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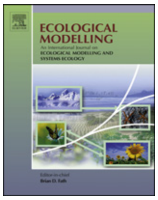

Ecodynamics: Towards an evolutionary thermodynamics of ecosystems☆

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ABSTRACT

This paper collects, with few minor formal changes, two of the latest scientific contributions (Tiezzi, 2006a; Tiezzi et al., 2010) written by Prof. Enzo Tiezzi, where he introduced new concepts and tools to formalize and understand the role of thermodynamics in ecosystems theory.

Particular attention is devoted to goal functions, to the relation of matter, energy, space and time and to the interdisciplinary approach connecting thermodynamics and biology. Entropy is discussed as a fundamental goal function in the far from equilibrium framework. The relationship between entropy, as a non-state function, and the state-function energy is stressed and discussed, at the light of the role of information. The theory of probability is also discussed in the light of new theoretical findings related to the role of events, also in terms of entropy and evolutionary thermodynamics.

Confined Ontic Open Systems (COOS) represent the latest model proposed by Prof. Tiezzi based on his Ecodynamic theory, evolutionary thermodynamics, Ulanowicz's ontic. The model has a wide range of applications, including ecosystems, ecological economics, urban organization, the supra-molecular structure of water and global biosphere's models. The model is explained in terms of evolutionary thermodynamics and Jørgensen's ecosystems theory.

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1. The time paradox

The basic laws of physics from Newton to the present day have been time reversible; on the contrary, reality is constituted by phenomenological aspects: macromolecular organization, cellular differentiation, life processes, characterized by irreversibility of time. The reason for this lies in dynamical interactions that take place in complex systems. The analysis of reality requires major modification of current physical chemistry equations and theories. What is now clear is that complex systems and their behaviour can only be analyzed by means of relations including time as directional factor: on one hand, the use of time-reversible classical and quantum physical chemistry approaches for studying matter at the molecular level and the behaviour of simple molecular systems has greatly improved man's understanding; on the other hand, we need new approaches and new time-irreversible theories able to describe the behaviour of complex systems.

The recognition that time is "real" and plays a fundamental "constructive" role in nature leads to Prigogine's time paradox (Prigogine, 1991): "how is this possible that on one hand the basic equations of dynamics, classical or quantum, are time reversible and that on the macroscopic level, on the other hand, the arrow of time plays a fundamental role. How can "time" come from "non-time"?

Prigogine believes that "we are therefore indeed at the beginning of a 'New Physics' which incorporates both dynamics and irreversibility. Until now, our view of nature was dominated by the theory of integrable systems, both in classical and in quantum mechanics. This corresponds to an undue simplification. The world around us involves instabilities and chaos, and this requires a drastic revision of some of the basic concepts of physics."

As Kuhn (1996) remarks, the passing of time often brings anomalies which existing theories are no longer able to explain. The divergence between theory and reality may become enormous and consequently a source of serious problems. This is exactly what is happening today between current scientific theories and the natural situation of the planet. In Kuhn's terms this means a shift towards a new paradigm. As Palomar in Italo Calvino's novel observed: "if the model does not succeed in transforming reality, reality must succeed in transforming the model."

Based on the assumption that the interaction between biophysical constraints and evolution is not satisfactorily described by current scientific theories, this paper is an attempt to present a new model to be used in ecological physical chemistry as concerns entropy, energy and time fluctuations in biological and ecological systems. The epistemology of the model derives from interdisciplinary cross-fertilization between physical chemistry, mainly thermodynamics, and ecology, mainly systems ecology. The logical consequence is a complete change of point of view or a "gestalt"

☆ This paper has been edited by Enzo's co-workers of the Ecodynamics group of the University of Siena.

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shift in modelling the relationship between biophysico-chemical parameters and the global environment.

The starting point is Boltzmann's statement that the struggle for life is not a struggle for elements or energy, but rather a struggle for entropy (negative) available from solar energy (Boltzmann, 1886).

2. Steps towards ecodynamics

In the framework of evolutionary physics we deal with goal functions (or "orientors") instead of state functions and therefore ecodynamic models have to be based on relations evolving in time; far from equilibrium thermodynamics assumes upon itself the role of foundation of a new description of nature. Table 1 summarizes the main concepts related to this paradigm's shift.

