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Biologically-controlled multiple equilibria of tidal landforms and the fate of the Venice lagoon

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[1] Looking across a tidal landscape, can one foresee the signs of impending shifts among different geomorphological structures? This is a question of paramount importance considering the ecological, cultural and socio-economic relevance of tidal environments and their worldwide decline. In this Letter we argue affirmatively by introducing a model of the coupled tidal physical and biological processes. Multiple equilibria, and transitions among them, appear in the evolutionary dynamics of tidal landforms. Vegetation type, disturbances of the benthic biofilm, sediment availability and marine transgressions or regressions drive the bio-geomorphic evolution of the system. Our approach provides general quantitative routes to model the fate of tidal landforms, which we illustrate in the case of the Venice lagoon (Italy), for which a large body of empirical observations exists spanning at least five centuries. Such observations are reproduced by the model, which also predicts that salt marshes in the Venice lagoon may not survive climatic changes in the next century if IPCC's scenarios of high relative sea level rise occur. **Citation:** Marani, M., A. D'Alpaos, S. Lanzoni, L. Carniello, and A. Rinaldo (2007), Biologically-controlled multiple equilibria of tidal landforms and the fate of the Venice lagoon, *Geophys. Res. Lett.*, *34*, L11402, doi:10.1029/2007GL030178.

1. Introduction

[2] Lagoons and estuaries host typical tidal ecosystems and landforms. They are sites characterized by extremely high biodiversity and rates of primary productivity and host important socio-economic activities worldwide, such that their ecosystem services are acknowledged as fundamental [e.g., *Mitsch and Gosselink*, 2000; *Cronk and Fennessy*, 2001]. The ecological and morphological components of the embedded transition zones between marine and terrestrial ecosystems are dynamically coupled by complex interactions between intertidal vegetation [*Cronk and Fennessy*, 2001; *Silvestri et al.*, 2005; *Marani et al.*, 2006a, 2006b], benthic microbial assemblages [e.g., *Paterson*, 1989], erosion and deposition processes [*Allen*, 1990; *Day et al.*, 1999; *D'Alpaos et al.*, 2005; *Fagherazzi et al.*, 2006; *D'Alpaos et al.*, 2007], hydrodynamics [e.g., *Rinaldo et al.*, 1999a, 1999b; *Fagherazzi et al.*, 1999; *Marani et al.*, 2004], eustatism and/or relative sea-level change [*Allen*, 1990]. However, our understanding of the coupled eco-geomorphic evolution of tidal systems is still very limited and has so far evolved within separate disciplines, like e.g., those concerned with the morphological evolution of tidal flats, marshes and channels [*Allen*, 1990; *D'Alpaos et al.*, 2005; *Fagherazzi et al.*, 2006] or with specific compartments of tidal ecosystems, such as halophytic vegetation or microphytobenthos [e.g., *Paterson*, 1989; *Mitsch and Gosselink*, 2000; *Cronk and Fennessy*, 2001]. Indeed eco-geomorphological modelling of intertidal areas is in its infancy [*D'Alpaos et al.*, 2007; *Kirwan and Murray*, 2007] and we still lack a comprehensive and predictive theory of the joint evolution of tidal landforms and biota. Here we introduce a fully coupled conceptual eco-geomorphic model for the elevation of a tidal platform regularly inundated by the tide and possibly colonized by benthic assemblages and intertidal vegetation. This approach allows the study of system equilibria as jointly determined by physical and biological processes.

2. Model Structure

[3] The time evolution of the spatially-averaged elevation of a tidal platform, $z(t)$ (computed with respect to the local mean sea level), is described by mass balance:

$$\frac{dz}{dt} = Q_S(z,B) + Q_T(z,B) + Q_O(B) - E[z,B,MPB(z)] - R \quad (1)$$

B is the annually-averaged above-ground halophytic vegetation biomass. $MPB(z)$ indicates the functional dependence on microphytobenthos, controlled by elevation. R is the rate of relative sea level (RSL) change, i.e. sea level variations plus local subsidence. $Q_S(z,B) = 1/T \int_T C(z,B,t) w_s/\rho_s dt$ is the average sediment settling flux over a tidal cycle, with period T, chiefly depending on the instantaneous sediment concentration, $C(z, B, t)$, in turn determined by a sediment balance equation for the water column forced by the average sediment concentration, C_0, resulting from past re-suspension events and possible (e.g., fluvial) sediment inputs [*Krone*, 1987] (see the auxiliary material[1] for details). w_s is the settling velocity, ρ_s is the sediment density. $Q_T(z,B) = 1/T \int_T C(z,B,t) \alpha B^\beta/\rho_s dt$, is the average over a tidal cycle of the deposition rate due to trapping of suspended sediment by the canopy (α and β are parameters accounting for vegetation and flow characteristics [*Mudd et al.*, 2004]). $Q_O(B) = \gamma B$ is the production of organic soil due to vegetation (combining above- and below-ground biomass production) [*Randerson*, 1979]. $E(z, B, MPB) = 1/\rho_s \ \nu \ \overline{(\tau - \tau_c)}/\tau_c$ is

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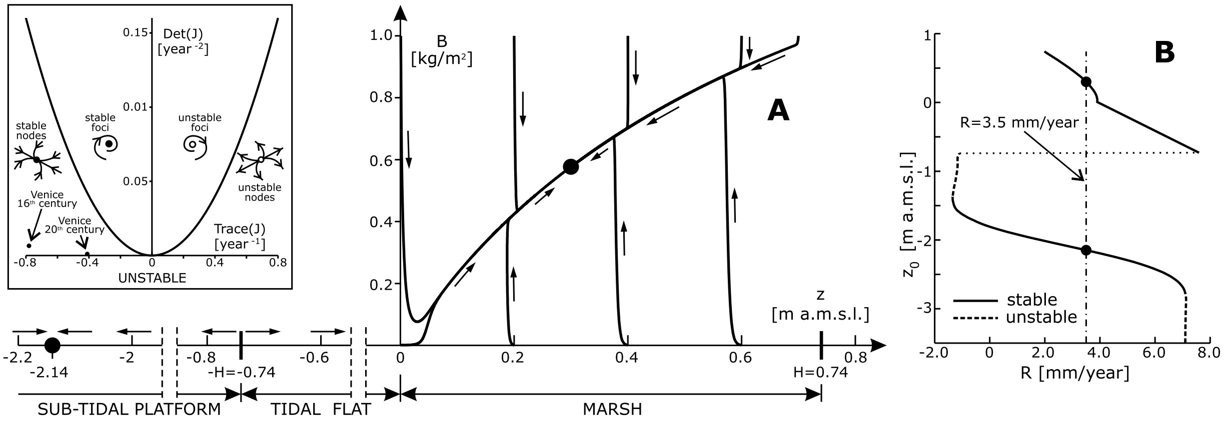

Figure 1. (a) Phase portrait of the dynamics of a Venice-like tidal system in the 20th-century scenario. (inset) The determinant and the trace of the Jacobian of the system of equations (1) and (2) determine the nature of the equilibrium states. (b) Bifurcation diagram showing the ranges of R for which stable and/or unstable states exist. The dash-dot line indicates the best-estimate R = 3.5 mm/year for the Venice lagoon in the 20th century.

the tidally-averaged erosion rate due to wind-induced waves. The erosion rate depends, through the erosion coefficient ν, on sediment characteristics, an effective bottom shear stress τ (a complex function of water depth, wind velocity, fetch [*Carniello et al.*, 2005], and vegetation presence, which efficiently dissipates wind waves [*Möller et al.*, 1999]), and a threshold shear stress for erosion, τ_c, strongly dependent on stabilizing polymeric biofilms produced by benthic microbes [e.g., *Paterson*, 1989; *Amos et al.*, 1998]. Because microphytobenthos growth is light-limited, we assume a sharp increase in erosion thresholds when the platform elevation yields sufficient incoming solar irradiance for microbial photosynthetic activity to occur [*MacIntyre et al.*, 1996] (see the auxiliary material for details).

