

Ecology of the Mountainous Environment as a Complex System

Saturnino Leguizamón

Departamento de Investigaciones Científicas y Tecnológicas, University of Mendoza, Argentina

Abstract

The study and applications of “complex systems” in the last decade have gained a great importance for dealing with physical and even social problems. The reason of the increasing interest in these sort of systems stems mainly in the change of attitude taken by contemporaneous scientists who are more prone to admit the holistic point of view in the studies of Nature, as well as the advances produced by computer technology that make easy the simulation of their particular models and the application of their special tools (cellular automata, chaos theory, ..., etc). On the other hand, the study of ecosystems from a complex systems approach is an interesting and challenging task in every environment, but the analysis of ecosystems in a mountainous environment brings to us a lot of further difficulties. The cause of this additional difficulty stems mainly in the presence of the relief and its influence on the behaviour of any parameter we are trying to model or to study. The main goal of this paper is to emphasize the importance of the study of complex systems and their particular tools in order that this approach be seriously taken into account in the education of geographers, environmentalist, and also managers of the mountainous landscape.

KEY WORDS: Complex systems, ecosystems, mountainous environment, mathematical modeling, chaos, cellular automata

1. Introduction

Understanding the behavior of Nature has been always a challenge for the human being. To that end, the fields of Physics and Mathematics have played an important role. When it has been possible, a lot of practical experiences have been carried out and based on ingenious hypothesis, many mathematical models have been developed to simulate natural phenomena. The appearing of the digital computer in the second part of the last century has been a cornerstone in the field of scientific research. This new tool made possible to solve complicated equations and the need of new computational techniques emerged. Studies carried out by the use of this device allowed scientists to understand the behavior of the real world which is not as simple and linear as it was considered in former times. Gradually as scientists of all disciplines explored the world from with new eyes, a new theory emerged: "complexity theory". A theory based on relationships, unpredictability and iterations. A theory that maintains that the universe is full of systems: weather systems, immune systems, social systems, etc.

In the last decade, the study and applications of the theory of complex systems have gained a great importance for dealing with physical and even social problems. The reason of the increasing interest in these sort of systems stems mainly in the change of attitude taken by contemporaneous scientists who are more prone to admit the holistic point of view in the studies of Nature, as well as the advances produced by computer technology that make easy the application of their particular tools (cellular automata, chaos theory, ..., etc).

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2. Complex systems, general concepts

At present, there is no a definition totally accepted for the concept of complex system. There is however, an agreement in recognizing that a system may be considered complex when it is constituted by diverse elements, and these elements are interconnected. That is, the attributes of distinction and connection characterize complex systems. Intuitively, it can be thought that the degree of complexity of a system is in direct relation with the number of diverse elements that compose it and the intensity of the connectivity that exist among them. For this reason, when a system is studied under the optics of

complex system, more attention is paid to the interconnection of the elements instead of the elements that compose it. Another feature which is associated to the concept of complex system is that of order; that is to say, from the dynamic point of view, systems in general can fall in one of the following three categories: a) ordered; are those systems which are stables and predictable, b) disordered; those systems that have a high level of unpredictability (chaotic), or c) systems that are in an intermediate situation between the order and the chaos. The last ones are considered as complex systems, in such a way that they have a certain order, but their dynamics is far from the equilibrium, therefore they also display a certain degree of unpredictability.

Characteristics of complex systems

This intermediate dynamic position gives to the complex systems a degree of structural mobility that produces another important quality of such systems, that is the property of self-organization. In this way, complex systems have a global behavior quite different from which each of their parts exhibits (property of emergency). That property gives them the possibility of adapting to the environment in which they evolve. For this reason, it is also possible to consider the theory of the complex systems as that that studies the systems that are organized to themselves, or self-organized. Although this feature is easy to understand and admit in organic systems (alive beings) it is also a property that can occur in inorganic systems. As examples of complex systems we can mention social or economic systems, dynamic problems of urban development, ecological systems of transport, etc.

As it was mentioned in the previous section, the chaotic behavior is one of the possible characteristics in the complex systems. This characteristic arises because in the modeling of these systems the nonlinear components have been taken into account those components are left aside by the reductionist approach of systems theory. The concept of chaos is associated to the dynamics of a deterministic process that displays an extreme sensitivity to the initial conditions. In summary, complex system exhibits some of the following characteristics or properties:

- Unpredictability: due to their sensitivity to initial conditions, the prediction is not always possible
- Interaction: the relation between the components is very important
- Emergency: the whole is more than the sum of its components
- Order/disorder: complex systems are located in an intermediate position

These properties arise from the study of the structural attributes of such systems. Among the most important it

worth to mention: dynamics near the chaos, non-linearity and self-organization (Richter et al 2002). Some of these characteristics can easily be found in the ecosystems and the environment

3. Fractals, Chaos and self-organization

Although these three concepts were born and evolved separately, they appear frequently in complex systems and, in some cases, chaos and fractals are closely related. Therefore, in order to understand the properties of complex systems is useful to explain the main features of these particular attributes.

