Complexity, space and cognition: A puzzle for the new science of landscape

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Introduction

Human society is rapidly transforming the Earth into an intricate net of energy depending infrastructures and computerized information, replacing natural systems by urban and industrial sprawls, and by intensive fossil-fuel powered agricultural ranges.

It appears urgent to find solutions able to maintain the eco and the biodiversity of eco-regions, and contemporarily to assure a sustainable future to humanity. Ecology seems a good candidate to play the role of problem-solving science. But ecology looks young among the natural sciences, and despite the tremendous progresses of new knowledge obtained in the last time, a lot of elements remains to discover and to understand as recently argued by Maurer (1999).

Nevertheless, the agenda of the ecology is very dense of promises and societal expectations. To make the state of art of the present time ecology is a very hardy task, especially for the massive amount of produced data and disputed ideas. In this decay, some good points have been addressed by Lubchenco et al. (1991), proposing a dense agenda, reconsidered and updated by Thompson et al. (2001) ten years later. These last authors have delineated the frontiers of ecology, but ecology is di per se a science of frontier!

Complexity, space and cognition, when combined together impose a shift to the paradigm of the "standard" ecology. It is not by chance that landscape ecology appeared at the end of 60' as reply to the new cultural ferments inside the ecology, a science too often prisoner of the extreme reductionistic pragmatism adopted to investigate and interpret the ecological systems.

But the exploration of the spatial dimension of the ecological systems has soon revealed ontological limits. Landscape ecology has been reduced to the ecology of landscape, that means the study of the ecological processes at larger scale than the ecosystem ecology studies were doing (Wu & Hobbs 2002).

To recover the holistic dimension of the landscape as a fundamental domain in which humanity encounters all other organisms and related processes, it is necessary to create paradigms able to open innovative cultural perspectives. This is, definitively, the goal of this contribution, I aware of the great difficulties either epistemological, either methodological to resume and to boost new ideas into the ecology and more specifically into the landscape basket.

In order to clarify these arguments it is necessary to discuss in advance some points that are preliminary to better understanding the dimension of our narrative. For this, I need to discuss themes like the bio and eco-complexity, the information theory, the biosemiotic and the landscape ecology (*sensu strictu)*.

Firstly, I intend present a short review about the state of art of the landscape ecology, then I discuss the cognitive landscape, a relative new field of the ecological research few investigated, and that represents a real frontier for the modern ecology.
I alert the reader about new terminologies like "eco-field" and landscape ontogenesis that can create concern at a first sight.

The landscape ecology, *reason d'etre*

Most of the modern ecology considers the ecosystem paradigm central and standard idea to develop ecological theories (Muller 1997, Odum 1983, Holling 1986), but as recently criticized by Bob O'Neill (2001), this model is largely obsolete and needs new conceptual integrations.

Contemporarily to the crisis of ecosystem science, landscape as a new dimension in which to investigate the ecological processes, emerges in 60' in Europe (Naveh & Lieberman 1984) and later (80') in United States (Forman & Godron 1986), unveiling a new era for field research and applications (Turner et al. 2001,Turner 1987, 1989, Farina 2000, Gutzwiller 2002, Liu and Taylor 2002, Forman et al. 2003).
The landscape paradigm places processes and spatial arrangement of objects, in the physical dimension of the geographical space, assigning importance of such spatiality for the functioning of the entire system.

The definition of landscape: an ontological perspective

Few attention has been paid to develop theories and new paradigms in landscape ecology, too often simplicistly labelled as an applied discipline (Phillips 1999), and an unitarian definition of landscape is not still available. Apparently, the failure of an agreement is largely due to the different ontological level at which ecologists are operating. For instance, when the landscape is defined like a sequence of repeated patterns (Forman & Godron 1986), this definition cannot be compared with the definition of landscape as holistic entity (Naveh & Lieberman 1984). The two definitions pertain to different ontological levels, the first occupies a realistic level, and the second is relegated to a pragmatic level. Both definitions have a sense and can be accepted, but cannot be compared.

