



## Contributions of the complexity paradigm to the understanding of Cerrado's organization and dynamics

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### ABSTRACT

The Brazilian Cerrado is a vegetation mosaic composed of different physiognomies. Discussions remain open regarding the factors and processes responsible for the dynamic and spatial organization of the Cerrado - in its different physiognomies. The contributions of the complexity paradigm in this context are still less exploited, despite its great potential for explanations and predictions presented in previous diverse dynamic systems of complex behavior researches, a category in which the Cerrado can be included. This article has the intention of contributing to the construction of this new perspective, discussing - from theoretical concepts - the paradigm of complexity for the understanding of the organization and the dynamics of the Cerrado.

**Key words:** Cerrado, complexity, complex system, dynamics, self-organized criticality.

### INTRODUCTION

Being a mosaic of phyto-physiognomies distinguishable by their spatial patterns, the Brazilian Cerrado covers approximate 2 million km<sup>2</sup> of the Brazilian territory (Silva and Bates 2002). This mosaic follows a gradient starting with a totally open formation, covered only by the herbaceous extract (*campo limpo*, *i.e.*, clean field), up to a forest (*cer-*

*radão*, *i.e.*, big cerrado). There are also intermediate formations, as *campo sujo* (dirty field), a grassland with sparse shrubs; *campo cerrado* (cerrado field), an open scrubland with few trees; and *cerrado stricto sensu*, a woodland with closed shrubs and spaced trees (Gardner 2006). The density of the area covered by trees and their level of grouping are indicators defining the typical spatial pattern of each physiognomy.

The nuclear areas of the Cerrado occur on crystalline and sedimentary plateaus of the central region of Brazil (Silva and Bates 2002), with altitudes of 300 up to 1700 meter. The

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annual precipitation is over 1000mm, mostly concentrated from October through March. In the dry season, vegetation water supply is assured by the groundwater accumulated at depths of 10 to 20 meters, which is absorbed by the deep roots (Silva and Bates 2002). In general, the Cerrado vegetation occurs on nutrient-poor, well drained acidic soils (Furley and Ratter 1988). The same soil characteristics are present in the peripheral areas of the Cerrado, located in other vegetation domains such as the Amazon and the Atlantic Forests. These fragments of Cerrado vegetation result from quaternary climatic oscillations characterized by the alternation between cold-dry and hot-wet periods, causing the expansion and contraction of the Cerrado distribution.

Despite the incomplete understanding concerning the natural fragility of the Cerrado, anthropogenic actions have been causing strong environmental alterations, specially related to the degradation and fragmentation of the Cerrado (Furley and Ratter 1988). Changes have been intensified throughout the last four decades, mainly due to the extensive use of techniques in order to improve soil fertility and the cultivation of plant varieties adequate to the environmental conditions of the Cerrado, turning its nuclear region into one of the most important agricultural fronts in Brazil (Klink and Moreira 2002).

For explaining spatial distribution of distinct Cerrado physiognomies, climate conditions, bushfires and chemical soil characteristics are the factors traditionally hypothesized (Furley and Ratter 1988, Silva and Bates 2002). Different interpretations, however, derive from the same perspective: a view centered in the concept of equilibrium and in the consideration of isolated factors acting on the organization of the Cerrado.

Significant contributions were provided by this approach, which exists since the pioneer studies of Peter Lund and Eugene Warming in century XIX, as well as in those studies performed by impor-

tant researchers throughout century XX, among which it is highlighted: P. T. Alvim, W. A. Araújo, K. Arens, L. M. Coutinho, G. Eiten, M. G. Ferri, R. Goodland, M. Pavageau, M. Rachid, G. Ranzani, J. A. Ratter, F. K. Rawitscher and L. Waibel. All cited studies have significantly helped unveiling important parts of the intriguing “puzzle” represented by Cerrado to those who study it. However, the complete picture remains a great challenge, since having the parts is not enough, it is also necessary to know how they fit in the mosaic. Attempts to unite the parts from a reductionist perspective of cause and effect have been made based on the view of climatic succession of the physiognomies, according to a single environmental factor. Nevertheless, there are still several blanks left in the puzzle by this approach.

The complexity paradigm may enable not only the discovery of previously unknown parts, but also specially provide another view for solving the puzzle. This article intends to contribute to the construction of this new perspective by discussing – from theoretical concepts – how the complexity paradigm helps the understanding of the organization and the dynamic of the Cerrado.