[4] Vegetation dynamics is described through a logistic model [*Levins*, 1969], which expresses biomass as the product of vegetation fractional cover, p, and the carrying capacity of the system, d (maximum biomass per unit area), i.e., $B = p\ d$. Rates of biomass change are given by:

$$\frac{dB}{dt} = \frac{r(z)B}{d}(d - B) - m(z)B \qquad (2)$$

$r(z)$ and $m(z)$ are elevation-dependent reproduction and mortality rates, respectively, reflecting the physiological responses of halophytic species to the controlling environmental conditions, chiefly soil water saturation, locally surrogated by elevation [*Silvestri et al.*, 2005; *Marani et al.*, 2006c].

[5] We compare two typical and contrasting situations: (1) a *Spartina alterniflora*-dominated case (characteristic of many North-American and U.K. sites, indicated as *Spartina*-dominated scenario in the following), in which biomass is a decreasing function of elevation between mean sea level (z = 0) and mean high water level (z = H), reflecting the adaptation of *Spartina spp.* to hypoxic conditions [*Morris et al.*, 2002]; and (2) a case in which biomass increases with soil elevation, e.g., because of the competition among species adapted to progressively more aerated conditions [*Marani et al.*, 2004; *Silvestri et al.*, 2005], typical of Mediterranean tidal environments, such as the Venice lagoon (Italy) [e.g., *Belluco et al.*, 2006], or of sites in northern continental Europe (indicated as multiple-species case in the following, even though a biomass increase with elevation is also observed at sites dominated by *Spartina anglica*). The physiological adaptation of *Spartina alterniflora* to waterlogged conditions is described using a reproduction rate which linearly decreases with elevation, while the mortality rate increases linearly with z. We also assume an isolated plant to produce at most one daughter plant per year in the most favourable conditions, i.e. $r(0) = 1$ year^{-1}, while $m(0) = 0$ year^{-1}. In order for the steady-state biomass at $z = H$ to be equal to zero, as observed [*Morris et al.*, 2002], we take $r(H) = m(H) = 0.5$ year^{-1}. Similarly, the multiple-species case is modelled by assuming $r(H) = 1$ year^{-1} and $m(H) = 0$ year^{-1}, whereas $r(0) = m(0) = 0.5$ year^{-1} in order for the steady-state biomass to be zero at $z = 0$, according to observations [*Marani et al.*, 2004; *Silvestri et al.*, 2005].

3. Results and Discussion

[6] As an illustration of the approach, which is of a general nature, we first analyze the case of landforms within the Venice lagoon, whose dynamics have been documented for several centuries and whose fate is of great concern. The tidal excursion is $2H$ = 1.48 m and the tidal period is T = 12 hours. We also take C_0 = 20 g/m^3 as a characteristic suspended sediment concentration, based on long series of water turbidity observations (see the auxiliary material). The settling velocity is w_s = 0.2 mm/s (computed for a typical d_{50} = 50 μm), the erosion coefficient is $\nu = 10^{-4}$ kgm^{-2}s^{-1}, while the sediment density is ρ_s = 2650 kg/m^3. The values of the vegetation parameters are: $\alpha = 1.0 \cdot 10^6$ m$^{1+2\beta}$s^{-1} kg$^{-\beta}$; $\beta = 0.38$; $\gamma = 2.5 \cdot 10^{-3}$ m^3 kg^{-1} year^{-1}. We first consider a 20th-century scenario, which assumes the characteristic rate of sea-level rise of 2 mm/year [*Intergovernmental Panel on Climate Change* (*IPCC*), 2001; *Carbognin et al.*, 2004], and a local subsidence of 1.5 mm/year [*Carbognin et al.*, 2004], for a total R = 3.5 mm/year. The dynamics of the system may be represented in phase space (Figure 1a), in which two