I consider more useful to work on the definition of landscape from a broad ontological perspective. In fact, landscape is an entity with physical as well as conceptual properties and it can be efficiently described according three distinct perspectives: The domain perspective, the unit perspective and the system perspective.

The domain perspective considers the landscape " a delimited universe in which a process happens, evolves or is maintained" (Farina & Hong 2004). It is a very general and holistic vision of the landscape. Landscape architects, planners and landscape historians often use such ontological vision of the landscape to delimit their interest and competencies.

The American school of landscape ecology considers the landscape as emerging units (patches) from an indistinct background (the matrix). This vision of the landscape has strong geographical influences. Units can be distinguished across a broad range of spatial scales. Shape, dimension and spatial arrangement (dispersion), are the major attributes to evaluate patches, and the geographical mosaic is the appearance of the clustered patches.

When the landscape is considered a system, are the processes and not the patterns the focal subject. Fragmentation, connectivity, resilience are some of the attributes of such a system. Often the unit vision (patches) is posed at the same paradigmatic level of the system vision (emergent properties), but from an ontological point of view are two distinct visions of the landscape. If we consider the landscape as a system we must ignore the properties of the distinct elements composing the system. Like football player, the game is the product of the team and not the sum of individual performances. The systemic vision of the landscape emerges when species like birds, select a place in which to live. Such selection is determined by an evaluation that mainly considers the services that the place offers in terms of food, shelter, pairing opportunities or predatory avoidance. Organisms are not looking details but have an ensemble vision of the selected place.

The complexity paradigm

Complexity appears at every level of our intricate world from the macro-molecules to the largest ecological systems like the biomes. And, as pointed out by Li (2004), the investigation in ecological complexity it is still at a very early stage of development, although in the last years has made some encouraging progresses.

Probably complexity is a common character of our world but has been considered explicitly after the presentation of theories like the autopiesis (Maturana & Varela 1980), the General Theory of System (von Bertalanffy 1968) and the description of the hierarchical architecture of the ecological systems (Allen & Starr 1982, Allen & Hoekstra 1992, O'Neill et al. 1986).

In the present time complexity is identified with the current life of people and incorporated into the ecology paradigmatic framework (f.i. Lewis 1992, Merry 1995, Cilliers 1998, Arthur 1999, Levin 1999, Bossomaier & Green, 2000, Manson 2001, Taylor 2001).

Complexity is an emergent social phenomenon due to the increase of connectivity between societies in which the chaotic behavior of many processes create further intricate conditions (f.i. Gleick 1988, Cushing et al. 2003).

Bradbury et al. (2000) have considered the ecosystem as complex systems but adding the chorological dimension, and considering the landscape, the complexity seems to increase (Maurer 1999, pag. 24, Farina & Hong 2004). Finally, landscape is one of the best candidate to investigate the complexity.

The emergence of the complexity

Actually a plethora of mental constructs try to explain the complexity (see f.i. Wu & Marceau 2001, Loehle 2004), moving from neurosciences to genetic, through biological, biosemiotical and social sciences.

Complexity is not a self-explicating concept, is not a structure but a state of the interacting processes and it needs robust paradigms to be adequately analyzed. We could argue that complexity emerges when a system has a complicated behavior, but again appears difficult to explain the word complicate. It seems that a semiotic closure forces to maintain the complexity concept prisoner of itself. In order to find a possibility to couple complexity, not as a simple metaphor, but as an emergent property of the living and not living systems, with the ecological processes, three hypotheses have been recently presented by Farina (2004):

a. The uncertainty hypothesis (UH)
b. The inter-domain hypothesis (IH)
c. The connection hypothesis (CH)

a. The uncertainty hypothesis (UH)

According to this hypothesis, complexity emerges from the unpredictability of the phenomena. This means that the behavior of the (ecological) systems can not be forecasted. New solutions open the road to new processes and this create a world more and more complex because divergent and unpredictable. Any new event creates new unexpected conditions in which the system, originated under different conditions, must gain experience.