#### ORIGINS OF THE COMPLEXITY PARADIGM

The complexity paradigm arose from the confluence of ideas and theories of several knowledge areas, which had in common the study of complex-behavior, nonlinear systems out of thermodynamic equilibrium. As these ideas gained consistence and the practical results corroborated theoretical models of a specific area, other areas started incorporating them to try explaining and predicting the behavior of systems of their interest. The reached success enabled establishing basic principles regarding the organization and functioning of either complex physical, biological or social systems (Morin 1977, Auyang 1998).

Among the theories and models linked to the complexity paradigm, there are: general

systems theory, cybernetics, dissipative structures theory, hierarchy theory, percolation theory, self-organized criticality, catastrophe theory, and fractal geometry (Naveh and Lieberman 1994, Bak 1996, Christofolletti 1999, Érdi 2008, Farina 1998, Li 2000).

Created by the Austrian biologist Ludwig von Bertalanffy, the general systems theory is one of the bases of the complexity paradigm (Érdi 2008). Bertalanffy categorized the systems according to their intrinsic characteristics and their relationships to the external environment, and defined the basic organizational principles of biological or social systems. The mechanistic-reductionist vision rupture provided by the general systems theory made way for other theories with stronger focus on certain aspects of the system organization and dynamics.

It is the case of the hierarchy theory, which arose as an attempt to explain the organization of complex-behavior systems. Having Hungarian writer and philosopher Arthur Koestler as one of its precursors, the hierarchy theory understands that such systems organize themselves in a peculiar manner: a system is formed by subsystems of lower hierarchical level and composes, at the same time, along with other systems, a higher hierarchical level system. Thus, the systems organize themselves in a hierarchically nested manner from which arise the so called “emerging properties”: attributes appearing at a hierarchical level related to the relationship among the subsystems, therefore, cannot be deduced from the analysis of the lower hierarchical levels (Allen and Starr 1982, Odum 1988, Naveh and Lieberman 1994, Érdi 2008).

Cybernetics also arose as a development of the systems theory, but it took hold of ideas and concepts from the information theory. Focused on the feedback mechanisms available in the systems, cybernetics tries understanding how such mechanisms influence the behavior of the systems and their relationship to the external environment

(Érdi 2008). Once the origin of cybernetics is strongly related to the study of information control and transmission systems, several of its principles and concepts come from the information theory. Information entropy is one of these essential concepts, which enables assessing the organization of the system from the amount and redundancy of information.

Understanding how the transition among different states occurs is a common denominator of several theories arose in distinct knowledge areas (Érdi 2008), and which have relevantly contributed to the development and consolidation of the complexity paradigm. Among them, the dissipative structures theory, the catastrophe theory, the percolation theory and the self-organized criticality theory deserve highlighting. In general, these theories aim at modeling and explaining the tendency of systems out of thermodynamic equilibrium for evolving to critical, unstable points at which qualitative changes may occur.

Finally, the study of complex dynamic systems demand the use of mathematical theories and tools – from several of its subareas: algebra, statistics, geometry – which are more suitable for describing and modeling the behavior of such nonlinear systems. One example is fractal geometry, a theory conceived by Benoit Mandelbrot to deal with the irregular patterns found in nature (Mandelbrot 1983). Fractal geometry is appropriate for dealing with objects which do not have an exact geometric form, that is, which are not points, nor lines, nor planes, but are within these geometric forms and have topological dimensions represented by whole numbers (Mandelbrot 1983, Christofolletti 1999, Souza and Buckeridge 2004, Érdi 2008). The dimension of a non-regular object is therefore a fraction, fact that inspired Mandelbrot to name it *fractal dimension*.

The term fractal is also associated to the geometrical figures or objects showing repetition of forms in different scales, a characteristic named

self-similarity, an essential property of *exact fractals* (Milne 1990, Christofolleti 1999), such as Sierpinski's carpet and Koch's curve. Even though a strict self-similarity would hardly be possible in nature, it can present itself in the statistical analysis of patterns for distinct scales (Stanley 1986 apud Milne 1990). Thus, natural fractals show statistical self-similarity related to the scale dependency of the processes (Farina 1998).

