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A THERMODYNAMIC APPROACH TO INTERPRET THE ECOSYSTEM COMPLEXITY

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Abstract – The authors present a thermodynamic outlook of some significant processes and phenomena in plant evolution and ecology. The same approach is attempted to exhibit the main steps starting from the vegetation science to the ecosystem studies.

Aim is not to write a usual article, but to propose a re-reading of methods and results in the vegetation research field offering a new point of discussion, in which changes in the entropy of systems are displayed in plants such as in human world.

According to the Second Law of Thermodynamics, inanimate matter tends toward a continuous increasing of randomness and the accompanying spreading out of energy. The Living State appears to move in the opposite direction, generating ordered structures with low entropy and high negentropy/ syntropy. At morpho-physiologic level the leaf represents the most specialized organ to capture sun energetic clean source making the photosynthesis the process through which the negentropy trend is recognizable. Syntropic structures and functions are also generated at the community and ecosystem level. Interestingly in studying ecosystem complexity, the ecoindicators application is comparable to a mind process which reduces "entropy" of the traditional vegetation analysis integrating it in a more suitable and efficient-syntropic- way.

Keywords: entropy, synentropy, ecosystem complexity, community, vegetation, soil, humus, ecoindicators

Introduction

From entropy to negentropy and syntropy: the thermodynamic of the living State (LS). A synthetic overview

Many processes or phenomena that take place in Nature are known to occur in a way that minimizes or maximizes entropy production (Arcidiacono & Arcidiacono, 1991; Baldwin, 2009). Entropy is used for describing different phenomena involving both biological and inanimate systems, such as animal locomotion, vegetation, organ size, water basins and social organization too (Bejan & Lorente, 2010).

It is often thought that the structural complexity of living organisms, which seems to increase as the evolutionary tree is ascended, may place Life outside the laws of Physics. According to the Second Law of Thermodynamics, inanimate matter tends toward constantly increasing randomness and the accompanying spreading out of energy: this process implies an entropy increase (Fig.1).

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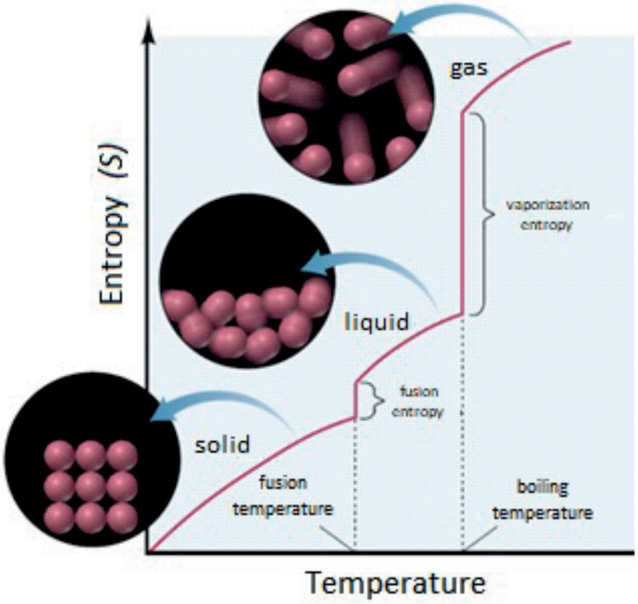


Figure 1. An example of entropy (S) increase in the matter changes: when (a mass) 1Kg of water is heated from < (fusion T°) 0° to > (boiling T°) 100°, a change is observed from a more ordered structure in the ice to a less ordered one of water in the gaseous state.

The Living State appears to move in the opposite direction towards negentropy/syntropy increase. This has been a theme of active debate, which continues, for over 70 years, with no definitive resolution in sight. What is the "vital force" that urgens the Living State (LS) to move toward ever increasing levels of complexity? It is well known that in the physical universe matter and energy are spontaneously degraded into more simple and more random states, as is predicted by the Second Law of Thermodynamics. However, at first sight, this appears not to be the case in the Evolution of the LS as far as order is concerned, is apparently produced from less ordered states. "Order" may be intuitively understood in terms of the complexity of biological structure which modifies (decreases) the degrees of freedom of the molecular and multi-molecular constituents of the system (Arcidiacono, 2005).