Fractals

A fractal is a geometric shape that is similar to itself at different scales. More clearly, a fractal shape will look almost or even exactly the same, no matter what scale it is viewed at. This property is known as self-similarity. Fractal shapes can frequently be observed in Nature (Mandelbrot 1983). As an example, Fig. 1(a) shows the branch of a fern in which it is possible to observe that leaves are similar to branches. Depending on the plant or specie it is also possible to observe that the shape of leaves is similar to branches and branches are also similar to the respective tree. The self-similarity property can also be obtained by repeating mathematical operations on a geometric form. One interesting figure obtained in this way is the snowflake of von Koch, named after the Swedish mathematician Helge von Koch, who in 1904 proposed the procedure to obtain this figure (Schroeder 1991). Fig. 1(b) shows two steps in the construction of part of the snowflake. It is evident that the basic shape shown in the step 2 is also observed in the figure obtained in the step 3.

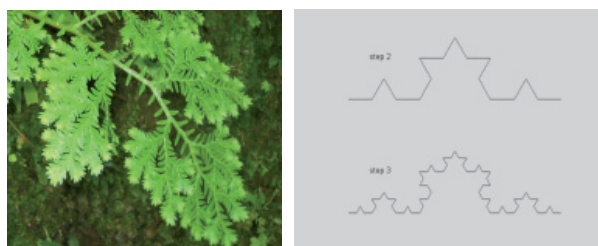


Figure 1: (a) Self-similarity in Nature: picture of a fern. (b) Two steps in the generation of the von Koch fractal.

Chaos Theory

Although does not exist a precise definition of chaos, not even a formal chaos theory, the collection of techniques and features observed in the dynamic of certain nonlinear systems are grouped under the name of chaos theory. This “theory” describes the behavior of some systems that under certain conditions exhibit a phenomenon known as

chaos and therefore these systems are called “chaotic systems”. Chaotic systems share at least two main features: first, they are mathematically described by deterministic equations, they are not random although they may appear to be. Second, chaotic systems are very sensitive to the initial conditions. A very slight change in the starting point can lead to quite different results later on. This characteristic, that makes the system fairly unpredictable, is often called the “butterfly effect”. The name comes after the computer experiences carried out in the 1960’s by the American meteorologist Edward Lorenz, who suggested that the flapping of a butterfly wings over Tokyo might create a tornado in Texas (Eckhardt 2004).

A typical graphical representation for nonlinear systems is the state space. The curves or lines generated by the “state” along a given time period are called trajectories. The trajectories described by a system in a state space characterize the dynamic behavior of the system. Mathematically the state space is an n dimensional vector space which is determined by n axis, where n is the number of independent variables describing the system. Sometimes the trajectories of the system move on a limited region or converge to a given point of the state space. The set of points where the system evolves after a long enough time is called “attractor”. For the set to be an attractor, trajectories that get close enough to the attractor must remain close even if slightly disturbed. Geometrically, an attractor can be a point, a curve, or even a complicated set with fractal structures known as a “strange attractor”. Fig. 2 shows the shape of one of the most popular attractors, that is the Lorenz attractor. It worth to emphasize that there is a strong link between chaos and fractals.

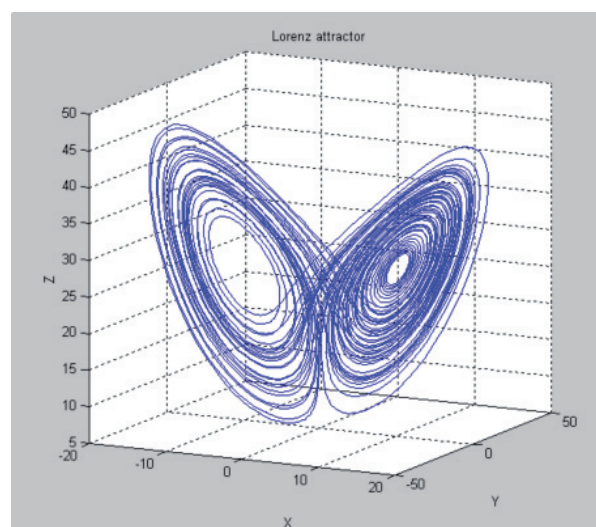


Figure 2: Graphic of the Lorenz attractor in the state-space.