Prigogine's studies opened a window on nature. For the first time in the history of physical chemistry, tools, methods, equations and models were developed to describe the essence of the evolutionary properties of nature. This was a true change of paradigm. This change in paradigm: (a) implies that the intrinsic irreversibility of time has erupted in the basic equations of chemistry and physics; (b) it sustains Pascal's view that the whole is greater than the sum of its parts and hence negates the statement of Descartes that the world should be divided into the smallest possible parts in order to understand it; (c) it suggests that form and aesthetics (and hence quality as well as quantity) play a role in the evolution of nature. Nature is therefore conceived as φυσισ (*physis*, the word from which *physics* is derived) in the original Greek sense, a nature in which time, relations and aesthetics play a fundamental role.

The epistemological and historical foundations of this concept (c) are explained by Bateson (1972, 1979) (I) and in relation to Archimedes in Plutarch's *Parallel Lives* (Plutarch, 2001) (II):

(I) Modern science takes the antiaesthetic assumption attributed to Bacon, Locke and Newton to an extreme. This assumption was that all phenomena can and must be studied and evaluated only in quantitative terms. However, the role of form, colour, flavour, sound, scent and beauty was fundamental for biological evolution, and is still fundamental today for a scientific view of complexity. Nature is threatened by the linear, mechanistic, crude approach of science at the service of a society that "knows the price of everything and the value of nothing."

(II) Archimedes is known for certain useful discoveries: his famous principle based on the concept of density led to imprisonment of merchants doping gold with other metals and he used solar energy to burn the sails of Roman ships. When asked to write these useful things or to invent others, he replied that he only concerned himself with "fine and beautiful" things.

Pascal's concept (b) brings thermodynamics and evolutionary biology to the centre of research on nature, relegating particle physics, molecular chemistry and molecular biology to the background. Obviously they still have a central role in the study of non-living matter and mechanics. This type of approach was guessed many years ago by Liquori (2003), professor in physical chemistry at Rome "La Sapienza" University and often nominated for the Nobel prize in chemistry.

Liquori wrote:

> "In the case of proteins, molecules owe their stability to the same intermolecular forces that stabilise crystals: Van der Waals forces and weak electromagnetic interactions. In living organisms, very weak forces hold DNA molecules together, as well as proteins and membranes. *Because they are weak, they allow these structures to change conformation in order to change function*." He adds: "The path chosen by many physicists, not Schrödinger (Schrödinger, 1944) of course, was to try to use quantum mechanics, which is a mistake (except for the phenomenon of sight) because among other things, the maths of quantum mechanics is unwieldy."

Erwin Schrödinger, winner of a Nobel prize in physics and one of the fathers of quantum mechanics, introduced the concept of negentropy into his lessons in Dublin in the 1950s:

> "How would we express in terms of the statistical theory the marvelous faculty of a living organism, by which it delays decay into thermodynamical equilibrium (death)? We said before that it feeds on negative entropy, attracting, as it were, a stream of negative entropy upon itself, to compensate the entropy increase it produces by living and thus to maintain itself on a stationary and fairly low entropy level."

Moreover in the foreword of "The Essence of Time" (Tiezzi, 2003a) Prigogine wrote:

> "The first part of this book deals with the passage 'from a space to a time culture'. This is indeed an essential part of the scientific revolution we are witnessing at the end of the 20th century. Science is a dialogue with nature. In the past this dialogue has taken many forms. We feel that we are at the end of the period which started with Galileo, Copernicus and Newton and culminated with the discovery of quantum mechanics and relativity. This was a glorious period but in spite of all its marvelous achievements it led to an oversimplified picture of nature, a picture which neglected essential aspects. Classical science emphasized stability, order and equilibrium. Today we discover instabilities and fluctuations everywhere. Our view of nature is changing dramatically. At all levels we observe events associated with the creative power of nature. I like to say that *at equilibrium matter is blind, far from equilibrium it begins to 'see'*."

Although quantum mechanics and general relativity are revolutionary, as far as the concept of time is concerned, they are direct descendants of classical dynamics and carry a radical negation of the irreversibility of time.

Irreversibility is not related to Newtonian time or its Einsteinian generalization, but to an 'internal time' expressed in terms of the relations between the various units of which the system is composed, as are relations between particles."

