

**Efficient tidal channel networks alleviate the die-off of salt marshes:  
implications for coastal restoration and management**

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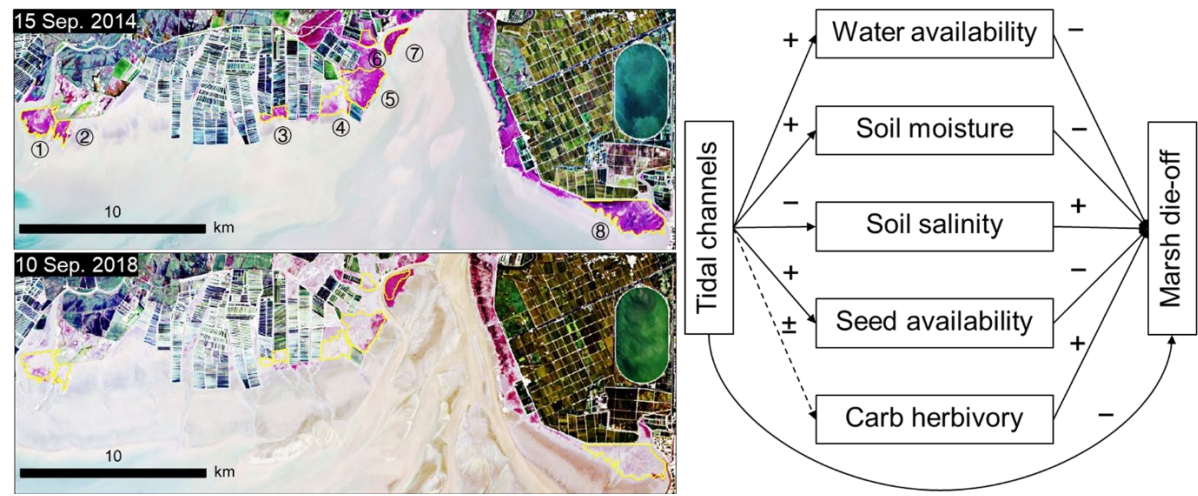
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Graphical abstract



Highlights

- *Suaeda* marshes in the northern Liaodong Bay have experienced large-scale die-off.
- Vegetation along channel networks was less degraded than that in the interior of the marsh.
- Salt marshes with efficient tidal channel networks can mitigate vegetation degradation by droughts.

## Abstract

Massive die-off in salt marshes is one of the most common examples of widespread degradation in marine and coastal ecosystems. In salt marshes, tidal channel networks facilitate the exchange of water, nutrients, sediments and biota with the open marine environments. However, quantitative analyses of the role of channel networks in alleviating vegetation die-off in salt marshes are scarce. Here we quantified the spatial-temporal development of marsh vegetation die-off in the northern Liaodong Bay by analyzing aerial images before, during, and after a drought (from 2014 to 2018). We found that *Suaeda* marshes have recently experienced large-scale die-off. The extent of vegetation die-off increases with increasing distance from the channel network. Moreover, our results suggest that efficient tidal channel networks (high drainage density, low mean unchanneled path length) can mitigate die-off at the watershed scale. We present possible abiotic & biotic processes in channel networks that explain this spatial dynamics. Our study highlights the importance of efficient tidal channel networks in mitigating die-off and enhancing the resilience of marshes to droughts, and call for incorporating these dynamics in coastal restoration and management.

**Keywords:** Coastal wetlands; *Suaeda salsa*; Die-off; Tidal channel networks; Resilience; Drought

## 1. Introduction

Coastal saltmarshes are one of the most valuable coastal ecosystems because of their functions and services, such as protection from storms (Temmerman et al., 2013; Kirwan et al., 2016), carbon storage (Arriola and Cable, 2017), water purification (Negrin et al., 2012), food production (Lynne et al., 1981), education and recreation (Costanza et al., 1997; Barbier et al., 2011). However, they are also one of the most vulnerable ecosystems, because of their high sensitivity to human activities, global climate change, and extreme climatic events, such as droughts and storm surges (Silliman et al., 2009; Deegan et al., 2012; Silliman et al., 2012; Ganju et al., 2017; Fagherazzi et al., 2019). Therefore, degradation of coastal marshes, including vegetation die-off and conversion to open water, is observed worldwide, followed by loss of ecosystem functions (Gedan et al., 2009; Brisson et al., 2014; Ganju et al., 2017; Schepers et al., 2017). To effectively protect and recover coastal marshes, a deep understanding of the resilience of these ecosystems to stresses is necessary (Silliman et al., 2005; Leonardi et al., 2016; Chapple et al., 2017).

Droughts can cause an extensive die-off of coastal plants and are likely to increase due to global warming (Silliman et al., 2005; Alber et al., 2008; Angelini et al., 2016; Watson et al., 2016; Brown, 2017). Severe drought in the salt marshes of the Mississippi Delta triggered a 43,000 ha die-off of *Spartina alterniflora* (McKee et al. 2004; Silliman et al., 2005). Extreme droughts in California significantly reduced plant richness and cover in salt marshes (Copeland et al., 2016), and severely slowed down the recovery of vegetation (Chapple and Dronova 2017). Similarly, wetlands in the Yellow River delta and the Liaohe delta in China are also threatened by extreme droughts (Zhao 2015; He et al., 2017). During a drought, the lack of rainfall reduces freshwater discharge and elevates soil salinity due to persistent evapotranspiration (Dai et al., 2011; Hughes et al., 2012; Chapple and Dronova 2017). These abiotic environmental stresses often act in conjunction with consumer outbreaks to cause a

widespread die-off of coastal plants, resulting in a decline of biodiversity and ecosystem functioning (Silliman et al., 2005; He et al., 2017; Angelini et al., 2018). Because severe droughts can become widespread and more frequent with climate change, it is imperative to identify whether natural ecosystems can mitigate the degradation through their geomorphic structure.