A considerable number of academics have developed the general notion, as mentioned above, that the highly ordered nature of the LS represents a violation of the Second Law, or have at least expressed surprise and perplexity in so much as evolution proceeds along a path of increasingly ordered structures (Levins & Lewontin, 1985; Vannini, 2005; Di Corpo & Vannini, 2011; Tooby et al., 2003; Beichler, 2017). "Given the belief that the physical universe is moving toward a static death rather than a thermodynamic balance in which molecular motion continues, it is no surprise that evolutionists believe organic evolution to be the negation of physical evolution." A clear example of this line of thought was expressed by the well-known physiologist Szent-Gyorgyi (1977) who summarized his thoughts on the matter with the rather extremist statement "A major difference between amoebas and humans is the increase of complexity that requires the existence of a mechanism able to counteract the law of entropy". In other words, there must be a force that is able to counter the universal tendency of matter toward chaos and energy toward spreading out. Life always shows a decrease in entropy and an increase in complexity, in direct conflict with the law of entropy. Tooby et al. (2003) write "Thus, to study organisms scientifically it is to be compared with the following questions: Why is it that living things exhibit a miraculously high level of order not found among the non-living? Where does this high level of order come from?", a question posed but not answered.

A line of thought developed, in which the basic studies of the mathematician Fantappiè (1942) played a central role.

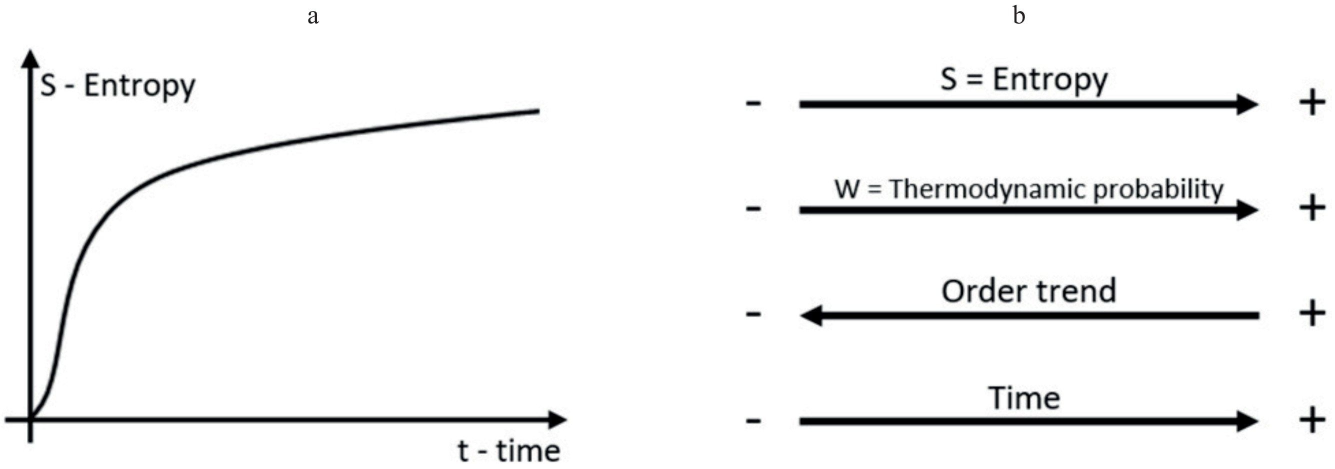


Figure 2. In an isolated system, without exchanges with the outside, entropy (S) increases (a) and, according to Boltzmann (1872), has a favored direction toward disorder (b).

