BIOLOGIC-GEOMORPHIC FEEDBACKS THAT SCULPT TIDAL LANDSCAPES

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1. INTRODUCTION

We present modeling and observational results on the spatial distribution of morphological and vegetational patterns in tidal marshes arising from feedbacks between biomass production, inorganic sediment deposition, and soil accretion. We show, in a one dimensional context, how different, species specific, adaptation to local edaphic conditions leads to a set of almost discrete equilibria determined by these biogeomorphic feedbacks. We identify the presence of multiple competing stable states arising from a two-way feedback between biomass productivity and topographic elevation. In contrast with traditional views we propose that biota in tidal environments is not just passively adapted to morphological features prescribed by sediment transport, but rather it is fundamentally constructing the tidal landscape. The proposed framework allows us to identify the observable signature of the biogemorphic feedbacks underlying tidal landscapes and to explore the response and resilience of tidal bio-geomorphic patterns to variations in the forcings.

2. THE MODEL

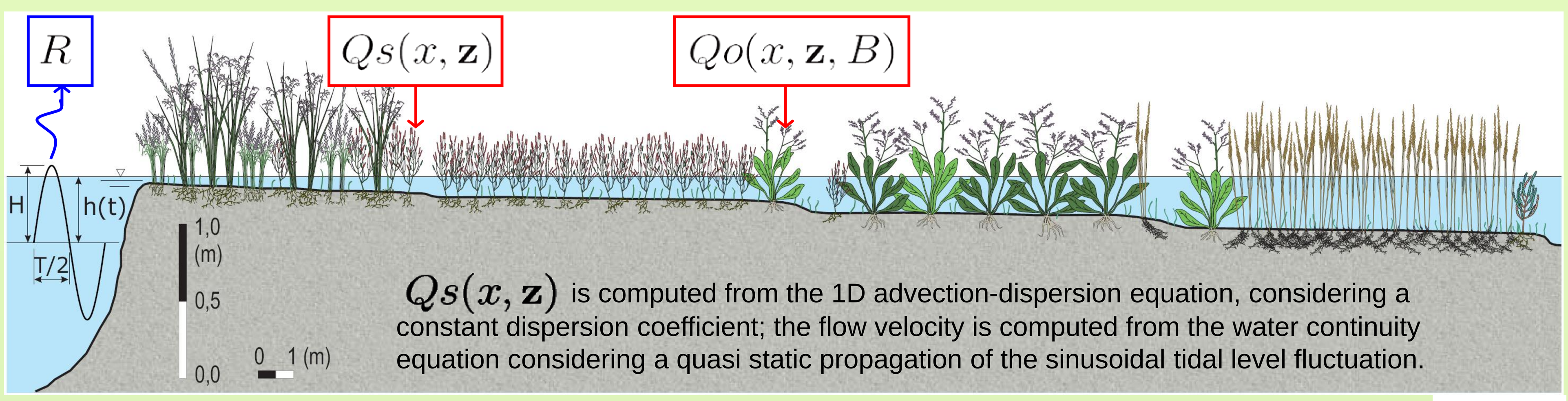

Figure 1

Evolution of topography

$$\frac{dz}{dt} = Qs(x,\mathbf{z}) + Qo(x,\mathbf{z},B) - R$$

Evolution of vegetation biomass

$$B(x,\mathbf{z},t) = f(\zeta,t)B_0 \qquad \zeta = z/H$$

B_0 = maximum biomass areal production

Where:

- B = annually-averaged above-ground vegetation biomass;
- Q_S (x,z) = average sediment settling rate over a tidal cycle;
- Q_O(B)= production of organic soil due to vegetation;
- R = rate of relative sea level rise