Tidal channels are a key feature of the marsh landscape and play important roles in the transfer of material, such as water, nutrients, sediment, seeds and other cross-boundary subsidies (Fagherazzi et al., 2012; Kearney and Fagherazzi, 2016). There is growing evidence that tidal channels control the distribution and growth of marsh plants (Sanderson et al., 2000; Wu et al., 2020). In general, these studies suggested that tidal creeks affect vegetation by influencing topography, soil water content, soil salinity, soil nutrient levels, and other edaphic conditions (Sanderson et al., 2000; O'Brien and Zedler 2006; Wu et al., 2020). In recent years, the excavation of tidal creek has been regarded as an important approach to restore coastal marshes in Europe (Wolters et al., 2005), North America (Burdick et al., 1996; O'Brien and Zedler 2006), China (Liu et al., 2016), and in many other countries (Smith & Warren, 2012; Flores-Verdugo et al., 2015). Creation or reestablishment of tidal creeks can re-introduce tidal flooding, improve tidal exchange, and help to recover the structure and function of marsh ecosystems (Burdick et al., 1996; Flores-Verdugo et al., 2015). China's largest coastal marsh restoration project (~5, 600 ha) is being carried out in the Liaohe Delta. The excavation of tidal creeks is the main approach to recover *Suaeda* marshes (The People's Government of Liaoning Province, 2017). Therefore, quantification of the relations between the efficiency of channel networks and the health of *Suaeda* marshes is urgently needed to provide practical guidance for coastal restoration projects.

The northern Liaodong Bay in China experienced the second-worst drought on record in 2015 (Zhao 2015). However, detailed quantitative studies of the vegetation die-off patterns

caused by the drought and their relation to the tidal channel network are largely lacking. In this study, we quantified the spatio-temporal development of vegetation die-off by analyzing aerial images before, during and after the drought (from 2014 to 2018). We examined whether the die-off patterns were consistent in different drainage basins. We put forward the hypothesis that the efficiency of the tidal channel network is the key determining factor explaining the spatial die-off pattern. Moreover, we examined whether effective tidal channel networks can enhance the resilience of marshes to drought at the watershed scale. Finally, we explain possible processes acting in channel networks that mitigate the degradation and highlight the important implications for coastal restoration and management.

## 2. Materials and methods

### 2.1 Study area

Our study area is located in the northern Liaodong Bay of Northeast China, near the mouth of the Daling and Liaohe rivers (also known as Shuangtaizi river, [Fig. 1](#)). The study area has a temperate semi-humid monsoon climate, with an annual average temperature of 8.4°C and annual precipitation and evaporation of 623 mm and 1669 mm, respectively ([Ye et al., 2015](#); [Liu et al., 2018](#)). Rainfall is uneven, with 62.9% of it occurring between May and September. Evaporation can be more than ten times higher than precipitation in spring ([Lang et al., 2012](#); [Li et al., 2014](#)). In 2015, the study area experienced the second-worst drought on record, with a nearly 70% reduction in rainfall in June and July ([Zhao 2015](#)). This region has an irregular and semidiurnal tide, with an average tidal range of 2.7 m ([Zhu et al., 2010](#)). The coastal area of the Liaohe estuary is a tide-dominated estuary ([He et al., 2018](#)). The average rates of elevation change and vertical accretion in the *Suaeda* marshes in the Liaohe estuary are 5.8-6.3 mm yr<sup>-1</sup> and 13.6-14.8 mm yr<sup>-1</sup>, respectively, which suggest that *Suaeda* marshes could keep pace and gain elevation with respect to the local rate of sea level rise (2.4–5.5 mm yr<sup>-1</sup>).

(Wang et al., 2016). Dominant plant species in the intertidal zones of the study area include *Suaeda salsa* and *Phragmites australis* (Jia et al., 2015). In our study, we selected eight areas dominated by the annual non-clonal halophyte *S. salsa* (Fig 1), which experienced a dieback during the drought of 2015, converting the marsh to a bare flat. Only one plant species, *S. salsa*, is present in all study areas, except for *P. australis* encroaching into *S. salsa* community in area 7 after 2016. However, this *P. australis* population is scattered and very small in areal extent (Fig S3). To our knowledge, all study areas we selected were almost free of human interference (e.g. new reclamation project, mowing) from 2014 to 2018.