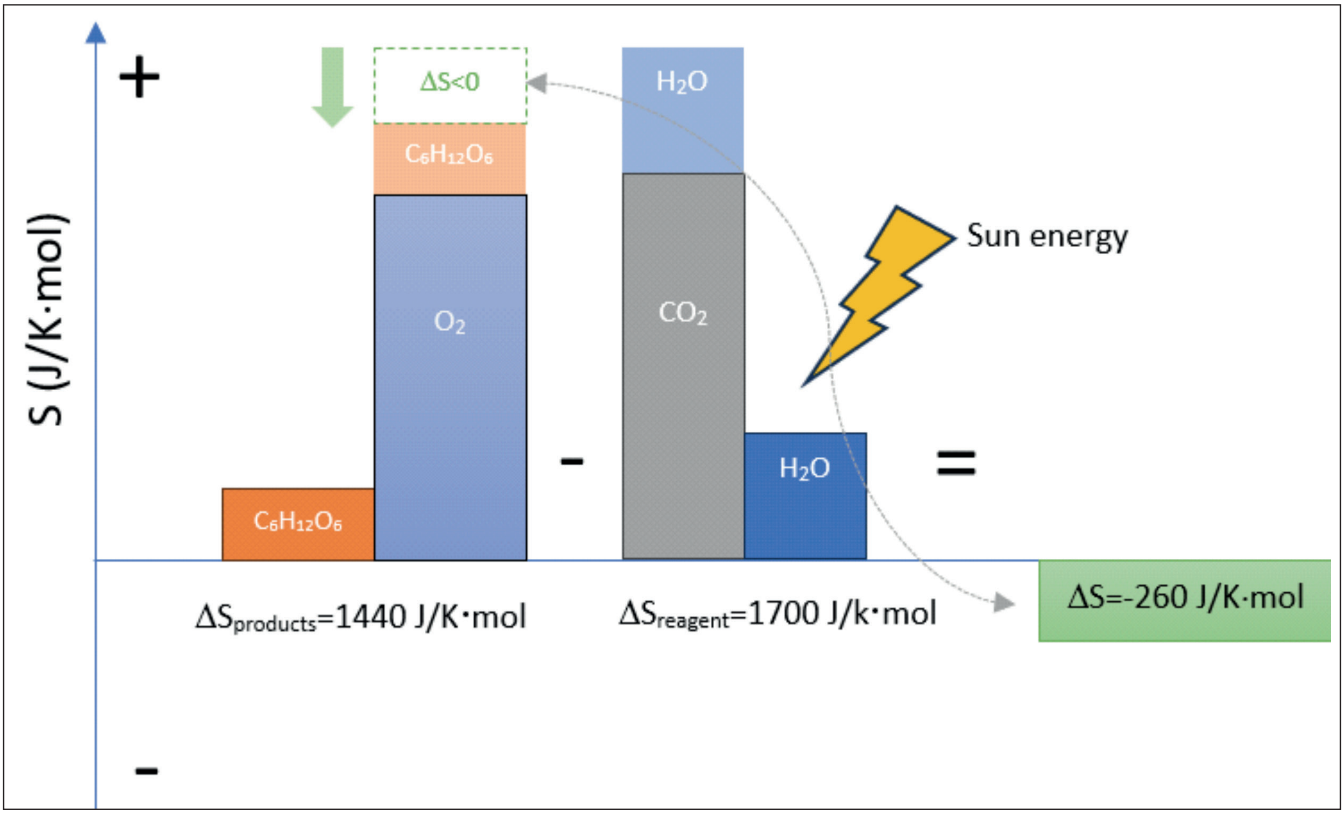


Figure 3. Entropy difference, expressed by J/K ·mol, between photosynthesis reagents and products is < 0.

During his study on the positive and negative time energy, he discovered that the positive time energy is subjected to entropy law (Figs. 2 a, b), while the negative time energy is governed by a complementary law which he called "syntropy", combining the Greek words syn (convergency) with tropos (tendency).

In approximate terms, syntropy is considered to represent the spontaneous creation of order, much as the negentropy of Schrödinger (1963) and is supposed that life phenomena are governed by a principle which is symmetrical to entropy.

Syntropy in plant evolution: structures, functions, relationships as indicators of syntropy

Although the photosynthesis is recognized as the only mechanism which supports the life on the Earth, and that plants are the only living organisms able to capture solar energy, botanical scientist has not investigated enough the changes of energy status following a thermodynamic point of view. Instead, the entropy aspects of the photosynthesis more intrigued the physical scientists, especially regarding the Schrödinger assumption: "there must be a continuous influx of enough negentropy to at least balance the increase of entropy that inevitably accompanies the irreversible processes inside the organisms which rapidly would decay into the lifeless state of maximum entropy" (Yourgrau & Merwe, 1968). Green plants acquire negative entropy along with energy during photosynthesis from the sunlight incident on their leaves (Yourgrau & Merwe, 1968). Nearly the 30% of the incident photon energy gets converted into electron energy that powers the sugar production; the solid glucose is more ordered and complex molecule than gaseous carbon dioxide adsorbed by leaves as reagent (Fig. 3).

In the photosynthesis process there are five entropic components to consider:

1. The declining entropy in the glucose formation
2. The increasing entropy of glucose breakdown
3. The increasing entropy of the environment heat-receiving
4. The declining entropy of biological matter being assembled
5. The declining entropy of energy concentrating in new matter

It should be emphasized that in more complex and ordered structures and functions (points 1,4,5), entropy decreases. The leaf, absorbing solar energy, plays a central role in the mechanisms above mentioned (Tsukaya, 2018).