3. FITNESS FUNCTIONS

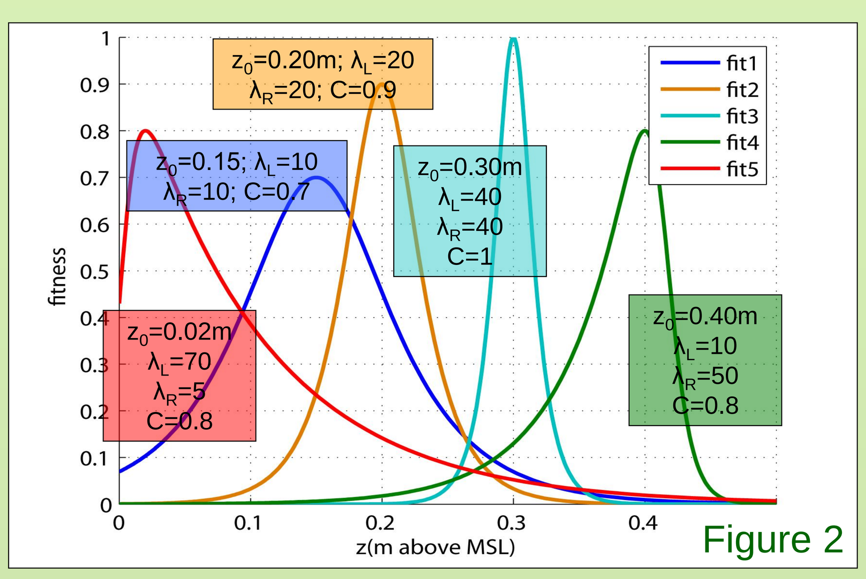

Figure 2

$$f(\zeta) = C \cdot \frac{1}{sech(\zeta_M)} \cdot \frac{2}{exp(\lambda_R(\zeta-\zeta_0)) + exp(-\lambda_L(\zeta-\zeta_0))}$$

Figure 2
The main physiological characteristics of each species are described by the fitness function $f_i(z)$, which is commonly observed to take a maximum value at a small range of elevations (characteristic of each plant) and decrease (scale parameter λ) as elevation departs from this optimal range. This function describes the biomass productivity depending on the bottom topographic elevation computed with respect the local MSL and the associated edaphic conditions.

