1.000
	Intercept	-209.256	-3.537	0.002		
Mean UPL	Tidal range	5.296	0.993	0.330	0.449	2.226
	Density	58.584	3.602	0.001	0.137	7.295
	Height	0.238	2.762	0.011	0.753	1.328
	Diameter	99.753	2.153	0.041	0.154	6.489
Sinuosity	Intercept	2.024	20.980	<0.001		
	Elevation	-0.470	-4.932	<0.001	1.000	1.000
UVVR	Intercept	0.234	7.460	<0.001		

Tidal range	-0.041	-2.921	0.007	0.990	1.010
Height	-0.001	-2.562	0.016	0.990	1.010

Discussion and conclusions

In recent years, the effect of vegetation on channel formation in salt marshes have received particular attention. Recent results suggest that salt marsh plants affect drag and turbulence, promoting channel formation on an initially bare tidal flat (Kearney & Fagherazzi, 2016; Schwarz et al., 2018). Our results indicate instead that the difference in the geometric properties of fully developed tidal networks is mainly driven by physical factors (elevation and tidal range), and only secondary by vegetation parameters (Fig. 4 and 5). Therefore, we suggest that hydrodynamic conditions, sediment availability and marsh elevation might have a strong control on the geometry of the channel network, even within the same region and for homogeneous vegetation covers. For example, Liu et al., (2020) found that drainage density and mean UPL of *Suaeda salsa* marshes vary by a factor of four and eight, respectively, due to different elevations and distances from the fluvial source of sediments. The influence of specific vegetation species seems secondary for the final configuration of the tidal network, but it might be important during marsh evolution and channel development (Fig. 4 and 5).

Abiotic processes affect the geometry of tidal networks

Previous studies suggested that channel network formation occurs more rapidly when the tidal range is high or when the initial basin depth is low (Vandenbruwaene and Temmerman 2012; Van Maanen et al. 2013; Zhou et al., 2014). Our results also found that marsh surface elevation had significant negative correlation with channel drainage density (Table 1). The sites selected here for *S. patens* and *C. lyngbyei* are mesotidal, and the marsh platform is at high elevation with respect

to mean sea level (Fig. 1a and 2a). Such a high platform reduces the tidal prism, and therefore the flux of water flooding the marsh decreases. Reduced tidal fluxes lead to a less developed tidal networks, with lower drainage density, narrower channels, and a smaller unvegetated area (Fig. 3) (O'Brien 1931; Jarrett 1976; Vandenbruwaene et al., 2013). Few long channels are present (higher Hortonian length) because they are not in competition among themselves for drainage area (Scheidegger 1968; Kirchner 1993; Iwasaki et al., 2013). On the contrary, a salt marsh low in the tidal frame, as those dominated by *S. virginica* and *J. roemerianus* in this study (Fig. 2a), have likely a larger tidal prism and higher tidal discharges that scour more channels thus increasing the drainage density and reducing the mean UPL (O'Brien 1931; Jarrett 1976; Vandenbruwaene et al., 2013). These channels are larger, reducing the overall vegetated area (high UVVR) (Fig. 3). Large tidal prism in low-elevated marshes dominated by *S. virginica*, *S. alterniflora* and *J. roemerianus* might increase tidal velocities, which favor the formation of meanders (Peakall et al., 2012, Fig. 3e).

Mesotidal and microtidal marshes are also more susceptible to tidal inundation than macrotidal marshes. Based on field-based observations and numerical models of marsh evolution, Kirwan et al. (2010) found that an increase in inundation depth produces a faster expansion of the channel network in microtidal marshes than in macrotidal marshes. Previous studies also suggest that extensive ponds formation and expansion are more common in low tidal range environments, increasing the UVVR (Redfield, 1972; Kearney et al., 1988; Turner and Rao, 1990). When tidal oscillations are small, even limited meteorological variations in water levels can increase the tidal prim, favoring channel formation. Therefore, it is not surprising to find that *S. patens* and *C. lynbyei* marshes with a large tidal range and high elevation with respect to mean sea level have tidal channel networks with smaller drainage density, higher UPL, and lower sinuosity (Fig. 4).