This simply means that we no more deal with state functions, but rather with evolving ecodynamic functions.

Table 1
Comparison of ecodynamics, classical physics and ecology.

	Classical physics	Ecology	Ecodynamics
Basic world view	Mechanistic dynamic molecular	Evolutionary molecular	Evolutionary systemic
Time	Reversible	Evolutionary	Irreversible evolutionary
Focus	Object subject quantity nature	Object subject quality quantity nature	Relations between quantity-quality and between subject-object
Viewpoint	Reductionist	Reductionist holistic	Holistic
Goal	Knowledge	Survival of species	Sustainable development
Modelling	Deterministic	Evolutionary	Evolutionary systemic irreversible

Faced with the evolutionary character of nature and life, classical science (physics and chemistry) encounters three paradoxes:

- Prigogine's time paradox;
- the paradox of negentropy that cannot be calculated on the basis of conservative, deterministic and purely quantitative terms (energy and classical entropy) but which must consider information, forms and quality;
- the probability paradox (probability is an aseptic, atemporal mechanistic concept) which has to account for events, emerging phenomena, choices made by plants, animals and ecosystems, random fluctuations of evolutionary biology and the phenomena of far-from-equilibrium systems.

The second and third paradoxes will be discussed in the following paragraphs.

3. Entropy in ecosystems

The role of thermodynamics in scientific thought boils down to defining relations and identifying constraints; thermodynamics is the science of what is possible and is to physics as logic is to philosophy. Entropy is the enigma of thermodynamics because it has the intrinsic properties of time irreversibility, quality, and information that other thermodynamic functions lack. This is why entropy is a central concept in biology and ecology: entropy is the basis of *ecodynamics*.

The Second Law of Thermodynamics states that the universe, or each isolated section of it, tends towards maximum entropy. Statistical mechanics and kinetic theory tell us that maximum entropy implies maximum disorder within the framework of the constraints of the system. Hence when we think about evolution in this context (Boltzmann's H theorem) (Boltzmann, 1964), we think of evolution towards increasingly disordered states of the system.

This idea is strikingly at variance with our knowledge of biology. Clearly the trend of living organisms is towards the creation of order where previously there was disorder: it is the trend to organize and self-organize. Life seems to contradict the Second Law of Thermodynamics. The solution to this apparent contradiction between biological and physical theory, according to Morowitz (1979), lies in the realization that the Second Law of Thermodynamics applies to systems close to equilibrium, whereas the surface of the Earth, the matrix of biological evolution, belongs to a different class of physical systems. Biosphere is a far from equilibrium system, as all the living systems are (open systems far from the thermodynamic equilibrium).

Prigogine (1991) gives a clear and simple description of the ecodynamic peculiarities of the biosphere: the biosphere is far from equilibrium because it is characterized by instability, bifurcations and dissipative chaos; time is therefore real and plays a fundamental constructive role.

Prigogine introduces the concept of the arrow of time to describe irreversible changes. The main issue derived from the theory of dissipative structures is that the evolution and maintenance of open systems far from equilibrium are possible only if irreversible thermodynamic processes occur. Such processes dissipate energy and matter, increasing Entropy in the environment.

The evolutionary process is such that systems become more and more complex and organized. Biological diversity is the product of long-term interactions at a genealogical and ecological level: the genealogical interactions regard the dissipation of Entropy by irreversible biological processes; the ecological interactions regard Entropy gradients in the environment.

In his MOA lecture (1994) Ilya Prigogine underlined the following statements, which explain this behaviour:

> "Classic laws of nature are *deterministic* and *reversible*"
>
> "Thermodynamics and Entropy describe an *evolutionary* view of nature"
>
> "Entropy means evolution"
>
> "Irreversible processes, which *create* Entropy, distinguish between past and future"
>
> "*We cannot describe nature without making a distinction between past and future*"

Many years before Landsberg (1972) reviewed a book by Glansdorff and Prigogine (1971) and reached the following conclusion:

> "Zeroth law: empirical temperature exists. First law: internal energy exists. Second law: entropy and absolute temperature exist. Third law states that $T = 0$ do not exist. Fourth law: for a class of non-equilibrium states, and for equilibrium states, extensive and intensive variables exist."