4. ZONATION PATTERNS

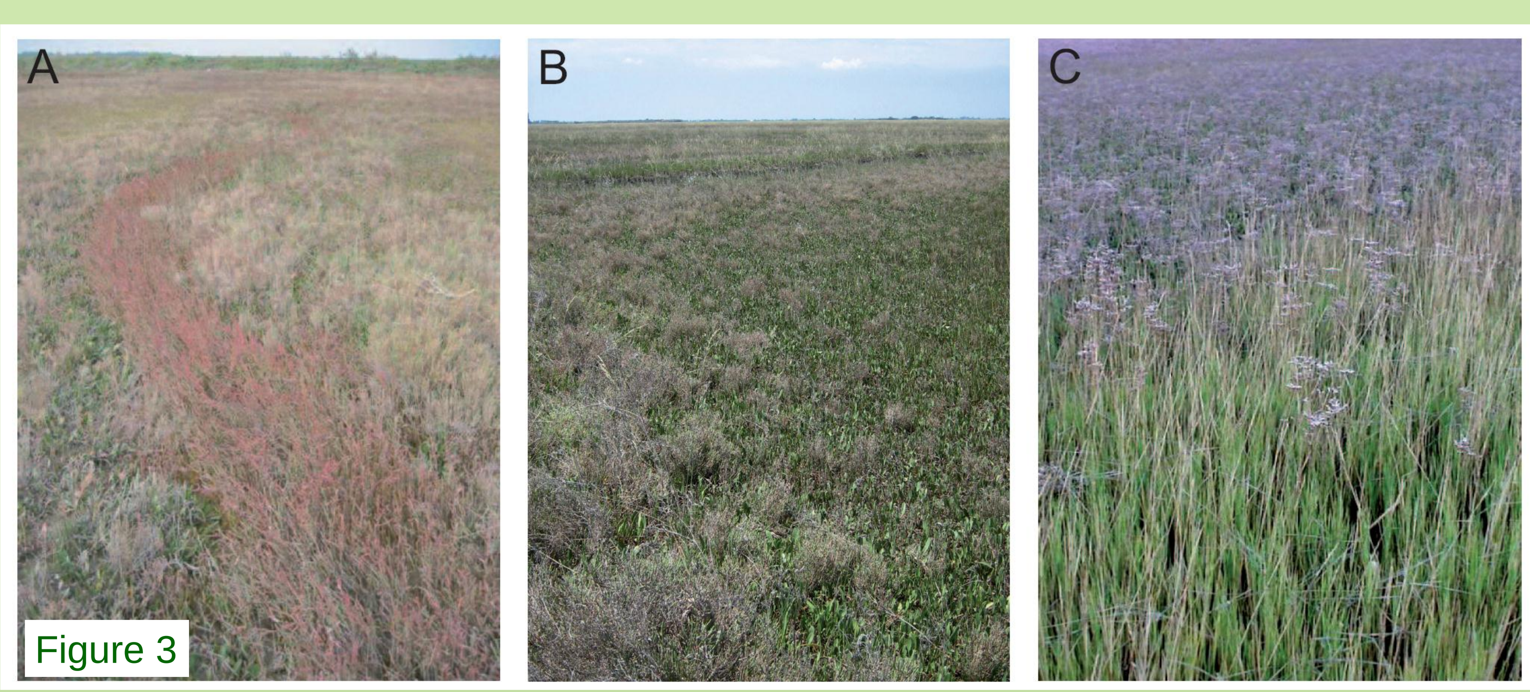

Figure 3
(A) A tidal creek roughly 10-20 cm wide and about 10 cm deep is colonized by *Salicornia veneta*, a pioneer species adapted to hypoxic conditions, while the rest of the marsh is colonized by *Sarcocornia fruticosa*.
(B) Transition from a mixed vegetation cover near a tidal creek (left and background) to a *Limonium Narbonense* patch. (C) Sharp transition between *Limonium narbonense* (above) and *Spartina maritima* below).

5. ECOSYSTEM ENGINEER "FITTEST-TAKES-IT-ALL" FORMULATION

Figure 4
(A) The time evolution of transect topography was here started from a linear initial condition but several other initial conditions were explored with analogous results. Monospecific vegetation patches, very similar to observed zonation patterns (see inset), and terrace-like topographic structures emerge as result of multiple stable states defined by $\partial z / \partial t = 0$ and $\partial / \partial z (\partial z / \partial t) < 0$.
(B) Sites with initial elevation between $z^{(u)}_i$ and $z^{(s)}_i$ move towards $z^{(s)}_i$, while sites with initial elevation below $z^{(u)}_i$ move towards $z^{(s)}_j$,j being the species with optimal elevation located immediately below that of species i.
(C) Shows the fitness function of the species populating the marsh, which defines the rate of organic soil production as $Q_o = B_0 \cdot f_i(z)$ (incorporates typical vegetation characteristics and the density of the organic soil produced, B_0 is the biomass density of a fully vegetated marsh).

