Early Indicators of Abrupt Desertification Transitions

Cecilia Pennetta[1,3]
Raffaele Corrado[2] and Anna Maria Cherubini[1]

[1]Dipartimento di Matematica e Fisica «Ennio De Giorgi», Università del Salento, Lecce
[2] Istituto di Scienze dell'Atmosfera e del Clima (ISAC), CNR , Lecce
[3]INFN, Sezione di Firenze

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cecilia.pennetta@unisalento.it

Introduction:
motivations and aims of the works

- Regime shifts in ecosystems can imply severe looses of biological resources with relevant economic and social effects.
- This is especially true when they involve abrupt transitions occuring on a relatively short timescale.
- A special case of regime shift is given by desertification transitions of arid or semi-arid ecosystems.
- These ecosystems are rather fragile when subjected to strong external stresses.
- They can be strongly affected by anthropogenic and climatic factors, like an increased frequency of extreme climatic events

A crucial issue in this field concerns the identification of early and reliable transition indicators, providing not only an estimate of the desertification risk, but also a tool to monitor the effectiveness of actions devoted to contrast this risk.

To this purpose, several new transition indicators have been recently proposed (*).

Many indicators are based on the analysis of the vegetation patterns and in particular on their patchiness (*).

* S.Kèfi et al, PLOS ONE 2014, R. Corrado et al , PRE, 2014

Patchiness: mosaic of vegetation patches and bare soil

Typically, arid landscapes near desertification are characterized by less than 60% of vegetation cover

Several experimental techniques are now available (*) for a fast and efficient measure of the vegetation patchiness:

Satellite remote sensing,
Automate CLASlite technique:
http://claslite.ciw.edu/en/index.html
LiDAR techniques

* S.R. Levick , G.P. Asner, Biol. Conserv., 157, 2013.
S. Palminteri et al., Rem. Sensing of Environment , 127, 2012.

Several models have been introduced to study desertification, some of the more recent:

S. Kèfi et al. Nature, 2007 and Theor. Popul. Biology, 2007

N. M. Shnerb et al., PRL, 2003

V. Guttal et al. Ecological modelling, 2007

M. Rietkerk et al., American Naturalist, 2002

Both simulated and observed vegetation patterns agree in reporting a power-law behavior of the patch-size distribution $\Pi(s)$ when the system is in "good" conditions, far from desertification and, for contrast, the emergence of an exponential cut-off in $\Pi(s)$ at high external stress.

The emergence of this cut-off has been proposed as an early indicator of desertification (S. Kefi et al. Nature, 2007).

Recently, we have used the SCA model (*) to simulate an arid (or semi-arid) ecosystem undergoing a desertification transition with realistic patchiness dynamics

We have analyzed the resulting vegetation clusters in terms of percolation theory, assumed as an effective tool for analyzing the geometrical properties of the clusters

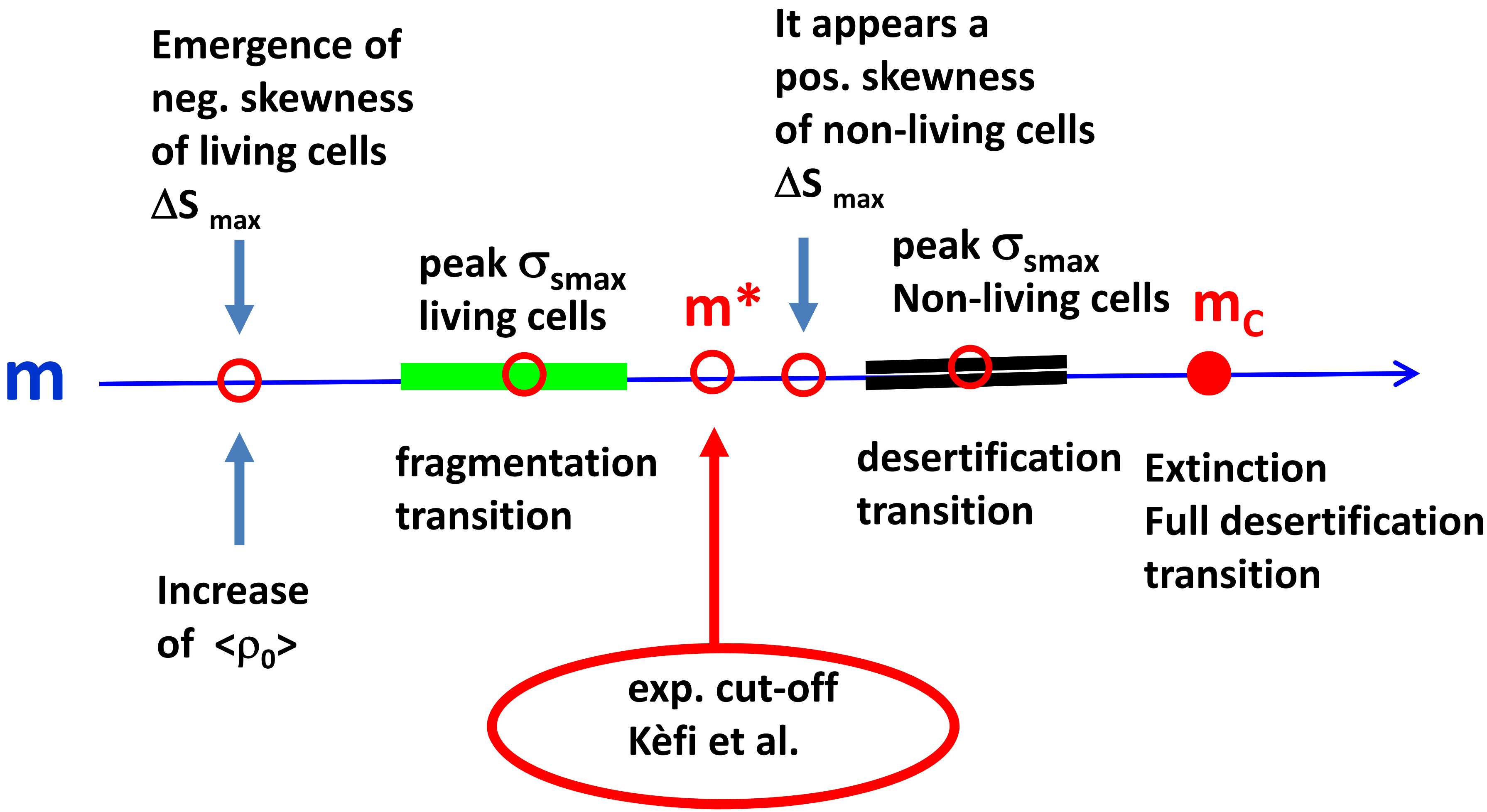
We have found that a percolation analysis of the geometry of the clusters is very fruitful to extract several new early transition indicators (**).

i.e. we showed that a geometric characterization of the patchiness generated by the "true" system's dynamics, can be very effective for understanding some basic features of the desertification transition.

* S. Kèfi et al. Theor. Popul. Biology, 2007

** R. Corrado et al , PRE, 90, 062705, 2014 ⬅

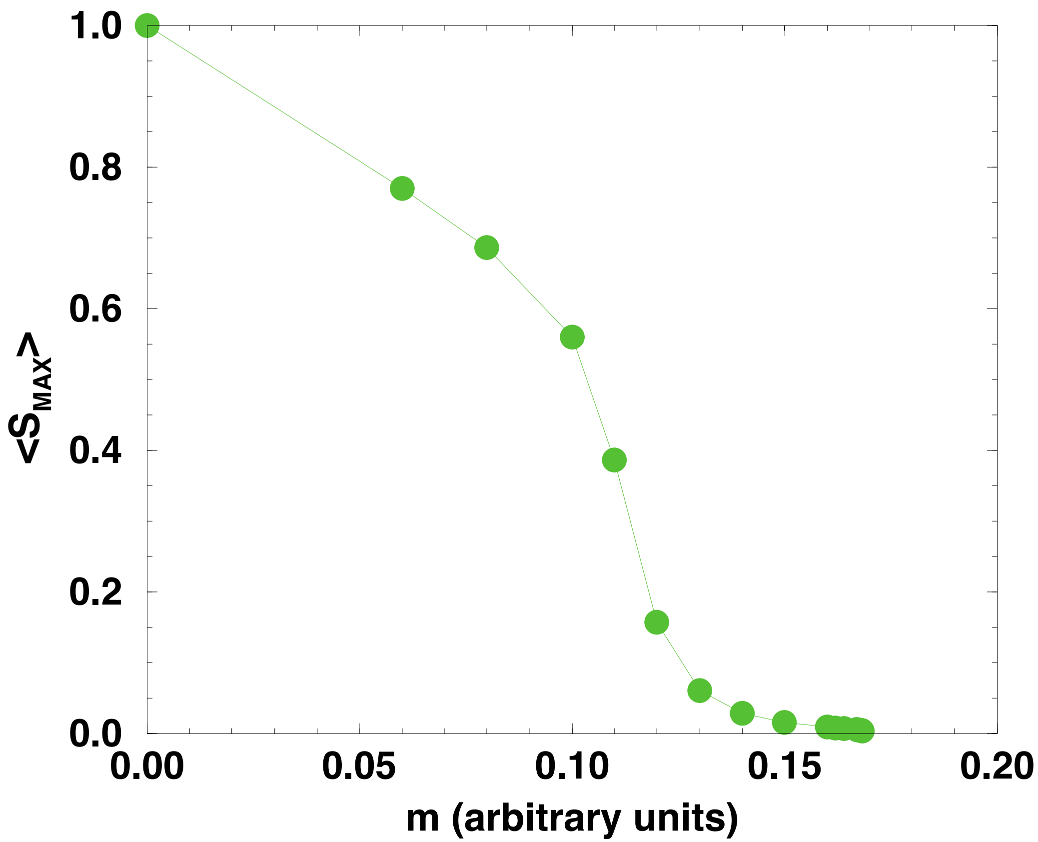
At increasing mortality rate m (strength of external stress, driving parameter of the transition):



