Salt marsh response to changing hydrodynamics: the case of Ancão inlet migration (Ria Formosa coastal lagoon)

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Abstract: Given the high economic and ecological value of salt marshes, it is important to improve our knowledge on the physical processes and main sedimentary sources controlling their evolution. This study analyses the morphological feedbacks of a salt marsh to varying hydrodynamics due to inlet migration. The studied salt marsh patch is located near the Ancão Inlet, in the Ria Formosa barrier system. A 67-year dataset of aerial photographs was used to assess salt marsh sedimentary evolution. The results focused on the analysis of horizontal displacements of the salt marsh and tidal flat morphologies over time. Inlet migration stages and the related distance to the inlet throat were identified as a critical factor for the progression/recession of the morphologies. As the salt marsh generally grew, the tidal flat receded, and more intensely after inlet relocation. Results showed an interlinked evolution of tidal flat and marsh, with the former providing a sedimentary boost to the development of the later.

Key words: inlet migration, marsh evolution, ria Formosa, sedimentary sources.

1. INTRODUCTION

Tidal marshes are among the most productive ecosystems, providing key services, such as shoreline protection, water quality improvement, provision of fish habitat (Gedan *et al.*, 2009), and carbon sequestration (McLeod *et al.*, 2011). Marshes have persisted for thousands of years, despite being naturally dynamic, expanding and contracting in extent and in response to changes in river flow and tidal dynamics (Redfield, 1972). Their spatial-temporal variability results from the influence of abiotic (e.g. soil capping, type of groundcover, salinity, flood depth) and biotic (e.g. canopy cover, plant age and type, grazing) factors (Bhattacharjee *et al.*, 2009; Morris *et al.*, 2002); in some cases, these alterations are induced by human activities (Day *et al.*, 2008). Regarding the economic and ecological importance of salt marshes, it is extremely important to improve our knowledge on the physical processes that control marsh evolution, as well as the limits and degree of interaction with surrounding sedimentary sources. Two specific goals are addressed in this study: (a) to determine the influence of the Ancão Inlet natural migration stages and human relocation to the surrounding salt marsh development over the last 67 years; and (b) to determine how the diverse sand contributors (e.g., tidal flat and flood delta), present in the lagoon system, interact and influence the salt marsh development.

2. METHODS

2.1. Study Area

Ria Formosa coastal lagoon, located in the Algarve region, in the southern coast of Portugal, is protected by a multi-inlet barrier chain, presently composed of five islands and two peninsulas separated by six tidal inlets. Due to its triangular shape, Ria Formosa develops along two different flanks in terms of wave exposure (Costa *et al*, 2001). The western flank, where the study area (Ancão Peninsula and Barreta Island) is located, is more energetic, being under the direct influence of the dominant wave conditions (Vila-Concejo *et al.*, 2004).

The studied salt marsh area is located north from the Ancão Peninsula and the Ancão Inlet (Fig. 1). This inlet presents a progressive easterly migration cycle, as result of the dominant alongshore sediment transport from west to east (Pilkey *et al.*, 1989), and an ebb-dominated behavior (Salles, 2001; Vila-Concejo *et al.*, 2004). Each migration cycle starts with a new inlet opening in a western position and migrating eastwards with a mean rate of about 67 m/yr (Dias *et al.*, 2009).

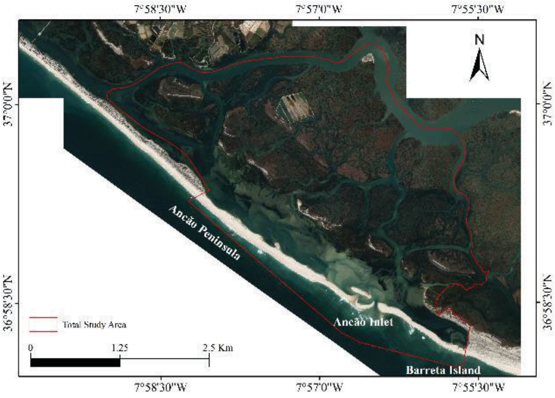

Fig. 1. Aerial view (2014) of the study area, where the red polygon delimits the Salt Marsh patches relevant to the study.