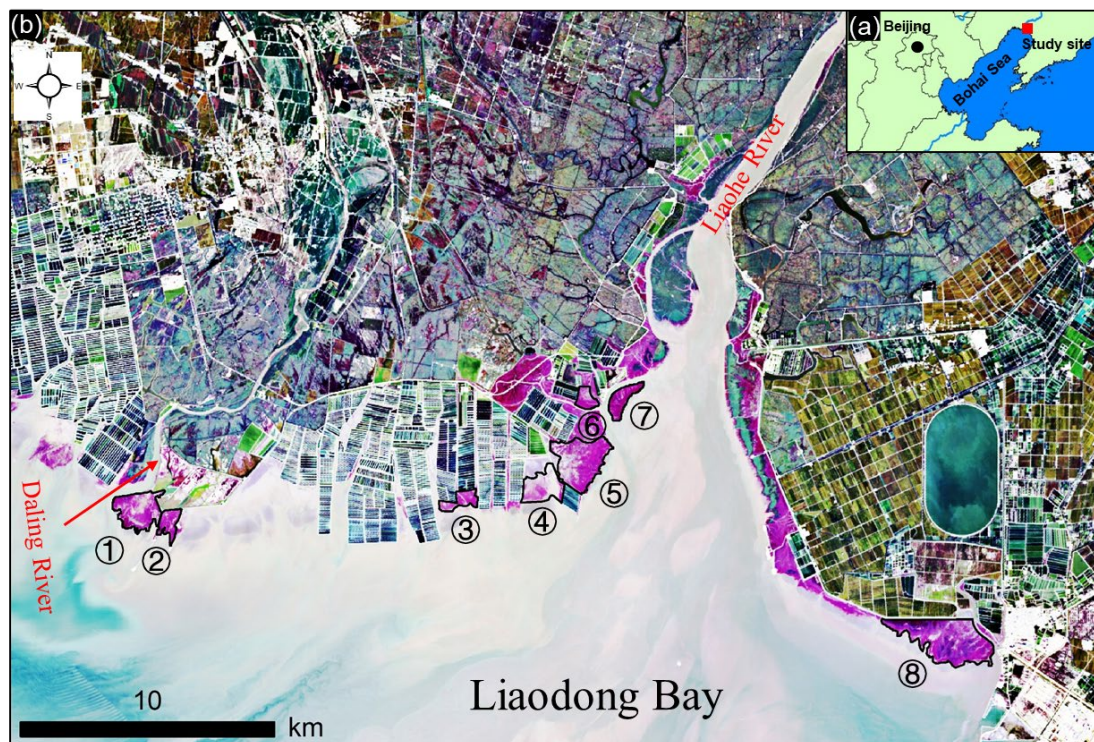


Figure. 1. Map of the study area and selected marshes in the northern Liaodong Bay, China. (a) location of the Liaodong Bay in China. (b) true color remote sensing images on September 15, 2014. The encircled numbers (1–8) represent the areas used in the spatial image analyses.

## 2.2 Die-off measurement

To estimate the extent of marsh die-off, we used Landsat 8 imagery to identify the vegetated

and bare flat surface in our study areas between 2014 and 2018. The images were retrieved on 15 Sep. 2014, 2 Sep. 2015, 20 Sep. 2016, 23 Sep. 2017 and 10 Sep. 2018. All the Landsat 8 Operational Land Imager (OLI) imageries (downloaded from the USGS Earth Explorer Database) were taken at low tide on clear, cloud-free days in the fall (September). All standard corrections (e.g. radiation correction, atmospheric correction and geometric correction) were processed with ENVI 5.3 image processing software. Then, we extracted *S. salsa* areas from true color remote sensing images through visual interpretation, because *Suaeda* areas and bare flat areas are easy to distinguish. For a more detailed study of plant growth performance, we calculated nine vegetation indexes in each pixel of the images (Table S1). Based on the linear regression between *Suaeda*'s aboveground biomass measured in the field (Fig S1) and the corresponding vegetation indices collected at the same time, we found that the Ratio Vegetation Index (RVI) and the Normalized Difference Vegetation Index (NDVI) are the best indicators of vegetation biomass (Fig S2). NDVI is the most common index for vegetation detection in remote sensing, therefore, we used NDVI to represent the growth performance of *Suaeda*. We defined the change rate of NDVI in 2018 as  $(NDVI_{2018}-NDVI_{2014})/NDVI_{2014}$ .

### 2.3 Channel network geometry

To calculate the geometric properties of the channel network, we manually extracted the tidal channels from Google Earth imagery taken in 2018, based on visual interpretation (Vandenbruwaene et al., 2013; Kearney and Fagherazzi, 2016). We down-sampled all images to 1.0 m pixel resolution, and neglected those parts of the channel networks with channel width less than 1m (Fig S4). Then, we calculated the Drainage density ( $D$ , the ratio of channelized network length to the watershed area) and Hortonian length ( $I_h$ , the inverse of drainage density) of each study area. To evaluate the effectiveness of tidal channels in each pixel ( $1m \times 1m$ ), we also calculated the shortest distance from any marsh platform point to a marsh edge or to a

channel bank using the Euclidean Distance tool in ArcGIS 10.2. We calculated the distance to marsh seaward edge (*De*) as the shortest distance from any marsh platform point to the marsh seaward edge, and unchanneled path length (UPL) as the distance from any marsh platform point to the nearest channel or marsh seaward edge (Marani et al., 2003).

