The ephemeral life of a salt marsh

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Salt marshes are disappearing around the world at an alarming rate. A common tenet of marsh vulnerability is that, for elevated rates of sea level rise, accretion of the marsh platform is unable to keep pace with sea level leading to marsh drowning (Reed, 1995; Morris et al., 2002). Recent research indicate that salt marshes are relatively stable along the vertical direction if enough sediment is available (Kirwan et al., 2010), whereas they are inherently unstable along the horizontal direction (Mariotti and Fagherazzi, 2010). Physical and ecological feedbacks promote sediment deposition and below-ground organic production when marsh flooding increases, thus facilitating marsh accretion and counteracting sea-level rise (Morris et al., 2002; see Fagherazzi et al., 2012, for a review). On the contrary, lateral erosion by wave attack is exacerbated by sea-level rise, because wave energy increases if bays and tidal flats deepen (Mariotti et al., 2010). The only mechanism that can counteract lateral erosion is seaward marsh expansion driven by deposition of large amounts of sediment in sheltered areas as, for instance, beyond barrier islands or promontories (Mariotti and Fagherazzi, 2010). A marsh could also expand landward after flooding of land regions, but this expansion is often impossible due to the presence of human settlements and infrastructure along the coastline (Doody, 2004). Here I only focus on the migration of the marsh/sea boundary, while the marsh/land boundary deserves a separate, broader discussion.

The lack of feedback between the processes responsible for lateral erosion and those leading to marsh expansion suggests that the marsh/sea boundary is seldom in equilibrium, and the marsh is always either expanding or contracting (Fagherazzi et al., 2013).

The results of Gunnell et al. (2013, p. 859 in this issue of *Geology*) are extremely important because they indicate that the lateral expansion of a marsh can be a very fast process, up to several meters per year, when terrigenous sediments are available. I advocate that the lack of horizontal equilibrium and the fast time scale of migration of marsh boundaries make salt marshes ephemeral landforms at the geological time scale. Marshes are constantly reworked by coastal processes within a few thousand years, in a rejuvenation process.

To place the results of Gunnell et al. in a broader context, and to estimate the typical geological lifecycle of a salt marsh, I have compiled rates of marsh erosion and expansion from around the world, together with the horizontal dimensions of the marsh at the same locations. I define the saltmarsh lifecycle as the ratio between marsh extension and the rate at which the marsh is destroyed or built (Fig. 1). Surprisingly, the average lifecycle of a marsh is of the order of few thousand years, with very few locations having enough marsh area to survive common horizontal erosion rates of the order of 1 m/yr for more than 5000 yr.Even large salt marshes, for instance those present along the Mississippi Delta (United States), can be degraded in a relatively short time.

On average, marsh expansion is much faster than marsh erosion (a time scale of hundreds of years compared to a time scale of thousands of years; see Fig. 1). This is because large areas of tidal flat can become emergent and vegetated in a short time, as indicated by Gunnell et al., if sediments are available. Erosion of a marsh boundary by wave action is instead a slow process, usually on the order of 1 m/yr or less.

The geological lifecycle is estimated using current rates of marsh erosion and expansion, but these rates might have been different in the past under lower rates of sea-level rise. However, marsh extension is faster when sea level is not rising, and a sensitivity analysis of wave energy at

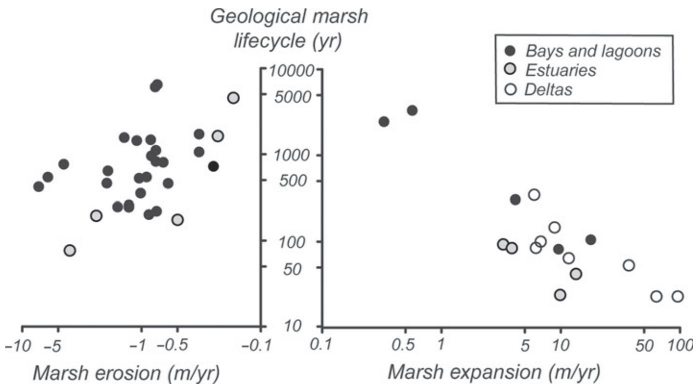

Figure 1. Geological marsh lifecycle as a function of lateral erosion or expansion rate. The marsh lifecycle is defined as the ratio between total marsh extension and the erosion/expansion rate. The highest expansion rates are measured in deltas. On average, marsh erosion is slower than marsh expansion, so that the time scale for marsh expansion is smaller (hundreds of years) than that of marsh erosion (thousands of years). (Data from Schwimmer, 2001; Wilson and Allison, 2008; Mattheus et al., 2010; Marani et al., 2011; Cox et al., 2003; Gunnell et al., 2013; Redfield, 1965; Oertel and Overman, 2004; Hood, 2006; GoogleEarth™).

marsh boundaries shows that a sea-level rise of 30 cm increases potential erosion by only 50% (Mariotti et al., 2010), so that the order of magnitude of marsh boundary retreat is likely to remain the same. An estimated lifecycle on the order of thousands of years is therefore plausible even in absence of sea-level rise.