2.2. Morphological analysis

This work is based on the analysis of aerial images, used to determine the horizontal spatial evolution of the salt marsh and morphologies around it, that may, or may not, have influenced its evolution. The analysis focuses on an average long-term approach (years to decades) of the changes that occurred over 67 years (1947-2014). The available data include aerial photographs and orthophotographs, with a total of 11 rasters available for this period. The entire process, from scanning and georeferencing to mapping and analysis is described in Amado (2019).

Seven different morphologies (vegetated and non-vegetated), present in the study area, were mapped as: Salt Marsh (SM), Marsh Detached Beach (MDB), Fish Farming (FF), Tidal Flat (TF), Sand Banks (SB), Flood Delta (FD), and Barrier (Fig. 2). The remaining area (fixed in time), after subtracting all previous morphologies, was characterized as Secondary Channels and Others (SCO; Fig. 2). Computed areas were used to calculate correlations between morphologies and horizontal displacements between consecutive mappings. The results presented are mostly focused on the SM and TF dynamics.

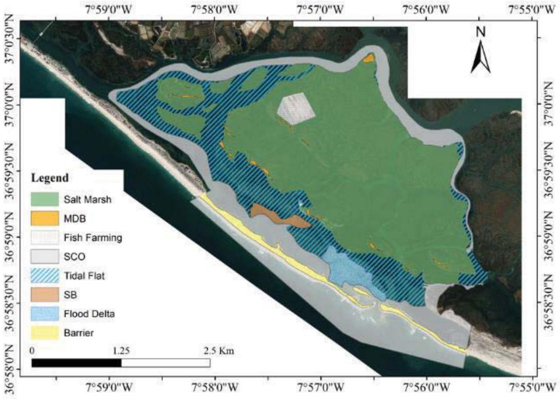

Fig. 2. Representation of the different morphologies present in the study area: SM, MDB, FF, SCO, TF, SB, FD, and Barrier.

Landcover transitions occurring between 1947 and 2014 were validated by using the Markov chain analysis method, presented in Gonzalez *et al.* (2005). Shoreline rate-of-change statistics for the SM and TF boundaries were calculated from multiple shoreline positions during the study period, using the DSAS tool (Thieler *et al.*, 2009). This technique was also used to calculate short-term rates of SM and TF changes near the Ancão Inlet, that were associated with the inlet migration phases. This data was also compared with inlet tidal prisms obtained by Popesso *et al.* (2016), to identify the existence (or absence) of correlation between them.

3. RESULTS AND DISCUSSION

With exception of SM and TF, the morphologies show a loss in total area during the 67 years of analysis (**Error! Reference source not found.**). SM and TF exhibited an increase of 2.23×10^5 m^2 and 8.14×10^5 m^2, respectively (**Error! Reference source not found.**a). The overall marsh evolution (**Error! Reference source not found.**a) shows two different episodes of variation (Amado, 2019): (a) a decrease of 2 % between 1958 and 1989; and (b) an increase of 3 %, relative to its initial area, between 1996 and 2001. The most variable SM patch was located fronting the Ancão Inlet. Regarding the TF area (**Error! Reference source not found.**a), overall growth is noted over the years (1.4×10^4 m^2/yr: $R^2 = 0.7$). This increase in the TF can be strongly associated with the decrease in sedimentary deposits (FD and SB; **Error! Reference source not found.**b).