## 2.4 Relations between die-off and channel network

To determine the relationship between vegetation die-off and geometry of tidal channels for each pixel, we down-sampled Landsat 8 imagery to 1.0 m resolution to match the resolution of the channel networks images. Therefore, each pixel ( $1\text{m} \times 1\text{m}$ ) in our study area has four values: vegetation present or absent, NDVI change rate, *De* and UPL. We divided the distances (*De* and UPL) in 5 m bins and calculated within each bin the proportion of plant die-off and NDVI change rate. Then we plotted the distances (*De* and UPL) against the corresponding die-off fraction and NDVI change rate. To determine the relationship between the efficiency of channel networks and marsh resilience to drought at the watershed scale, we plotted the average distances (*De* and UPL) against the corresponding average values of die-off fraction and NDVI change rate in each studied watershed. A logistic regression method was applied to examine the potential relationship between vegetation die-off and the efficiency of the channel network. We performed all data analyses with the MATLAB R2016b software.

## 3. Results

### 3.1 Temporal evolution of vegetation die-off

Our remote-sensing analysis revealed dramatic die-off of *Suaeda* marshes following the 2015 drought, except for area 7 (Fig. 2). The extent of vegetation die-off increased in the 3 years following the drought (2016-2018), except for study area 7 and study area 5 in 2017. The degree of degradation in areas 3, 4 and 8 is the most serious, followed by areas 2, 5, 1, 6 and 7.

Up to 90% of *Suaeda* marshes were lost and converted to bare flats in area 4 and 8 in 2018, and the mean NDVI in both areas dropped below 0.2. Study area 7 displayed a mild degradation in 2015, but quickly recovered in the following year. The NDVI of area 7 after the drought is higher than the value before the drought, probably due to *Phragmites australis* encroachment (Fig S3), which has been reported in many studies (Lu et al., 2018; Cui et al., 2019). In area 7, *P. australis* has expanded into *Suaeda salsa* communities after 2016, but its population is scattered and with a small spatial footprint.

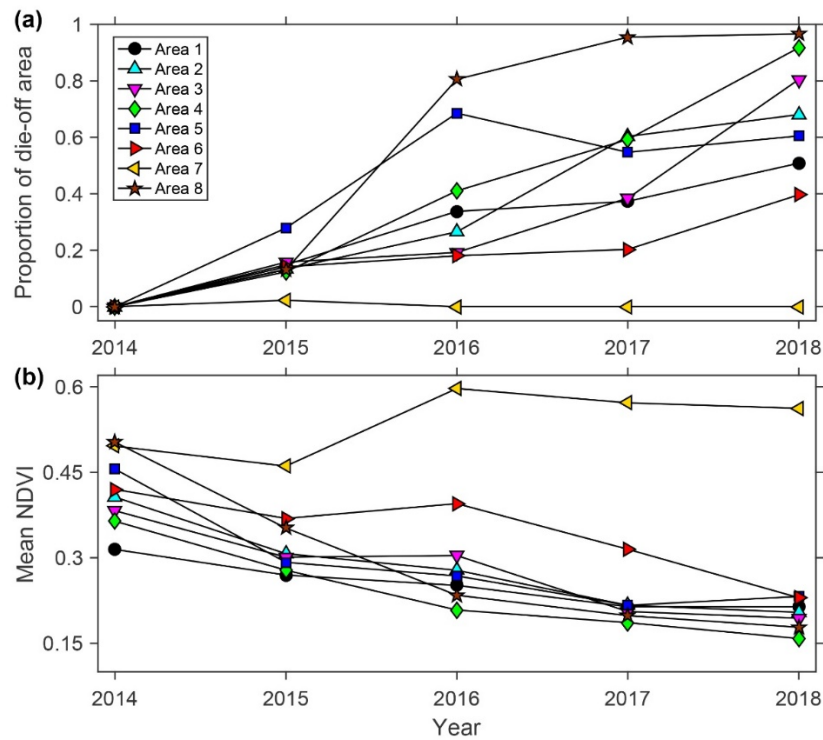


Figure. 2. Proportion of vegetation die-off area (a) and mean NDVI change (b) before, during and after the 2015 drought.