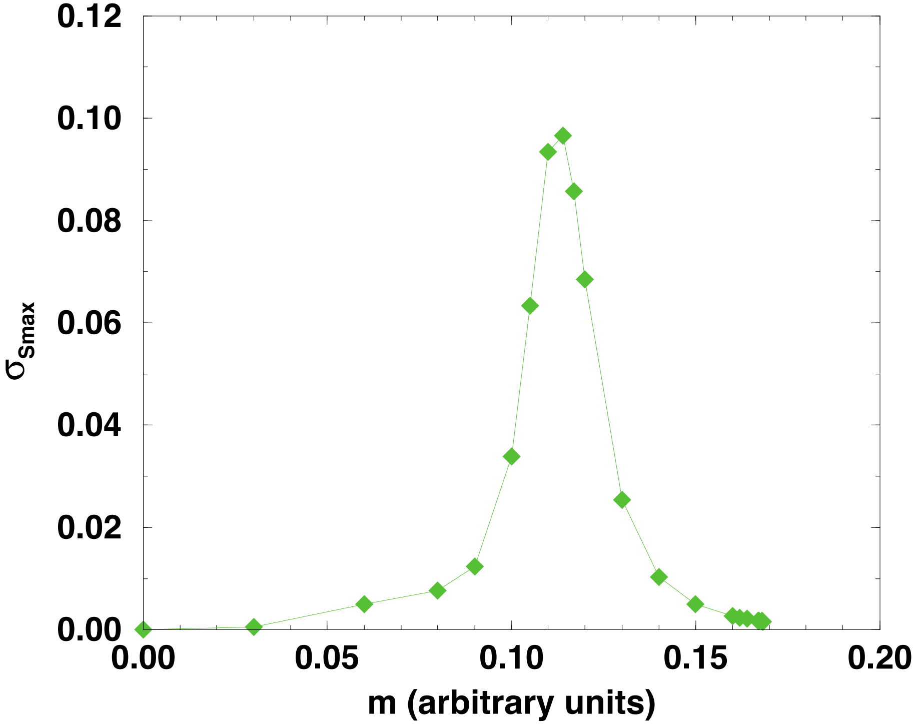
Importance of considering multiple and indipendent indicators for analyzing real world, <u>short</u> time series

In particular, we have found that many information can be extracted from the analysis of

Size of the biggest vegetation cluster



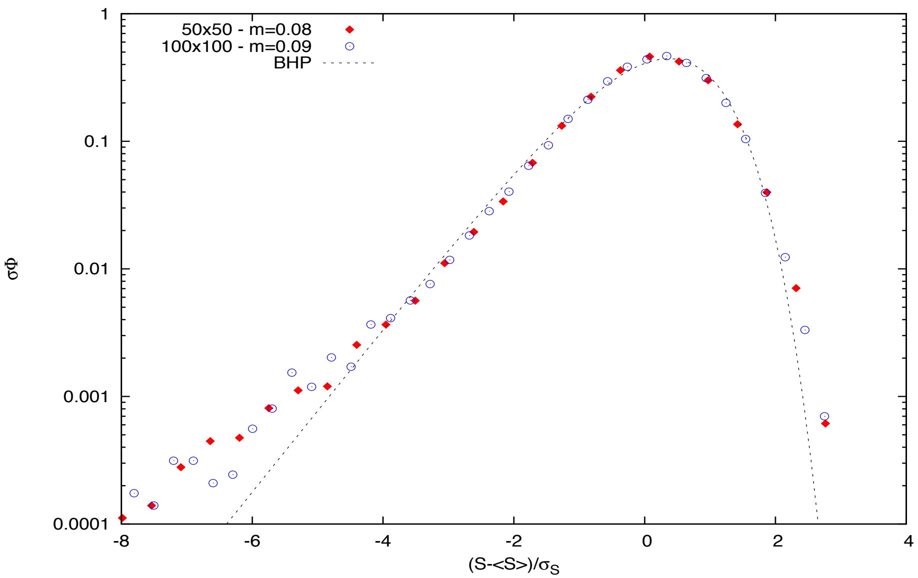
Fluctuations of size of the biggest vegetation cluster

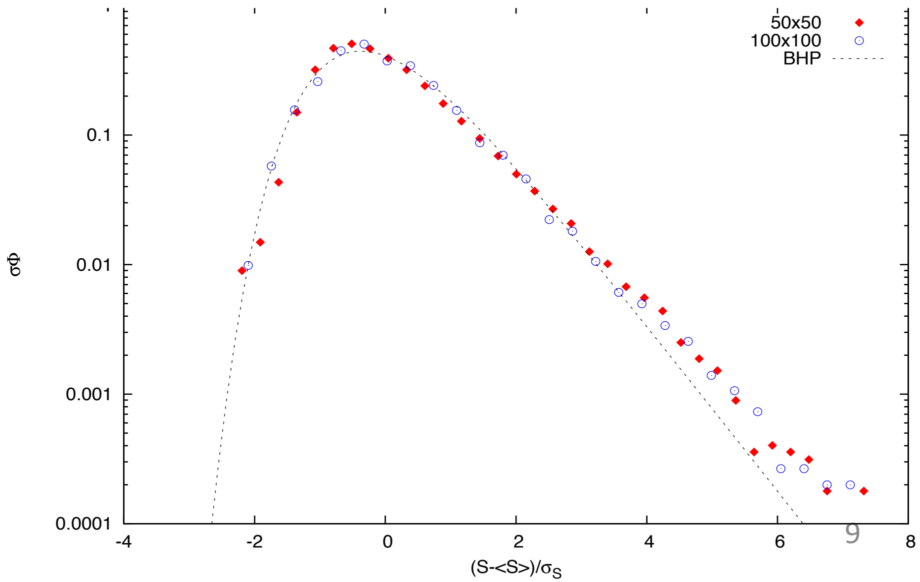


Peak of the root mean square deviation at the threshold for fragmentation transition

R. Corrado et al , PRE, 90, 062705, 2014

Change of the skewness sign of the fluctuation disribution





However, our previous percolation analysis concerned the case of a system undergoing a continuous or nearly continuous transition in terms of the fraction of vegetation cover ρ^+ (order parameter)

Therefore the aim of the present study is to extend the analysis to the very important case of abrupt transitions

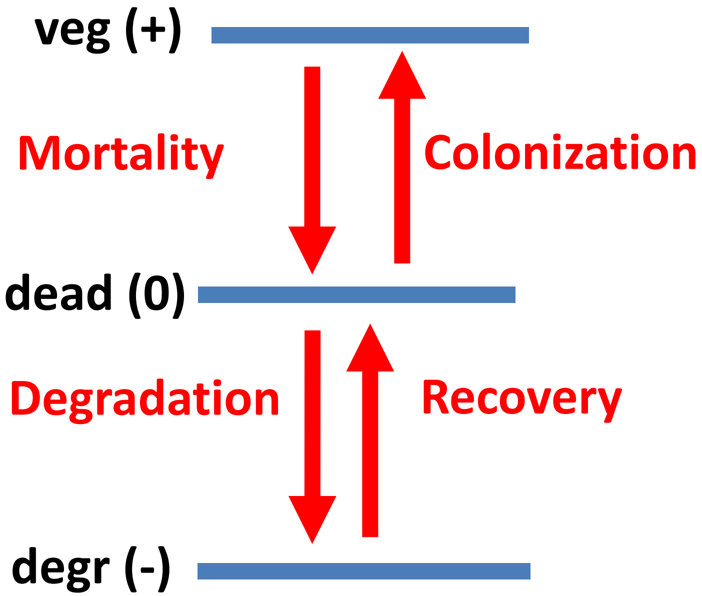
In particular we want to explore the validity of the early indicators based on the properties of the biggest vegetation cluster also to the case of abrupt desertification transitions.

The SCA model

A <u>three states</u> stochastic cellular automaton (CA) on a square lattice ($N \times N$) with periodic boundary conditions. Each cell can be in:

- a vegetated state (denoted by +)
- a dead state, empty of vegetation but colonizable (denoted by 0)
- a degraded state empty of vegetation but not directly colonizable (denoted by −).
  a degraded cell need first to be recovered to the state 0 before being colonizable.