Along the same direction, analyzing the input–output entropy flows, Aoki (1988, 1990) stated:

- The first law formulates the Energy concept; the second law formulates the Entropy concept.
- The first law deals with flows of the *conservative quantities*: energy and matter. The second law deals with flows of the "*non-conservative quantity, entropy*."

It is possible to summarize this paragraph saying that entropy exists, is a non-conservative function and is related to evolution.

4. The entropy paradox: energy vs. entropy

The last conclusion is a big step because it overcomes the old dilemma of whether entropy was the shadow of energy or vice versa, and does not reduce the ingenious invention of entropy to a purely energy dogma. The First Principle formulates the concept of energy in a conservation framework; the Second formulates that of entropy in an evolutionary framework. This is where evolutionary biology and mechanics meet. Schrödinger's introduction of the concept of negentropy was an inspired one: a living system absorbs negentropy from the external environment, structuring itself and evolving on the basis of this interaction. In other words, energy and entropy can be related, as is done in classical thermodynamics and statistical thermodynamics, but from the point of view of time, the two concepts are irreducible and different. In an evolutionary Gestalt, entropy has an extra gear which is the key necessary for studying living systems and ecology. It is important to study flows of energy and matter, quantities which are intrinsically conserved; it is also important to study entropy flows, an intrinsically evolutionary and non-conserved quantity. The appearance of a term of entropy production, or "source term" as Aoki (1988, 1990) calls it, is the watershed dividing the evolutionary world from the special case of conserved energy and mass. *But if energy and mass are intrinsically conserved and entropy is intrinsically evolutionary, how can entropy be calculated on the basis of energy and mass quantities (entropy paradox)?* This question is still unanswered (Coveney, 1990) and all we can do is to note that the ecodynamic viewpoint is different from that of classical physics and classical ecology (see again Table 1).

Let us observe the different relations of energy and entropy vs. information.

An energy flow can lead to destruction (increase in entropy, for example a cannon ball) or organization (decrease in entropy, for example photosynthesis). The same quantity of energy can destroy

Table 2
The death of the deer.

Far from thermodynamic equilibrium	ENTROPIC WATERSHED	Towards thermodynamic equilibrium
m		m
E		E
S		$+\Delta S$
$-\Delta S$		$-\Delta S_{lost}$
information		Information lost

a wall or kill a man; obviously the loss of information and negentropy is much greater in the second case. Energy and information are never equivalent.

The classical example of the mixing of gases in an isolated system shows us that there can be an increase in entropy without energy input from outside. The point is that E and S are related functions, but energy is intrinsically reversible whereas entropy is not. Entropy has the broken time symmetry of which Prigogine speaks. In other words, entropy has an energy term plus a time term that energy does not have.

Entropy has an intrinsic temporal parameter. Energy obeys spatial and material constraints; entropy obeys spatial, material and temporal constraints.

If history and the succession of events are of scientific relevance, the concept of function of state should be revised at a higher level of complexity. The singularity of an event also becomes of particular importance: if a certain quantity of energy is spent to kill a caterpillar, we lose the information embodied in the caterpillar. But were this the last caterpillar, we should lose its unique genetic information forever. The last caterpillar is different from the *n*-th caterpillar.

Stories take place in a setting, the details of which are not irrelevant to the story. What happens in the biosphere, the story of life, depends on the constraints of the biosphere itself. Hence it is important to have global models of the biosphere in terms of space, time, matter, energy, entropy, information, and their respective relations.

Finally if we consider the evolutionary transition from anaerobic to aerobic living systems, the ratio of energy to stored information is clearly different. The information that led to an evolution and organization of the two types of system is not proportional to the flow of energy.

Thus entropy breaks the symmetry of time and can change irrespective of changes of energy, being energy a conservative and reversible property, whereas entropy is evolutionary and irreversible *per se*. The flow of a non-conservative quantity, negentropy, makes life go and the occurrence of a negentropic production term is just the point that differs from analysis based on merely conservative terms (energy and matter).

The situation is explained in Table 2 "The death of the deer": mass and energy do not change, whereas entropy does. There is an entropic *watershed* between far from equilibrium (living) systems and classical systems (the dead deer or any inorganic-not living system).