#### CONCEPTS RELATED TO COMPLEX SYSTEMS

The focuses of interest on the complexity paradigm are the complex-behavior dynamic systems, be they physical, biological or social (Morin 1977, Auyang 1998). As pointed by Macau and Grebogi (1999), complex systems have involved behavior that is not well modeled by a reductionist perspective. Such system is known as complex due to the amount of elements (or subsystems) it has, and to the diversity of these elements, in addition to the amount and variety of relationships among them (D'Ottaviano and Brescianni-Filho 2004). Consequently, a system composed by few elements may show complex behavior due to the network of relationships among the elements; whereas a system with innumerable elements may not be necessarily complex, depending on how the elements relate to one another. Besides, it is worth mentioning that complexity is not necessarily a synonym for complication: the complex behavior of a system may result in simple operational rules (Cadenasso et al. 2006), as several models have shown. This complexity arises partly due to emerging properties (or synergy) of the system, characteristics resulting from the interactions among elements of the system and which do not exist when isolated, making the system different from the superposition of its parts (Mattos and Perez-Filho 2004).

Jensen (2009, p. 1268) synthesized these ideas as follow: "*Complex systems consist of a large number of interacting components. The interactions give rise to emergent hierarchical structures. The*

*components of the system and properties at systems level typically change with time. A complex system is inherently open and its boundaries often a matter of convention.*"

The dynamic character of a complex system is a product of the time dependence showed by at least one of its state variables<sup>1</sup>, *i.e.*, some greatness that characterize the elements constituting the system varies throughout time (Monteiro 2002). An essential characteristic of complex dynamic systems is that the time dependence occurs in a nonlinear form, which means that there is not always a proportionality between the input (cause) and the output (effect). The nonlinear characteristic of the complex systems derives, to a great extent, from the feedback links established among the elements of the system, which causes a disproportionate system response in relation to the magnitude of a given environmental disturbance. Whereas negative feedback mechanisms minimize the effects of this disturbance, positive feedback circuits amplify the effects (Christofolleti 1979, Odum 1988, Mattos and Perez-Filho 2004).

The temporal evolution of a complex system may be mathematically described by means of one or more differential equations. Nonlinear differential equations, which describe the dynamics of nonlinear dynamic systems, hardly present exact analytical solutions (*i.e.*, there is no general method for obtaining, for any parameter values<sup>2</sup> or initial conditions, a unique solution that expresses how dependent variables change throughout time). However, certain properties associated with the temporal evolution of a dynamic system may be described from a process of linearization of these

<sup>1</sup> State variables are dependent variables related to elementary properties of the system, and which values are taken at a given moment specify the state of the system at that instant (Monteiro 2002, D'Ottaviano and Brescianni-Filho 2004).

<sup>2</sup> Parameters are greatnesses influencing the behavior of the system, but which values vary quite slowly in comparison to what occurs with the variables (Monteiro 2002).

equations, especially in terms of their stability (Auyang 1998, Monteiro 2002).

The qualitative study of a dynamic system is carried out by the analysis of the *phase space* (or state space) (Monteiro 2002, D'Ottaviano and Brescianni-Filho 2004). It consists of a n-dimensional graphic in which each axis represent a state variable. At a certain moment, the state of the system is conveyed by the values of its state variables at that instant, represented by a point in the phase space. Next, the state variables may or may not have the same values of the previous state. In case there is a change in value for one or more variables, the system is represented by another point in the phase space; otherwise, it will occupy the same place as before.

Throughout time, a state succession of the system describes a trajectory along the phase space. Along this trajectory, the system may come to certain points of the phase state – equilibrium points – that represent stationary solutions for its equations. When the system reaches a point of equilibrium it ceases its trajectory along the phase space and remains indefinitely in that state, represented by that point.

A point of equilibrium may be classified as unstable or stable. If trajectories that started near the point of equilibrium tend to draw away from it, it is said that the point of equilibrium is unstable. If these trajectories remain close to the point of equilibrium, but without ever reaching it, this point is classified as neutrally stable. If trajectories close to the point of equilibrium tend to converge to it along time, the point is considered asymptotically stable. In this case, the point of equilibrium is called attractor, once it “attracts” the trajectories to its neighborhood. The set of all conditions converging to an attractor is called basin of attraction.

The concept of stability described above is in respect to the behavior of the points of equilibrium, and consequently of the solutions for the disturbances in the initial conditions. That is, by

means of analyzing the phase space it is possible to verify if variations of the initial conditions produce the same final state. If this occurs, the system may be considered stable; otherwise, it is unstable when subjected to disturbances on the initial conditions.