We are wrongly convinced that the natural world is a perfect machine with capacity to maintain in any condition strict expected feedback mechanisms. This is a true utopia, in fact, moving into the reality we discover the attitude of every natural system to modify some behavior according to the new conditions. When a system experiences a new condition it cannot use the ecological memory and the surprise of the new conditions cannot be incorporated. For this reason the system can collapse or change abruptly (Holling 2004).

b. The inter-domain hypothesis (IH)

According to this hypothesis, complexity emerges through the communication mechanisms connecting two or more different domains (sensu Farina et al. 2004). In order to communicate, that means exchange of information, energy and matter, a domain that operates inside a specific spatio-temporal or organizational universe, must utilize a specific (organic) code (sensu Barbieri 2000). Coding and related mechanisms are the expression of complexity. This hypothesis has been considered, although not in explicitly way, by different authors that have elaborated the theory of the ecological scale (f.i. Allen & Starr 1982, O'Neill et al. 1986, Allen & Hoekstra 1992).

c. The connection hypothesis (CH)
Finally, complexity emerges when many objects are connected each other with a broad possibility to move energy, matter, and information in every direction. Connection produces a very rapid exchange or an overflow of information among the systems and this can disrupt the insulation required by a system to self-maintaining and self-organize into an autopoietic manner (sensu Maturana & Varela 1980). In fact, the kinetic information has no time and space to be transformed in structured information (but see Stonier 1990, 1996, for details).

The ontogenesis of the landscape

The ontogenesis of the landscape is a theory that explains, using a probabilistic approach, how landscapes develop structures and functions (Farina 2004). "Novelties", "Opportunities" and "Events", are the three main steps by which a landscape changes and evolves. Every step shows a distinct pattern according to probability of occurrence, energy requirement and acting drivers.
Energy involved into the landscape ontogenesis increases moving from opportunities to events and novelties. The energy that is used in the opportunities step is energy available in situ, as the result of gradient exchange between subjects acting in the same place and operating at the same spatio-temporal scale. Events uses energy operating as result of difference of gradient between two o more neighboring patches. Such energy is the result of an internal process of differentiation at patch level. The energy operating during the Events step, is responsible of the organization of the land mosaics.
Novelties are characterized by low frequency of occurrence, by energy and drivers that enter into the system from outside, and represent the most dramatic step that a landscape may face. Novelties step is characterized by low frequency of occurrence and high energy involved that disrupt the system that has no information into the ecological memory to react and to incorporate such condition.
A system is also modified by a subtraction of energy. For instance a dam along a river dramatically disturbs the cycle of erosion/deposition along river with cascade effects on the biodiversity of the river continuum.

Drivers are consider every process that can be described by specific patterns and that guide the evolution of a system. The driver metaphor is useful to understand the behavior of complex systems.
Drivers can be external and unknown to the system, may be well known and internal to the system (for instance the key species), or acting at the intermediate level between the different components of a system.

Novelties are activated by drivers external to the system, opportunities by internal drivers, and finally events by drivers positioned at the border of every patch composing the system.

Complexity and Landscape Ontogenesis

The landscape is a good candidate for complexity, because it is a meso-scale system, in which the ambiguous behavior of several processes is the rule. For instance the percolation (Stauffer 1985) has been considered a process with ambiguous (complex) attribute.

The complexity hypothesis requires an environmental frameworkto be verified. I believe that landscape ontogenesis may be the phenomenological context in which complexity can be verified (Farina 2004, Farina & Hong 2004). Most of the processes that we describe during the landscape ontogenesis can belong to complexity phenomena.