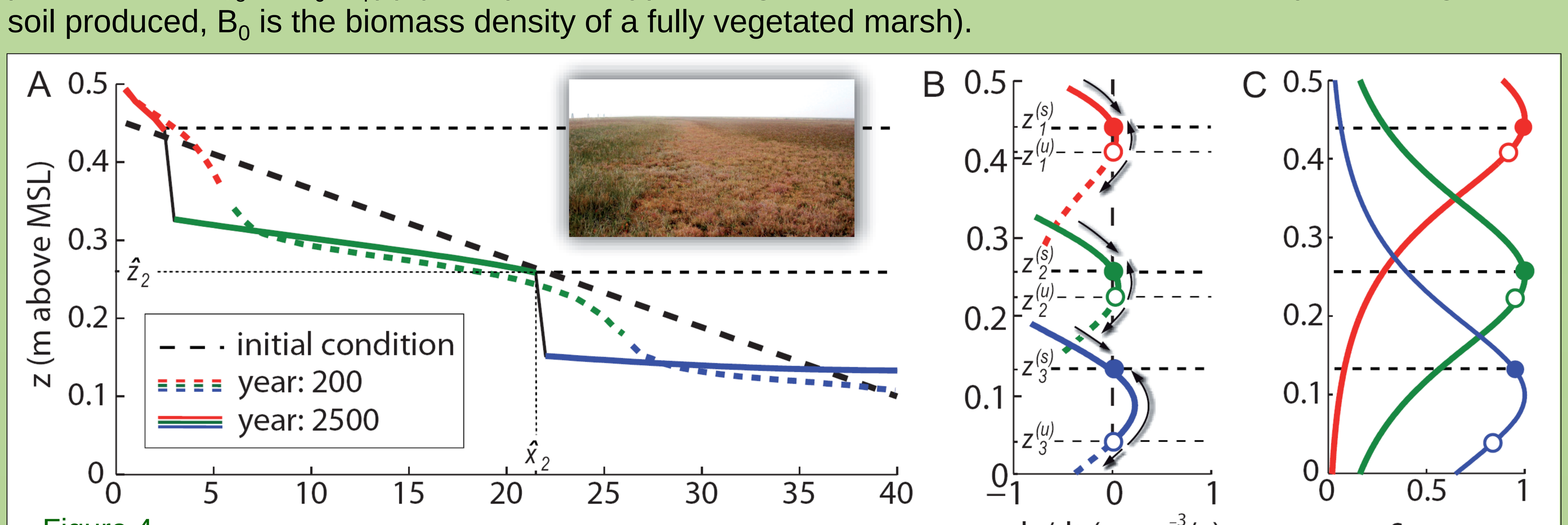

Figure 4

6. RATE OF RELATIVE SEA LEVEL RISE

Figure 4
(a) Equilibrium topography: terrace structures develop due to the existence of multiple stable states. As external forcings we assume C_0=20 mg/l and R=5.0 mm/yr;
(b) Accretion rates as a function of perturbations in the local elevation. Solid circles represent the stable equilibria, open circles the unstable equilibria;
(c) Fitness functions of the species (scale parameter λ=5);
(d, e, f) The same as (a, b, c) except R=7 mm/yr.