We may conclude that in far from thermodynamics equilibrium systems (biology and ecology) *entropy is not a state function, since has intrinsic evolutionary properties*, strikingly at variance with classical thermodynamics.

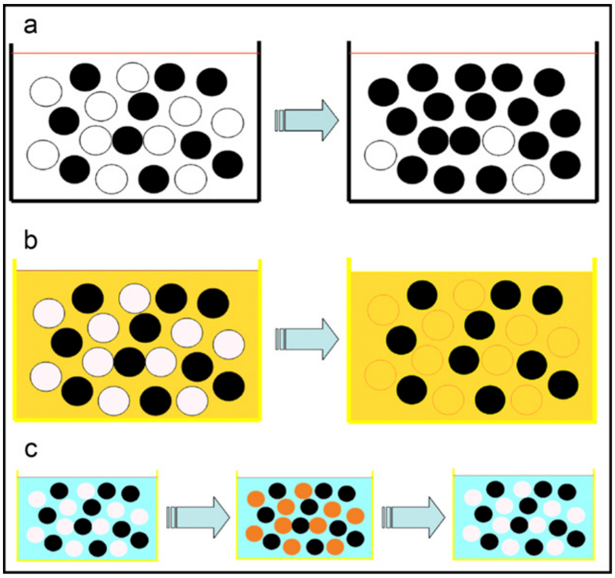

Fig. 1. Unexpected events that may occur in living systems: (a) oxidation; (b) chameleon effect; (c) oscillating reaction.

5. The probability paradox

An event occurs in a stochastic manner because it is preceded by others. There are genetic and environmental constraints. Evolutionary events proceed in a manner that depends on time: they show a direction of time; they are irreversible.

Past time has determined the constraints; the future is largely unpredictable, and always has a stochastic or probable element.

Previously unobserved events cannot be predictable; rare and extreme events may completely change the dynamics of complex systems.

Fig. 1 shows the *emergence* of a probability paradox in the presence of events:

a) suppose that an oxidation (chemical event), unknown to the observer, arises in the classic "white and black spheres" game: the probability white/black is no more fifty-fifty (only if the oxidation is changing the white sphere to grey, I may know what happened),
b) suppose that an evolutionary event also occurs, related to the "*chameleon" effect* (sensible to the environment): again the probability is no more fifty-fifty; moreover the event's interval depends on the "chameleon";
c) suppose an oscillating event occurs, like the well known Belousov-Zhabotinsky reaction: the situation is more complex and depends on many parameters. Again the observer has no possibility to predict which sphere will be picked up from the container.

It is possible to conclude that in the far from equilibrium framework a classical probability approach does not apply and new models have probably to be developed for the Boltzmann's relation $S = k \ln W$.

6. COOS: Confined Ontic Open Systems

COOS is an acronym for *Confined Ontic Open Systems* from the name of the Greek island (Kos, Coo or Coos) where the science of medicine originated at the time of Hippocrates. In Greek mythology, Asclepius, the first great doctor, ascended Mount Olympus as a god and was the first to love water. The primordial element water was considered essential in traditional Asclepiadean therapy, where the ritual of bathing was a form of purification before offering gifts to the great god of health. Hippocrates of Coos separated medicine from religion, magic and philosophy and used it in various fields. He was the first to describe the properties of water as one of the four elements (with fire, earth and air) of human nature on which perfection (health, well-being) depends. Health was impaired if one or more of these elements were out of balance. Hippocrates had the merit of describing the power of water and of identifying the origin and characteristics that contribute to knowledge of diseases arising from the environment, as distinct from those of human origin. He not only trusted the religion of the gods, but tried to coexist with it, teaching his students that Nature has its own life which is not always tied to the supernatural and magic. The major problem of his studies was therefore to give medicine a theoretical instrument of effective explanation and a method of assessment that justified and upgraded the link between theory and experience. The development of the theory was seen as a new approach to medicine that was the forerunner of greater knowledge and the exchange of ideas with doctors operating outside Coos. Hippocrates therefore improved fundamental knowledge that was based on the tradition of religion, magic and observation of natural phenomena (Moffitt, 1922).

