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# *Interactive comment on* "Non-linear power law approach for spatial and temporal pattern analysis of salt marsh evolution" *by* A. Taramelli et al.

**A. Taramelli et al.**

loreta.cornacchia@nioz.nl

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# Response to Anonymous Referee # 1 comments on "Non-linear power law approach for spatial and temporal pattern analysis of salt marsh evolution"

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**General Comments:**

**- In this paper titled "Non-linear power law approach for spatial and temporal pattern analysis of salt marsh evolution", Taramelli et al. analyze the spatial distribution of vegetation pattern sizes and show that the probability distribution of cluster size might not follow a power law relationship. In the tail of the distribution, in fact, data may show a non-linearity (in a log-lo plot) and lie outside of a power law. The Authors argue that changes in the main climatic and hydrodynamic variables are responsible for such a behavior.**

**Although the manuscript addresses a timely issue of interest to ESurfD, I do not find the key findings of this paper particularly capturing nor capable of bringing new insight into our current knowledge of salt-marsh geomorphological and ecological dynamics. Many parts of the paper seem to be poorly written and the paper is often cloudy and unclear.**

**Most of the paper focuses on methodology, whereas the causal effects between the distribution of vegetation patterns and environmental stressors, which could be the novel aspect of this paper, are overlooked. Overall, I do not feel that at this stage, this is a strong enough paper to merit publication in ESurfD.**

The authors are thankful for the reviewer's comments and suggestions, which will be taken into account for an improved version of the manuscript. Using observations from innovative remote sensing method, we propose that the presence of vegetation may promote channel sinuosity accordingly with already present literature [D'Alpaos et al., 2006. Estuarine, Coastal and Shelf Science, 69:311–324; Temmerman et al., 2007. Geology, 35:631-634] and influence the planimetric evolution of tidal channels in relation to climate and physical parameters. Not limited to bigger channels, the hypothesis we explore pertains to sinuosity as a geomorphic pattern at different scale. On certain occasions, the actual distribution of vegetation through different years does not follow a power law for all its values: in the tail of the distribution, data may lie outside of a model power law relationship and show a non-linearity, in other words a variance in the scale invariance. If patches are found to lie outside and deviate from the power law relationship, they are usually considered as statistical anomalies: as a consequence, the non-linearity in the power law tail may often be disregarded. The deviation from power laws represents stochastic conditions under climate drivers that can be hybridized on the basis of a fuzzy Bayesian generative algorithm.

We will also add the analytical reasons to choose a fuzzy naïve Bayes classifier, namely the ability of the naïve Bayes to find unobserved equilibria in complex patterns, the reduction of the dimensionality of a complex problem, and the esplicitation of the uncertainty inherent to the result [Störr, H.P., 2002. Pages 172-177 in Proceedings InTech/VJFuzzy; Viertl R. and D. Hareter, 2004. ZAMM. Zeitschrift für Angewandte Mathematik und Mechanik 84: 731-739; Zadeh, L. A., 1965. Information and Control 8:338-353; Zadeh, L. A., 1968. Journal of mathematical analysis and applications 23:



421-427; Lewis, D.D. 1998. Lecture Notes in Computer Science 1398: 4-15].

In addition, we will provide a more detailed explanation of the application of a fuzzy naïve Bayes compiler regarding the extent of the fuzzy sets, the fuzzyfication functions we have used and the fuzzy partition of the domains.

**Specific Comments: A crucial point is that the purported correlation between the distribution of vegetation patches, salinity, rainfall and water height completely lacks a physical explanation. The same observation holds for the link between the existence of a relationship between areas of different vegetation patches and sinuosity. The description and discussion of such relationships is very vague and suggests the authors mistake correlation with causation. Some of these issues have already been studied (a list of papers follows) through the attempt of finding a causal relationship between the interaction of physical and ecological processes and their effects on vegetation distribution.**

We agree with the reviewer that the description and discussion of our findings would greatly benefit from a thorough consideration of the physical aspects of the analysis and the results. Nevertheless, we would like to clarify what we see as the relevance and novelty of our approach, compared to previous studies on physical and ecological processes. We will work on that section a lot. We agree with the reviewer that some of these issues and dynamics have already been studied, but we argue that there are difficulties in describing the interactions between these dynamics using deterministic approaches. This is mainly due to the difficulty to linearly reconstruct a complex result starting from individual components.