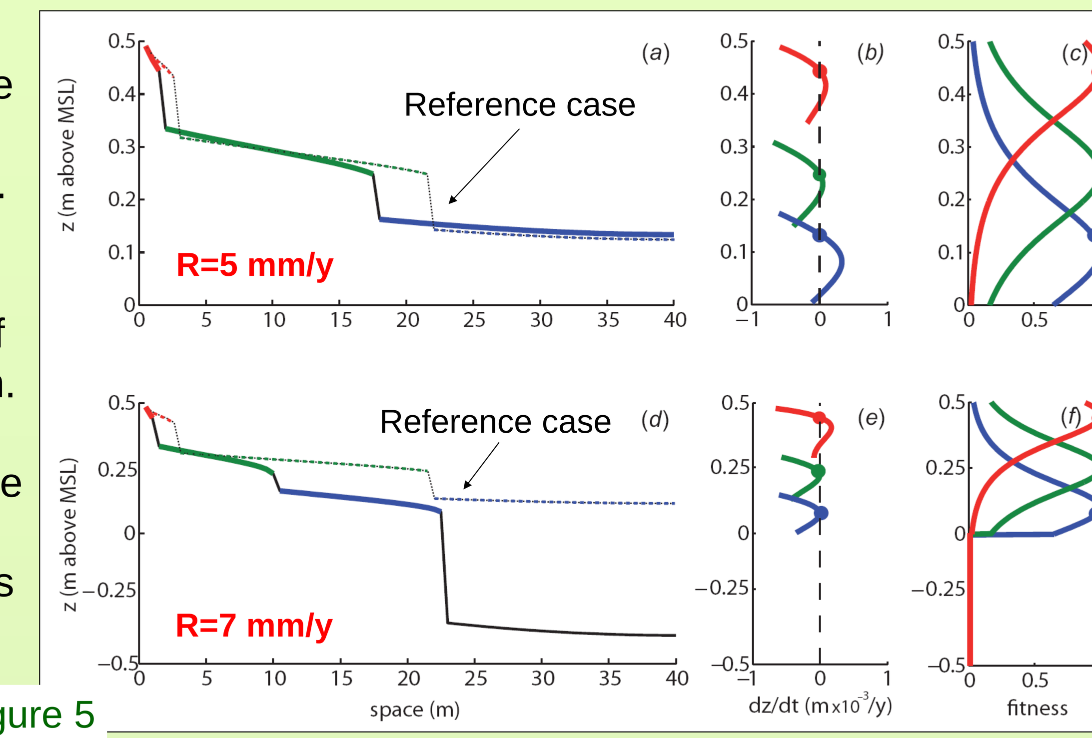

Figure 5

7. VEGETATION SPECIALIZATION

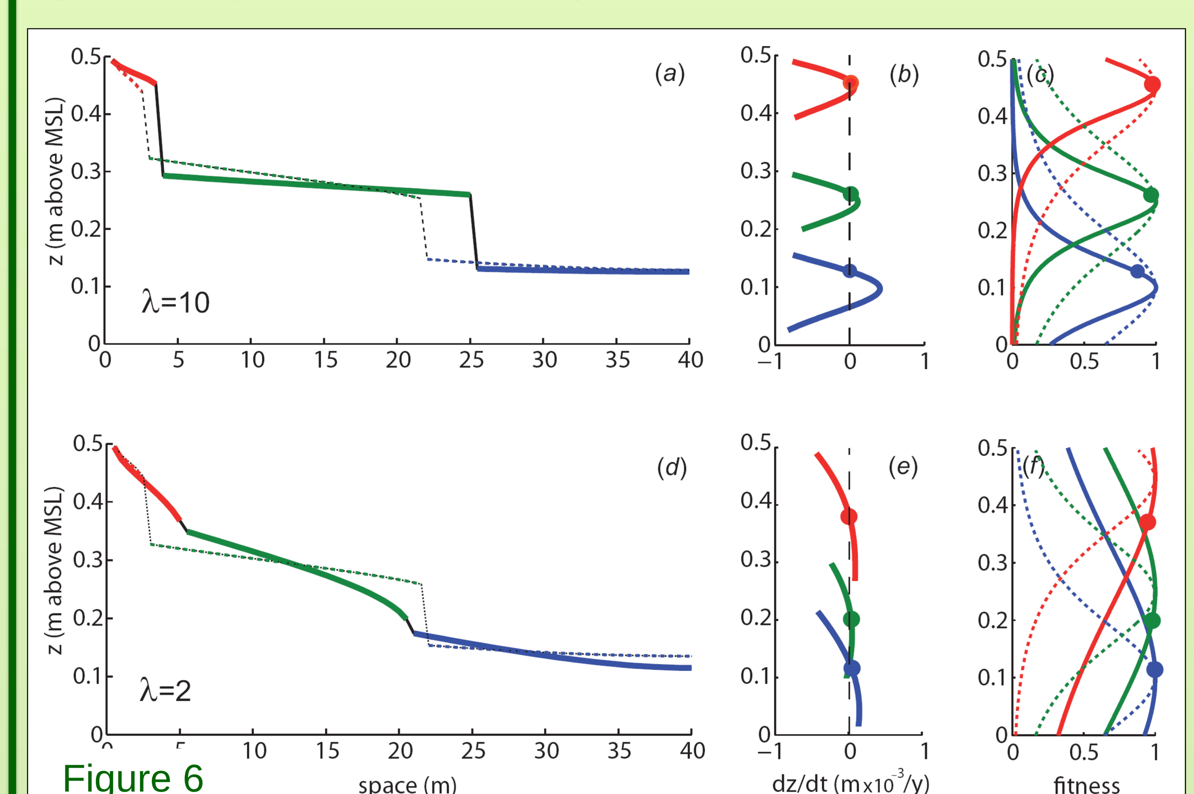

Figure 6

Figure 6
(a) Equilibrium topography with terrace structures. Multiple stable states emerge assuming C_0=20 mg/l and R=3.5 mm/yr. The dashed line represents the equilibrium elevation state of the reference case;
(b) Accretion rates as a function of perturbations in the local elevation. (c) Fitness functions of the species populating the transect with scale parameter λ=10. Solid circles represent the stable elevation equilibria.
(d, e, f) The same as (a, b, c) considering the scale parameter λ=2;

8. WHAT ABOUT THE REAL SPATIAL DISTRIBUTION OF VEGETATION?

Figure 7
Observed zonation patterns in the Venice Lagoon. An accurate topographic survey reveals a multimodal frequency distribution of soil elevation, highly suggestive of the major role played by the biomass-elevation feedback in tuning marsh topography. Each bar is color-coded according to the vegetation species which is most abundant within the pertinent elevation interval.