The acronym COOS was coined to describe thermodynamic systems *open* to interactions with the outside, but that also maintain their own historical identity (*ontic*), because they are bound to the memory of their origins. Confined Ontic Open Systems are here presented as a new thermodynamic model for understanding evolutionary dynamics that create new structures and enable complexity to emerge, increasing the information in a great variety of systems, more commonly known as living systems capable of self-organization. In order to achieve this, living systems need to be protected (*confined*).

In order to introduce this new thermodynamic model, it is necessary to distinguish between isolated, closed and open systems. Isolated systems do not exchange energy or matter with their surroundings. Closed systems exchange energy but not matter with the outside. Open systems exchange both energy and matter with their environment.

The second step is to recognize that some types of open systems have *confined ontic openness*: they evolve in time and space due to flows of energy and matter across their boundaries that make self-organization possible. Thus a substantial difference distinguishes living from non-living systems: the former have ontogenetic evolution, whereas the latter can only go towards disorder in time with the exception of some dissipative structures that can show a spontaneous generation of complexity, like Bénard convection cells and Belousov-Zhabotinsky (BZ) reactions (Marchettini and Rustici, 2000; Rossi et al., 2008).

The COOS model is based on Prigogine's evolutionary thermodynamics and on the idea of ontic openness proposed by Ulanowicz (2000), revolutionary concepts that challenge the classical thermodynamic principles.

Entropy of COOS may increase but also decrease depending on its capability to self organize. Thus a non-equilibrium steady state is generated that must not be confused with thermodynamic equilibrium and in which order may be created from disorder. Order created in this way no longer violates the laws of thermodynamics. Equilibrium is no longer the only attractor of the system, but the world becomes more complex: in fact, it can lose its thermodynamic stability in order to acquire new oscillating states characterized by highly organized structures or chaotic structures (Prigogine and Stengers, 1979).

For a correct interpretation of processes that characterize the emergence of novelties and self-organization, it is also fundamental to calculate the negative entropy (i.e. order) produced inside open systems and the positive entropy (i.e. disorder) created by them in their environment. The increase in order is only apparent, being at the expense of order in the environment. Overall disorder increases (Tiezzi, 2003a).

All living organisms have these thermodynamic properties. They are open systems with their own evolutionary autonomy and the following characteristics:

- they are *confined* inside a bounded space in which they develop their processes;
- they are *ontic*, maintaining their internal evolutionary memory which cannot be deleted because it obeys the arrow of the time.

Confined Ontic Open Systems may be simple or complex: cells, plants, animals, ecosystems and the planet Earth, all systems capable of self-organization, capable of creating order out of chaos (Tiezzi, 2006b; Jørgensen et al., 2007).

Like all living organisms, pre-biotic systems and physical prototypes of self-organization seem to violate the second principle of thermodynamics: they embody extremely ordered structures that evolve in the direction of increasing order, or decreasing entropy. Emergence of new structures and different organizational levels is related to the presence of liquid water molecules, since these play a fundamental role in the evolution of living systems and generation of chaotic structures. In fact, water is the element that created the fundamental chemical–physical principles for the survival of organisms on the planet Earth and enabled their ontogenetic development. It has been recognized (Szent-Gyorgyi, 1957; Del Giudice and Preparata, 1995, 1998; Voeikov, 2006) that a simple liquid water molecule self-organizes in extended regions and induces organisms to select and make interactions between different molecular species, causing a high level of complexity inside the system.

Pollack (Pollack, 2001; Zheng et al., 2006) showed that there is a thick layer of "special water" (EZ water) at the interface with the walls of a vessel. This water has special properties: it readily donates electrons, so that it is chemically reducing, whereas normal bulk water is oxidizing. There is therefore a higher probability of chemical reactions that give rise to vital processes at the interface between the two layers of water.

In the ancient books, the Terrestrial Paradise (Eden) is also called a confined garden. Thus the concept of *confined ontic openness* is related to the "ecological niche", coined by Elton (1946), which expressed the situation of an organism living with others in a particular environment, involving several types of interaction. The term ecological niche not only includes physical space but also explains the functional role of the species in the biocenosis and its position in the ecosystem. The interactions between the constituents of the system, then are neither isolated nor completely free, determine the beginning of a process of continuous mutual adaptation; all specimens act and react in response to the others in the system (Tiezzi, 2006b). Ecological systems must therefore be open, allowing continuous flow of energy and matter to and from the outside, but they must also have some boundaries, so that species can achieve a high degree of adaptation to the environment and also give rise to new species. Such evolution is related to the idea of *confined ontic openness*. In fact, ecosystems must also have physical constraints for exchanges with the outside, favouring differences in temperature between source and sink, so they can continue to create order and self-organize.