Another difficulty of a deterministic approach towards complexity is due to the non-repeatability of the phenomenon we observe: in other words, the phenomena are very highly dependent on the boundary conditions [Levin, S. A. 1998. Ecosystems 1: 431-

436; Levin, S. A. 2005. Bioscience 55: 1075-1079; Jensen, H. J. 1998. Self-Organized Criticality: Emergent Complex Behavior in Physical and Biological Systems. Cambridge University Press, Cambridge, UK; Camara, B. I. 2011. Nonlinear Analysis-Real World Applications 12:2511-2528].

A statistical approach allows us to simultaneously consider these components and their dynamics in a context which is uncertain with respect to the processes, but elastic with respect to the structure of the system—a system which varies continuously according to the strength of the environmental drivers and the series of feedback processes.

In addition, the statistical approach is able to provide an uncertainty value which is not only associated with the error in the results, but also represents a value indicating the possibility of occurrence of a given phenomenon. In fact, the highest values of uncertainty are related to the more extreme (i.e. rarer) phenomena, in our case to the most marked deviations from the power law model.

The statistical approach is also justified by the high level of dependence on even small variations of the boundary conditions, in which apparently insignificant correlations represent instead the basis for the evolution of the system. This is particularly true and has been clearly shown in salt marsh systems [van Belzen, 2011. Chess at the mud-flat. Using power-laws as indicator of salt-marsh ecosystem status and development. Master of Science thesis, Open University Netherlands].

**- As I said, most of the paper focuses on methodology, whereas the description of the salt-marsh environment and of the physical and ecological processes which control its evolution is lacking or addressed superficially. Moreover, the authors do not discuss existing results which their analyses could be building upon. While reading the manuscript one has the feeling that almost no work has been done in the fields of remote sensing methods in salt-marsh systems and of salt-marsh eco-geomorphology. While the consideration of related works is not**



**adequate at all, it seems that the authors indulge too much on their own contributions referring also to submitted papers (this should be avoided, in my view).**

This will be modified accordingly in a revised version of the manuscript. Some of the submitted papers were accepted so we will change them with the published results. The authors will of course consider the related and important topics suggested by the reviewer as hydrodynamics of salt marsh channels [e.g., Boon, 1975; Pethick, 1980; French and Stoddart, 1992; Rinaldo et al., 1999a, 1999b; Temmerman et al., 2005b; Fagherazzi et al., 2008], and their morphometric features [e.g., Fagherazzi et al., 1999; Rinaldo et al., 1999a, 1999b; Marani et al., 2003; Novakowski et al., 2004; Feola et al., 2005; Marani et al., 2006].

**- The spatial distribution of halophytic vegetation over salt marshes, characterized by the existence of typical vegetation patches (zonation) has been largely studied, and possible physical-ecological interactions leading to the development of these patterns have largely been addressed. This is completely overlooked in this paper. A short list of contributions on this issue follows:**

**- Adam P. (1990), Saltmarsh Ecology, Cambridge Univ Press, Cambridge;**

**- Chapman V.J (1964), Coastal Vegetation. Pergamon Press, Oxford the Macmillan Company, New York;**

**- Bertness M.D (1991), Interspecific interactions among high marsh perennials in a New England salt marsh, Ecology 72, 125–137;**

**- Bertness M.D. and A.M. Ellison (1987) Determinants of pattern in a New England salt marsh plant community, Ecol Monogr 57(2):129–147;**

**- Bertness M.D et al. (1992), Salt tolerances and the distribution of fugitive salt marsh plants. Ecology 73, 1842–1851;**

- Bockelmann A.C., et al. (2002), The relation between vegetation zonation, elevation and inundation frequency in a Wadden Sea salt marsh, Aquatic Botany 73, 211–221;

- Marani M. et al. (2013), Vegetation engineers marsh morphology through multiple competing stable states, Proc. Natl. Acad. Sci. USA 110, 3259–3263;

- Moffett K.B. et al. (2012) Salt marsh ecohydrological zonation due to heterogeneous vegetation – groundwater – surface water interactions, Water Resources Research, 48, W02516;

- Pennings S.C., and R.M. Callaway (1992), Salt marsh plant zonation: the relative importance of competition and physical factors, Ecology 73, 681–690.