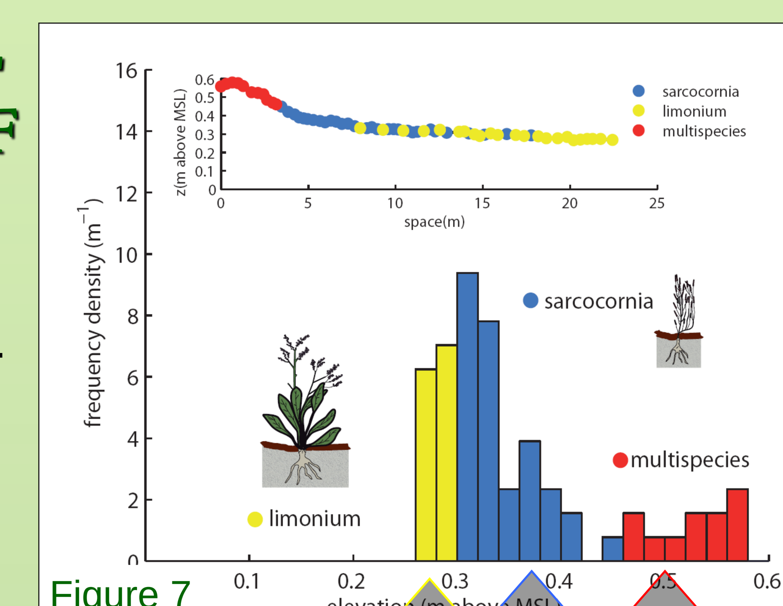

Figure 7

9. " STOCHASTIC COMPETITION " FORMULATION

$$p(i, x_k) = \frac{f_i(z_k)}{\sum_j f_j(z_k)}$$

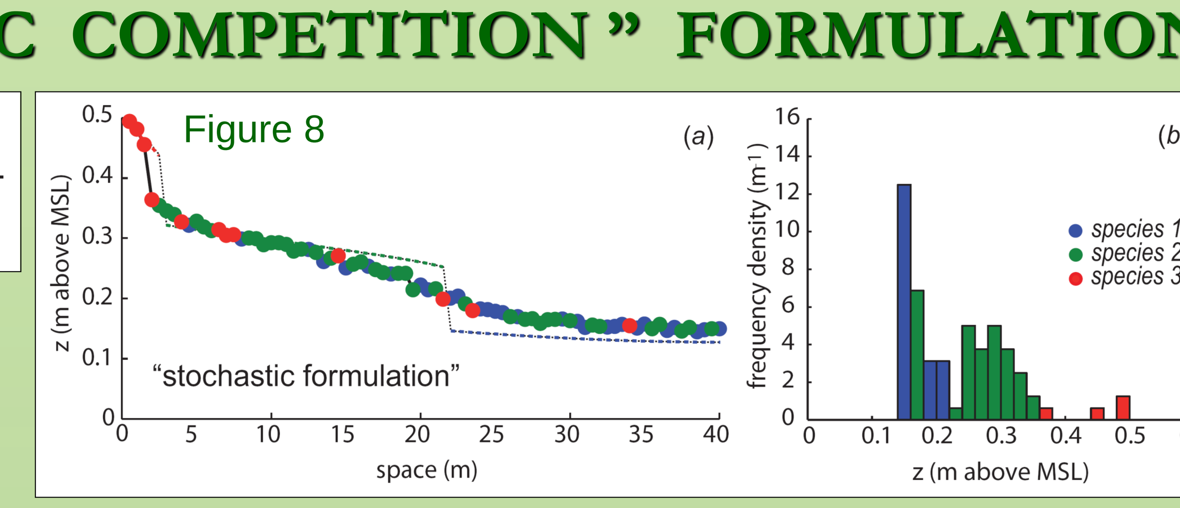

Figure 8

Figure 8
(a) Multiple stable states assuming as external forcings C_0=20 mg/l and R=3.5 mm/yr.
"Stochastic compatition" formulation is assumed as spatial competition mechanism. The dashed line indicates the topography reference case, where we adopted the "fittest-takes-it-all formulation";
(b) Multimodal frequency distribution of topographic elevations. Each peak (color-coded, according to the most abundant species in each interval) is associated with the unique species that generates it;

10. CONCLUSIONS

We show that landscape zonation patterns in tidal environments are the results of vegetation-controlled competing alternative stable states. Specialized vegetation species actively engineer marsh landscapes, by tuning bottom elevations within narrow ranges of preferential adaptation, thus promoting the development of spatially extensive tabular structures.
Our modelling results are shown to be in good agreement with observational evidence, and emphasize that the coupled vegetation-topography dynamics is responsible for the emergence of spatially coherent morphological-biological structures in marshes.
We also show that some marsh bio-geomorphic components may disappear for changes in the forcings to which the system as a whole seems to be resilient in a spatially-lumped analysis.

REFERENCES

This poster summarizes some of the analyses and results described in detail in:

- Marani M., Da Lio C., D'Alpaos A. (2013), Vegetation engineers marsh morphology through multiple competing stable states, *PNAS*, 110 (9), 3259-3263.
- Da Lio C., D'Alpaos A., Marani M., Emergent bio-geomorphic patterns in tidal environments, *in review*.