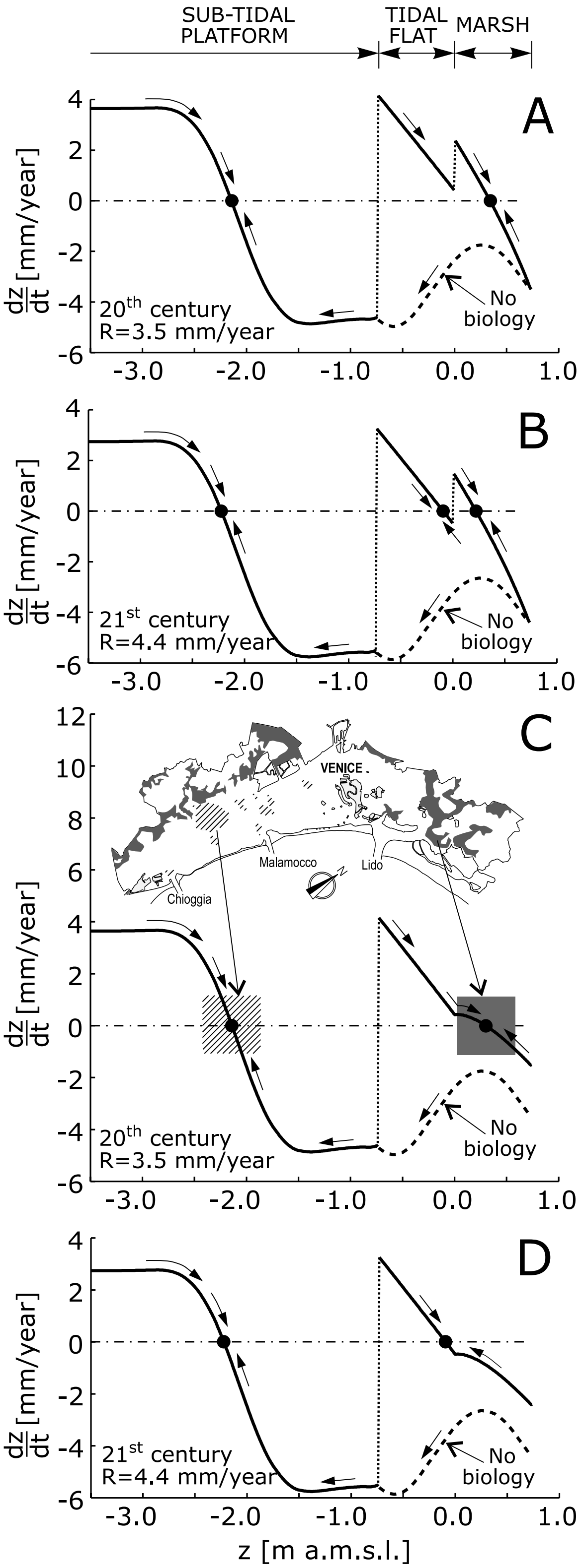

Figure 2. Stable states under different scenarios of RSL change for (a, b) the *Spartina*-dominated and (c, d) multiple-species cases. The discontinuity at z = 0 in the rate of accretion (Figures 2a and 2b) or in its derivative (Figures 2c and 2d) is due to vegetation colonization. The hypothetical case in which no biological activity is present (i.e., no microphytobenthos and no vegetation) is described by dashed curves in Figures 2a–2d.

stable equilibria are present: A sub-tidal (i.e. permanently submerged) platform and a vegetated marsh. The arrows in phase space represent the time evolution of the system out of equilibrium and highlight the stable nature of the equilibria identified (solid circles in Figure 1a). The stability of the equilibrium for $B > 0$ is controlled by the eigenvalues of the Jacobian matrix associated to equations (1) and (2) [*Strogatz*, 1994]. In this case the values of the determinant and of the trace of the Jacobian (inset in Figure 1a) are such that both eigenvalues are real and negative, and thus the marsh equilibrium state is a *stable node*. The nearly vertical trajectories for $z > 0$ (Figure 1a) show that biomass adjustments are quasi-instantaneous with respect to elevation changes. The bifurcation diagram (Figure 1b) shows the alternative system equilibria as a function of the rate of RSL change. We note that: (1) no equilibrium state exists for $R < -1.4$ mm/year. A relatively fast sea regression transforms the tidal environment into a terrestrial one; (2) for $R \geq -1.4$ mm/year a sub-tidal platform stable equilibrium appears; (3) a second equilibrium appears for $2 \leq R < 3.9$ mm/year, corresponding to a vegetated marsh (as e.g., for the 20th-century value $R = 3.5$ mm/year, Figure 1b); (4) values $R \geq 3.9$ mm/year lead to a transition from a marsh to a tidal-flat equilibrium; (5) for $R \geq 7.2$ mm/year the sub-tidal equilibrium disappears; whereas (6) for $R \geq 7.7$ mm/year all intertidal equilibria vanish.