There is another type of stability, called structural stability, which is linked not to solutions, but to differential equations describing the system dynamics (Auyang 1998). For this variety of stability, the behavior of the system is studied when such equations are disturbed on the account of changes in the parameters values of the equations (Monteiro 2002). If the trajectories formed from disturbances for the equations are topologically identical to those produced originally, then the system is considered structurally stable. On the other side, if a qualitative change occurs on the trajectories when the variation surpasses a certain critical value in a parameter, the system becomes structurally unstable. This topology change is called bifurcation, and when it happens, points of equilibrium can be created or destroyed and their stabilities changed (Monteiro 2002).

#### COMPLEXITY PARADIGM APPLIED TO THE STUDY OF CERRADO

The contribution given by complexity paradigm to the study of Cerrado is applied only in a few cases, despite its great explanation and prediction potential, which has already been demonstrated in researches concerning several complex-behavior dynamic systems, category in which the Cerrado can be framed into. In general, a reductionist view for studying the dynamics of the Cerrado, which is centered in the concept of equilibrium and in the isolated consideration of factors acting on the dynamics of its organization. On that account, the idea that there is an unidirectional succession (climatic) of physiognomies, beginning by open physiognomies until a forest formation, is very strongly accepted, and the explanation of the spatial organization and dynamics of Cerrado



areas is sought based on simple cause and effect relationships.

Thus, the understanding of the spatial distribution and evolution of the Cerrado still lacks an approach considering the complexity of this system. Such approach, based on the study of complex systems, considers equilibrium configures itself as an exception situation, since the disturbances are not only inherent by the dynamics of the system, but are also sources of its organization and innovation (Mattos and Perez-Filho 2004). Besides, the complexity paradigm is not limited to the isolated analysis of each one of the variables and parameters of the system and to the simple cause-effect relationship among them. Nevertheless, attempts to understand how interactions among these factors act on the system dynamics.

Having the complexity paradigm in sight when considering the Cerrado as a complex-behavior system, one must understand that the occurrence of a given physiognomy in a certain area derives from the inter-relationships among these aspects<sup>3</sup> (Fig. 1):

- *pedological factors* (such as texture, depth, fertility and soil acidity);
- *geomorphological factors* (such as topographic distribution, declivity, and area location);
- *hydrological factors* (such as soil drainage conditions and underground water level);
- *ecological factors* (such as pollination, seed dispersion, resistance to fire, and regrowth capacity of underground plant structures);
- *climatic factors* (such as annual distribution and average of rainfall, and minimum and maximum annual temperatures);
- *paleoclimatic factors* (responsible for the past distribution of different plant forma-

tions, therefore, for the initial floristic stock of the area and its surroundings); and

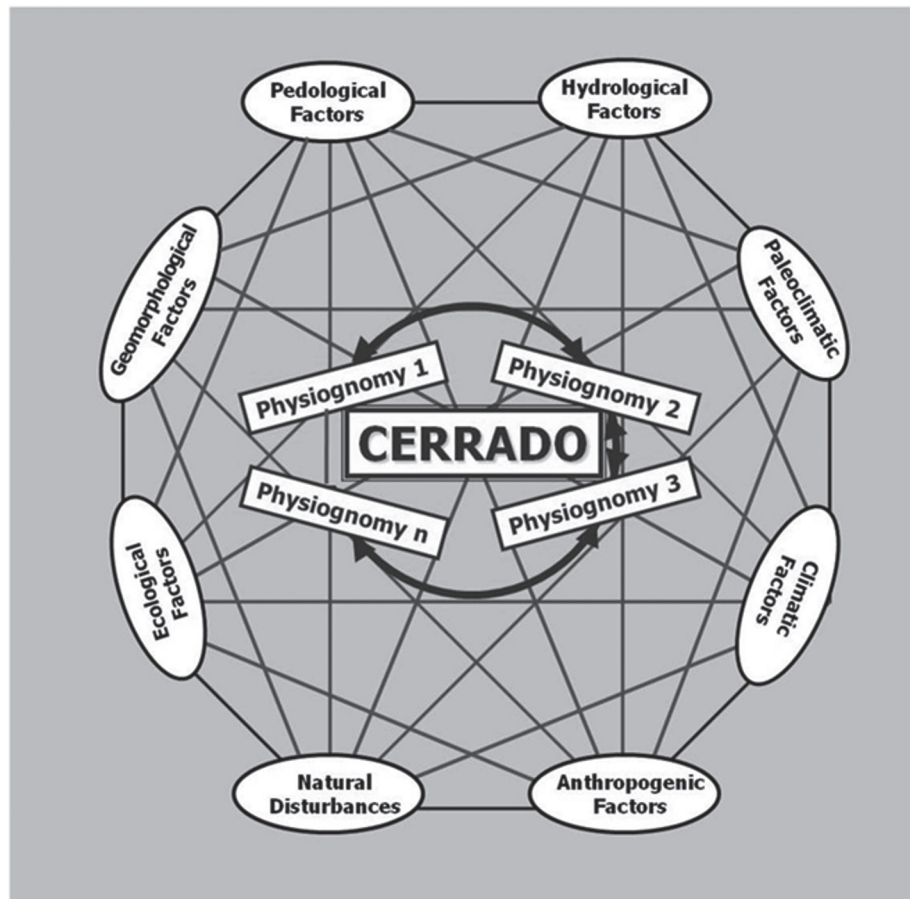
- *related to frequency and magnitude of natural and anthropogenic disturbances* (such as fire and introduction of commercial crops).