Self-organization

In complex systems dynamics, self-organization is a process in which the internal organization of a system increases in complexity without being managed by any external action. After the process of self-organization, the system, which normally is an open system, exhibits emergent properties. That is, the system as a whole has properties which are not present in any of their components or parts. The main causes for the occurrence of self-organization are the existence of multiple interactions among components and the presence of positive or negative feedback. A system that self-organizes by itself moves to a fixed structure. It can be said that the system is drawn to an attractor. Therefore, studying self-organization is equivalent to investigating the attractors of the system, their form and dynamics.

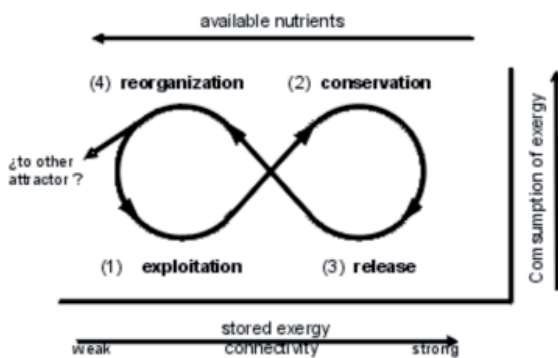


Figure 3: Eight-figure diagram (adapted from C.S. Holling, 1995).

Some self-organized systems have the ability to evolve in such a way that they approach a critical point, the so called “edge of chaos”, and then a system maintains itself at that point or goes to another attractor. This property is named self-organized criticality (SOC). Self-organized criticality has emerged as an important mechanism for understanding the appearance of scale-free structures in physics, biology and a variety of other disciplines. The sand pile model developed by the Danish physicist Per Bak in 1987, was the first to demonstrate self-organized criticality (Bak et al. 1988). The work on this model discussed “avalanches” through the system but, subsequently further studies showed that these concepts might be applicable to “snow piles” and snow avalanches. However, the release mechanism for snow avalanches is quite different from the granular dynamics of sand piles. One of the simplest and most interesting class of models in which self-organized critical behavior can be observed are finite state cellular automata. Per Bak and his collaborators used such models for representing a “pile of sand”.

4. Ecosystems

A generally accepted definition of ecosystem is the following: An ecosystem is an interacting system of plants, animals and humans and the atmosphere of its physical surroundings. An ecosystem contains alive and nonliving organisms where each one provides or contributes with some function or service from which other organisms also depend. Several authors (Holling 1995, Kay 1999, among others) have used concepts of complex theory for modeling ecological and environmental planning. A brief discussion of the model of Holling for the study of the dynamics of ecosystems can illustrate some of the concepts that can provide the approach of complex systems.

The conceptual model of Holling has deeply changed the way in which the ecologists and administrators of the environment see the dynamics of the ecosystems. Holling integrates in a frame based on complexity, the classic ideas of Clemens and the concepts of the theory of catastrophe, theory of the chaos and theory of the self-organization. Holling (1995) proposed a theoretical model to describe an ecosystem, that is the called “eight-figure” since in a graph which describes the trajectories of an ecological system when it follows the different stages that Holling supposed, takes the laid down figure of eight (Fig. 3).

The Holling’s assumption is that an ecosystem never is in a stable position; on the contrary, it goes through four different phases. If a forest is taken as ecosystem example the following things may happen: phase 1 is the stage of an area that is being colonized by different organisms and begins to take form. Phase 1 one goes to phase 2 when the organisms, in this case the trees, begin to grow. This stage may take a long period of time and the forest in growth is seen often like rather stable. Nevertheless, in reality the forest is highly sensible to disturbances. It has, for example, a great amount of wood that could easily catch fire. When this happens, and according to which Holling assumes, there will be a fire that takes the forest to phase 3, the release phase. After the disturbance, there is a reorganization stage that causes that the ecosystem goes to phase 4. In this point the substances and nutritious areas released by the fire give place to the origin of new species. The ecosystem goes consequently again to phase 1. So that “the new” ecosystem maintains the same functions that the previous one must have sufficient diversity of organisms and functions in phase 4 (reorganization). Holling calls to him to this type of diversity, that guides the ecosystem towards the same functions that before, “ecological memory”. The shape of this figure resembles quite well the shape produced in the “phase plane” by the trajectories of a Lorenz attractor (Richter et al 2002, Leguizamón 2006), although the Lorenz model describes the dynamics of a meteorological phenomenon.