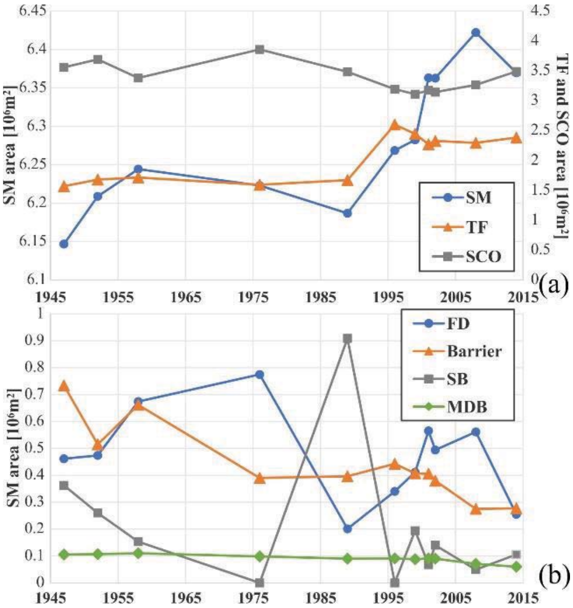

Fig. 3. Evolution of mapped morphologies (in 10^6 m^2) between 1947 and 2014: (a) SM (reference to left axis), TF and SCO (reference to right axis) and (b) FD, Barrier, SB and MDB.

A total of 532 land-cover changes were observed along the 10 time staps between 1947 and 2014; but only 175 are statistically important (Amado, 2019). From these 175 transitions, only 2 land-cover changes are found to be highly significant (p-value>0.05) throughout the analyzed period: TF to SM, SCO to Barrier. Between 1947 and 2014 the morphologies that keep most of their original area are SM and SCO, maintaining 94 % and 75 %, respectively (Table I). Transitions of other morphologies to SM do not seem very significant, as only 6 % of its final area has originated from other morphologies, with TF being the most significant (corresponding to 4 %). SM indirectly benefits by the conditions that lead to the TF development and needs the TF to develop, as stated by Cunha *et al.* (2005), Marbà *et al.* (1994) and Schanz and Asmus (2003). For the TF, the biggest transition occurred from SCO (23 %), FD (14 %) and SB (13 %; Table I).

Concerning horizontal change rates (Fig. 4), namely the progression/recession of the morphology boundary, the greater part of the SM boundary shows a general negative trend (erosion), although boundary progression was also present. The regions that showed higher progression are located along the South limit of the SM, with maximum values of approximately 4 m/yr (Amado, 2019). The TF boundary shows similar pattern, with higher recession rates along the northern and stronger boundary progression the southern one. However, unlike the SM, the TF shows a much wider region and higher values of progression in its southern region (about 8 m/yr), which can be related to the existence of deltaic deposits (Amado, 2019).

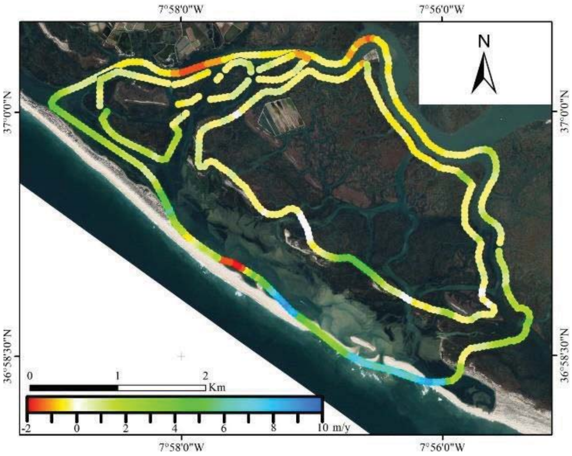

Fig. 4. Horizontal rates (in m/yr) for the SM (inner dots) and TF (outer dots) boundaries.

Table I. Percentages of morphology shifts between 1947 and 2014 (e.g. 63 % of SCO in 1947 transformed to FD in 2014). Values filled in grey represent the preserved area of each morphology, and dark green the transitions above 50 %.