S. Kefi et al., Theor. Popul. Biol. 71, 267, 2007



Rates of the allowed transitions:

$W_{+0} = m$ Mortality

$W_{0+} = [\delta\rho_+ + (1-\delta)q_{+|0}](b - c\rho_+)$ Colonization

$W_{0-} = d$ Degradation

$W_{-0} = r + f\, q_{+|-}$ Recovery

ρ_+ , ρ_0 , ρ_- fractions of cells in the states + , 0 , -

$q_{i|j}$ fraction of first neighbor cells in the state i for a given cell in the state j :

$$q_{i|j} = \frac{n_{i|j}}{N_{neig}} = \frac{n_{i|j}}{4}$$

Model parameters:

δ = fraction of seeds globally dispersed by wind, animals etc,

b = intrinsic colonization parameter (intrinsic properties of a vegetated cell: seed production rate, seed survival, germination, survival probabilities)

c = strength of global competition effects among plants

d = soil degradation rate, it depends on intrinsic soil characteristics, and on climatic / anthropogenic factors

f = local facilitation parameter, local cooperative interactions among plants and positive feedback between soil and plants.

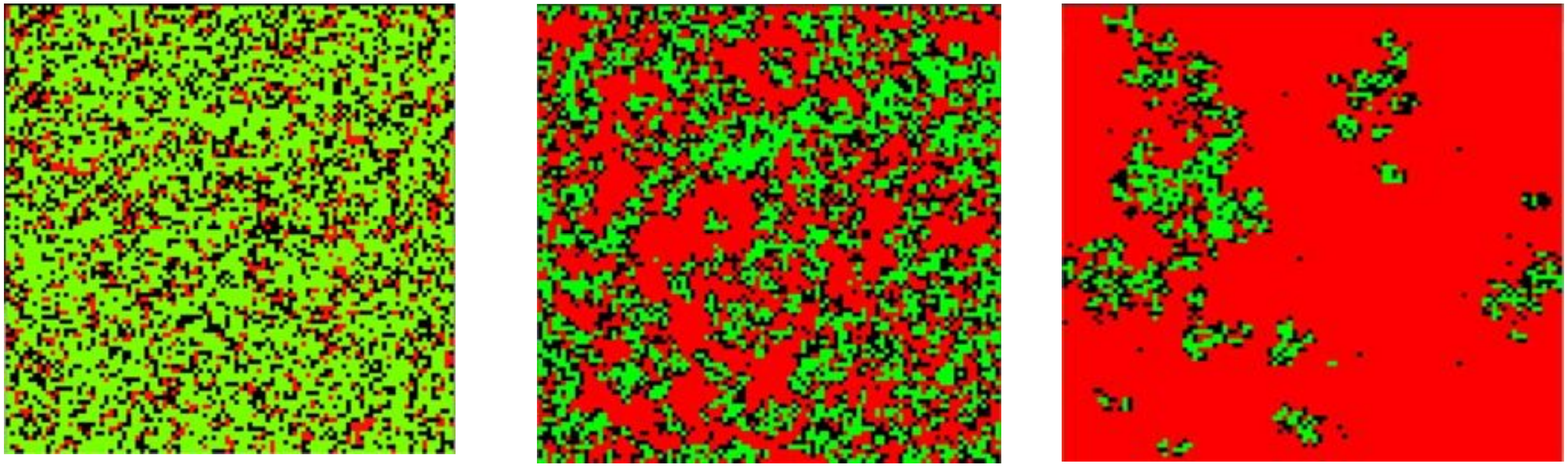
r = spontaneous regenerative rate of a degraded cell (in absence of vegetation over first neighbor cells).

Depending on the regions of the parameter space: continuous or abrupt transitions towards a single absorbing state or bistability

We focused on transitions towards a single absorbing state occurring at increasing values of the mortality rate m driving parameter of the transition, while the density ρ^+ is the order parameter

A threshold value of mortality rate exists above which:

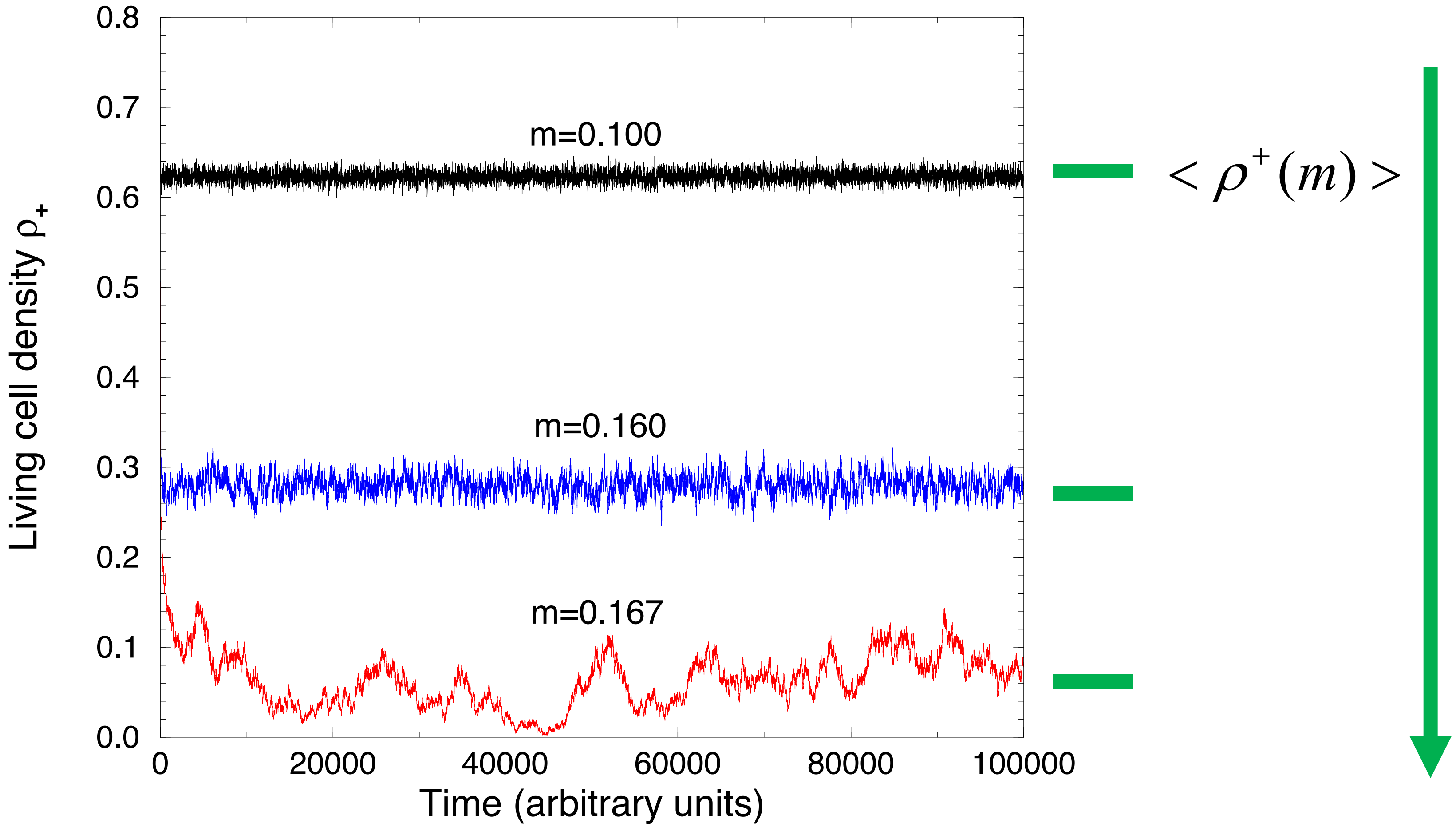
For $m > m_c$ → $<\rho^+> = 0$ → vegetation extinction and soil degradation



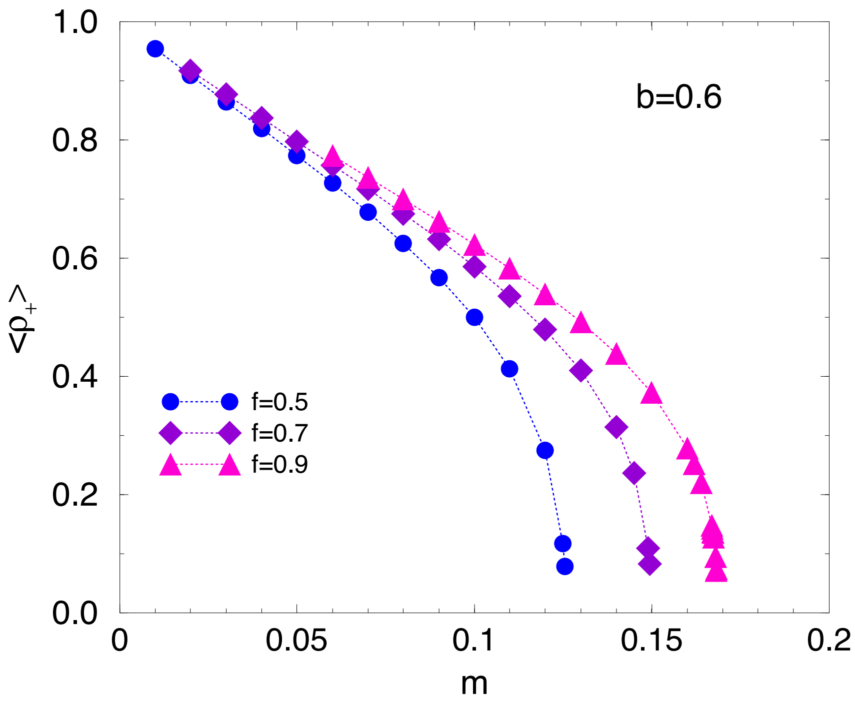
living cells   dead cells   degraded cells