Therefore, when modeling the organization and dynamics of the Cerrado, these are the factors providing the variables and parameters for equations of the system, as well as the initial conditions to be assumed. The selection of factors to be considered evidently depends on the objective of the modeling and on the spatial and temporal scales assumed. Thus, in the geologic time scale, climatic changes are raised as main factors for determining the spatial distribution of the different Cerrado physiognomies (Ab'Saber 2003), whereas in the historic time scale (decadal) the anthropic disturbances have played a decisive role in the changes undergone by the Cerrado.

Precisely, one of the topics to which the complexity paradigm can strongly contribute in the study of the Cerrado is to understanding the stability of the Cerrado towards disturbances – both anthropogenic and natural. The application of the *multistability* (or multiple stability) concept may be very useful for understanding the dynamics of the Cerrado. The idea of multistability is used for systems presenting alternative stability states, and may oscillate among them throughout time, depending on the disturbances befalling them (Scheffer et al. 2001). It may be pondered that the different Cerrado physiognomies – or at least some of them – represent distinct states presenting local stability and, depending on the resilience of the system<sup>4</sup>, the occurrence of a disturbance may or

<sup>3</sup> Based on Eiten (1990), Oliveira-Filho and Ratter (2002), Passos (2003), Durigan (2004).

<sup>4</sup> Resilience (also called elasticity by some) is defined as the capacity of a disturbed system to return to the state it was before the disturbance happened (Westman 1978, Christofolletti 1999). If regarding to the stability state as being represented by the attractor of the system, resilience can be understood as the capacity of the system to return to its attractor after its trajectory has been diverted by a disturbance.



**Figure 1** - Schematic representation of the inter-relations among types of factors acting on the configuration of different Cerrado physiognomies.

may not take it to a new state (*i.e.*, physiognomy). In other words, the physiognomies would be attractors of the system. Maybe not all Cerrado physiognomies represent stable states; some may be understood as transitional states between stability situations, therefore, unstable. The disturbances considered so far, relate to disturbances to the initial conditions and the consequent behavior of the stationary solutions. Therefore, it regards to the concept of stability from a point of equilibrium. As it has already been discussed, the analysis of this kind of stability enables knowing which initial set of conditions result in one equal final state, *i.e.*, enables verifying which values of the variables and parameters linked to the factors listed at the beginning of this item lead the Cerrado to assume a given physiognomy.

The application of the structural stability concept to the study of the evolution of the Cerrado is of great relevance, since anthropogenic actions have great potential for provoking changes to the system, up to the point of unleashing processes which would only be manifested due to natural disturbances during a much longer time scale. This seems to be the case of the sandification process observed in different regions of Brazil in which the Cerrado occurs on quartzipsamment soils that are highly fragile and susceptible to processes of erosion. It may be conjectured that the formation of sand cells in areas previously occupied by the Cerrado is characterized as a structural stability loss of the system, mainly due to anthropogenic disturbances (especially from agricultural activity), altering the parameters values to beyond

critical, and result in qualitative changes, perhaps irreversible, to the evolution of the system.