Mountain Ecosystems

Mountain ecosystems are very distinct from lowlands, being particularly fragile and highly susceptible to erosion, landslides, avalanches, lava flows, earthquakes, torrents, and rock falls; having variable climates with slow recovery of flora, fauna or soil; encompassing heterogeneous habitats resulting from altitudinal and climatic variations. The main threats arise from deforestation, poaching of wild plants and animals, destruction of habitat by fire regimes and unsustainable grazing. All these factors, most of them caused by the action of people, produce an important negative impact in the mountainous regions. Not to mention the increase of tourism activities in those areas that in the last decades has reached important figures. These recreative activities not only produce an environmental impact but also cause a rapid loss of indigenous culture and traditions of the mountain people (Hickey 2002, Bloemer 2002).

As it was mentioned above, advances in satellite image processing and computer analysis have made possible to evolve a realistic, accurate, and uniform database. Geographic Information Systems' (GIS) technology is regarded as a tool for adapting and disseminating knowledge and experiences from mountainous areas, and can be used as an integrated approach to development and environmental management in mountainous regions. Mountain areas present a great challenge for the application of GIS technology due to their diversity, marginality and strategic importance, as well as their different physical, biological, and societal systems. When compared with the plains in the lowlands, the physical characteristics of the mountain environment are more complex and need to be analyzed using a three-dimensional approach, in order to arrive at an approximate representation of their aspect, slope and topography of the mountains (Trapp 1995). Mountainous regions present a great range of both ecological and development problems that have physical as well as socio-economic dimensions. Isolated solutions have proved to be inefficient, since most of the problems are interconnected. Research studies and development interventions must, therefore, be formulated and implemented in an integrated manner.

5. Tools for complex systems

The main tool used by researchers working in the field of complex systems is, undoubtedly, computer simulation. By using appropriate computer programs it is feasible to calculate and visualize the dynamical behavior of many systems. To this end, computer programs make use (resort to) classical as well as modern mathematical theories and techniques, many of them has been developed (or are still in developing) in the last decades. Among these tools

it is worth to mention: nonlinear differential equations, cellular automata, game theory, neural networks, fractal theory, chaos theory, genetic algorithms and time series analysis. Following this paragraph, a brief description of the most popular tools and techniques used in the study of complex systems will be given.

Cellular automata

Cellular automata (CA) are mathematical models of dynamic processes characterized by a regular grid of cells, where each one of them can be in one of a finite number of possible states. These states are updated in a synchronous way, in discrete time steps, according to a rule of interactions among a surrounding neighborhood of cells. CA have been used extensively to study phenomena such as chaos, attractors and for the implementation of complex systems dynamics by computer simulation. The grid can be linear; that is to say, a succession of cells that interact to each other, a bi-dimensional matrix or a three-dimensional solid.

The first system extensively calculated on computers was a popular game called the Game of Life. In the late 1980's, as computers become more powerful and widely available, the interest in the CA arises intensively. Today a set of accepted applications in simulation of dynamical systems are rapidly growing.

The essential characteristics of a CA are then:

- the state in which each cell of the array is founded (it can be a number or a property)
- the neighborhood of the cell considered in each step.
- the rule that controls the interaction between the central cell and their neighborhood.

6. Applications

The approach of complex systems, including their computational techniques, is appropriate for the study of different environmental problems (Leguizamón 2005). Some of these problems can be:

- Forest fires (studies of fire propagation and extinction)
- Diseases in the vegetation (contagion effects)
- Deforestation (soil degradation and land sliding)
- Population dynamics of some species (bound to the biodiversity)

In order to illustrate the application of the CA technique let us show the result of its application in solving a typical ecological problem: the population dynamics in a prey-predator environment. To that end we will consider as a region of study a lattice of 60 x 60 cells. We will take a cell and its neighborhood, 8 cells that surround it, as working

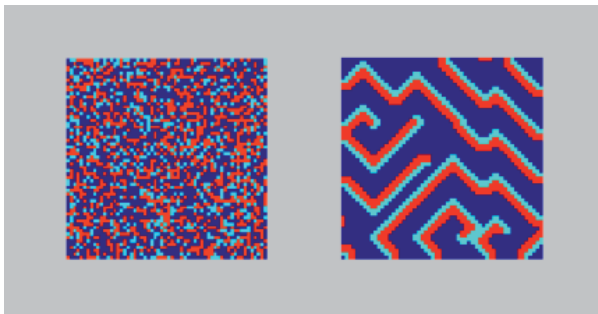


Figure 4: (a) Initial random state of the area of study. (b) The same region after 200 time units. Colors have the following meaning: cyan: prey, red: predator, dark blue: empty cell.

area in each step (neighborhood of Moore), then we will define an interaction rule between the central cell and the neighbors. The rule will be the following: The states that can take each cell will be 3 values: 0, 1 and 2. The value will be 0 if the cell is empty: there is neither prey nor predator; the value will be 1 if the cell is occupied by a prey and 2 if the cell is occupied by a predator.

