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BOUNDARIES, INTERACTIONS, AND ENVIRONMENTAL SYSTEMS

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Abstract. This paper presents a working definition for environmental systems that clearly distinguishes them from systems centred in each of the environmental spheres, the biosphere included. It also argues that natural phenomena result from a collection of interacting things, their classification in physical, chemical, bio-chemical, biological etc being associated to two factors: the complexity of the organisation in the phenomenological units and the clearness of boundaries in the phenomenon. Based on this definition and these arguments, it discusses some distinctive characteristics of environmental phenomena and how to define environmental states in such a way as to include these special characteristics.

1 INTRODUCTION

The literature about our Environment and environmental systems is overwhelming. The terms environment, system, and environmental system are used with a variety of meanings that are often inconsistent. This lack of precision and focus arises from an intrinsic epistemological contrast of the environmental sciences. They not only deal with nebulous objects but also need to encompass decision-making processes while analysing environmental changes and properties like sustainability, what challenges our present epistemological tradition (Haag and Kaupenjohann, 2001; Wu, 2006). Conflicts in environmental studies are largely fueled by the fundamental difficulty of defining and delineating environmental systems by means of existing scientific tools.

Therefore, there is an urgent need to understand our Environment as a natural phenomenon and to know how to handle its subsystems, if not how to control them, as a contribution to the more complex analyses of man-nature interaction. With this purpose, many studies of portions of the environment have been undertaken, with the net effect of revealing the enormous complexity and difficulties that environmental systems present with respect to our current way of reasoning (Ulanowicz, 1986; Jørgensen and Müller, 2000; Jørgensen and Svirezhev, 2004). Recently, more and more studies point to the importance of changes in effective and possible channels of interaction among phenomenological units which is part of the relational structure of a system (Rosen, 1991). Not less important in the understanding of environmental systems (Ruiter et al., 2005; Pascual and Dunne, 2006), are the connections between the structure of these relations and the system dynamics (Kritz and dos Santos, 2010, in print). As a consequence of the difficulties in linking relational and dynamical behaviour, the most delicate environments like those in the Amazon region remain utterly beyond our comprehension (Junk, 1997; Kritz et al., 2008).

One reason for this state of affairs is the unusual characteristics of the systemic elements that provoke the changes we observe in phenomena related to our environment. The most relevant components in phenomena related to our Environment are ecosystems, which boundaries cannot be easily detected or ascribed. Another characteristic, is the high interdependency among events and interactions at a variety of scales in time, space and complexity. A good deal of these multiple-scale-dependent events are driven by biological interactions. Biological phenomena are the onset of interactions that do not require physical contact or proximity in space and time to occur and that do not necessarily lead to exchanges of mass or energy between the interacting elements. These characteristics impose enormous difficulties in singling out a portion of a landscape to investigate rending useless the traditional methods of identifying systems, that are grounded on proximity (see section 2.1).

There is a vast literature allegedly about environmental systems which are either centred in subsystems confined to one environmental sphere or do not consider long term influences of biosphere sub-systems on the environmental system. Moreover, there is little consensus about what shall be considered as an environmental system. Most systems discussed in the literature available to us fail to conform to the working definition introduced below.

The present paper examines the basic elements of natural phenomena, their components and their representations and introduces a working definition of environmental systems, as a basis to discuss the problems of delineating and representing them. Subsequently, it suggest changes in our usual way of thinking about the state of natural systems, which address some common difficulties in the description and modelling of environmental systems. These changes lead to a sharper manner of representing the state of a system, to a more refined description of boundaries, and to an augmented way of describing states, that integrates quantitative and relational data.

This paper is formated as follows. The next section establishes the perspective under which we shall be looking to environmental problems in the text. A recollection of scientific phenomena and their classes, as well as, of concepts concerning systems is undertaken, highlighting characteristics relevant to the present discussion and establishing notation and perspectives. In the third section, our Environment is discussed and a working definition of environmental systems presented. This section is a condensed version of a companion paper under development. The fourth section addresses the problems of electing and delineating a portion of the environment to be studied as an environmental system and of defining its state. The fifth section presents some final comments and finalises the text.

2 PERSPECTIVES

Natural phenomena is the essential subject of scientific investigation. However, there is an ongoing dispute about which phenomena can be considered *natural* and scientific. A large number of people tend to consider as scientific only phenomena amenable to be studied by the traditional methods arising from physics and chemistry. The purpose of this chapter is to unveil some key aspects of the scientific enterprise that may be useful in putting our views about scientific tractability on a firmer ground. No position is taken towards any particular standpoint.

2.1 Natural Phenomena

Natural phenomena arise out of a collection of interacting things and the changes these interactions provoke in the aspects we observe. An *aspect* is understood as anything that can be observed about a phenomenon. Aspects are generally attached to things that interact. The interacting things possess, though, an enormous variety and enable an universe of interactions and changes. Two characteristics of things are relevant for the present discussion.