### 3.2 Tidal channel networks properties

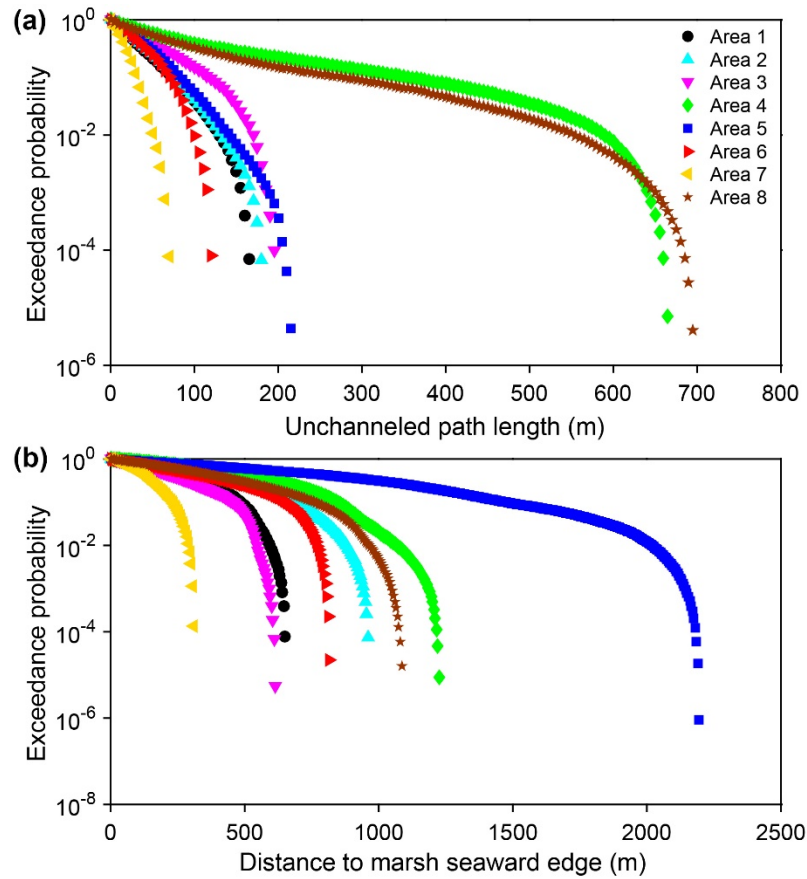
The values of the relevant network parameters for each study area are given in Table 1. The drainage density ( $D$ ) of area 7 ( $0.0188 \text{ m}^{-1}$ ) is the highest, nearly four times that of area 4 ( $0.0048 \text{ m}^{-1}$ ) and area 8 ( $0.0046 \text{ m}^{-1}$ ). This corresponds to a Hortonian length ( $l_h$ ) of 53.21 m,

207.54 m and 218.62 m for area 7, 4 and 8, respectively. The drainage density ( $D$ ) of area 3, 5 and 6 is similar, nearly half of that of area 7. The drainage density ( $D$ ) of area 1 and 2 is slightly higher than that of area 3, 5 and 6. On the contrary, the mean unchanneled path length (UPL) of area 7 (14.33 m) is only one-eighth of that of area 4 (109.95 m) and area 8 (103.12 m). UPL of area 1, 2, 5 and 6 are similar, nearly a third of that of area 8. The mean distance to the marsh seaward edge ( $De$ ) of area 5 (742.23 m) is the highest, nearly twice that of area 2, 6 and area 8. The mean distance to marsh seaward edge ( $De$ ) of area 1 (243.78 m) and 3 (218.38 m) is similar, nearly a third of that of area 5. The mean distance to marsh seaward edge ( $De$ ) of area 7 is the lowest. The probability distribution of unchanneled path lengths and distance to marsh seaward edge show similar patterns of the corresponding mean values (Fig 3). Based on drainage density, the order of efficiency of channel networks is area 7 > area 1 > area 2 > area 6 > area 5 > area 3 > area 4 > area 8. Based on mean UPL, however, the order of efficiency of channel networks is area 7 > area 1 > area 6 > area 2 > area 5 > area 3 > area 8 > area 4.

Table 1. Channel network properties.

| Sites  | Marsh<br>area (ha) | Channel<br>area (ha) | Total channel<br>length (m) | $D$ (m <sup>-1</sup> ) | $I_h$ (m) | Mean UPL (m)<br>(Max) | Mean $De$ (m)<br>(Max) |
|--------|--------------------|----------------------|-----------------------------|------------------------|-----------|-----------------------|------------------------|
| Area 1 | 218.66             | 8.70                 | 24082                       | 0.0110                 | 90.80     | 31.51 (167.59)        | 243.78 (653.39)        |
| Area 2 | 72.70              | 2.03                 | 7238                        | 0.0099                 | 100.44    | 34.61 (184.00)        | 333.66 (962.75)        |
| Area 3 | 71.46              | 2.12                 | 5555                        | 0.0078                 | 128.64    | 48.55 (199.62)        | 218.38 (616.33)        |
| Area 4 | 156.83             | 3.85                 | 7555                        | 0.0048                 | 207.54    | 109.95 (666.91)       | 455.18 (1228.03)       |
| Area 5 | 325.14             | 15.07                | 26252                       | 0.0081                 | 123.85    | 37.71 (216.62)        | 742.23 (2195.90)       |
| Area 6 | 54.91              | 1.98                 | 4615                        | 0.0084                 | 118.98    | 32.32 (121.43)        | 323.10 (816.81)        |
| Area 7 | 89.92              | 6.05                 | 16899                       | 0.0188                 | 53.21     | 14.33 (73.24)         | 113.07 (312.16)        |
| Area 8 | 495.97             | 13.07                | 22686                       | 0.0046                 | 218.62    | 103.12 (697.60)       | 364.99 (1089.99)       |

220  $D$ : Drainage density;  $I_h$ : Hortonian length; UPL: Unchanneled path length;  $De$ : Distance to  
 221 marsh seaward edge  
 222



223  
 224 Figure. 3. Semi-log plots of the exceedance probability versus unchanneled path length (a)  
 225 and distance to marsh seaward edge (b) for each study areas. Note the data are binned in  
 226 intervals of 5 m.