As to the effects of environmental forcing on salt-marsh vegetation patterns, I have included below a short list of references:

- Moffett K.B. et al. (2010) Relationship of salt marsh vegetation zonation to spatial patterns in soil moisture, salinity and topography, Ecosystems, 13: 1287-1302.

- Moffett K.B. et al. (2010) Salt marsh–atmosphere exchange of energy, water vapor, and carbon dioxide: effects of tidal flooding and biophysical controls, Water Resources Research, 46, W10525;

- Pennings S.C. et al. (2005) Plant zonation in low-latitudes salt marshes: Disentangling the roles of flooding, salinity and competition, J Ecol 93:159–167;

- Pezeshki S.R. (2001), Wetland plant responses to soil flooding, Environmental and Experimental Botany 46, 299–312;

- Sanchez J.M. (1996), Relationships between vegetation zonation and altitude in a salt-marsh system in northwest Spain, Journal of Vegetation Science 7, 695–702;



- Silvestri S. et al. (2005), Tidal regime, salinity and salt-marsh plant zonation, Estuarine, Coast. and Shelf Sci. 62, 119-130.

Salt-marsh vegetation patterns have already been studied through remote sensing analyses, as well as the probability distribution of cluster vegetation size (analogous to what is done here):

- Belluco, E. et al. (2006), Mapping salt-marsh vegetation by multispectral and hyperspectral remote sensing, Remote Sensing of Environment, 105, 54–67;

- Eastwood, J. A. et al. (1997), The reliability of vegetation indices for monitoring saltmarsh vegetation cover. International Journal of Remote Sensing, 18(18), 3901-3907;

- Marani M. et al.(2006), Analysis, synthesis and modelling of high resolution observations of saltmarsh ecogeomorphological patterns in the Venice lagoon, Estuarine Coastal Shelf Sci., 69, 414–426;

- Marani M. et al.(2006) Spatial organization and ecohydrological interactions in oxygen-limited vegetation ecosystems, Water Resour. Res., 42, W06D06;

- Ramsey E. W. and S.C. Laine (1997), Comparison of landsat thematic mapper and high resolution photography to identify change in complex coastal wetlands, Journal of Coastal Research, 13(2), 281-292;

- Schmidt, K.S. et al. (2004). Mapping coastal vegetation using an expert system and hyperspectral imagery, Photogrammetric Engineering and Remote Sensing, 70(6), 703-715.

- Silvestri S. et al. (2003), Hyperspectral remote sensing of salt marsh vegetation and morphology, Physics and Chemistry of the Earth, 28 (1-3), 15-25;

- Thomson A. G. et al. (1998), Ground and airborne radiometry over intertidal surfaces: Waveband selection for cover classification, International Journal of

**Remote Sensing, 19(6), 1189-1205;**

**- Thomson, A. G et al. (2003), The use of airborne remote sensing for extensive mapping of intertidal sediments and saltmarshes in eastern England, International Journal of Remote Sensing, 24(13), 2717-2737.**

**- Wang C et al. (2007), Mapping mixed vegetation communities in salt marshes using airborne spectral data, Remote Sensing of Environment, 107 (4), 559-570.**

The reviewer is right in suggesting these relevant and recent publications. We have gone through most of these references in the introduction section of the revised manuscript. Nonetheless we argue that a tidal ecosystem may be understood as a multi-layered network with fundamental theoretical (modeling) and empirical (morphological) aspects. It also has deterministic and probabilistic elements: these may describe and predict the potential for changes over time and space (the term potential describes a propensity measured by probability). Ecosystem changes are generally observed at different intervals of time, and not all of the factors contributed to those changes can be studied at those times. The probabilistic aspects involve probability distribution functions that range from the normal probability distribution function to probability distribution functions with infinite first and second moments; use data such as time series characterized by short- and long-term correlation structures. Correlation functions are of limited use in non-linear systems. This occurs because the signals are broadband and thus the correlations are indistinguishable. Information entropy methods can capture the essential aspect of hidden structures in the data associated with those non-linear systems, including correlations. So the multitemporal satellite analyses represent one of the first attempts in that direction.