Thus, the study of the Cerrado based on the complexity paradigm – especially in terms of its stability – is essential for the production of knowledge regarding the dynamics of this complex system, thus enabling knowledge of resilience degree for its different physiognomies facing the disturbances; therefore, planning and adopting adequate preservation and management practices.

#### SCALAR INVARIANCE AND SELF-ORGANIZED CRITICALITY IN CERRADO – NEW PUZZLE PIECES?

The existence of scale invariance characterized by self-similar patterns at different scales (*i.e.*, fractals) has been suggested as a manner of organization present in various environmental systems. As shown by Milne (1990), the importance of scalar invariance is: from self-similarity is possible to quantify the landscape dynamics at different scales, representing a major breakthrough in the quest for understanding the processes operating in the system.

According to Li (2000), the scalar invariance means that the scales are ecologically equivalent; hence, the same ecological conclusions may be statistically obtained at any scale. This happens because there are structural and functional patterns passing through different hierarchical levels, responsible for the self-organization of the system. However, it is important to remember that this scalar invariance is not infinite; for natural fractals, unlike exact fractals, it is limited to few scales.

The occurrence of recursive patterns at different scales may be understood as a consequence of the type of the hierarchical organization of the complex system, specially the landscape. This organization shows hierarchical nesting, in which a system of a given hierarchical level is formed by systems of inferior levels (subsystems) and, at the same time, integrates systems of superior hierarchical

levels (Allen and Starr 1982, Mattos and Perez-Filho 2004). Each entity (system) composing a hierarchical level is called “holon”, therefore this kind of organization is called “holarchical” (Allen and Starr 1982, Naveh and Liberman 1994).

The scalar invariance is a remarkable characteristic of systems that develop far from equilibrium (Li 2000). Furthermore, it is a great indication that the system manifests self-organized criticality (Bak 1996, Murray and Fonstad 2007), even though this is not always true (Li 2000, 2002).

The concept of self-organized criticality, created by Bak (1996), is applied to complex systems out of the thermodynamic equilibrium, which evolve to a critical state characterized by spatial or temporal scalar invariance. At this state, small disturbances are more frequent than greater ones, but the transition from one state to another may happen due to an event of any magnitude. This critical state is an attractor for the system, and its sensitivity limit to disturbances (represented by the dimension of its basin of attraction) determines its stability; consequently, its sensitivity to the occurrence of a change in state. Thus, self-organized criticality is linked to phase transition, another important concept related to complex dynamic systems.

As previously discussed, the phase state is a system state with characteristics that are qualitatively distinct from those of other states from the same system (Li 2000). Still, according to the same author, phase transition is the act of passing from one state (phase) to another, and it may be triggered by a disturbance, represented by the change of one order parameter in the system. This transition can be twofold:

- 1) continuous: when the phase transition is accompanied by a continuous change in state;
- 2) discontinuous: when the transition is accompanied by an abrupt change in state, also known as catastrophe.