To solve the problem we start from an arbitrary initial "configuration" where preys and predators are randomly located in a given grid (Fig. 4 (a)); that is, each cell is in a determined state. The CA technique consists in applying iteratively a rule to each of the cells. The rule can be considered as an updating function with a local effect: to obtain the new value assigned to an element, we need the element itself, and the values of all its neighbors. After a given number of steps (or clock pulses) we obtain a new configuration of the grid. (Fig. 4 (b)). Naturally, this process can be represented in a graphic with the population in ordinates and the discrete time as abscissa. This representation gives an idea of the dynamical behavior of the problem.

7. Conclusions

Complex systems are characterized for particular attributes or behaviors. The most important attributes are: non-linearity, self-organization and a near-to-chaos dynamics. Most of these features can easily found in the mountainous environment and ecosystems. In order to take profit of the speed and memory of modern computers, many computational tools have developed to support studies in the field of complex systems. These tools included cellular automata, genetic algorithms, neural networks, etc. These tools, which are still under development, should be understood and used by modern scientists who are carrying on environmental studies in the mountainous regions.

Mountainous regions present a formidable range of both ecological and development problems that have physical as well as socioeconomic dimensions. Isolated

solutions have proved to be inefficient, since most of the problems are interconnected. Research studies and development interventions must, therefore, be formulated and implemented in an integrated manner. Consequently, complex systems approach is an appropriate way to face such a formidable task.

References

- BAK, P. et al., 1988: Self-organized criticality, *Phys. Rev A*, vol. 38, 1.
- BIRKELAND, K. W. et al, 2002: Power-laws and snow avalanches, *Geophysical Research Letters* 29(11),
- BLOEMER, H. L., 2002: Tourism and Mt. Kilimanjaro, *Grazer Schriften der Geographie und Raumforschung*, Universität Graz, Band 37, Graz, Austria
- BRIGGS, J. and PEAT, F. D., 1989: *Turbulent Mirrow. An Illustrated Guide to Chaos Theory and the Science of Wholeness*, Harper and Row, New York. (also in German: *Die Entdeckung des Chaos*, DTV)
- ECKARDT, B., 2004: *Chaos*, Fischer Taschenbuch Verlag, Frankfurt am Main
- HICKEY, T., 2002: Eco-Tourism Development in the Context of Ethiopia, *Grazer Schriften der Geographie und Raumforschung*, Universität Graz, Band 37, Graz, Austria
- HOLLING, C. S., 1995: What barriers? What bridges?, *Barriers and bridges to the renewal of ecosystems and institutions*, eds. L.H. Gunderson, C.S. Holling and S.S. Light, New York: Columbia University Press.
- KAY, J. et al., 1999: An Ecosystem Approach for Sustainability: Addressing the Challenge of Complexity, *Futures* 31(7): 721-742.
- LEGUIZAMÓN, S., 2005: Simulation of snow-cover dynamics using the cellular automata approach, *Proceedings of the 8th International Symposium on High Mountain Remote Sensing Cartography*, La Paz, Bolivia, p. 87-91.
- LEGUIZAMÓN, S., 2006: Modeling land features dynamics by using cellular automata techniques. *Proceedings of the ISPRS Technical Commission 7 Mid-Term Symposium "From pixels to Processes"*. Enschede, The Netherlands. (in Press, available on CD).
- MANDELBROT, B., 1983: *The Fractal Geometry of Nature*, W.H. Freeman and Company, New York.
- RICHTER, K. and ROST, J. M., 2002: *Komplexe Systeme*, Fischer Taschenbuch Verlag, Frankfurt am Main.
- SCHROEDER, M., 1991: *Fractals, Chaos, Power Laws*, W. H. Freeman and Company, New York.

TRAPP, H. (Ed.), 1995: Menris Case Study Series, No. 3, ICI-MOD, Kathmandu, Nepal



Correspondence to:

SATURNINO LEGUIZAMÓN

Departamento de Investigaciones Científicas y Tecnológicas (DICYT)

Universidad de Mendoza

Arístides Villanueva 773, 5500 Mendoza, Argentina

e-mail: sleguiza@um.edu.ar