Biotic processes affect the geometry of tidal networks

While vegetation type seems having a secondary role with respect to physical drivers, it still exerts a control on the geometric characteristics of the tidal channel network. In particular aboveground biomass, which is often used by scientists to characterize vegetation cover in salt marshes (e.g. [Mudd et al. 2004](#); [Mudd et al. 2010](#)), is significantly correlated to all network parameters. Our results found that a salt marsh with higher vegetation biomass has lower drainage density, higher mean UPL, and lower sinuosity and UVVR ([Fig. 4](#)). A thick vegetation cover can in fact prevent erosion and reduce channelization (low drainage density, high mean UPL), the few channels draining the marsh become longer (higher Hortonian length) for lack of competition. Dense vegetation also protects channel banks from erosion, hindering channel migration (low sinuosity) and enlargement (low UVVR).

Numerous studies showed that the flow concentration between vegetated patches is responsible for enhanced erosion. As a result, during marsh formation drainage density increases with denser vegetation ([Temmerman et al., 2007](#)). Our results indicated, however, that vegetation may reduce the overall drainage density of a mature marsh, and biomass has a significant positive correlation with mean UPL ([Fig. 4](#)). A possible explanation of these contrasting results is that vegetation plays different roles during the life of a marsh. In the early stages of development, patches of dense vegetation favor incisions by deflecting water in channels ([Temmerman et al., 2007](#); [Vandenbruwaene et al., 2013](#); [Schwarz et al., 2014](#)). These patches have merged by lateral encroachment when the marsh is mature. The resulting dense, homogeneous vegetation cover reduces sediment mobility, stabilizing the substrate. Thick vegetation would hamper headward erosion and lateral migration of the channels, thus affecting the final geometry of the network

(Coops et al., 1996; Hughes et al., 2009; Silliman et al., 2019).

All these effects are therefore captured by vegetation biomass. When we analyze specific vegetation parameters (stem density, height, and diameter), the relationships become weaker and more confused. For example, vegetation density increases mean UPL, but stem height decreases it (Fig. 5). We therefore conclude that biomass is a more robust predictor of the role of vegetation in wetland hydrodynamics, in line with recent modeling efforts that link hydrodynamic parameters to biomass (Fagherazzi et al. 2012; Fagherazzi et al. 2020).

Biomass and vegetation parameters used here were derived from the literature, and were collected at very few locations, sometime in nearby marshes (Table S2). Very often we had only one value per species, failing to capture differences in vegetation across sites having similar vegetation. We ascribe the weak predictive power of vegetation parameters to the lack of high-resolution data, particularly for stem density, height and diameter. We believe that in the future, when spatially distributed data on vegetation characteristics derived from remote sensing data will be available (e.g. Sun et al. 2018; Fagherazzi et al. 2020), the link between vegetation and the geometry of tidal networks will be fully determined.

In this study, we show that the different marsh networks have a statistically identical geometric efficiency (Fig. 3). In terms of network efficiency, the main difference is therefore whether the surface is vegetated or not, rather than what kind of plants colonizes the platform. The impact of different marsh grasses on hydrodynamics and channel development might therefore be subtle, and detectable only with high resolution data. It would be of interest to compare our results to channels developing in mangroves. Mangrove trees and shrubs are geometrically very different from grasses, and might control the tidal propagation in very different ways (Wolanski et al., 1980;

413 [van Maanen et al., 2015](#)). Future research will shed light on the difference between tidal networks
414 in salt marshes and mangroves.

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Authors' contributions

S.F. developed the research idea and study design. Z.Z.L. collected and analyzed the data. All authors wrote the manuscript and contributed to revisions.

Conflict of Interest

None declared.