[7] Because of the instantaneous adjustment of biomass to elevation changes equilibrium states can also be identified by posing $dz/dt = 0$ in equation (1) upon assuming $B = B(z)$, the steady-state biomass, defined by the condition $dB/dt = 0$ in equation (2). This type of analysis for a *Spartina*-dominated system retrieves the same unvegetated equilibria as in the multiple-species case. The vegetated marsh stable equilibrium exists for $0 \leq R < 5.9$ mm/year (Figure 2a, where the arrows show that small perturbations in z near equilibria are dissipated by the system dynamics, thus marking their stable nature). Three stable equilibria coexist for $3.9 \leq R < 5.9$ mm/year (Figure 2b), as a stable tidal flat equilibrium makes its appearance. For $5.9 \leq R < 7.2$ mm/year the marsh equilibrium is no longer possible and only the sub-tidal-platform and the tidal-flat equilibria coexist (not shown). In the multiple-species case one retrieves the results of Figure 1b: Figure 2c represents the 20th century scenario characterized by the coexisting sub-tidal and marsh equilibria. Figure 2d shows that salt-marsh accretion is unable to balance RSL rise for $R \geq 3.9$ mm/year and that, as a consequence, the system evolves towards a stable tidal flat. Hence, coastal marshes may not survive climatic changes in the next century as global rates of sea level rise are predicted in the range 0.8–8.5 mm/year [*IPCC*, 2001].

[8] The geomorphic role of biological processes is best appreciated by considering the hypothetical situation in which microphytobenthos and vegetation are absent (Figure 2, dashed lines). In this case a tidal flat equilibrium is possible only for narrow ranges of rates of RSL rise ($-1.5 < R < -1.1$ mm/year and $0 < R < 1.8$ mm/year) and the basin of attraction of stable equilibria lying within the tidal range (tidal flats or salt marshes) is much narrower ($0.27 < z < 0.74$ m a.m.s.l) than in the presence of bio-stabilization ($-0.74 < z < 0.74$ m a.m.s.l). The abiotic scenario also provides insight into the dynamics of the system in the case of a sediment poor in polimeric biofilms owing to external