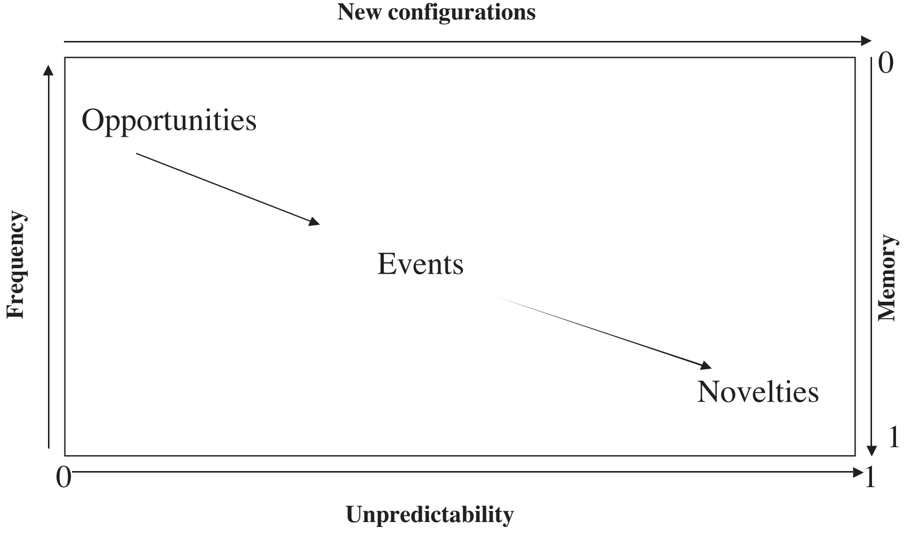

Fig. 1 - The three major steps of landscape ontogenesis sorted according to the chronosequence in which are acting in the landscape. Frequency, Unpredictability, New configurations and Memory are some of emergent properties that differentiate the three steps.

Each step of the landscape ontogenesis is particularly sensible to one of the complexity hypotheses as reported in tab. 1.
Novelties are consistent with the probability hypothesis, opportunities with the connection hypothesis, and finally events fit with the inter-domain hypothesis. This narrative has been produced adopting an epistemological perspective, but confirms the possibility to extend the complexity theory to the field of the landscape ecology, founding that paradigms formulated in a complete independent reasoning, converge toward a common theory.
The discover of a complex world that can not be manipulated in a linear fashion, and this requires new paradigms, new procedures to forecasting the future trends. This has tremendous economic and social consequences, and for this reason, such apparently theoretical approach assumes in reality an extraordinary importance for our common future.

Landscape ontogenesis, integrated into the complexity theory, can represent a new cultural dimension in which to investigate processes and interpret the patterns of the present day landscape.
If humanity depends for most of the ecological services to the landscape, an affordable theory on the dynamics and evolution of landscapes seems of strategic value for the maintenance of resources and more in general to preserve the entire life system.

Tab. 1 - Epistemological coincidence between complexity hypotheses and landscape ontogenesis steps (Farina 2004).

		Landscape ontogenesis		
		Probability Perspective	Energy Perspective	Driver Perspective
Complexity	Uncertainty Hypothesis	Novelties		
	Interdomain Hypothesis		Events	
	Connection Hypothesis			Opportunities

The cognitive landscape

Every living system, from cell to colonial organisms, interacts with the environmental context using cognition. Cognition is the capacity of a living entity to communicate with the surrounding world. Cognition has been considered by different theoretical perspectives like the biosemiotic theory (Hoffmeyer 1997, Kull 1998a,b) and the meaning theory (von Uexkull 1940). When the cognition is applied to the landscape we must consider the subjectivity of the perceived landscape that is the opposite of the landscape currently described in the standard landscape ecology. Every landscape can be imagined like a container good for all, in which species find the conditions for living. To apply the cognition to landscapes it is necessary to recognize that exists a landscape for every species and not just a unique landscape with "neutral" properties. This consideration requires a shift in our paradigms. The rationale that we must use to explain the cognition requires to start from a compress matrix from which, the organisms as operators, extract or expand such matrix into a spatially explicit details (Farina et al. 2004).

