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## Biophysical self-organization of coastal wetlands

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## Summary

### ***Biophysical self-organization of coastal wetlands Unraveling spatial complexity on tidal flats and marshes, from the Precambrian to today***

While flood risks along the world's densely populated coastlines are predicted to increase strongly over the next century due to sea level rise, increased storminess and land subsidence, scientists and policy makers across the globe are seeking for sustainable methods to protect coastal communities. Located on the interface between land and sea, coastal wetlands could serve this purpose. In addition to being highly biodiverse ecosystems and carbon sinks, many types of wetlands, such as tidal flats and marshes, provide natural flood defense. These landscapes are typically dissected by channel networks, which form the main transport conduits within the wetland; they govern the transport of water, sediment, organisms, etc. As such, the development and response of wetlands to, e.g., sea level rise are largely determined by the spatial structure of the channel network. Network geometry varies greatly between wetlands, from spatially "simple" parallel channels to highly "complex" branching networks. During Earth's geological history, as earlier studies have shown, biological processes have strongly affected landscape complexity: while most channelized sedimentary landscapes were spatially simple in the Precambrian (more than half a billion years ago), prior to the evolution of physiologically complex lifeforms, such landscapes became increasingly complex over the course of millions of years, simultaneously with the evolution of vegetation. In present-day ecosystems, as other studies demonstrate, interactions between biological (sediment stabilization by algae and plants) and physical processes (sediment- and hydrodynamics) are a widely accepted mechanism behind the spontaneous formation of spatially simple, regular patterns, through the process of self-organization. However, whether similar self-organization processes can also explain more complex wetland patterns remains less well studied. In this thesis, I therefore aim to understand the spatial complexity of coastal wetlands, focusing on channel patterns on tidal flats and marshes, from the Precambrian to present-day.

As a first step, in **Chapter 2** I study the spatially simple channel patterns that can be observed on tidal flats. The investigated pattern consists of regularly spaced, parallel channels, bordered by elevated sedimentary ridges that are colonized by primitive (i.e., physiologically simple) filamentous algae (*Vaucheria sp.*). Regular spatial patterns in ecosystems are typically explained by self-organization, wherein localized feedbacks cause an initially disordered landscape to organize into a regular pattern. I conduct remote sensing measurements, which reveal that the channel pattern is indeed spatially regular and has emerged from an initially irregular configuration. I perform laboratory and field measurements to test the hypothesis that the observed pattern is

formed by scale-dependent feedbacks, i.e. a short-range feedback with positive effect (algal-induced sediment stabilization leads to ridge formation; algal growth is facilitated on top of these ridges) and a long-range feedback with negative effect (water flow is deflected around the ridges into the channels, there decreasing algal growth conditions and hence further increasing channel incision). Remote sensing data and sediment cores reveal that the algal pattern has persisted for several years, giving rise to internally laminated ridge sediments. These observations are strikingly similar to the layered microbialites (microbially shaped sedimentary rocks) that are abundant in fossil records dating back to the Precambrian. This implies that spatial self-organization has been an important landscape-shaping process throughout the geological history of Earth, dating back to some of the first fossil ecosystems.

However, many coastal wetlands are characterized by more complex channel networks than the regular channel patterns studied in Chapter 2. In **Chapter 3**, I therefore investigate whether the same scale-dependent feedback processes could also explain the formation of such complex patterns. I develop an idealized mathematical model accounting for the coupled hydro-, sedimentary- and vegetation dynamics in a simplified coastal wetland system. My model results, supported by field observations, reveal that one scale-dependent feedback can generate patterns ranging from spatially simple to highly complex. Once a primary, large-scale regular pattern is formed, new water flow paths are induced by the sedimentary topography of this pattern, triggering the same scale-dependent feedback again, thereby forming a secondary, finer-scale regular pattern that is nested within the primary pattern. In turn, the topography of the secondary pattern can give rise to the formation of a third-order pattern, nested within the second-order pattern, and so on. Ultimately this feedback recursion can form channel networks with strong similarities to the networks in real-world wetlands. A stronger vegetation-induced scale-dependent feedback leads to a more complex channel landscape, with higher drainage and sediment accretion efficiency and improved vegetation growth conditions. Hence, this study highlights the impact of spatial complexity on coastal ecosystem functioning and the important role of biota therein.