The possibility of development of leaves with syntropic adaptations seems to be prevalent (and perhaps limited) in the most recent groups in the evolution of Angiosperms.

Plants evolution in the terrestrial environment, which occurred during the last geological periods, has led to deep modifications, both in the structures for the photosynthetic function (leaf characters) and in those for reproduction (flower development): in the latter, the development of a striking phenomenon of co-evolution with insects has been the most general driving factor for evolutionary processes, both in the morphological field and in the physiology of reproduction.

Scheme – Development of vegetative adaptations to obtain greater evolutionary efficiency

Dissemination	
anemophilous	entomophilous
Growing	
horizontal	vertical
Low diversity	high diversity
Poor organization	complex organization

At morpho-physiologic level the leaf represents the most specialized organ to capture sun energetic clean source, reaching the leaves after discharging entropy increase into other celestial bodies, to produce, through photosynthesis, organic matter that also turns out to be clean. This organic matter is concentrated in different organs of a tree, – leaves, branches, trunk, roots – to carry out specific functions with maximum efficiency.

Following the process of growing, woody species with notable vegetative development, develop eco-physiological conditions showing a clear difference between leaves directly exposed to sun radiation and leaves in the shade. In plants living in the shade, transpiration decreases, allowing an important water saving. The organic matter coming from plants is deposited and then concentrated in the upper layers of the soil, the humus, where consumer organisms live: bacteria and mycorrhiza. These differences are further marked in woody perennial plants, in which the living conditions in the shaded parts are clearly different from those exposed to direct sunlight. These conditions are already evident, in general, in shrub plants, but reach their maximum effect in plants with arboreal structure, in which the tree crown, as specialized photosynthesis site, is directly exposed to sun, and has a maximum of laminar development in the leaves. The lower parts are reduced just to the trunk, a cylindrical structure corresponding to the condition of minimum external surface, allowing the development of adaptations for saving water in the physiological transpiration processes: external insulating layer (cortex), no photosynthetic activity, the exclusive function of transferring liquids and dissolved substances. In summary plants, during a very long period of evolution (much longer than the terrestrial animals evolution), have developed a life cycle allowing them to use a "clean" energy source and to generate ordered structures in relationship with the photosynthesis process.

More generally, according to Capra (2021) and Von Bertalanffy (in Davidson, 1983), evolution of biological systems represents the product of their ability (individuals, species) to enact processes of self-organization such that new biological systems emerge.

Syntropy at community level

The whole process of colonization of the earth's surface by plant species occurs because of the action of sun energy, which, in turn, favors plants organization into plurispecific communities: phytocoenoses. Colonization process followed by selection occurs in all the environments of the earth. Lastly, phytocoenoses with peculiar characteristics and specific species composition settle down in a site. Summarizing, the phenomenon here described as **primary succession** or "development of polyphytic phytocoenoses" occurs through selection of stages among present species with different morphologic characters (herbaceous, shrubby, arboreal) and different ecological requirements (heliophilous/shady species, xerophilous/hygrophilous species).

In the phytocoenoses or communities, the presence of species is not regulated by random factors, but appears to be the result of a well-defined choice of "cyclical organization" which produces vegetation types differentiated according to the general environmental conditions. This cyclical organization of the system could be interpreted as a selection process, which distributes the species into distinct groups,

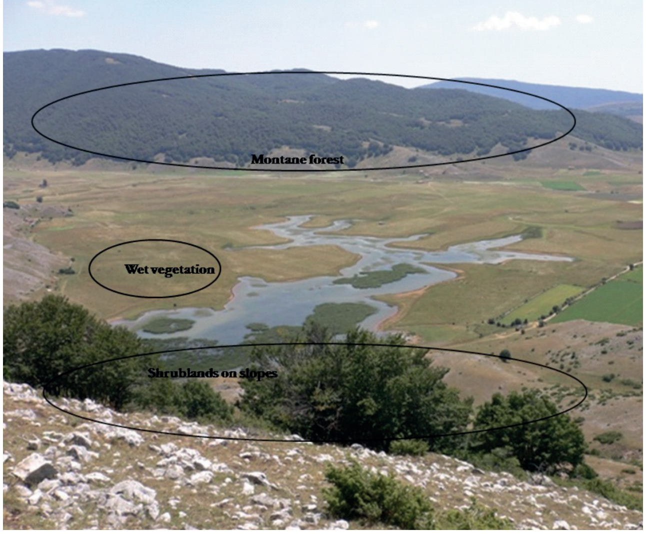


Figure 4. An example of distinct species groups (communities), in relationship with their adaptations to environmental factors.