According to this vision, three types of landscape can be defined:

a. the Individual-based Landscape (IbL) is the perceived surrounding as determined by the biological sensors (smell, vision, hearing, taste, touch). It is

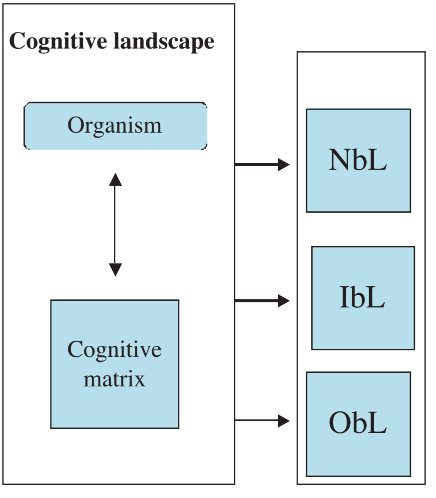

Fig. 2 - According to the cognitive landscape hypothesis, every organism de-codes from a common cognitive matrix three components: the Neutrality-based Landscape (NbL), the Individual-based Landscape (IbL) and the Observed-based Landscape (ObL).

strictly dependent by the organism characters and probably composes most of the "Umwelt", as described by von Uexkull (1940).

b. The Neutrality-based Landscape (NbL). This is the ensemble of patterns and processes that organisms do not perceive distinctly. The NbL can be considered the un-decoded landscape (background noise). Such lack of de-codification can depend either on the lack of specific decoders or by a temporary interruption of de-codification procedure. For instance when a bear is in hibernation most of the cognition is suspended. The same happens to bats during the daily torpidity and only a signal above a specific threshold can produce some reactions.

c. The Observed-based Landscape (ObL) is the component of a landscape that is perceived using a cultural operator. This could seems an exclusively competency of human mind but in reality culture, in broad sense, means accumulated experience into a memory. The ObL is important for those organisms that exhibit learning mechanisms and capacities to archive their experiences into a not-genetic memory. The ObL has no direct genetic basis, this means that every new generation has to build up its cultural background by learning.
The perception of the surrounding has a strong evolutive importance, the experience about the living context increases the survivorship of any organism. In honeybees, for instance, the presence of a learned mental map has been demonstrated as responsible of a scent-triggered navigation (Reinhard et al. 2004).

Eco-field versus habitat

Von Uexkull (1940) used in the first half of the past century the word Umwelt to describe the subjective surrounding of a species (see also Manning et al. 2004). According to this vision of a subjective environment, we call eco-field a perceived configuration of objects or processes, carrier of meaning, that a species intercepts in the neighboring, during the functioning processes (Farina & Belgrano 2004).

We assume that every function or life trait like roosting, foraging, pairing, migrating, territorial defense, requires a function-specific spatial configuration. Such spatial configuration is searched in the surrounding tuning the biosensors according the function that at that moment is activated, and it can be composed by trees, rocks, groups of other individuals, heating patches or what-

ever else, according the organisms.
The eco-field paradigm expands the concept of habitat and creates a linkage with the niche theory, when in habitat and niche theory rarely the spatial configuration of the mosaic is considered.

Two factors are important to defines an eco-field: the spatial configuration of the life trait's perceived environment, and the position of a life trait along a chrono-sequence. For every life trait a species requires a specific spatial configuration and such configuration ranges from one condition of unsuitability to one of optimum. The totality of the eco-fields creates the functional habitat of a species.
The eco-field paradigm allows to evaluate carefully the quality of the area occupied by a single individual or by a population. The difference in the eco-field quality has consequences at individual and at population level. It is reasonable to assume that the environmental pressure operates by single life-trait, and that the quality of each eco-field is responsible of species adaptation. Such mechanism is complicated by the chrono-sequence by which every function is uttered. Every life trait requires an eco-field with a quality that is not fixed a priori but that largely depends on the way the different life traits have been satisfied in the previous step. Quality of the eco-field and optimal sequence can