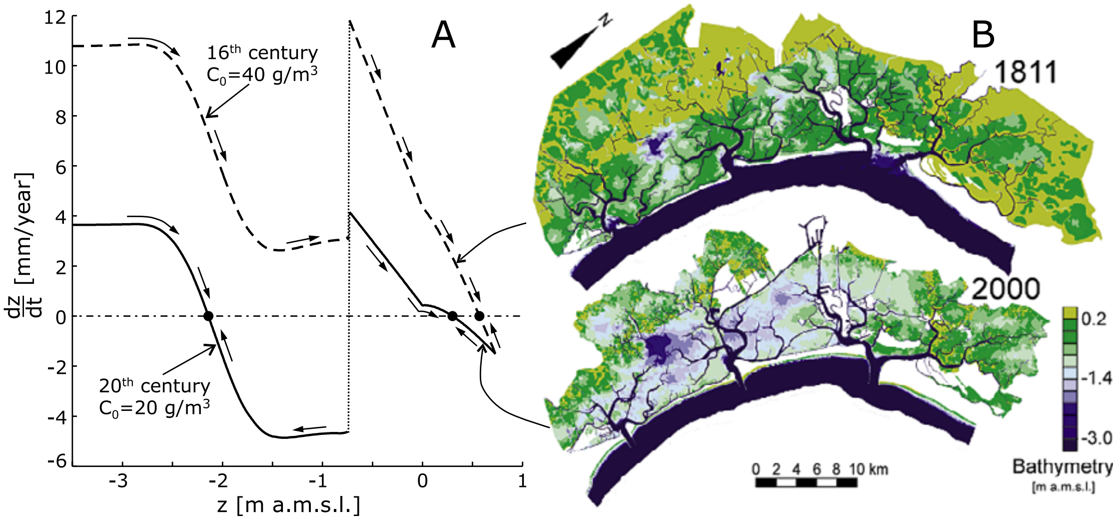

Figure 3. At the end of the sediment-poor 20th-century wide sub-tidal areas coexist with a moderate presence of intertidal marshes in the Venice lagoon, as predicted by the model (solid line in Figure 3a and lower image in Figure 3b). On the contrary, the sediment-rich 16th–18th century period led to a configuration dominated by marshes with very limited sub-tidal platforms (dashed line in Figure 3a and upper image in Figure 3b). Figure 3b modified after *D'Alpaos* [2004].

disturbances (such as clam harvesting mechanically disrupting the surficial biofilm [*Paterson*, 1989]), or bioturbation, e.g. due to grazing or invertebrates [*Daborn et al.*, 1993]. The disruption of the microbial biofilm radically changes the direction of the system evolution (compare the corresponding dashed and solid lines in Figure 2), leading to the demolition of tidal flats, which would be accreting in the presence of microphytobenthos. A sub-tidal platform is the only accessible stable equilibrium under the new conditions. Biological controls thus largely determine the existence of stable intertidal structures and the transition among them.

[9] In the 20th-century scenario for the Venice lagoon the sub-tidal platform stable elevation is $z \sim -2.14$ m a.m.s.l., whereas vegetated marshes stabilize at $z \sim 0.30$ m a.m.s.l. (Figure 2c), coherently with observations [*Day et al.*, 1999; *Marani et al.*, 2004; *Silvestri et al.*, 2005]. Model predictions are also confirmed by the observed erosional trend that caused a major reduction of salt-marsh areas during the 20th century in response to the diversion of the main rivers directly out to sea and to the construction of jetties at the lagoon inlets carried out in the 16th–19th centuries [e.g., see *Dorigo*, 1983]. In fact, the study of the lagoon geomorphology over the last century shows that, in response to these changes, the typical elevation of unvegetated platforms (approximately equal to -0.5 m a.m.s.l. in the early '900s) has been steadily decreasing. However, no increase in depth beyond $z = -2.4$ m a.m.s.l. has been observed [*Defina et al.*, 2007]. This suggests that indeed the average lagoon depth is increasing but that the maximum depth of a sub-tidal platform is bounded from below by a stable equilibrium for $z \cong -2.4$ m a.m.s.l., quite close to the value predicted by the model.

[10] The analysis of different scenarios of sediment availability can elucidate trends and mechanisms characterizing different phases in the life of a tidal system. The largely positive sediment balance of the Venice lagoon typical of pre-16th century conditions is represented here by assuming $C_0 = 40$ g/m^3, compared to $C_0 = 20$ g/m^3 characteristic of the 20th century case. The model shows that in the pre-16th century conditions deposition dominated over erosion and the lagoon tended toward a configuration dominated by high marshes, in which tidal flats and sub-tidal platforms were disappearing (Figure 3a). This picture is in agreement with various accounts [*Dorigo*, 1983] and 19th century bathymetries [*D'Alpaos*, 2004]: Marsh area amounted to about 150 km^2 in 1811, compared to a total lagoon area of 580 km^2 (see Figure 3b, top). In 2000, marshes extended for about 50 km^2 while the total lagoon area was 480 km^2 (reduced mainly because of land reclamation. See Figure 3b, bottom). Marsh surfaces were thus reduced from about 26% of the total lagoon area to just 10%.

[11] The model presented provides a concise description of the dynamics of tidal landforms which, in spite of its structural simplicity, yields a surprisingly rich variety of system responses to changes in forcings. We suggest that the complexity observed in tidal geomorphological patterns may indeed arise from the mutual influence of biotic and abiotic components, and that the fate of landforms and of their possible geomorphological restoration can be predicted, thus pointing at the importance of eco-morphodynamic approaches for conservation studies.

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