The highest expansion rates are measured in deltaic environments, and the lowest in coastal bays and lagoons, whereas estuaries have intermediate values (Fig. 1). This observation reflects the availability of sediment, which is highest in land-building deltas. Erosion rates are instead independent of marsh location, although marshes in estuaries have a shorter lifecycle given their smaller dimensions.

The short geological lifecycle offers a novel explanation for the limited evidence of basal peats older than 6000 yr in salt marshes (Engelhart and Horton, 2012; Rampino and Sanders, 1981). The ephemeral nature of a salt marsh at the geological time scale indicates that these landforms are continuously recycled, destroyed, and reformed in a very dynamic coastal environment. The organic carbon sequestered in the peat is thus released in the ocean and new, younger organic material is subsequently stored in the sediments when the marsh reforms. This explanation is alternative to the common hypothesis that marshes formed only in the last 9000 yr, when relative rates of sea-level rise were slower (Rampino and Sanders, 1981). Such cycles of marsh erosion and extension were already postulated by Van de Koppel et al. (2005), and excellent examples are presented by Pringle (1995) in Morecambe Bay, UK, and by Cox et al. (2003) in the Westerschelde Estuary, Netherlands.

The correct quantification of rates of lateral erosion or expansion is critical for the determination of the fate of salt marshes. Sea-level rise is only one component of the equation; what it is really important is the sediment budget between a salt marsh and the surrounding coastline (Fagherazzi et al., 2013). Based on a sediment budget approach, Mariotti and

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Fagherazzi (2013) determined a critical horizontal dimension of tidal flats above which the erosion of bordering salt marshes is irreversible. This is because the presence of larger and deeper tidal flats increases wave energy, which promotes marsh erosion and a further enlargement of the tidal flats. On the contrary, if the bordering tidal flats are too small and enough sediment is available in the water column, marsh expansion offsets erosion, further reducing tidal flat extension and related wave energy. Interestingly, this model predicts marsh collapse even in absence of sea-level rise, if the erosive processes become dominant and sediment supply is limited.

Another important finding of Gunnell et al. is, that salt marsh formation is driven by sustained physical deposition, while vegetation encroachment on the newly established platform occurs at the end of the formation process. This result is in agreement with the model of Fagherazzi et al. (2006, 2007), which indicates that the key mechanism for salt marsh formation is the attainment of a critical depth of tidal flat bottoms above which wave erosion is hindered. Once this depth is reached, the tidal flat is free to shoal and become emergent, morphing into a salt marsh. As documented by the results of Gunnell et al., the onset of persistent sedimentation occurs at low elevations and prior to vegetation colonization, indicating that vegetation is not the main cause of shoaling. Therefore high sedimentation rates promoted by sediment availability in sheltered areas are responsible for marsh formation, while vegetation encroachment is important only in the last phase of marsh emergence.

This result has important consequences for restoration projects of coastal wetlands based on river diversion. Several researchers advocate the reintroduction of the Mississippi sediment discharge in bays and sounds of the Mississippi Delta in order to build new marshland and mitigate the current erosive trend (Nittrouer et al., 2012; Edmonds, 2012). The results of Gunnell et al. indicate that this strategy is viable only if sediments are discharged in sheltered areas where currents and waves are limited, and enhanced deposition is possible. The presence of healthy halophytic vegetation has only a secondary effect on marsh formation, and is important only at the final stages of formation. These results clearly show the dominance of sedimentological processes on ecological processes, something neglected by scientists and coastal managers.

To conclude, salt marshes are ephemeral landforms from a geological perspective, with a very short lifecycle. The typical size of a salt marsh does not exceed a few kilometers, and measured erosion/extension rates can destroy/build this landform in a few thousands of years or less. Compared to the history of Earth, a salt marsh resembles a gorgeous butterfly. After emerging from the cocoon, it extends its wings under the morning sun, rises in the sky during the day, and when the night falls, it folds its wings and dies.

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