### 228 3.3 Relations between vegetation die-off and the efficiency of channel networks

229 Excluding area 7, our results show that the proportion of marsh die-off area increases with  
 230 increasing UPL. A 100% die-off is reached in study area 2, 3, 4, 5 and 8 at a certain distance  
 231 from the channels (Fig. 4a). Similarly, there is a decrease in the change rate of NDVI of *Suaeda*  
 232 marshes with increasing UPL (Fig. 4c). The change rate of NDVI in area 1 and 2 first increases  
 233 near the channels and then decreases with higher UPL (Fig. 4c). The relationship between die-

off area, change rate of NDVI and distance to marsh seaward edge is more complex, due to the presence of tidal channels dissecting the marsh (Fig. 4b, d). Except for area 7, the die-off area reaches 100% at a large distance from the marsh edge (Fig. 4b). Near the marsh edge, the change rate of NDVI is higher (Fig. 4d) and the fraction of area affected by die-off is zero in 5, 6 and 7 (Fig. 4b).

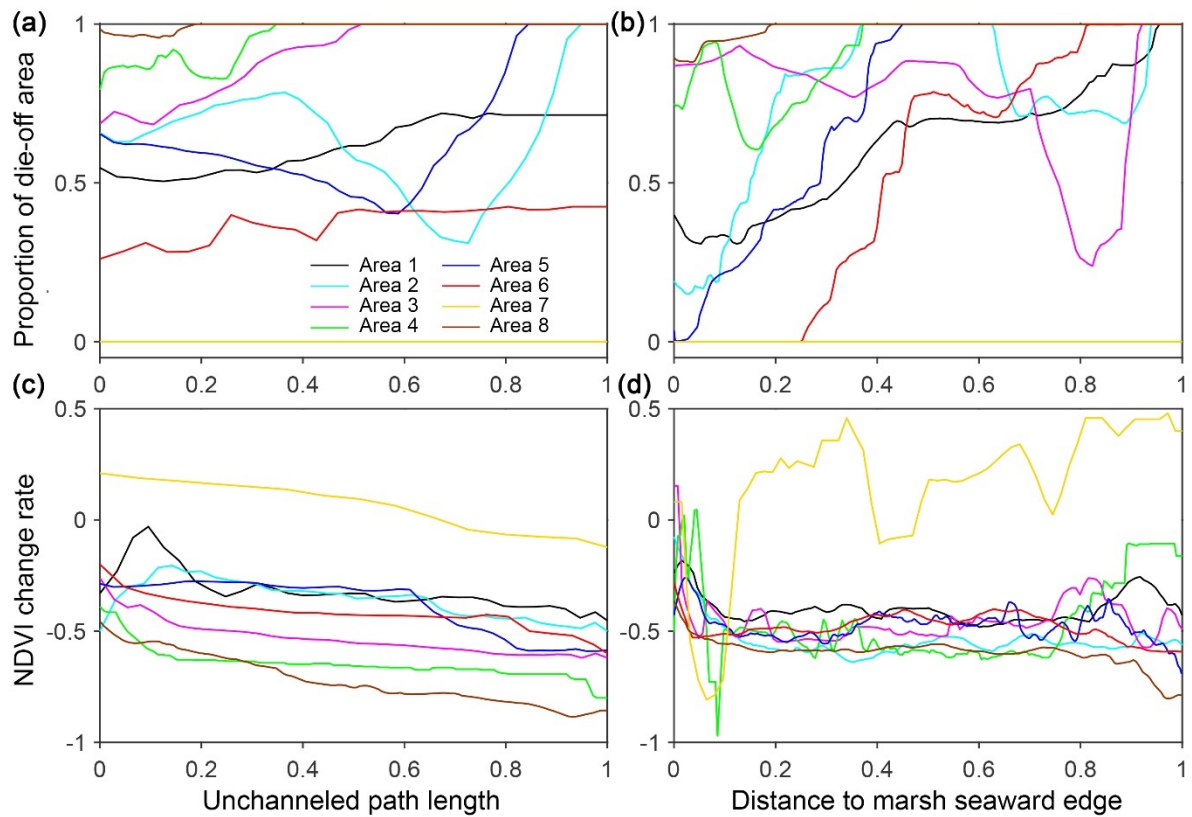


Figure. 4. NDVI change rate and fraction of pixels with die-off as a function of distance to channel networks and marsh seaward edge. Note the data are binned in intervals of 5 m for unchanneled path length and distance to marsh seaward edge. Unchanneled path length and distance to marsh seaward edge are normalized to 0-1 range.

At the watershed scale, die-off area and NDVI change rate significantly increase with increasing drainage density (Fig. 5a, d), and significantly decrease with increasing mean UPL (Fig. 5b, e). NDVI change rate significantly decreases with increasing mean  $De$  (Fig. 5f), but

the relationship between proportion of die-off area and mean  $De$  is not significant (Fig. 5c).

Therefore, our results suggest that efficient tidal channel networks (high drainage density, low UPL) at the watershed scale can mitigate die-off.