**- The Authors have some work to do in order to clarify the importance of their results and in particular to interpret their findings in view of the physical and**



**ecological processes which control salt-marsh geomorphological and ecological features. In general, I suggest the Authors do a better job in identifying what may be new in what the propose to do (the non-linear relationship between the percentage of flooded salt-marsh area and tidal elevation is known since the 1955, to my knowledge).**

**Specific/Technical Comments:**

**- Lines 17-18. This is called zonation and a wide literature exists describing zonation patterns in salt-marsh systems e.g., Adam (1990);**

We will modify the manuscript to include the reference to zonation patterns and the relevant literature.

**- Lines 21-22. Please rephrase.**

As for the comments of Reviewer #2, we have completely rewritten the abstract for clarity. We would rewrite it as follows:

"Self-organized pattern formation has been found in an increasing number of ecosystems, among them salt marshes. The mechanisms underlying spatial pattern formation, with implications on ecosystem functioning and degradation, can give rise to scale-invariant patterns, but not much is known on whether the scale invariance can hold over a wider range of environmental variables.

We asked whether the statistical distribution of spatial vegetation patterns could be described by changes in environmental variables acting on salt marshes, and we speculated the conditions under which a shift from a scale-invariant (power law) distribution to patterns characterized by a dominant patch size could be expected.

We quantified the temporal change in patch-size distribution of vegetation patches through satellite images and we developed a fuzzy Bayesian generative algorithm to relate their statistical distributions to the climatic and hydrological drivers acting on them.

The results show that the approach is able to accurately simulate the changes in the statistical distribution of vegetation over time, providing uncertainty ranges that closely fit or fall within the values of the target variable.

Our findings highlight the potential of the fuzzy Bayesian stochastic model, which is able to quantify the uncertainties in the response of salt-marsh vegetation to the short-term environmental drivers used in the simulations. Changes in the distribution of vegetation patches can thus be used to forecast potential deviation from steady states in intertidal systems, taking into account the climatic and hydrological regimes."

**- Lines 23-24. Why "the presence and typology of vegetation and channel sinuosity" should be "monitored simultaneously"?**

We refer to our previous response to state that ecosystem changes are generally observed at different intervals of time, and not all of the factors contributing to those changes can be studied at those times. The use of time-series of data on both vegetation and channel network characteristics may be useful in this context. In our opinion, the presence and typology of vegetation and channel sinuosity should be monitored simultaneously with the aim of investigating the feedbacks between vegetation colonization and channel network development. Although it would not constitute a necessary condition for this type of analysis, we argue that such a dataset would be preferable.

**- Lines 28-29: Why "the deviation from power laws" should represent "stochas-**



**tic conditions under climate drivers"?**

In real world both erosion and deposition are stochastic in nature, with infrequent events like storms, and heavy rainfalls producing most of the geomorphic work. Vegetation establishment on a bare tidal flat, usually by pioneer species of the genus Spartina, has a strong impact on changes in channel network properties [Temmerman et al., 2007; Vandenbruwaene et al., 2012. Earth Surface Processes and Landforms, 38:122-132]. We argue that vegetation patches follow a power law not only for external influences, but also for autocorrelative issues. Plants tend to aggregate into patches (as a normal exploitation of space around a point of origin and development) and are thus able to decrease hydrodynamic forcing and increase sedimentation on local scales, leading to a positive feedback due to improved growth conditions. This strongly auto-correlative process is expected to give rise to scale-invariant patterns, since it is at the same time accompanied by a negative feedback due to flow deflection and increased erosion around the patches themselves. Although a power law is the general model to which self-organized patches can be ascribed, changes in environmental conditions may vary the intensity of this process. The fact that we never observed the same power law twice also suggests this interpretation. We argue that, in salt marshes, the auto-correlative process is in general valid but its magnitude is influenced by environmental conditions: over time, variations in tidal level and rainfall can shift the system towards different states. During these shifts, the system may also locally regress towards previous states, although the irreversibility principle [Prigogine, I. 1987. European Journal of Operational Research 30: 97-103] implies that the future evolution will never be (deterministically) the same as before but will follow other paths, which can be similar but differentâĂŤhence there is an uncertainty component. Thus, a method is needed which can give a range of uncertainty within which the result is found, instead of a "punctual" result.