Dead cells mainly located at the interfaces

Simulated time series at increasing mortality rate m



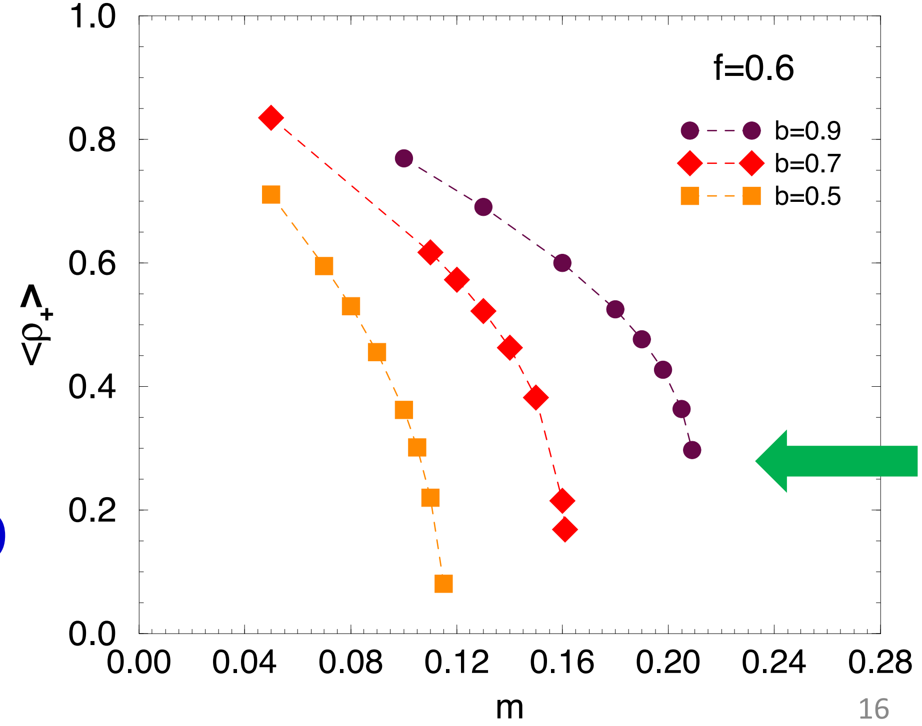
Continuous, nearly continuous or abrupt transitions