There are things which boundaries can be readily distinguished and things which boundaries cannot be readily distinguished. The boundary of something can be very weird and complex, even a phenomenon in itself, like the membrane of cells or the skin of multi-cellular organisms, and still be readily distinguishable. Nevertheless, in other cases, they cannot be easily distinguished even if they are simple. Among the latter we list: fields in physics (the electromagnectic and temperature fields, for instance), the boundaries of a lake, the borders of a cloud or of any unconstrained gas, or the limits of an ecosystem.

Difficulties in distinguishing these boundaries arise either because the boundaries depend on things external or estrange to the focused phenomenon that are incompletely known, or because their boundaries are moving and fuzzy, or yet because they are dynamically determined by the phenomenon itself. Dynamically determined boundaries occur, for instance, in phenomena where they are stablished by the spatial location of interacting things, like in clouds and biological populations, or by the strength of ever changing interactions (See Subsec. 3.3). They differ, though, from free boundaries in physics and chemistry because these latter refer to boundaries internal to the phenomenon, being more akin to phase transitions than to the borders that distinguish a phenomenon (See Subsec. 2.3).

The first group of things, those which boundary is readily distinguishable, will be termed *objects* while things which boundaries are not readily discernable will be termed *entities*. Moreover, changes in things are generally identified through aspects associated directly to them. Nevertheless, there are aspects, like the thermodynamical variables pressure and temperature or vorticity in fluids, that arise from the interaction of a great number of things and are attached to collectivities, rather than to individual things. Summarising, we have the following working definition:

Definition 2.1 *Natural phenomena are such that:*

1. *they arise from collections of interacting objects and entities — the 'who's,*
2. *changes in objects and entities are perceived by means of aspects attached to them — their 'what's,*
3. *there are aspects that result from the interaction of a multitude of things,*
4. *all things and aspects in natural phenomena have a location in space and time and, whenever concrete, occupy a volume in space-time — the 'when's and 'where's.*

Answers to the question 'how' detail the dynamics of interactions and changes occurring in a phenomenon, and are part of its description.

There is no enforcement, however, that a given collection of interacting things would give rise to a natural phenomenon. The quality of being natural is debatable and depend on the phenomenon and on standpoints and values of the scientist observing it. More often than not, this discussion cannot be brought to a stable ground and remain a matter of taste and background. Nevertheless, there are tools that we use when scientifically addressing a phenomenon. Some are the subject of the next subsections. The next two sections are strongly intertwined. Their ordering does not reflect any logical precedence.

2.2 Classes of Natural Phenomena

A collection of interacting things can be inspected from quite a number of stances: physical, chemical, bio-chemical, biological, ecological, social etc (See Fig. 1). Each of them focus on specific types of interactions and examine changes in aspects that are relevant to these interactions.

Physical interactions exchange momenta, charge and energy. To describe them, we record aspects mainly related to the movement of things and the status of collectivities. Chemical interactions (inorganic), besides exchanging the physical aspects, also exchange atoms and portions of molecules among molecules. Chemical phenomena sorts matter into classes and are grounded on the transfer of matter between these classes. Chemical aspects register changes in the proportions of matter belonging to each class and characteristics attached to transfers among classes, like the affinity of substances, rates of transference, energy and proportions requirements etc. Taking into account that molecules are organisations of atoms (matter), we may say that chemical reactions re-organise matter by re-arranging parts thereof.

Although charge divides physical 'who's in tree classes (positive, negative and neutral), physical interactions do not preclude objects of one class to interact with objects of another. Any object interacts with any other object irrespectively of classes, although the nature of interaction (force) between things may depend on the classes to which the interacting 'who's pertain. In contrast, chemical objects and entities are distributed among N classes and may interact or not at all depending on the classes. When interacting they do it in a variety of ways depending on which class they belong to, sometimes requiring energy or a supportive molecular environment surrounding them to interact.

Chemical reactions describe not only which chemical interactions are possible and what proportions of the classified matter are necessary for them to occur, but also absence of reactions connecting certain substances in a phenomenon's reaction set indicate which groups of 'who's cannot interact chemically. Rules about reactions distinguish chemical interactions into classes: isomerisation, reduction, synthesis, decomposition etc. Likewise in biochemistry, chemical knowledge may be depicted as a network where nodes are associated to substance types, while connections between nodes are associated to possible transformations (reactions) between these types — the graph of (possible) interactions (Kritz and dos Santos, 2010, in print).