**- Line 49. Change "permit" to "permits".**

Done accordingly.

**- Line 56. Please specify what equations you are referring to.**

In the text we were referring to the concepts originally proposed by Taylor (1950) [Proc. R. Soc. Lond. Ser. A., 201, 192-196]. We will rephrase to state that the dynamics of such systems can be described by nonlinear differential equations that could be linearized for short ranges in time and space.

**- Line 57. "times" should be "time".**

Done accordingly.

**- Lines 60-63. This needs be rephrased. It is not clear to what power laws the authors are referring to. Do you mean that power law relationships describe the characteristics of estuarine systems?**

The vegetation patchiness we observed in satellite images actually follows a power law distribution, as it was empirically tested on the data. In general, vegetation patchiness follows a power law distribution due to autocorrelative properties that maintain its invariance of spatial scale, related to the size of the patches. It was previously observed that around critical transitions, as for example on the onset of desertification [Kéfi et al., 2007. Nature, 449, 213-217], power law distributions become progressively truncated, thus indicating a state shift. The estuarine environment is considered a transitional



environment because of the variability in the physical parameters, including the ones we have considered in our work. It is characterized by a dynamic equilibrium which normally shows large fluctuations, with a mechanism comparable to critical transitions in a more stable habitat. It seemed therefore reasonable for us to consider the power law as a basic distribution law on which to investigate the non-linearity thresholds as a function of the environmental drivers describing the transitional character of the habitat.

**- Lines 64-66. Please rephrase. "element" should be "elements"; "small changes perturbation that: : :" does not make sense.**

Modified accordingly. We would rephrase as "small perturbations and undergo continuous adjustments".

**- Lines 70-79. My feeling is that the Authors indulge too much on their own works, neglecting a large body of literature which has addressed analogous issues in tidal landscapes, e.g.:**

**- Eastwood et al. (1997) [International Journal of Remote Sensing, 18(18), 3901-3907];**

**- Ramsey et al. (1997) [Journal of Coastal Research, 13(2), 281-292];**

**- Thomson et al. (1998) [International Journal of Remote Sensing, 19(6), 1189-1205];**

**- Thomson et al. (2003) [International Journal of Remote Sensing, 24(13), 2717-2737];**

**- Silvestri et al. (2003) [Physics and Chemistry of the Earth, 28 (1-3), 15-25];**

**- Schmidt et al. (2004) [Photogrammetric Engineering and Remote Sensing,**

**70(6), 703-715];**

**- Belluco et al. (2006) [Remote Sensing of Environment, 105, 54–67];**

**- Marani et al. (2006) [Estuarine Coastal Shelf Sci., 69, 414–426];**

**- Wang et al. (2007) [Remote Sensing of Environment, 107 (4), 559-570].**

We thank the reviewer for the suggested references. These will be integrated in the revised version of the manuscript.

**Line 84. "on certain occasions" is very vague. Please clarify.**

We have observed a deviation from the model power law in 9 out of the 12 vegetation distributions that we extracted from satellite images, in what apparently seemed to be independent from environmental conditions.

**- Line 105. "represent" should be "represents".**

Done accordingly.

**- Lines 124-126. This sentence does not make sense. Please rewrite.**

We would rephrase as: "Patches of Spartina anglica, Salicornia europaea, and to a lesser extent Scirpus maritimus and Puccinellia maritima, colonize the pioneer zone."

**- Line 127. What do you mean with "strong climate forcing"?**



The sentence will be rephrased to clarify that the salt marsh is influenced by climatic and hydrologic forces, such as tidal fluctuations and variations in rainfall.

**- Lines 157-159. I wonder why the "starting and ending points" were chosen at channel bifurcations.**

We have identified the channel segments as delimited by the points of channel bifurcations, and then we calculated sinuosity on the length of these segments. The points of channel bifurcations have been used to delimit channel segments in the morphometric analysis techniques for terrestrial river systems [Horton, R. E. 1945. Geological Society of America Bulletin 56:275-370; Strahler, A. N. 1952. Geological Society of America Bulletin 63:1117-1142].

**- Line 163. I fairly do not think that you need to specify that you have used Pythagoras' theorem to compute the distance between two points.**

Done accordingly.