For $m > m_c$ ⟹ $<\rho^+> = 0$

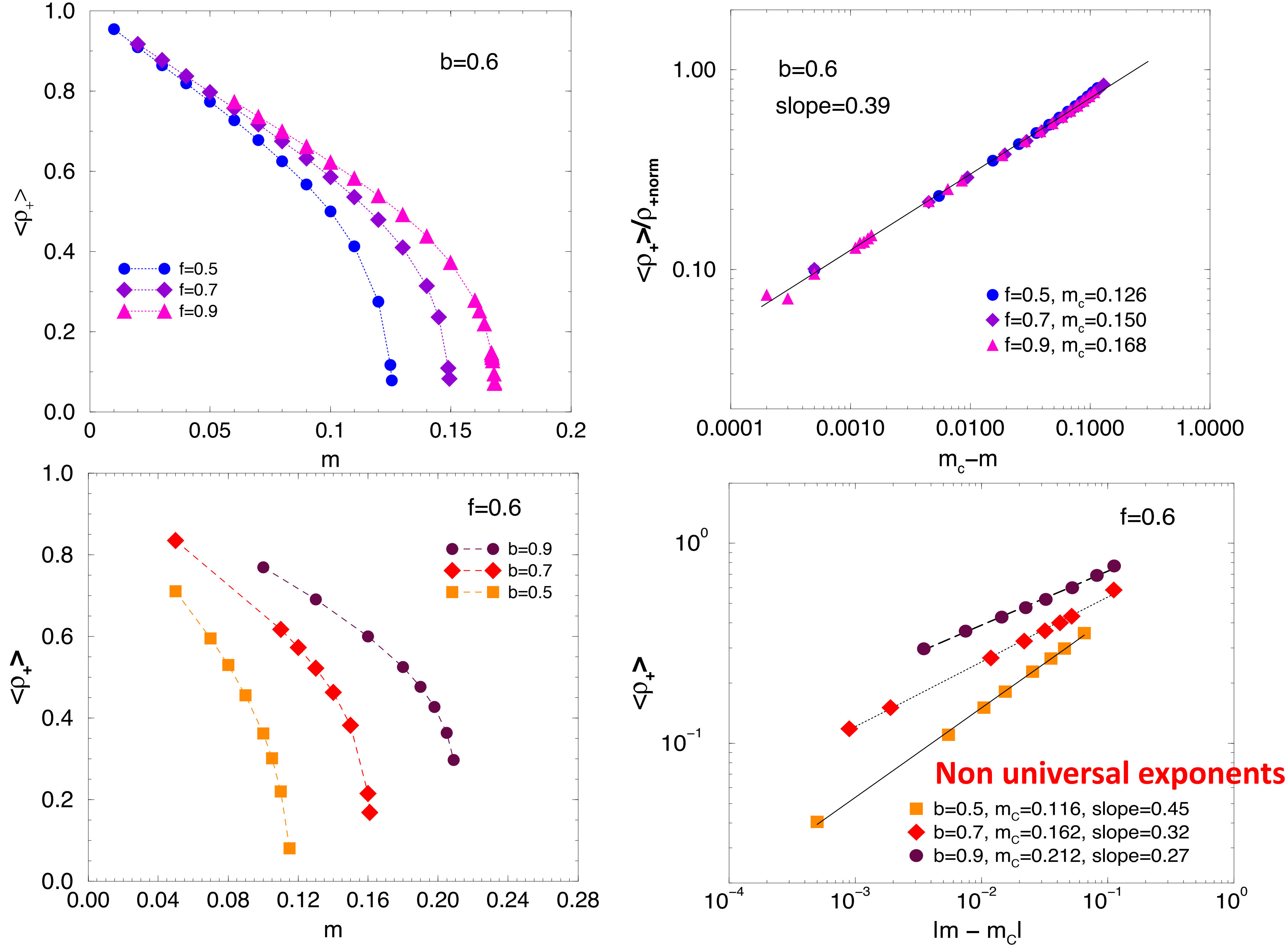
For $m = m_c$ continuous $<\rho^+> = 0$

nearly continuous $<\rho^+> \approx 0$



For $m = m_c$ ⟹ $<\rho^+> \neq 0$

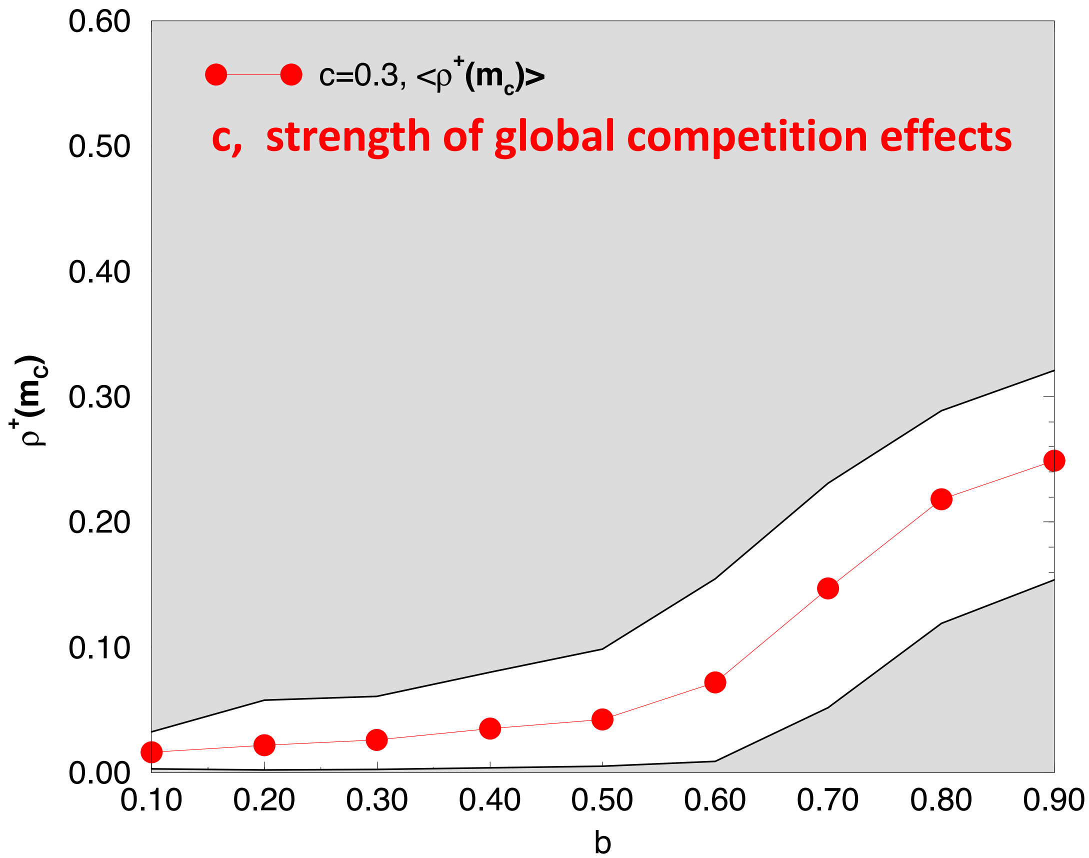
Abrupt transition



R. Corrado et al. CNSNS, 2015 and Procs. ISCS'14, Springer Series on ECC, 2015.

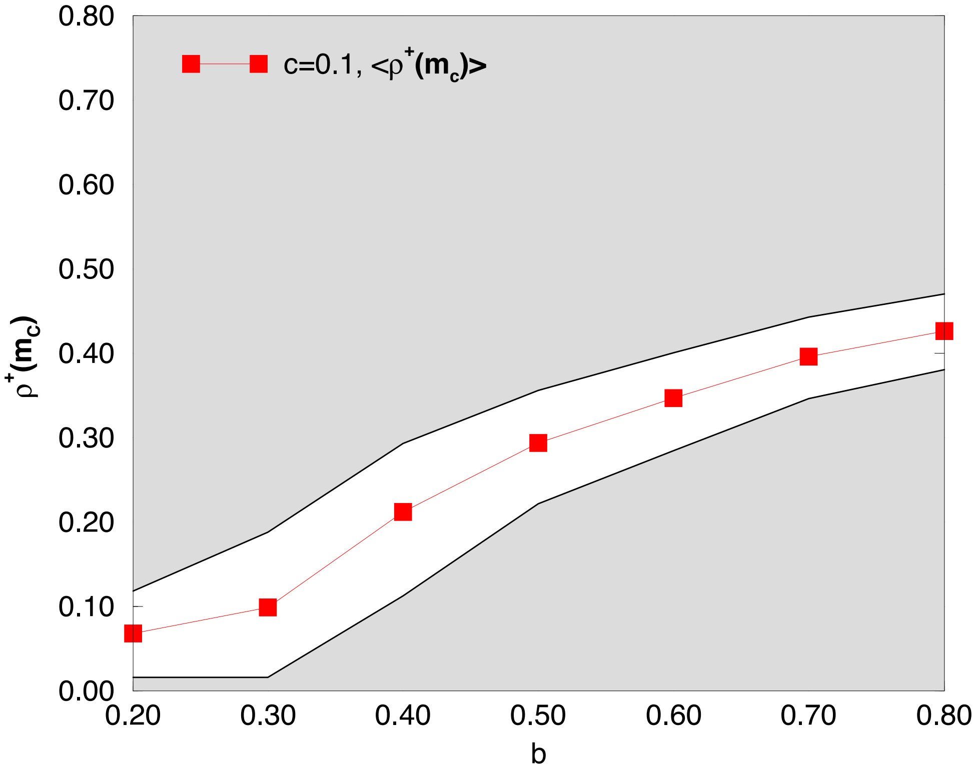
Early indicators previously identified for continuous transitions keep their validity also for abrupt transitions?

To answer this question, we need preliminary to state more clearly the character (nearly continuous or abrupt) of the transition corresponding to a given set of values of the model parameters



Average, minimum and maximum values of $<\rho^+(m_c)>$ over an ensemble of 50 realizations vs. b, intrinsic colonization parameter

Increasing b the transition becomes more and more abrupt



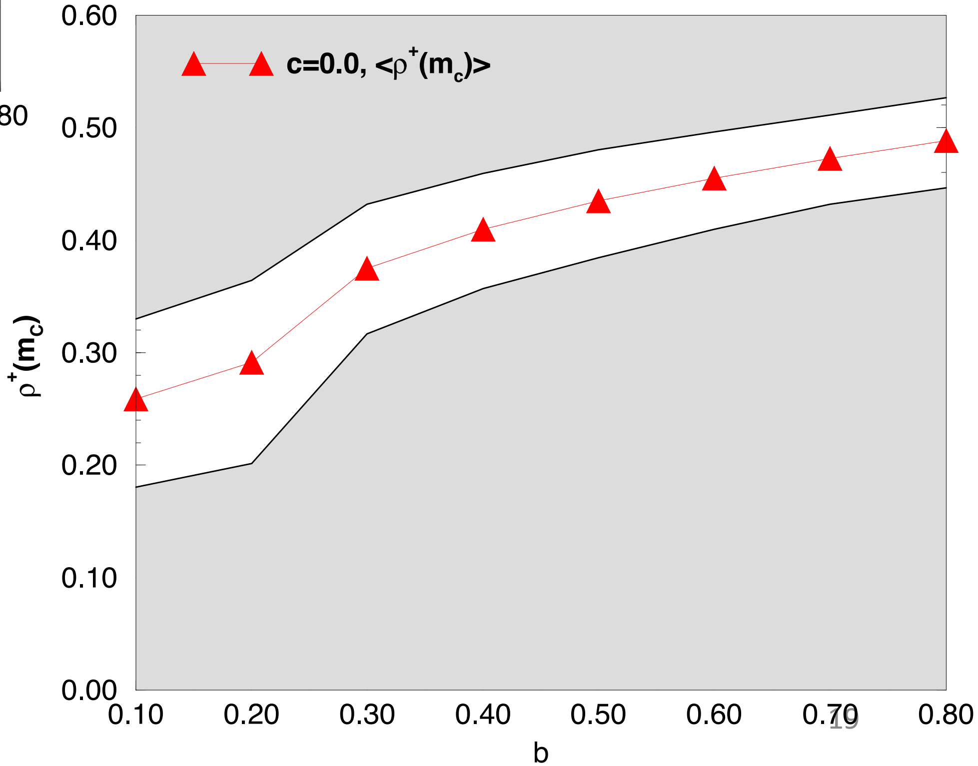
weak strength of global competition effects:

c = 0.1

No global competition effects:

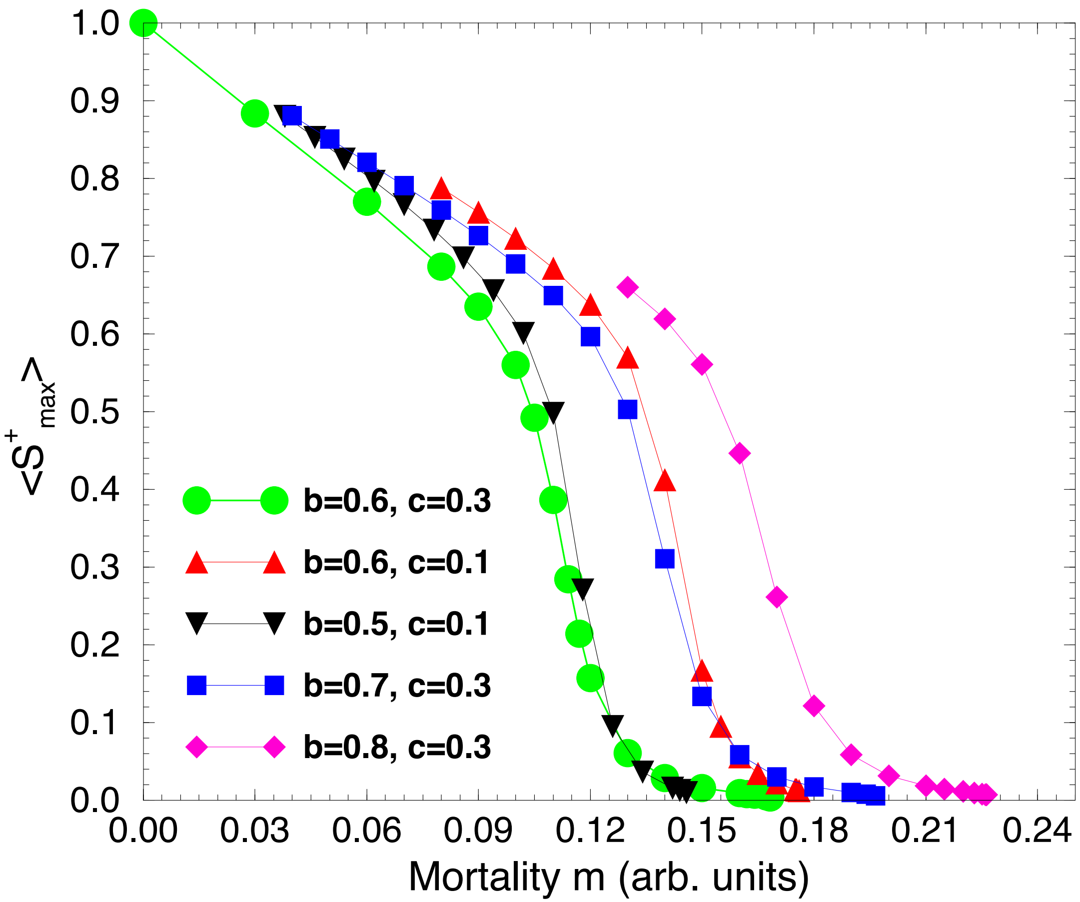
c = 0

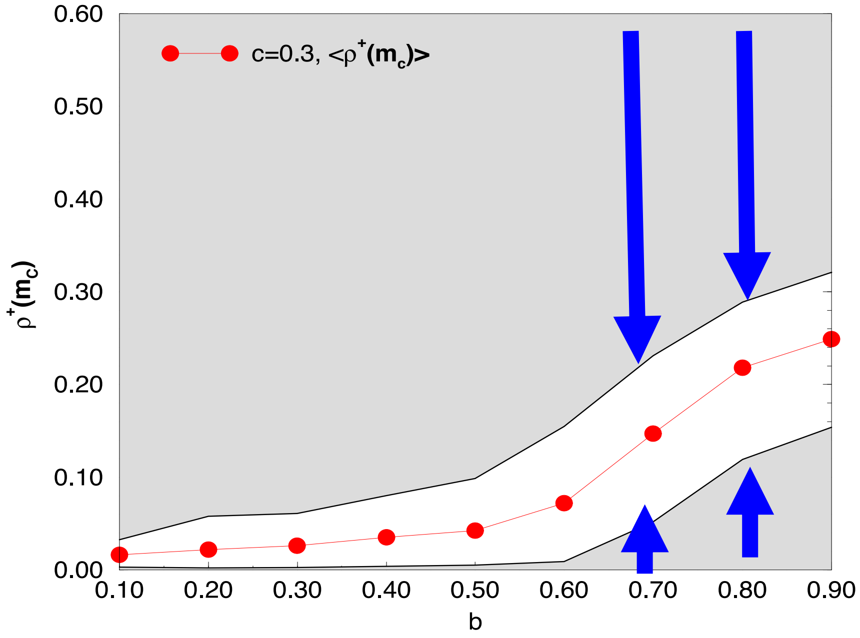
Only abrupt transitions



$\langle S^{+}_{max} \rangle$ size of the biggest vegetation cluster vs. mortality rate for different values of b and c parameters

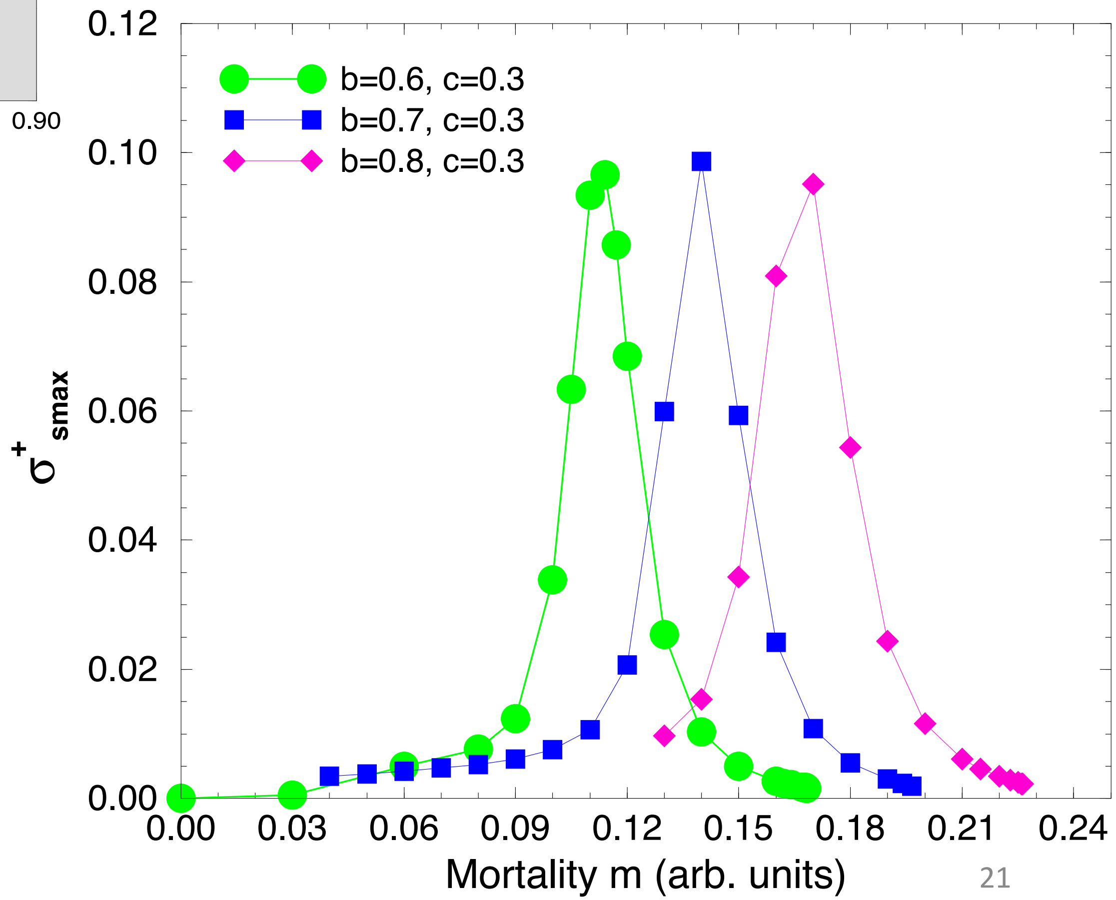
(averaged over the stationary part of the time series)