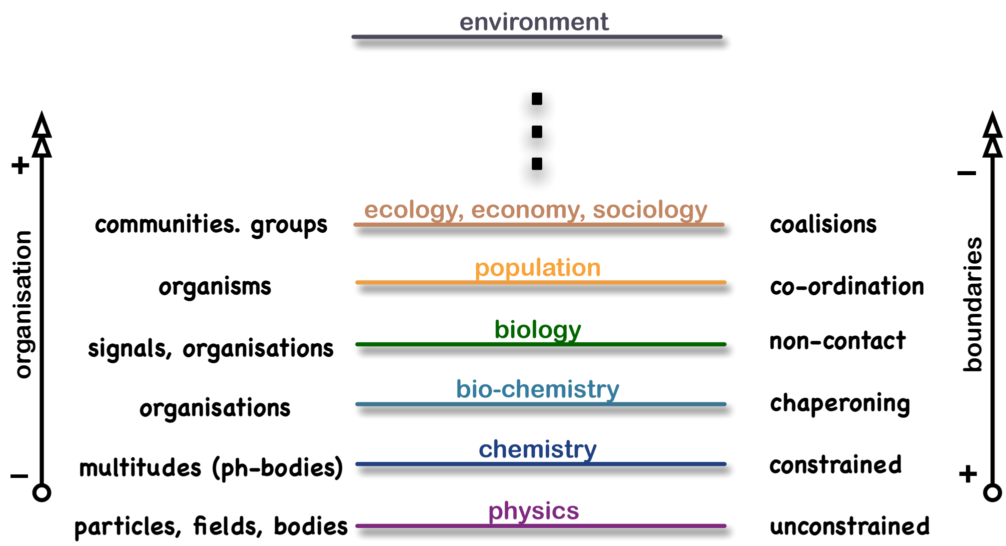

Figure 1: **Classes of Natural Phenomena.** Both the arrow and terms on the left part of the Figure refer to things in a phenomenon while, on the right, terms refer to behaviour of interactions and the arrow to the system's boundaries.

Both chemical and biochemical phenomena exchange molecule organisations besides energy and momenta. Biochemical phenomena, however, differ from chemical due to two basic facts: substances amenable to biochemical reactions are large carbon based compounds and biochemical interactions cannot occur under normal conditions. Biochemical reactions do not depend only on molecular encounters and require at least catalysts to occur. Enzymes are biochemical catalysts that lower the energy requirements in a biochemical reaction and regulates its velocity.

Often they require also chaperonage in synthesis and folding. Chaperones are molecules that help other molecules to stay 'in place' as to enable an efficient encounter of two reactants or to ensure the right final conformation of reaction products. That is, they aid molecules to stay in a spatial position and orientation propelling their correct binding to other molecules. Their necessity is due to the high complexity of their spacial conformations. Biochemical phenomena push forward the dependence of the occurrence of interactions on an adequate environment.

Biological phenomena are grounded on biochemistry and hence require chemical, biochemical and physical interactions to exist. They present, though, some distinctive characteristics. Biological interactions occur only inside organisms, between organisms or between their parts. In contrast to biochemical and previous interactions that require proximity to occur, biological interactions do not require the interacting 'who's to be close to each other either in space or in time, except for the sustaining biochemical and physical interactions. Beyond matter, energy and organisation, biological interactions exchange information, what can be done over larger distances (Roederer, 2005).

Phenomena involving populations in Fig. 1 refer to populations of organisms. Termites and ants are good examples of populations acting in total coordination. Grouping, aggregation and casts are common forms of organisation in animal populations and vegetal meta-populations. Interaction between populations is to be found in phenomena at several biological scales from the cell scale (pathogens and the immune system), to societies and landscapes (biological invasions, parasites, symbiosis and plant social behaviour).

Note that substrates and physical bodies can be considered as populations of huge numbers of particles and molecules. Nevertheless, they fail to present the organising characteristics distinguishing population of organisms that allow for their consideration as interacting and adaptive 'who's. Populations of particles and molecules are better interpreted as multitude phenomena, where a very large number of elements interact with another very large number of elements not necessarily of the same kind. They can be treated as continua and present collective aspects like vorticity, viscosity, pressure and temperature.

Ecological phenomena have populations and multitudes as interacting elements. They distinguish themselves from purely population phenomena by presenting interactions between elements at several scales and levels of organisational complexity (right arrow in Fig. 1), from physical and chemical multitudes to biological interactions and populations of organisms. The ecological stance focus on the exchange of aspects related to mass and energy transfer between the various 'who's that compose an ecological phenomenon (Ulanowicz, 1986; Jones, 1997; Jørgensen and Müller, 2000).

Economical phenomena are also population based. Notwithstanding, instead of focusing in the transfer of mass and energy associated to *parts of* the interacting things, it introduces the idea of goods, goods possession and goods exchange or trading (Samuelson and Nordhaus, 2005). Goods are concrete or abstract objects and entities, possibly related to mass and energy, that have a *value* but are not part of the interacting 'who's, being created, transformed or acquired by them. They are possessed by the phenomenological units but are not integral parts of theirs. Goods are passive and only affect the system dynamics by provoking changes in the propensities of the phenomenological unities. Goods can be thus freely given away or exchanged since they are not an organising part of any interacting element. In the description of economic phenomena, aspects are associated to: goods, their values, decisions about exchanging goods, cost of creating and transforming goods, and about how the goods affect the behaviour of individuals in a population and their decisions.