The planet Earth can also be considered a COOS, since boundaries that regulate the entry and exit of electromagnetic radiation from the troposphere protected and favoured the development of molecules essential for the survival of life and determined all the fundamental cycles that regulate the metabolism of this planetary super-organism (Tiezzi, 2003b).

If a thermodynamic system isolates itself, excluding contacts with the external environment, it is destined to degenerate into total disorder. Likewise, if it opens to limitless exchange of energy and matter with the outside, thermodynamic death is again inevitable. Both hypotheses make the evolution of biological, economic, social and regional systems unsustainable (Pulselli et al., 2008).

7. Conclusive remarks

"in order to understand reality, let us divide it into parts, as many as possible"
CARTESIO

"the whole is more than the sum of its parts"
PASCAL

We may conclude that:

In classical science:

- Geometric rules and mechanistic laws apply;
- Newton's laws are reversible deterministic laws.

Prigogine adds and counterpoises the concept of "events" to "laws of nature" of this kind. We know that such laws are not true for living systems, ecosystems, and the events of biology and ecology.

Far from equilibrium we witness new states of matter having properties sharply at variance with those of equilibrium states. This suggests that irreversibility plays a fundamental role in nature.

We must therefore introduce the foundations of irreversibility into our basic description of nature (evolutionary thermodynamics).

It is also important to underline that:

- *Space is, by its structure, reversible*;
- *Time is, by its structure, irreversible.*

In order to achieve an ecodynamic description we need to shift our attention from state functions to goal functions.

We may conclude also with the following two statements by Sven Jørgensen:

> "The presence of irreducible systems is consistent with Gödel's theorem, according to which it will never be possible to give a detailed, comprehensive, complete and comprehensible description of the world. Most natural systems are irreducible, which places profound restrictions of the inherent reductionism of science";
>
> "Many ordered systems have emergent properties defined as properties that a system possesses in addition to the sum of properties of the components – the system is more than the sum of its components. Wolfram (Wolfram, 1984a,b) calls these *irreducible systems* because their properties cannot be revealed by a reduction to some observations of the behaviour of the components."

and we may refer to the Jørgensen's book (Jorgensen and Svirezhev, 2004) for a complete review of Thermodynamic Theory for Ecosystems.

This will lead us to the concept of COOS, the "*conditio sine qua non*" for the emergence of novelties. In fact, like in the example of water (the molecule of life) and natural or artificial boundaries, the ontic-openness of the system enables new structures to form, trapping energy inside. Indeed, dissipative structures maintain their thermodynamic state of non-equilibrium by continuous dissipation of energy outside the system. The disorder produced by the dissipated energy outside the system creates order and self-organization inside. The order produced generates new order and new organization (autocatalytic structures) but if the flow of energy is interrupted or reduced, the structure may collapse and never return to its initial state (irreversibility).

References

Aoki, I., 1988. Entropy laws in ecological networks at steady state. Ecological Modelling 42, 289–303.

Aoki, I., 1990. Monthly variations of entropy production in Lake Biwa. Ecological Modelling 51, 227–232.

Bateson, G., 1972. Steps to an Ecology of Mind. Chandler Publishing Company, New York, USA.

Bateson, G., 1979. Mind and Nature: A Necessary Unity. Dutton, New York, USA.

Boltzmann, L., 1886. The Second Law of Thermodynamics. Ludwig Boltzmann: Theoretical Physics and Philosophical Problems: Selected Writings. D. Reidel, 1974, Dordrecht, Netherlands.

Boltzmann, L., 1964. Lectures on Gas Theory. University of California Press, Berekley, CA.

Coveney, P., 1990. Chaos, entropy and the arrow of time. New Scientist 127, 49.

Del Giudice, E., Preparata, G., 1995. Coherent dynamics in water as a possible explanation of biological membranes formation. Journal of Biological Physics 20, 105–116.