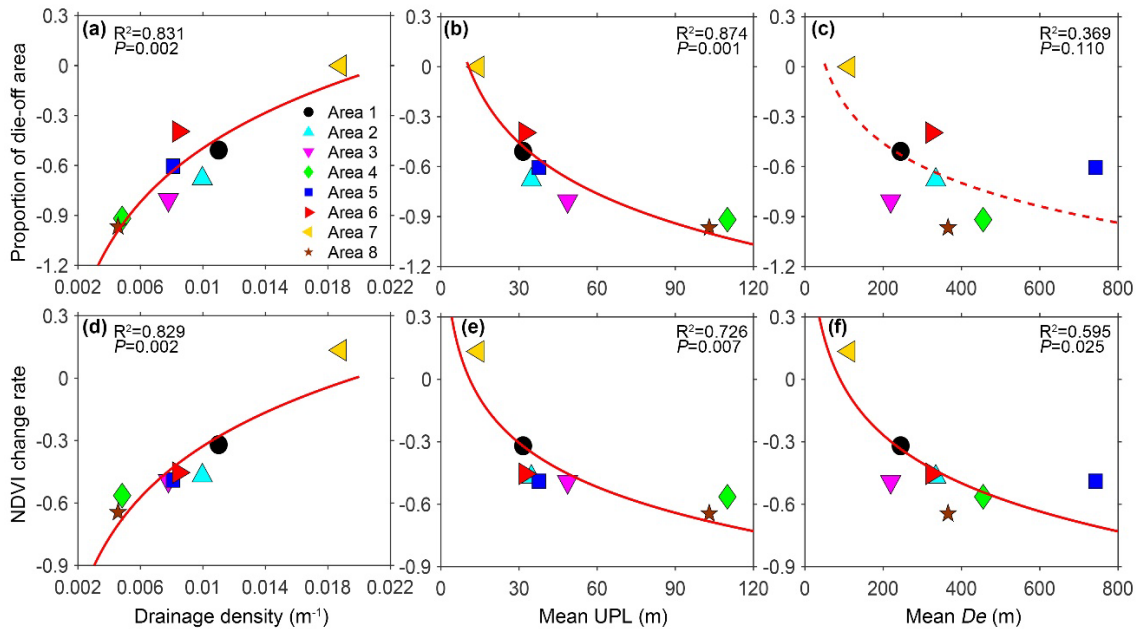


Figure. 5. Watershed-scale relationships between area fraction with die-off, NDVI change rate and channel network parameters. Area fraction with die-off as a function of drainage density (a), mean unchanneled path length (b) and mean distance to marsh seaward edge (c). NDVI change rate as a function of drainage density (d), mean unchanneled path length (e) and mean distance to marsh seaward edge (f).

## 4. Discussion

### 4.1. Spatial-temporal patterns of vegetation die-off

Our results show that *Suaeda* marshes in the northern Liaodong Bay have experienced large-scale die-off (Fig 2), which is consistent with previous studies in other marshes (Silliman et al., 2005; Alber et al., 2008; Angelini et al., 2016; Watson et al., 2016; He et al., 2017). Moreover, vegetation die-offs were more and more serious in the following years after the drought, except

for study area 7 (Fig 2). The die-back of *Suaeda* marshes could be attributed to plant life-history traits of *Suaeda salsa* and grazing by native crabs (Song et al., 2011; He et al., 2017; Brown 2017; Lu et al., 2018). *S. salsa* is an annual non-clonal halophytic grass, it germinates in April and May, then flowers in July and August, followed by seed dispersal in late fall (He et al., 2015; Zhou et al., 2017). The 2015 drought occurred during the flowering season and affected seeds production. In addition, grazing by the native herbivorous crab *Helice tientsinensis* also limited the recovery of *Suaeda* (He et al., 2017). Our results thus suggest that an extreme drought can trigger a dieback in *Suaeda* marshes. After the dieback, it is difficult for the vegetation to recover to pre-drought conditions.

It is therefore crucial to improve the resistance of *Suaeda* marshes to extreme events. To this end, we need to quantify the relations between the resilience of *Suaeda* marshes and the efficiency of channel networks both at the local and watershed scales. These relations are critical for the restoration and management of these valuable coastal ecosystems and help understanding the ecological processes driving wetland degradation. Our results revealed two key insights: 1) vegetation along tidal creeks and shorelines was less degraded than that in the interior of the marsh (Fig 4); 2) at the watershed scale, the extent of vegetation die-off depends upon the efficiency of the network of tidal channels (Fig 5). At the pixel scale, *Suaeda* marshes appear to be stable at short distances from tidal channels and marsh edge, and the extent of vegetation die-off increases with increasing UPL and *De* (Fig 4), which are consistent with previous studies in the Chesapeake Bay (Schepers et al., 2017), and in the Mississippi Delta (Morton et al., 2003). At the watershed scale, our results suggest that *Suaeda* marshes with higher drainage density and lower mean UPL have higher resilience to drought. The distance from the seaward marsh edge exert a weaker control on vegetation resilience (Fig 5), likely because the flooding of the marsh is controlled by the tidal channels in the marsh interior.

To our knowledge, this is the first time that the relationships between the properties of the

channel network and marsh resilience at the watershed scale has been quantified. Our results highlight that the presence of tidal channels is an indispensable factor in evaluating the resilience of coastal ecosystems, so that the structure and function of the channel network should be accounted for in projects of coastal restoration and management.