Social phenomena relates to organisations in a population, knowledge generation and transfer, and the rules that regulate organisation formation, dissolution and interaction, constraining behaviour. They will not be presently discussed because seeing the Environment as a natural phenomena requires that social phenomenology be put aside for a while. However, as in the case of biological and more complex interactions, keeping track of the interaction possibilities and impossibilities among the phenomenological 'who's is critical in describing and understanding these phenomena.

Other scientific studies may be interspersed between the phenomenological levels of Fig. 1. Notwithstanding, they do not present clearly identifiable 'who's or interactions and often can barely be considered as a separate class of phenomena. Sustainability studies, for instance, are right above the ecological-economical-social level. They are centred on interactions among these three types of systems which have the same class of 'who's, namely populations, distinguishing themselves through extremely different type of interactions. Sustainability studies need to consider all three types of interactions, even if each type of interaction is constrained to specific groups of intervening populations, and the effects the behaviour of one system as a whole has onto the behaviour of others (Jørgensen and Müller, 2000; Kritz and da Silva, 2007;

Alves, 2008; Kritz et al., 2008).

2.3 Systems, dualities and complexity

To observe a phenomenon scientifically, we need to clearly distinguish what gives rise to it. That is, to clearly distinguish what things are part of a phenomenon and what things are not part of it. We also need to distinguish which interactions are possible and how they occur, not only between components of the phenomenon but also between these components and things that are external to the phenomenon and influence its behaviour. This is generally achieved using the concept of systems (Mesarovic and Takahara, 1975; Klir, 2001; Kritz and dos Santos, 2010, in print).

Definition 2.2 *A system is a description as precise and formal as possible of a phenomenon or artifact of interest; clarly distinguing them to their surroundings.*

Taking into consideration that all things composing a phenomenon have definite locations in time and space, this distinction can be performed using two complementary strategies:

Strategy 1: A region may be delineated dividing space and time in two parts — things inside (respectively outside) this region belong to the phenomenon and those outside (respectively inside) do not.

Strategy 2: All elements composing a phenomenon together with their interactions are enrolled and the strength and quality of these interactions described.

Strategy 1 is common in continuous physics and chemistry, where the number of intervening particles interacting are too large to be individually described and enumerated and the complexity of the phenomenological-units' organisation simple enough. **Strategy 2** is used in particle centred physical phenomenon, where just a small number of particles intervene, and in general systems theory, that focus in phenomena which components are organisationally rich and complex requiring an individual description of their properties and function. Strategy 2 is crucial when interactions among elements of certain types are impossible. Strategy 2 is often used in particle centred physical phenomena without been noticed, due to the fact that physical particles interact without restriction (oscillators, penduli, planetary systems etc). Both strategies have proper characteristics and their own pros and cons. The clear statement of any natural phenomenon under study make use to a higher or lesser extent of *both* strategies, explicitly or not.

The establishment of a system enable a well-defined duality between the *inside* and *outside* of a phenomenon, henceforth identified to the system. It generates the dual perception of a *system* and its *environment*. The environment of a system is anything that does not pertain to the phenomenon distinguished by the system but that, nevertheless, affects its behaviour or with which the systems components can still interact.

The choice of what aspects to observe is a seminal activity in understanding a natural phenomenon. As stated in the previous section, aspects may be quantifiable or non-quantifiable. Whenever quantifiable, they may be either measurable or non-measurable. Although most aspects are quantifiable, many important observations supporting some studies are not quantifiable in any sensible manner. This by no means imply that they are not relevant in the construction of explanations for the phenomenon and for its understanding (Rosen, 1958, 1959; Katzner, 1983). Measurable aspects are a sub-class of the quantifiable aspects, since their quantification is obtained by comparison to a standard and by *measuring* how many times they fit into one another.

This process leads to the establishment of a state for the system. A *state* is a collection of aspects that reflect the system's past behaviour and allow for inferring its future behaviour (Mesarovic and Takahara, 1975; Rosen, 1991). Each aspect may be attached to individual elements of a phenomenon or to a collection or multitude of its elements. Examples of the first kind are mass, velocity, aggressiveness and vitality, while dynamic pressure, vorticity and population recruitment are associated with collectivities and sometimes represent system characteristics. The same aspects can be associated with distinct elements of a phenomenon, while others are associated with a single element or collectivity. The latter are termed distinctive aspects.

The complexity of a phenomenon clearly depends on the level of organisation of the things composing it (see Subsec. 2.2). Notwithstanding, complexity depends also on how intricate the possible interactions are and on how elaborate our description of them is.