Del Giudice, E., Preparata, G., 1998. A new QED picture of water: understanding a few fascinating phenomena. In: Sassaroli, E., et al. (Eds.), Macroscopic Quantum Coherence. World Scientific, Singapore, pp. 108–129.

Elton, C., 1946. Competition and the structure of ecological communities. The Journal of Animal Ecology 15, 54–68.

Glansdorff, P., Prigogine, I., 1971. Thermodynamic Theory of Structure, Stability and Fluctuations. Wiley-Interscience, New York.

Jorgensen, S.E., Svirezhev, Y.M., 2004. Towards a Thermodynamic Theory for Ecological Systems. Elsevier, Amsterdam.

Jørgensen, S.E., Fath, B.D., Bastianoni, S., Marques, J.C., Muller, F., Nielsen, S.N., Patten, B.C., Tiezzi, E., Ulanowicz, R.E., 2007. A New Ecology: Systems Perspective. Elsevier, Amsterdam.

Kuhn, T.S., 1996. The Structure of Scientific Revolutions. University of Chicago press, Chicago, IL.

Landsberg, P.T., 1972. The fourth law of thermodynamics. Nature 238, 229–231.

Liquori, A.M., 2003. Etica ed estetica della scienza. Di Renzo Editore, Roma.

Marchettini, N., Rustici, M., 2000. Effect of medium viscosity in a closed unstirred Belousov-Zhabotinsky system. Chemical Physics Letters 317, 647–651.

Moffitt, H.C., 1922. Clinicians past, present and future. California State Journal of Medicine 20, 229–231.

Morowitz, H.J., 1979. Energy Flow in Biology. Ox Bow Press, Woodbridge, CT.

Plutarch, 2001. Parallel Lives, Modern Library Paperback. Modern Library, New York, USA.

Pollack, G.H., 2001. Cells, Gels and the Engine of Life. Ebner and Sons, Seattle, USA.

Prigogine, I., 1991. In: Rossi, C., Tiezzi, E. (Eds.), Ecological Physical Chemistry. Elsevier, Amsterdam.

Prigogine, I., Stengers, I., 1979. La nouvelle alliance: métamorphose de la science. Gallimard, Paris.

Pulselli, F.M., Bastianoni, S., Tiezzi, E., Marchettini, N., 2008. The Road to Sustainability: Gdp and Future Generations. WIT Press, Southempton (UK).

Rossi, F., Lombardo, R., Sciascia, L., Sbriziolo, C., Liveri, M.L.T., 2008. Spatio-temporal perturbation of the dynamics of the Ferroin catalyzed Belousov-Zhabotinsky reaction in a batch reactor caused by sodium dodecyl sulfate micelles. Journal of Physical Chemistry B 112, 7244–7250.

Schrödinger, E., 1944. What is Life? Cambridge University Press, Cambridge.

Szent-Gyorgyi, A., 1957. Bioenergetics. Academic Press, New York, USA.

Tiezzi, E., 2003a. The Essence of Time. WIT Press, Southempton (UK).

Tiezzi, E., 2003b. End of Time. WIT Press, Southempton (UK).

Tiezzi, E., 2006a. Is entropy far from equilibrium a state function? International Journal of Ecodynamics 1, 44–54.

Tiezzi, E., 2006b. Steps Towards An Evolutionary Physics. WIT Press (UK), Southempton (UK).

Tiezzi, E., Cecconi, G., Marchettini, N., 2010. Confined ontic open systems. International Journal of Design and Nature and Ecodynamics 5, 3–9.

Ulanowicz, R.E., 2000. Ontic closure and the hierarchy of scale. Annals of the New York Academy of Sciences 901, 266–271.

Voeikov, V.L., 2006. Biological significance of active oxygen-dependent processes in aqueous systems. In: Pollack, G., Cameron, I., Weathly, D. (Eds.), Water and the Cell. Springer Press, NL, pp. 285–298.

Wolfram, S., 1984a. Cellular automata as models of complexity. Nature 311, 419–424.

Wolfram, S., 1984b. Computer Software in Science and Mathematics. Scientific American 251, 140–151.

Zheng, J., Chin, W.C., Khijniak, E., Khijniak Jr., E., Pollack, G.H., 2006. Surfaces and interfacial water: evidence that hydrophilic surfaces have long-range impact. Advances in Colloid and Interface Science 127, 19–27.