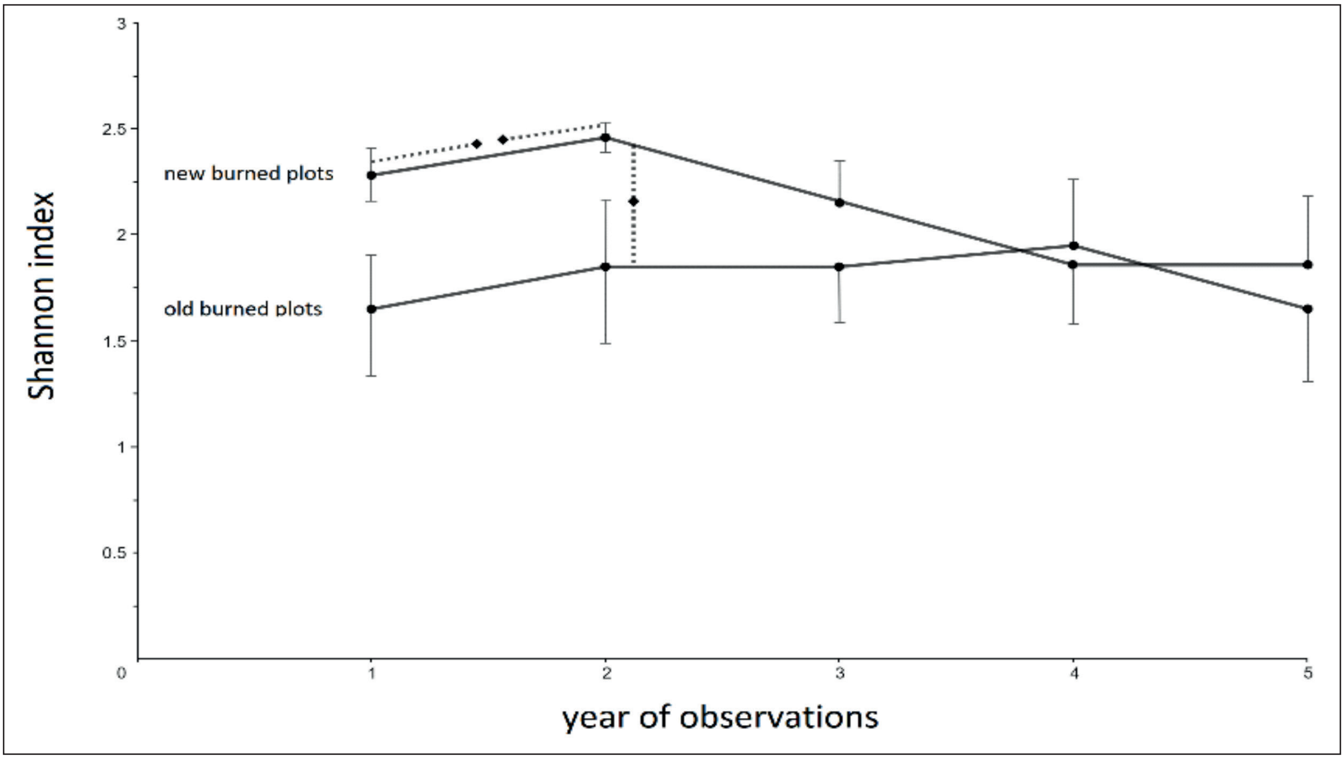


Figure 5. Shannon diversity values calculated in old and new burned plots: after fire species entropy increases and declines in the next years when the pre-fire community recovers.

based on their adaptations to physical-chemical factors, clustering plant species with similar ecological requirements into distinct units (Fig. 4).

All the process generates order increase in the system, entirely consistent with the general theory of the second law of thermodynamics, according to the formulation of Maxwell and Boltzmann (see Rowlinson, 2005). So, phytocoenoses formations can be considered as an entropy lowering in the system which can only occurs because of a high energy input, and which falls within the concept of syntropy (Arcidiacono & Arcidiacono, 1991).

In a **secondary succession** we observe a similar trend toward a syntropy *state*. After a natural or anthropogenic disturbance, *f.i.*, the community is subjected to species disassembly: new species move from the surrounding areas to colonize the soil provoking an entropy increase well described by Shannon diversity index (Shannon & Weaver, 1949), as measurement of the entropy (Fig. 5: De Lillis and Testi, 1992).