In **Chapter 4**, I study the effects of primitive sediment-stabilizing organisms, in particular the filamentous algae *Vaucheria* from Chapter 2, under controlled laboratory settings, to experimentally support the hypothesis (formulated in Chapter 2 on the basis of field measurements) that these algae can induce a scale-dependent feedback. My experimental results show that i) the growth of *Vaucheria* is facilitated on elevated sedimentary topography, ii) the binding force of algal filaments strengthens the sediment, and iii) an increase in sediment strength leads to an increase in relative sediment elevation, hence closing the positive feedback loop. Since increased sediment stability and elevation is theoretically expected to lead to a reduction of the mechanical perturbations and inundation stress felt by pioneer ecosystem species, my findings imply that simple biota like *Vaucheria* could “widen”

the Window of Opportunity for ecosystem establishment on tidal flats. This biological viewpoint goes beyond the typical view on Windows of Opportunity as being mainly physically (e.g., meteorologically) driven.

In **Chapter 5**, I further explore the notion that Windows of Opportunity for ecosystem establishment on tidal flats could be mediated by primitive biota, like *Vaucheria*. I use remote sensing data to show that, under the same elevation range (i.e. inundation conditions), tidal flats can either be i) topographically flat, without clear drainage channels and without pronounced algal or vegetation cover, or ii) characterized by drainage channels delineated by *Vaucheria*-covered ridges (as those in Chapter 2). In-situ measurements reveal that the density of pioneer vegetation is significantly higher on these algal-covered ridges than on tidal flat areas without clear sedimentary topography or algal cover. This supports the expectation raised in Chapter 4 that the biophysical feedbacks induced by *Vaucheria* could facilitate the establishment of vegetated ecosystems. I then use the mathematical model developed in Chapter 3, but reparametrized to represent *Vaucheria*, to show that *Vaucheria*-induced scale-dependent feedbacks can indeed explain the observed channel patterns. Both the observed and simulated patterns change morphology from flat to simple to complex as growth conditions improve (tidal flat elevation increases). The model predicts that, due to the strong algal-induced feedbacks, alternative stable states can co-exist under the same growth conditions, as my field observations also suggest. Moreover, the algal patterns can be used as indicators to reveal whether the ecosystem is developing towards favorable or unfavorable growth conditions, and when a degraded ecosystem (i.e. bare tidal flat) is in an elevation range where state transitions towards a restored ecosystem (algal patterns) would be possible. This knowledge can be highly valuable for wetland restoration purposes.

Collectively, the findings in my thesis highlight the importance of biophysical self-organization in the development of coastal wetlands, thereby focusing on channel networks on tidal flats and marshes. I orient my findings according to a temporal axis (geological evolution, from the Precambrian to the present) and a spatial axis (ranging from simple single-scaled to complex multi-scaled spatial patterns). Firstly, I show that even primitive biota, such as algal mats, can have a long-lasting (multi-year) impact on tidal flat development and that simple organisms may have shaped sedimentary landscapes through self-organization over hundreds of millions of years. Furthermore, my research shows that a wide range of spatial pattern morphologies, both single- and multi-scale, can be understood from a single feedback principle. Whereas self-organization theory classically assumes that small-scale processes collectively lead to larger-scale order, my findings reveal that it is necessary to study the opposite process as well, i.e. pattern refinement starting from a larger-scale “background” pattern, in order to understand the formation of complex spatial patterns. This new perspective, in combination with the idealized modelling techniques developed here, might be readily applicable to study complex patterns in various other (eco)systems. Finally, my

findings can be valuable for wetland restoration efforts that are being undertaken around the globe. My research indicates that primitive algae can actively improve the growth conditions for more complex vegetation species. The growth of these pioneer algae can be relatively easily triggered by creating artificial ridges and channels. Moreover, creating a spatially complex channel pattern can improve wetland drainage, hence increase sediment compaction and thus sediment strength, which will further facilitate ecosystem establishment. Once established, algal patterns can be used as indicators to guide wetland restoration, ultimately creating a sustainable and nature-based form of coastal protection.