In general, observing a phenomenon from 'outside' tends to reduce the importance of certain details as this is normally connected to a change in scales. This also assists in the identification and handling of aspects common to larger number of elements and their turning into collective or multitude aspects. From a complementary stand, observing a phenomenon from 'inside' allows for a better evaluation of the details' importance due to proximity and scale, while making it more difficult to identify aspects describing collective effects. At the same time, this blurs the phenomenon boundaries hampering the establishment of systems. Both latter facts favour more complex and intricate descriptions of a phenomenon.

3 EARTH ENVIRONMENT AND ENVIRONMENTAL SYSTEMS

3.1 The Earth environment

Our earthly Environment is an extension of the system's environment concept. It starts from everything surrounding us and with which we can readily interact. However, since we are *a fortiori* immersed in our own environment, it is difficult to see it from 'outside'. Setting any limit in our Environment violates the system's concept since its boundaries should be by definition our boundaries. In the systemic conceptualisation it is everything external to us. Thus, choosing another border to our environment depend on our ability to clearly specify the reach of our actions, our possibilities of interacting with things in the environment and the (long term) consequences of any such interaction. This is nowadays extremely difficult because our actions tend to propagate isotropically and quickly throughout the environmental slab. The statements below try to delineate what can be unambiguously considered as Environment.

The Earth is a sphere of viscous fluid at a high temperature and pressure that is surrounded by the almost void, deeply cold, outer space (see Fig. 2(a)). Squeezed between both these regions, there is a spheroid slab about 16km thick where milder temperatures occur as a consequence of the transition from the very hot core to an almost absolute cold void. Driven by a thermodynamical turmoil resulting from this enormous gradient and the inhomogeneities in energy distribution on this slab, a plethora of different substances distribute themselves isotropically throughout this slab. These substances also maintain portions in all four known thermodynamical phases of matter at normal temperature (see Fig. 2(b)), where solar radiation is considered to be in the plasma state. These phenomena give rise to diverse landscapes.

Besides these four states of matter, still another state of matter occurs in this slab driven by solar energy. We call this exquisite state the organised state of matter. Organisation is present in large biochemical molecules, biological processes and organisms. Organised matter can be

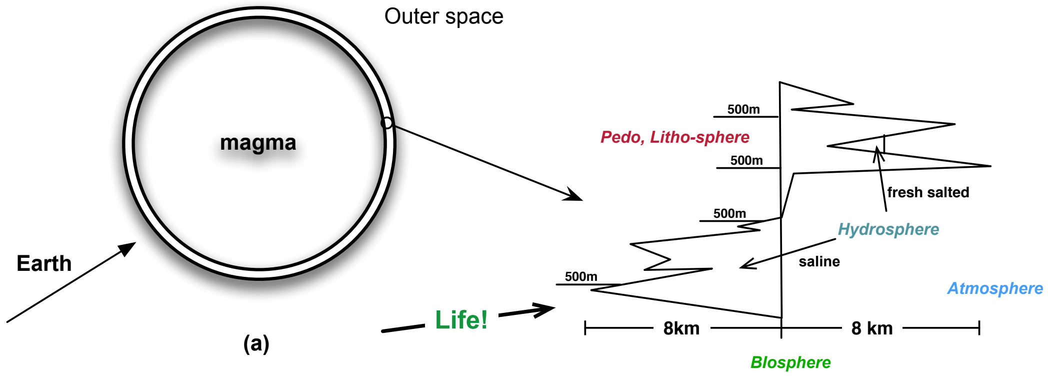

Figure 2: **The Earth Environment** (a) Our Environment: a boundary layer. (b) Phases in the boundary layer.

found at no more than 500m below soil surface and a little bit over the higher mountains. It is to be found only within the high dynamical processes of life phenomena. Life is the phenomenon giving rise and sustaining the organised state of matter. For some reason yet unknown it is confined to this thin slab of the Earth's boundary layer Jones (1997).

3.2 Environmental spheres

Due to the difficulties of singling out portions of this slab for any purpose, let us centre our analysis on the thermodynamical states of matter that occur throughout this thin slab while inspecting it. We may then divide it into spheres attached to each of these states (see Fig 3) most of which can be overwhelmingly close to each other. There are spheres that are solid for