		2014						
		FD	**SM**	**Barrier**	**SB**	**MDB**	**TF**	**SCO**
1947	**FD**	0%	1%	0%	62%	0%	14%	1%
	SM	0%	94%	0%	0%	0%	3%	3%
	Barrier	29%	0%	33%	0%	24%	1%	15%
	SB	0%	0%	0%	0%	0%	13%	1%
	MDB	0%	1%	0%	0%	58%	0%	0%
	TF	8%	4%	0%	0%	18%	46%	5%
	SCO	63%	0%	68%	38%	0%	23%	75%
		100%	100%	100%	100%	100%	100%	100%

Peak TF area is observed when the Ancão Inlet is in its easternmost position, in its phase of closure. This could be related to the presence of old sediment deposits and calmer hydrodynamic conditions, that can favor seagrass development, or it can be related to underestimation TF during mapping (SB could be overlying TF features). Decreases in the TF area can be connected to the formation of new sedimentary deposits over this morphology (due to the passage of the Ancão Inlet during its migration) or to the impacts of dredging, as proposed by Cunha *et al.* (2005). This work showed that the proximity of the inlet to the seagrass patches has a negative impact on their size, corroborating the obtained results and confirming the inlet's influence on this morphology. As shown before (Table I), changes in TF area are eventually translated to changes in the SM area.

Comparing the SM and TF areas variability with the data from Popesso *et al.* (2016), it was possible to associate periods of morphological change with intervals of inlet stability/instability; at the initial 2 phases of the inlet migration, when the inlet is under unstable (a; morphological adaptation) or equilibrium 1 (b; capturing prism and migrating) conditions, there is a positive impact on the SM area, but a negative impact on the TF. The opposite takes place during the final 2 stages of migration, when the inlet is in equilibrium 2 (c; migrating without capturing prism) or critical (d; toward closure/infilling) phase. Thus, the beginning of an inlet migration cycle (phases a and b Popesso *et al.* (2016)) will lead to TF erosion. Afterwards the TF will, likely, start accreting on the second half of the Ancão Inlet cycle (phases c and d Popesso *et al.* (2016)). The SM will have the opposite behavior. This, and the positive correlation of these morphologies, can indicate that there is a delay in SM development compared to the TF. After the inlet has started a new cycle, SM is expected to start gaining area, once the TF has had time to restore.

Based on the aforementioned and on the land-cover change results (Table I), it was possible to create a conceptual scheme (Fig. 5) with the significant land-cover interactions between morphologies for the study period (1947-2014). It is noteworthy the sequence of interactions FD → SB → TF → SM, reinforces the idea that the Ancão Inlet triggers SM development. The formation of FD by the Ancão Inlet starts a sequence of transitions that, in the long-term, will lead to SM development. Other interesting interactions are the highly significant connection of SM and TF with MDB. Despite the strong correlation between SM and TF, only the transition of TF to SM is a significant land-cover change, while the growth of the TF is mostly due to other morphologies (FD and SD).

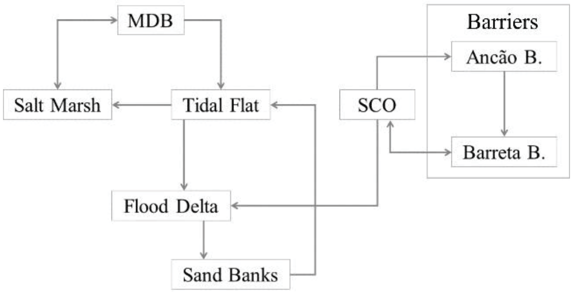

Fig. 5. Conceptual scheme, representing significant morphology land-cover changes for the entire study period (1947-2014).

4. CONCLUSIONS

The long-term analysis of SM dynamics in the west part of the Ria Formosa lagoon, showed that TF was the most relevant sediment contributor for SM development, providing 4 % of the SM total area, by 2014. The results showed that SM indirectly depends on the same drivers and forces that lead to TF development. Both morphologies are strongly influenced by the Ancão Inlet migration, with the observed progression/recession of the morphology boundaries highly related to the hydrodynamics of the inlet migration cycle. Further research, supported by field data, is needed to fully understand the complex relationships between these morphologies. However, the results presented provide a clear indication of the interconnections and dominant long-term dynamics.

Acknowledgments

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