#### 4.2. How does the channel network alleviate the die-off of salt marshes?

Tidal channels can alleviate abiotic environmental stresses, thus explaining the spatial pattern of vegetation die-off. Numerous studies suggested that soil moisture and salinity stress are the most crucial factors influencing *Suaeda* survival and growth (He et al., 2009; Song et al., 2011); the same factors are also important in other coastal marshes around the world (Adams et al., 1995; Pennings and Bertness, 1999; Snedden et al., 2015). In the absence of tidal channels, flooding frequency generally decreases with increasing elevation toward the inland, and salinity reaches a peak in the high marsh; soil moisture also decreases moving landward (Pennings et al., 1999; Wang et al. 2007; He et al. 2009). Tidal channels dissect marshes, bringing water to the inside of the marsh, thus changing gradients in soil salinity and moisture. Several previous studies have shown that soil salinity declines, and soil moisture increases near tidal channels, which could be directly attributed to an increase in flooding frequency and duration due to water spilling out from the creek (Morzaria-Luna et al., 2004; O'Brien and Zedler 2006; Wang et al., 2009; Flores-Verdugo et al., 2015). Moreover, tidal channels may also promote deposition, and provide nutrients to the marsh surface (Brown and Bledsoe 1996; Wang et al., 2009; Fagherazzi et al., 2012), which influence plant growth performance.

The recolonization of *Suaeda*, an annual non-clonal species, is highly dependent upon seed availability (Erfanzadeh et al., 2010). Tidal channels play a critical role in redistributing and transporting plant seeds (Chang et al. 2007; Shi et al., 2019); Some studies showed that the

extensive network of tidal channels allows for flow to suspend and deposit seeds throughout the marsh. Areas farther away from tidal channels are less likely to receive seed inputs because of low flooding frequency or interception by vegetation (Morzaria-Luna and Zedler, 2007; Hopfensperger et al., 2009; Smith & Warren, 2012). In addition, field studies suggest that a variety of herbivores, including snow geese, insects, snails, and crabs can also influence vegetation survival and growth (Silliman et al., 2005; He et al., 2017; Angelini et al., 2018). The native herbivorous crab *Helice tientsinensis* suppresses the growth of *Suaeda* in our study area (He et al., 2017). Some evidence suggested that tidal channels can create heterogeneous habitats and influence the distribution of crabs (Ge et al., 2005; Wang et al., 2009). Locations farther from tidal channels are more suitable for mature crabs (high herbivory strength), while juvenile crabs (weak herbivory strength) live near tidal channels, because this habitat provides sufficient water and organic matter for their early development (Mense and Wenner, 1989, Lerberg et al., 2000; Wang et al., 2009). Therefore, the distribution of crabs caused by tidal channels may also explain the spatial pattern of vegetation die-off.

At the watershed scale, differences in the degree of degradation could also be attributed to the distance from the mouth of rivers. Area 6 and 7 closer to the Liaohe river mouth and area 1 closer to the Daling river mouth were less degraded (Fig. 5a), while area 4 and 8 far from the river mouth experienced a severe degradation (Fig 5). The salinity of surface water in the estuaries of this region increases with increasing distance from river mouths (Mao et al., 2008; Liu et al., 2011; Qing et al., 2013), which is consistent with previous research in the Swan River Estuary, Australia (Hourston et al., 2009), and the Mersey Estuary, UK (Martino et al., 2002). Reduction in salinity and an increase of freshwater availability can enhance *Suaeda* survival and growth (Wang et al., 2011; He et al., 2017).

#### 4.3 Implications for coastal restoration and management

Our study has important implications for the restoration and management of coastal wetlands. Our results suggest that tidal channels play an important role in enhancing marsh resilience. Unfortunately, numerous studies indicate that land reclamation projects profoundly influence the morphology and evolution of tidal channel systems around the world (Xie et al., 2009; MacDonald et al., 2010; Zhang et al., 2013). Therefore, managers should try to preserve the natural tidal channels in future reclamation activities.

Our results also show that habitats far from channels and the marsh edge are not suitable for vegetation recovery due to harsh abiotic stresses and the unavailability of seeds. Therefore, managers and coastal engineers should pay more attention to these habitats, by artificially seeding, planting seedlings, or by creating a microtopography that promotes a reduction in salinity and an increase in soil moisture (O'Brien and Zedler 2006; Wang et al., 2018). In recent years, artificial addition of tidal creeks has been regarded as an important approach to restore coastal marshes (O'Brien and Zedler 2006; Liu et al., 2016). Based on our results, the effects of drainage density and distance from tidal channels on vegetation health should be taken into account in future restoration practices. Managers and engineers should design efficient tidal channel networks to ensure the success of restoration projects.

## 5. Conclusion

We found that an extreme drought triggers a dieback in *Suaeda* marshes with specific spatial patterns. The extent of vegetation die-off increases with increasing distance from tidal channels. At the watershed scale, efficient channel networks (high drainage density, low mean UPL) can mitigate die-off and enhance the resilience of the marsh to drought. Tidal channels can alleviate abiotic environmental stresses (enhancing soil moisture, decreasing salinity), improve the availability of seeds and regulate the interactions between plants and herbivores, thus explaining the observed pattern of dieback. Hence, our study highlights the importance of

efficient tidal channel networks in enhancing the resilience of marshes to drought, and call for incorporating tidal network geometry in coastal restoration and management.

### **Authors' contributions**

Ze Zheng Liu, Sergio Fagherazzi, and Baoshan Cui conceived and designed this study. Ze Zheng Liu, Xiaojun She, Xu Ma and Chengjie Xie analyzed the data. Ze Zheng Liu, Sergio Fagherazzi and Baoshan Cui wrote the original draft. All authors significantly contributed to the final manuscript.

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