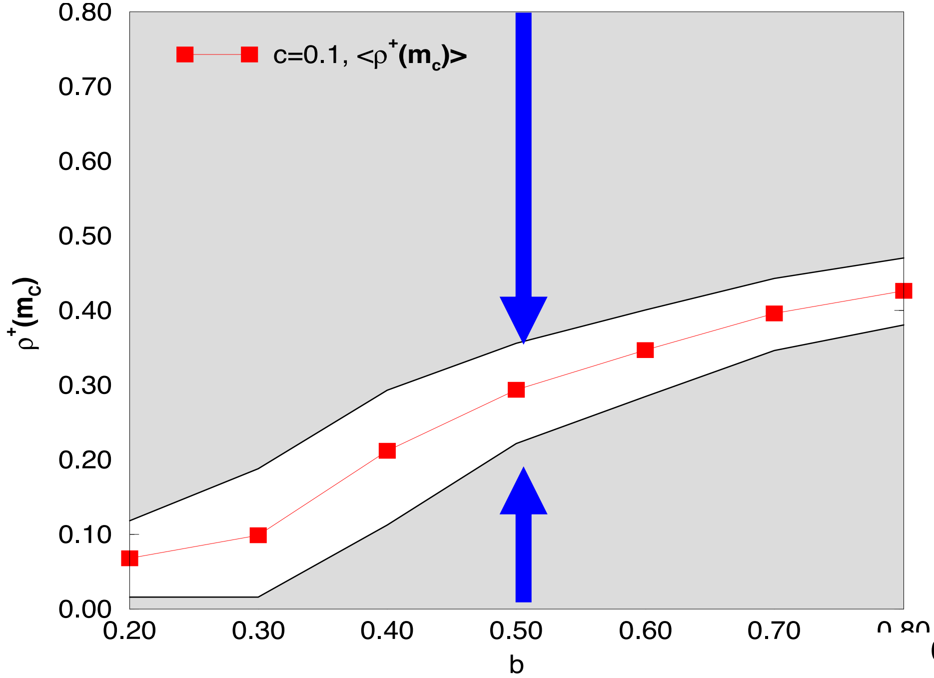
b = 0.7, 0.8 and c = 0.3

Abrupt transition



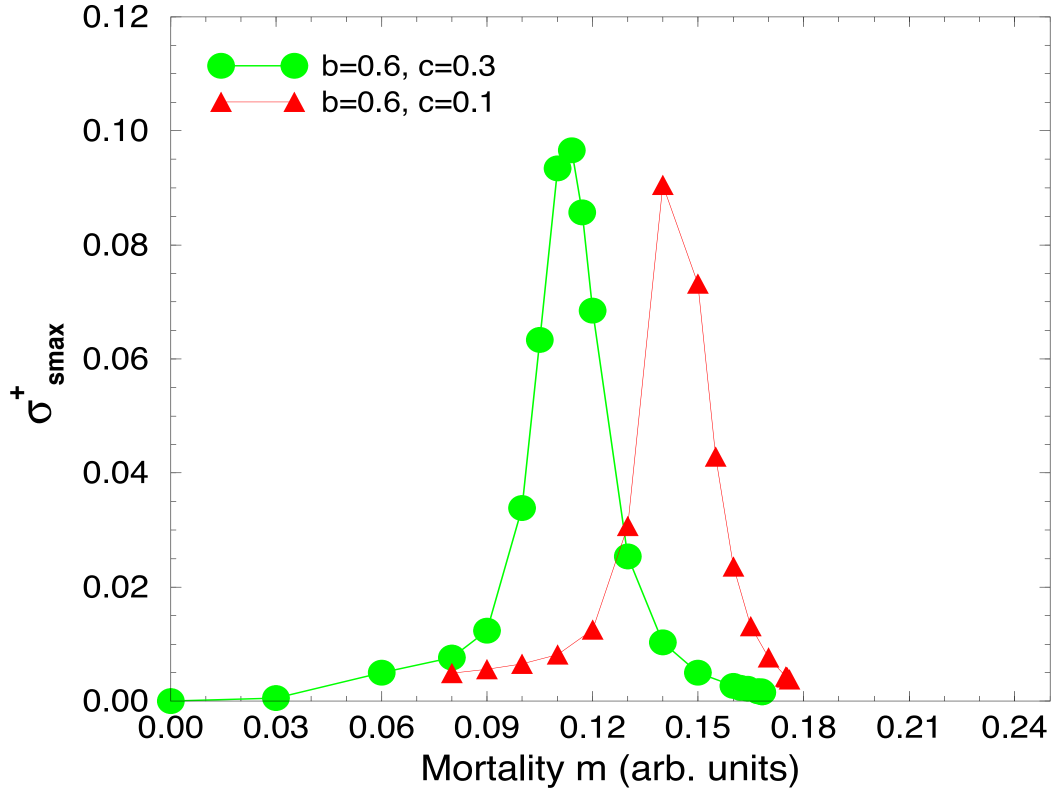
Only the position of the peak of σ_{smax} depends on the parameter values, the height and width depend only on the size of the system

M. Z. Bazant, PRE, 2000



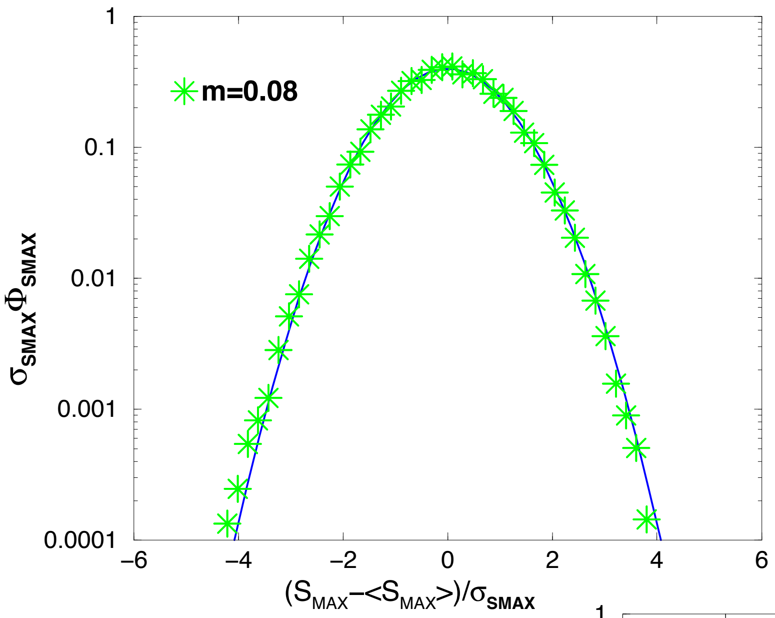
b = 0.6, c = 0.1

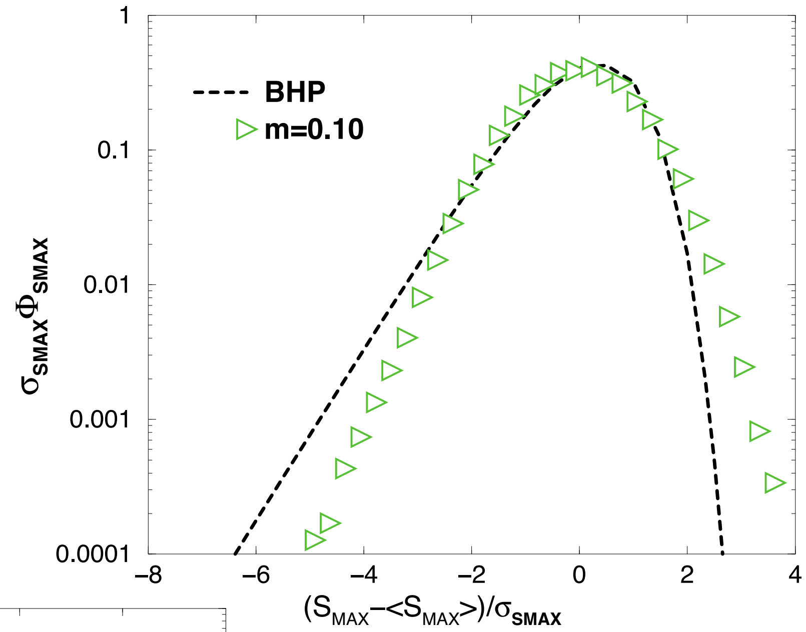
Abrupt transition

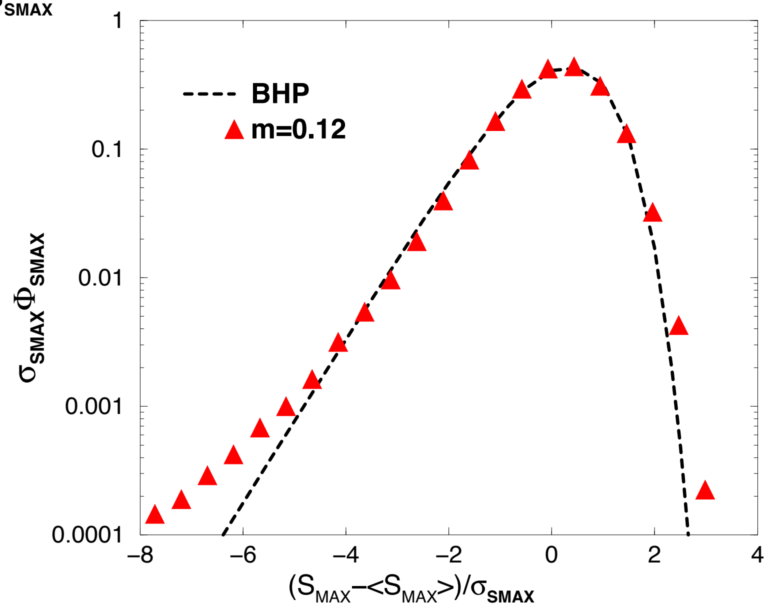


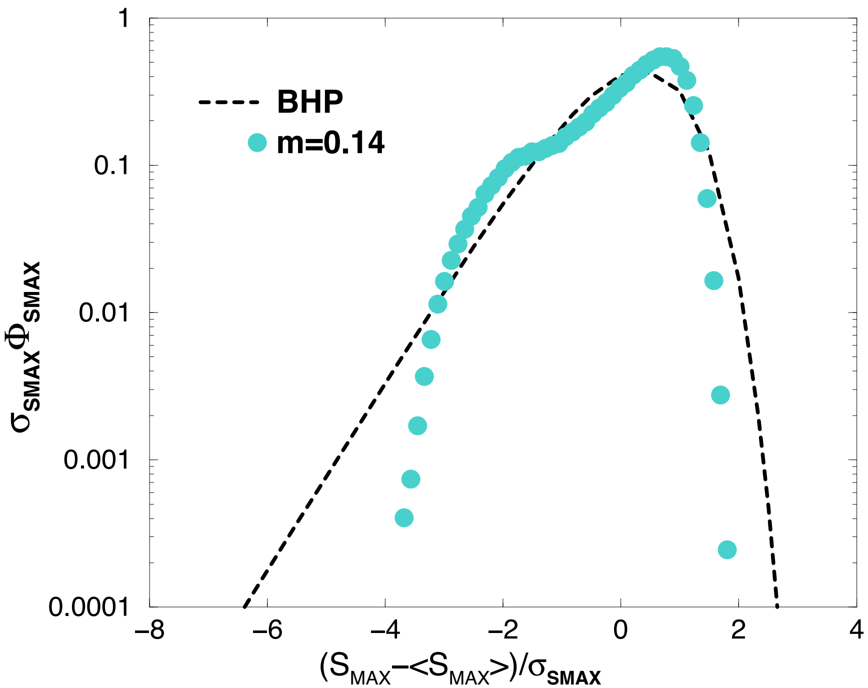
Only the position of the peak of σ_{smax} depends on the parameter values