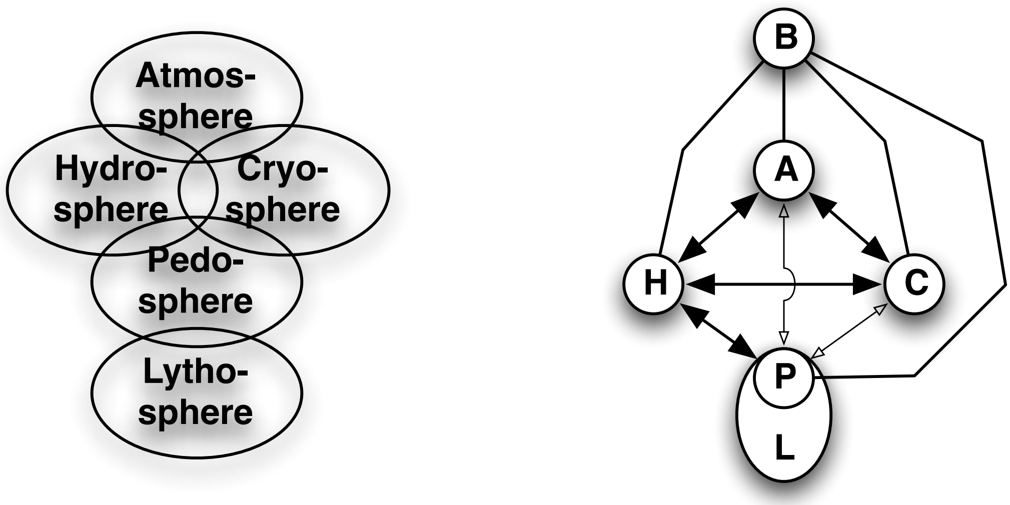

Figure 3: **The environmental spheres** (a) Environmental spheres phase proximity. (b) Interdependencies: first approach.

the most part: the lithosphere and pedosphere. The lithosphere is a rocky and hot layer resting over the magma and supporting all other spheres. The pedosphere sits over the lithosphere interfacing with the other spheres and is mostly rock grained to several extents. The hydrosphere encompasses all water in this slab that is in liquid form and the cryosphere is frozen water. The hydrosphere is further decomposed into fresh and saline water. The atmosphere is gaseous, being the only one sphere to have an interface with the outer space. The solar radiation (plasma) spreads everywhere and this state does not occupy any specific region in the slab. However, it drives and sustains the biosphere. The biosphere is well intermixed with all spheres above and alters their composition and condition. The biosphere strongly interacts with all other spheres, although at a slow pace. It is responsible for the present composition of the atmosphere and regulates several of its processes, it alters the salinity and quality of waters and transforms lithosphere's solid rocks into profitable soil (pedosphere). It also regulates the flow and quality of underground water and interacts with the cryosphere to a smaller extent.

3.3 Environmental systems

Talking about environment and environmental research requires an agreement about what is an environmental system, something yet to be achieved by the scientific community. Environmental systems are often taken to be whatever is not part of the ecological system under study (Vasseur and McCann, 2007). Environmental systems are ever more taken as the joint appreciation of the ecological, economic and social systems, or at least two of them (Wu, 2006; Jørgensen et al., 2007). As inferable from the nature of sustainability studies (see Subsec. 2.2), environmental systems certainly include individuals, groups, populations and systems as things interacting in different manners. Par extension, the main interacting environmental units should include populations and ecological, economic and social systems. Notwithstanding, since we are temporarily not considering social aspects, we shall focus on ecosystems, populations and individuals as the 'who's of environmental systems.

For the present discussion, environmental systems are portions of this thin boundary layer between Earth core and outer space. However, not any portion of it is an environmental system. To be representative of the essential characteristics of environmental phenomena happening in this slab, an environmental system must reflect all states of matter present within its limits. They must also represent interactions and dependencies between elements of all relevant spheres. Therefore,

Definition 3.1 (Environmental Systems) *An environmental system is a system contained in the Earth environmental slab that contains elements from more than one environmental sphere and that represents effects of biosphere elements onto elements of the other spheres. It should explicitly include phenomenological units at the level of organisms, individuals and populations.*

Environmental systems do differ from atmospheric (climate), ecological, hydrologic, underground and other systems by highlighting and emphasising the prominent role of biospheric elements and subsystems in the long range behaviour of the phenomenon under consideration (see Fig. 4). Despite the appearance of being just a matter of emphasis, it is important to note that the present day perspective on climate focus the medium to long range changes and has room for the effect of vegetation on climate (Dickinson, 1987). It is also largely acknowledged that the present configuration of the atmosphere, the hydrosphere and the soil is a consequence of organic phenomena during the past eons. Moreover, men is part of the biosphere and this definition houses sustainability concerns which address modifications and impacts that could alter the long range behaviour of environmental systems. There are many uses of natural resources that do not seem to substantially impact the Environment. Nevertheless, the whole problem of