**- Lines 164-166. I wonder why these network attributes were chosen. Is there a physical explanation? Does the number of bifurcation points or the total number of channels carry information on network structure and function?**

Due to the fact that vegetation establishment can have a strong impact on changes in channel network properties, and in order to investigate the possible mechanisms relating vegetation development to changes in channel sinuosity, we have considered the channel properties at the scale of the whole drainage network in the salt marsh. Thus, we have also taken into account the total number of channels and the number of bifurcation points for each time step, as well as the corresponding vegetation distribution. Such channel morphometric analyses can be used to describe a drainage configuration that satisfies the drainage function in tidal systems [Zeff, 1999. Restoration Ecology 7(22): 205-211].

**- Lines 170-171. Please clarify the reason for averaging tide levels over 14, 30 and 60 days before the acquisition.**

We would clarify the aspect as follows: "Environmental variables were averaged over 14, 30 and 60 days before the acquisitions, in order to take into account that different variables may have different timings in the way they affect the system. Different components should be considered together on multiple time scales, but that would be difficult to differentiate on a single differential equation. For this reason, we have considered time-based variables, so that the time scales are implicitly inserted in the calculation following a fixed modular structure (14, 30, 60 days), thus allowing us to observe possible cumulative effects on the evolution of the system."

**- Lines 176-177. I wonder if there is any evidence supporting the assumption that actual landscapes are not in "dynamic equilibrium".**

In the manuscript we referred to the view of actual landscapes according to Taylor (1950) and Scheidegger (1994) [Geomorphology, 10:19-25]. We would although rewrite accordingly as:

"We started from the fact that the aspect of actual landscapes corresponds to a dynamic equilibrium, which can be governed by a self-organized order at the edge of



chaos in an open dissipative system".

**- Line 198. Please define alpha.**

Alpha is defined as the scaling exponent of the power law. This will be revised accordingly.

**- Line 237. "aposteriori" should be "a posteriori".**

Done accordingly.

**- Lines 290-293. I wonder why channel sinuosity should be related to patch size. What are the biogeomorphic processes and feedbacks responsible for the relationship between channel properties and patch size distribution?**

The reason we investigate the relationship between patch size and channel sinuosity is based on the existence of feedbacks between vegetation colonization and channel network development [Temmerman et al., 2007; Vandenbruwaene et al., 2012]. The interactions between the organisms and the environment leads to a positive feedback on short scales, while a negative one inhibits their growth on larger scales. These so-called scale-dependent feedbacks [van Wesenbeeck et al., 2008. Oikos, 117(1):152-159; Bouma et al., 2009. Oikos, 118(2):260-268] have shown that flow deflection caused by the presence of vegetation patches can trigger channel erosion just outside the patches, and over time will lead to the formation of a marsh platform dissected by channels.

**- Line 297. "distribution" should be "distributions". The sentence in lines 297-298 is unclear, please rewrite and clarify.**

We would clarify accordingly as follows:

"Most of the observed distribution may be disregarded due to its deviation in the tail, although it has been shown that a decrease of the truncation in the patch size distribution can be a strong indicator of degradation in self-organized spatial patterns [Weerman et al., 2012. Ecology, 93:608-618]."

**- Lines 343-351. The non-linear relationship between inundated slat-marsh area and tidal height was observed by Ragotzkie and Bryson (1955) [Bull. Mar. Sci. Gulf Carib. 5, 297-314] and later used by e.g. Boon (1975) [Limnology and Oceanography 20, 71-80] and Pethick (1980) [Estuarine and Coastal Marine Science 11, 331-345] in their simplified models of tidal channel hydrodynamics. It is usually called hypsometric curve. The effects of an increase in the tidal level can be determined straightforward, with no need of "sophisticated" analyses. Moreover, I do not see any (non-trivial) linear relationship between the percentage of inundated area and the tidal level for elevations smaller than -50 cm NAP.**

We agree with the reviewer. These publications are relevant and we will integrate them in the section.

**- Lines 359-360. Where was this shown?**

We would rephrase the sentence as: "The applied non-linear power law shows that



vegetation patchiness could be accurately estimated from the surrounding environmental conditions (salinity, rainfall, water height)."

**- Lines 402-406. This speculation might be interesting, but need be supported by evidence in a scientific paper.**