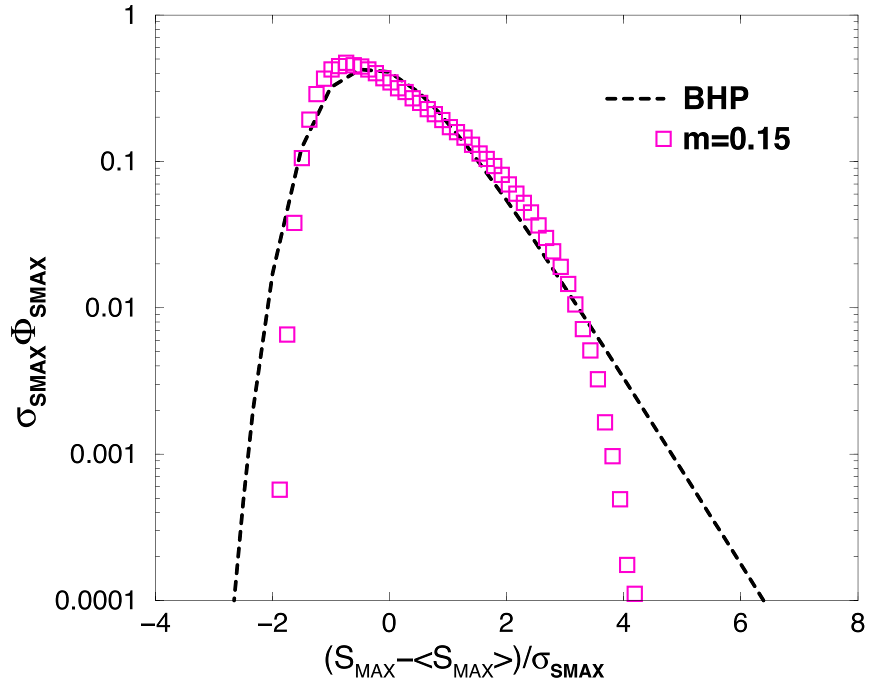
Fluctuation distribution for the size of the biggest vegetation cluster vs. m (b=0.6, c=0.1, abrupt transition)

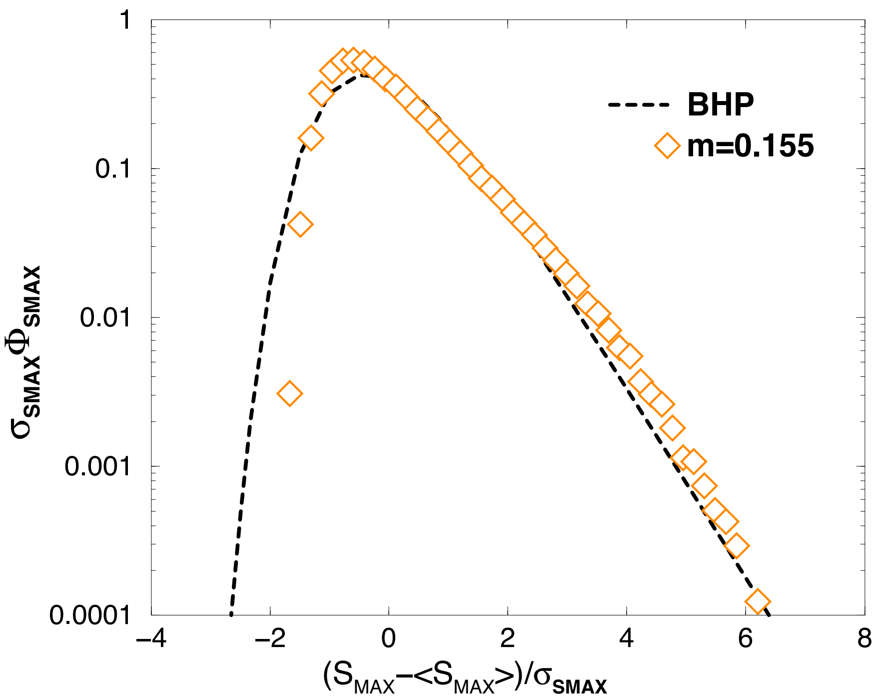




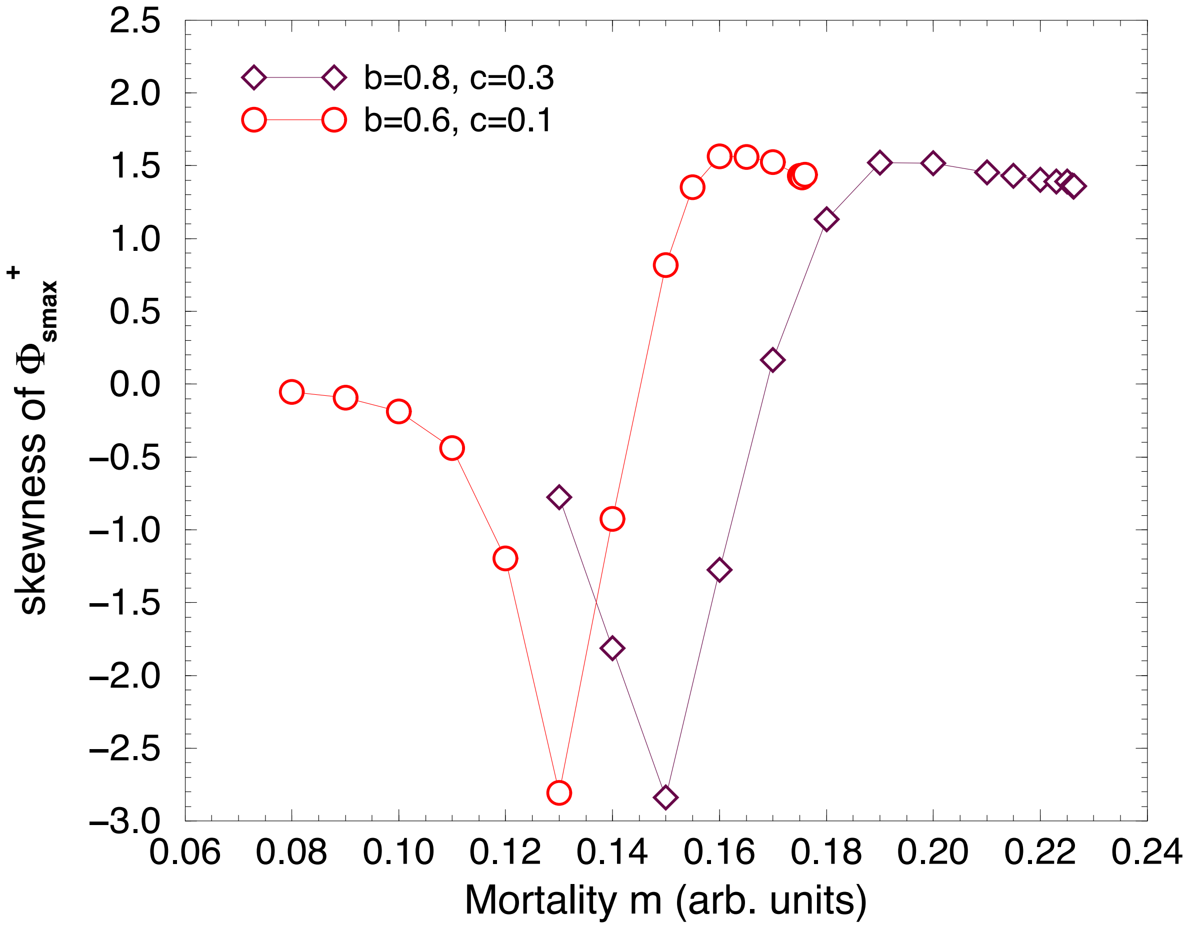



BHP
m=0.14
1
0.1
0.01
0.001
0.0001
−8
−6
−4
−2
0
2
4
$\sigma_{SMAX}\Phi_{SMAX}$
$(S_{MAX}-\langle S_{MAX}\rangle)/\sigma_{SMAX}$


BHP
m=0.15
1
0.1
0.01
0.001
0.0001
−4
−2
0
2
4
6
8
$\sigma_{SMAX}\Phi_{SMAX}$
$(S_{MAX}-\langle S_{MAX}\rangle)/\sigma_{SMAX}$


BHP
m=0.155
1
0.1
0.01
0.001
0.0001
−4
−2
0
2
4
6
8
$\sigma_{SMAX}\Phi_{SMAX}$
$(S_{MAX}-\langle S_{MAX}\rangle)/\sigma_{SMAX}$

Skewness of the fluctuation distribution of the size for the biggest vegetation cluster vs. m



Both abrupt transitions

Conclusions

- Recently, we have used the SCA model to simulate an arid (or semi-arid) ecosystem undergoing a desertification transition with realistic patchiness dynamics

- We have analyzed the resulting vegetation clusters in terms of percolation theory which offers a powerful tool for analyzing the geometrical properties of the clusters

- In the case of continuous or nearly continuous transitions, we have shown in a previous work that the study of the fluctuation properties of the size of the biggest vegetation cluster allow the identification of new transition indicators, including very early ones.

- Here we have shown that these new early indicators keep their effectiveness also in the very important case of abrupt desertification transitions.

Thanks for your attention!

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