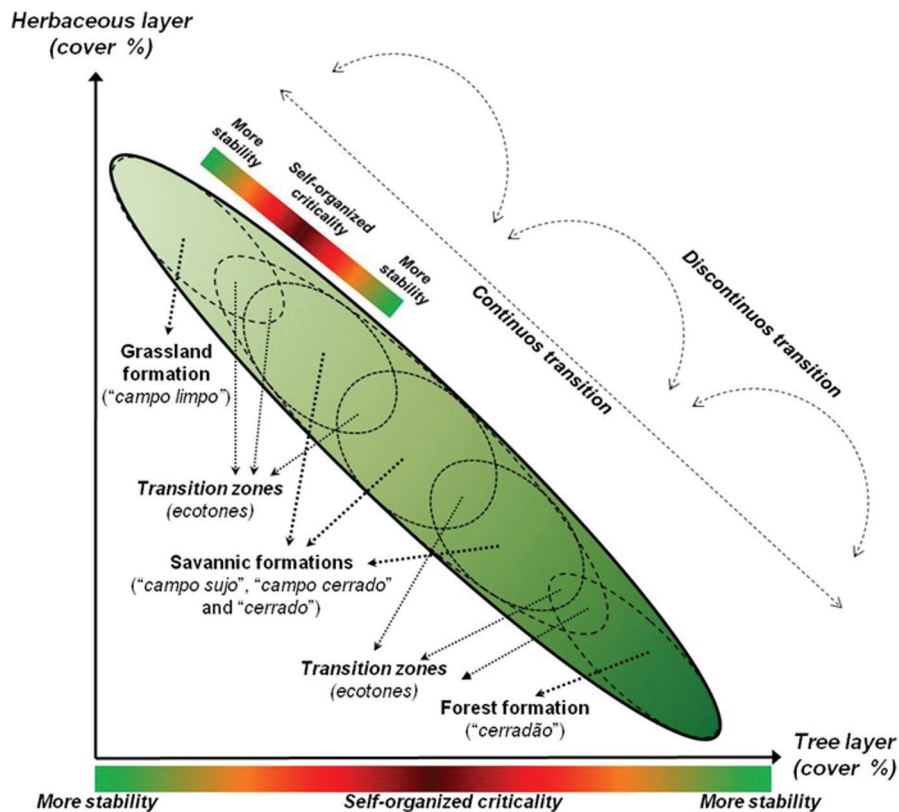


Figure 2 - Schematic representation of organization and dynamics of Cerrado.

According to Li (2000), the application of the phase transition concept is very useful for understanding the changes occurring in a landscape. For him, plant physiognomies may be considered system states, and great changes to ecosystem dynamics may be caused by nonlinear responses to changes in gradients of the physical environment. Even though he has doubts concerning the existence of a relationship among the self-organized criticality and the phase transition theories, the same author (quoting previous papers of his own authorship as well) states that self-organized criticality may explain the dynamics of the landscape, which would naturally evolve to a critical state showing scalar invariance (temporal and spatial) (Li 2000)<sup>5</sup>.

<sup>5</sup> "(...) we could approach criticality of patch dynamics since certain extended dissipative dynamical systems naturally evolve into a critical state, with no characteristic time and space scales (Li and Forsythe 1992)." (Li 2000).

From the concepts presented in the preceding paragraphs, some ideas on the organization and the dynamics of the Cerrado may be suggested (represented in Figure 2). The first is: physiognomies of the Cerrado represent attractors of the system. This attractor can be critically self-organized, which would be revealed by the scalar invariance of physiognomies. Self-organized criticality may be restricted to physiognomies located in the intermediate positions of the vegetation gradient of the Cerrado, indicating that they would organize themselves near the "edge of chaos" and, consequently, are unstable. As a result of this organization nearing critical points, disturbances of any magnitude can lead to loss of stability and consequent state transition.

On the temporal scale of the continuous type, the natural process of physiognomies for ecological succession may exemplify this transition; or, in

the case of a catastrophic transition, exemplified by the sandification process caused by changes in the land from its use. In terms of spatial scale, continuous transition may be represented by changes in physiognomy throughout a pedologic or morphologic variation gradient, whereas an uncontinuous transition may be exemplified by fragments of seasonal forest associated to the basalt outcrop within the Cerrado.

Fire at the Cerrado, on one side, may induce these two types of phase transition: the importance of natural origin fire (e.g., lightning) is well known for the dynamics of the Cerrado, which in this case would be responsible for a continuous phase transition. On the other side, anthropic origin fires, due to its magnitude and frequency, may cause abrupt changes to the system (in several cases, catastrophic ones).

Self-organized criticality may be restricted to physiognomies located in the intermediate positions of the Cerrado vegetation gradient, as *cerrado denso* (dense cerrado), *cerrado stritu sensu* and *cerrado* field, indicating that they are organized near the “edge of chaos” and, consequently, are more unstable. On the other hand, physiognomies located near the ends of the gradient - *cerradão* (big *cerrado*) and *campo sujo* (dirty field) - would present more stable states.

The organization and dynamics of the Cerrado suggested by this research are opposed to the traditionally accepted ones for explaining its spatial distribution and ecologic succession. Instead of a climatic succession, the Cerrado characterizes itself as a complex system out of equilibrium in which the more stable states would be represented by the more open physiognomies (*campo limpo* and *campo sujo*, for example) and by the more enclosed (forest formations, such as: *cerradão* and dry woodland), whereas intermediate physiognomies (including several savannah formations such as dense *cerrado*, *cerrado ss* and *cerrado* field) would self-organize in critical states, out of equilibrium

and subject to events of any magnitude that may lead to another state. Moreover, because it is a complex system, the configuration of each state would be conditioned to several inter-related factors, some of which would act inclusively on different scales, and be responsible for forming self-similar patterns, characterizing the physiognomies of the Cerrado.

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