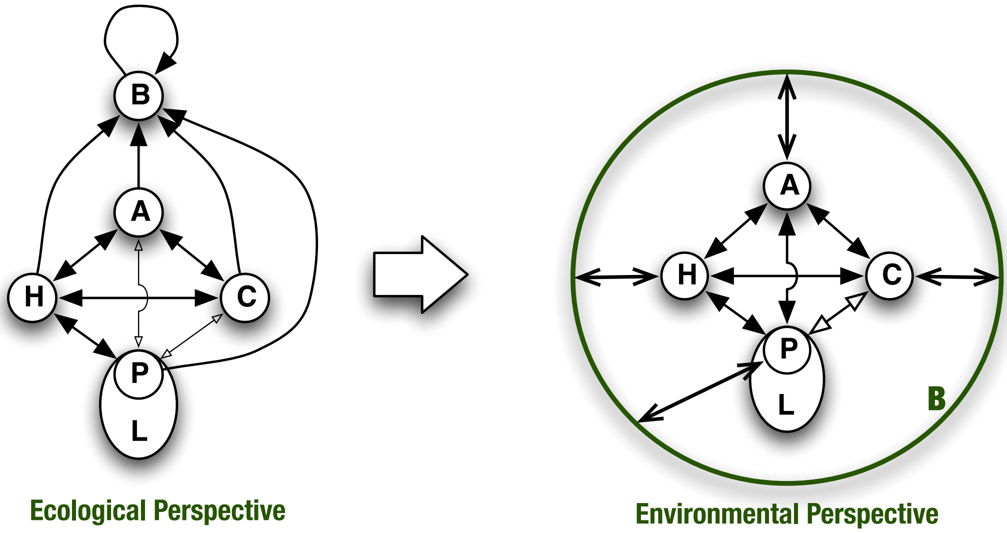

Figure 4: **From the ecological to the environmental perspective**

sustainable interventions into Nature is to know whether these small perturbations would or not rend the system unstable in the long run.

4 DELINEATING ENVIRONMENTAL SYSTEMS AND THEIR STATES

This section addresses the problem of distinguishing environmental systems. Operationally this means to identify which 'who's pertain to the systems and which don't, how they interact and how do they exchange aspects internally and with their surroundings. This implies the establishment of a border, however fuzzy, for the system. To support this task, a closer inspection of the concept of state of environmental system is needed.

4.1 Selecting environmental systems

It should be clear from the arguments in previous sections that the delimitation of environmental systems is a delicate matter. The borders of environmental systems are by definition fuzzy and depend on existing knowledge about spacial behaviour of populations and its constrains, dependencies in long time intervals and the strength of interactions. Populations may be highly mobile, even migratory, and this imposes a strong burden in establishing boundaries. Boundaries for focusing attention are though necessary unless we want to understand the whole environmental slab in its extreme variability all at once.

The sound establishment of an environmental system can only be achieved gradually. Certain elements, phenomenological units and interactions, are chosen as a basis for prospecting relevant objects and entities, as well as, about the strength and reach of interactions and their effects. The behaviour of the system, at any stage, must be understood to sort out inconsistencies that come from incompleteness of description rather than from the nature of the phenomenon depicted in the system. When there are inconsistencies, new elements must be sought and an analysis of the represented ones performed. This may result not only in the addition of entities, objects and relevant interactions but also in the deletion of some to keep the system manageable. This last point is often neglected.

4.2 Environmental changes

Environmental systems are out-of-equilibrium dynamical entities. Being "alive", their aspects are ever changing. What then should be considered as an environmental change. Guided by the common-sense, we could consider changes in the long run behaviour of environmental systems as environmental changes. But, as in all other biologically based phenomena, environmental systems adapt and it is not clear at our present stage of knowledge whether this will result in changes in behaviour or not. Therefore, tracking purely quantitative states and orbits is not an operational way of identifying changes in environmental systems. Otherwise, this may even be an error, unless it is possible to distinguish "natural" changes from "unnatural" ones.

Systems are attached to their interacting things and to their interaction possibilities not to the state (aspects) that each unit composing it may momentarily present (Rosen, 1991; Klir, 2001). Hence, we propose that changes in environmental systems be changes in their interaction graphs, or in interaction graphs of their components whenever they affect the behaviour of the whole. Such changes occur either by the addition and deletion of nodes (things) or of arcs (interactions). Note that the addition and deletion of arcs means that the associated interaction became possible, respectively impossible. A possible interaction in a system may not occur for a very long interval without indeed becoming impossible. Also, all aspects associated to some phenomenological unit may disappear for a while from the dynamical behaviour without meaning that the thing itself has been excluded from the dynamics. From the contrapuntal stand, an impossible interaction that momentarily occurs clearly has become possible at some earlier point.

4.3 The state of environmental systems

We have seen in section 2 that populations are the main phenomenological units of environmental systems. Aspects associated to them, like density, mortality, consumption, reproduction, resilience, information etc, are currently included in the state of environmental systems, providing a vector of scalar fields as a state:

$$\mathcal{S}(\mathbf{x}, t) = (a_{i,j}(\mathbf{x}, t)), i = 1, \ldots, M, j = 1, \ldots N_i$$

where $M \in \mathbb{N} \cup \{\infty\}$ is the number of units in the system and $N_i \in \mathbb{Z}$ the number of aspects associated to each unit i.