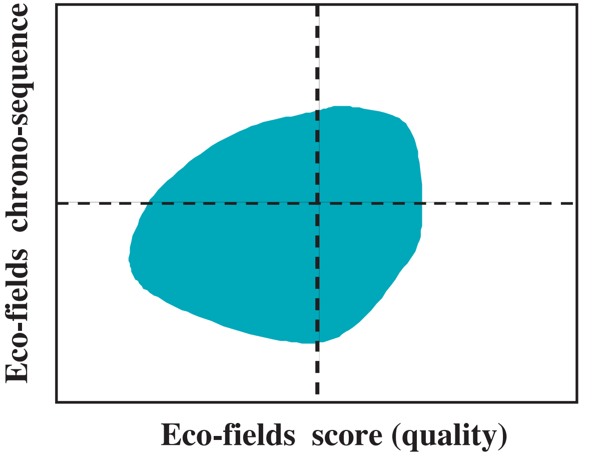

Fig. 3 - The phase space created plotting the eco-fields score and the chrono-sequences. Aproximately such space partially describe the ecological niche of a species.

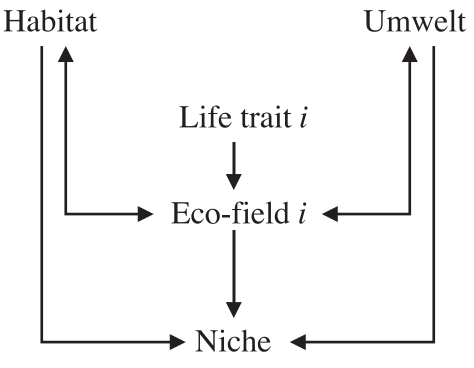

Fig. 4 - Relationships between habitat, Umwelt, niche and eco-field. Each paradigm has competences for a sepcific aspect of the ecological complexity. In this representation niche is element on which all other components converge.

be plotted into a phase space that is very close to the niche hyperspace.
Like for the sources-sinks model (Pulliam 1988, Dias 1996, Pulliam 1996) populations or habitats can be considered source or sink according to a demographic balance, in similar way the eco-fields quality better defines the habitat suitability and re-evaluate the niche dimension.
The eco-field paradigm opens a new perspective either in the advanced research on biosemiotic, either in application. In particular, the effects of environmental changes can be distinguished according the specific eco-field considered.

Conclusions

Complexity, space and cognition seem the ingredients to arrange a new way to investigate the ecological phenomena that have relevance for humanity. Complexity paradigm describes a world that is maintained, at some hierarchical levels, by non linear and stochastic processes . This could create panic in a society that founds its deep believe into a secure future. But the actual economic, political and social systems are manipulated more by complex unpredictable processes than by stability forces (see also Holling 2004).
The steps described in the landscape ontogenesis illustrate how the organizing forces act in the real world. The complexity is strictly connected with the scaling properties of the systems and such scaling emerge, for instance, from the landscape ontogenesis in which novelties, opportunities and events are the icones of the scalar properties of landscapes.

Quite late, ecology has discovered the space in which complexity occurs and the landscape ecology is evolving rapidly in a separate science, especially after to

have incorporated into models and applications, most of the human processes, too longer neglected or marginalized by traditional ecology.
Too often nature has been separated by human beings, assuming like a dogma that human intervention modifies always negatively our living support system. Most of the conservation ecology has roots in this paradigm, but a "full" world biologically used by the humanity is confronted with an "empty" world, were people is apart and not part of nature (Farina et al. 2003).

The inclusion of cognition into the ecological theory is a very recent phenomenon full of promises (Hoffmeyer 1997, Kull 1998a,b, Barbieri 2001). Cognition is a property of every organism and is the process that maintains the internal environment of organisms separate the external world. Cognition is species and individual specific and this opens innovative ways to explore biological and ecological adaptations through biological codes (Barbieri 2003a). The individual Umwelt (von Uexkull 1909, quoted by Barbieri 2001), is a concept discovered after several decades of oblivion by semioticians, ecologists and philosophers (Barbieri 2001, Deely 2001, Farina & Belgrano 2004, Manning et al. 2004). The eco-field represents the trait d'union between the Umwelt, the habitat and the ecological niche, reassuming the attributes of the life that are either autopoietic, stochastic and physically deterministic. The macro-ecology (Brown 1995) and scaling law (Brown & West 1997) have brilliantly demonstrated as the physical constraints are building the general rules that operate into the organismics architecture and functioning, and the individual aggregations.

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