However, given that environmental changes are changes in the system's interaction graph, the state of environmental systems must also contain descriptions of their interaction graphs. Interaction graphs are graphs $\mathbf{G} = \{N, A\}$, where N is the set of names of the scalar fields in $\mathcal{S}$, that is, $N = \{a_{i,j}, i = 1, \ldots, M, j = 1, \ldots N_i\}$ and the arcs $(a_{i,j}, a_{i',j'}) \in A$ indicate a possible exchange between aspects $a_{i,j}$ and $a_{i',j'}$. Things in a phenomenon are indirectly represented in the system's state by means of aspects associated to them that are part of the system's state. Tracing back to which things the aspects in a state are associated to, allows for the identification of the things in it. This can require some work but is feasible.

The same is true for the possible interactions, since they are reflected in the systems dynamics and in the orbits it state follows. The problem arises when we try to identify impossible interactions that are about to become possible. To simplify the ongoing discussion, let us assume that the things in the system will not change. Thus, an impossible interaction will become possible as long as an interaction channel is formed along things in the phenomenon. The information about these changes presently lay outside the description of the system and cannot be inferred from the dynamics represented by its state-vector.

However, to each dynamical system described in terms of differential or iterative equations there can be associated a graph that reflect the possible interactions. A graph can be indeed the interaction graph of several dynamical systems (Kritz and dos Santos, 2010, in print). Some properties of dynamical systems, like the existence of stable points, are connected to graph-theoretical properties of its interaction graph of a (mathematical) dynamical system. Moreover, graph properties like the presence of cycles are associated to special dynamical regimes and may show dependence on special values of the dynamical system parameters. A proper state for environmental systems, thus, should include interaction graphs $\mathbf{G}$ and a set of rules or algorithms able to conjointly analyse the dynamical behaviour and properties of the interaction graph of a system imposing modifications in the interaction graph and, consequently, in the dynamical system whenever certain *stress* conditions occur in the dynamical behaviour of environmental systems.

As an example of this necessity, we refer to the aquatic-terrestrial systems in the flooded areas of the central Amazon (Junk, 1997) and describe a very simple change in a food-web organisation (interaction graphs) under the assumption that the species in the region remain the same. Detailed descriptions of known changes can be found in the literature. In these areas we have a fairly periodical annual flood that keeps large portions of vegetation under water for a certain number of months. Supposing that the species living in water and land ecosystems in a certain area do not change annually, that is there is no migration nor extinction, the description of each system separately can rely on two state-vectors:

$$\mathcal{S}^l(\mathbf{x},t) = (a^l_{i,j}(\mathbf{x},t)), i = 1,\dots,M^l, j = 1,\dots N^l_i \quad \text{and} \tag{1}$$

$$\mathcal{S}^w(\mathbf{x},t) = (a^w_{i,j}(\mathbf{x},t)), i = 1,\dots,M^w, j = 1,\dots N^w_i. \tag{2}$$

During the low waters, the two systems are separated and no $a^l_{i,j}$ interacts any $a^w_{i,j}$. However, when the water rises, the situation changes. For instance, the densities of zooplankton and phytoplankton populations fall against the larger water volume and the fish need to find alternative sources of nutrients. Some species of fish eat the fruits and other parts of the submersed vegetation to complement their daily diet. This creates arcs of possible interactions between the nodes of graphs $\mathbf{G}^l$ and $\mathbf{G}^w$ generating another interaction graph for the flooded system. If the nutrition preferences of all species are well known, the algorithm is relatively simple to describe. Given the water height $H(t)$ and the species living in a certain region around each point in space $\mathbf{x}$, find the submersed vegetation in this area and add arcs $(a^l_{i,j}, a^w_{i,j})$ according to the known nutrition preferences.

5 CONCLUSIONS

In the previous discussions, the terms organisation, information and complexity have not been elaborated, trusting in the readers common-sense. They can, nevertheless, be formalised and a precise meaning given to statements like “the more detailed a system’s description is the more complex it looks”. Formalising them also gives a precise meaning to the organisation arrow in Fig. 1, although this arrow really subsumes a partial rather than total order. These developments are, notwithstanding, outside the scope of the present paper and will be the subject of future work.

The main message of the present work is the following. Whenever studying phenomena involving elements with complex organisation or presenting restrictions for interactions between objects in given sorts, it is important to include relational information, like the graphs of interaction, in the aspects that form the state of the system and to find means of tracing changes in this aspects as the system evolves, what mey be done either by means of formal methods, observational methods or a pairing of both. Doing this provides a greater control over the aspects needed at any moment to infer the systems future behaviour. Moreover, a better distinction between possible and impossible interactions enhance our ability to register changes in the strength of interactions and to distinguish the system's boundary, however blurred and moving it may be.

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