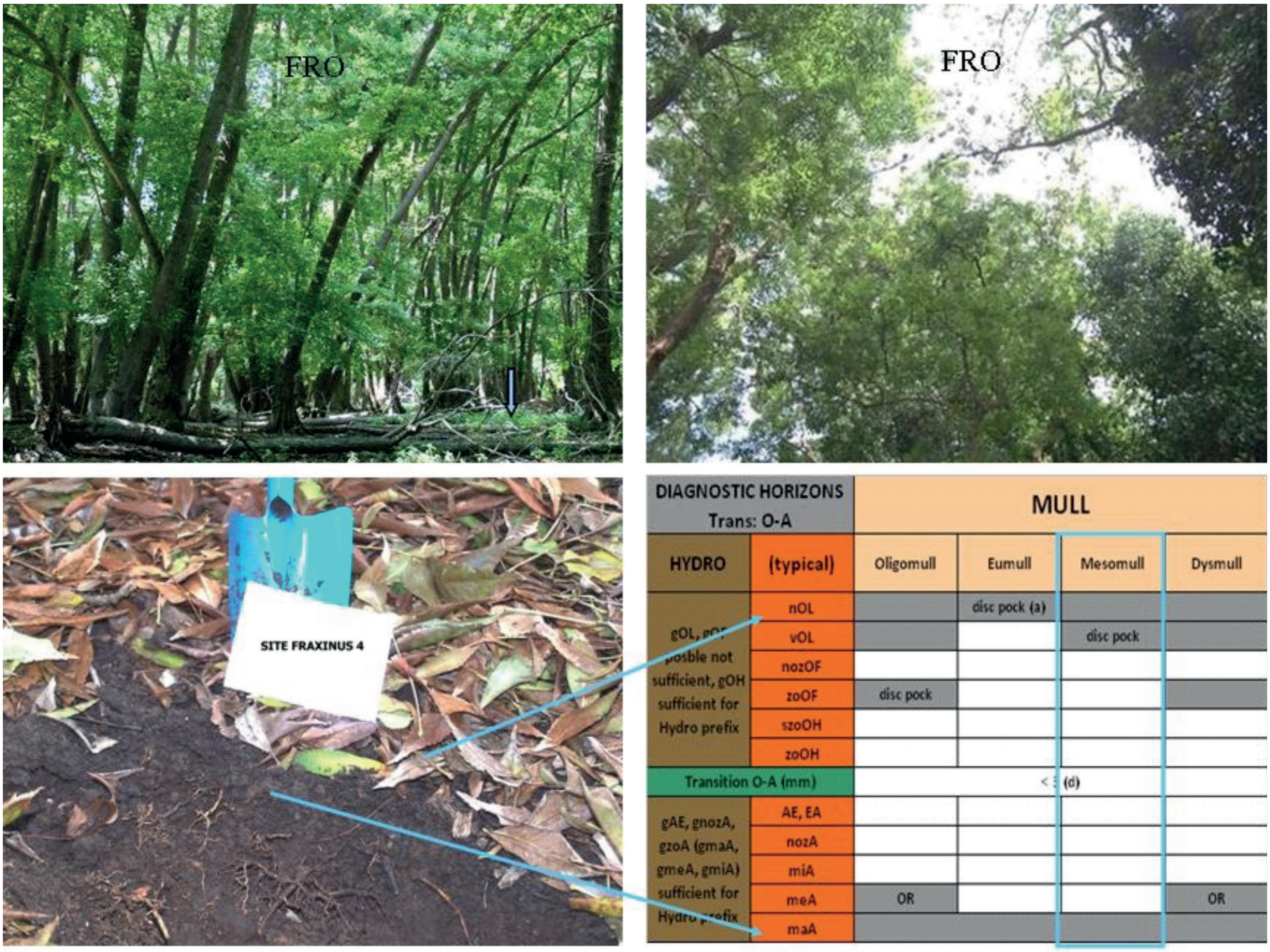
Syntropy at ecosystem level

The whole ecosystem, considering the network of linkages with animals and abiotic components, shows a chaotic condition with entropy increasing after fire (Dickman, 2021). In the last stages, instead, a new species composition and, in many cases, the recovery of pre-fire community is established. Entropy decreases and its symmetrical negentropy/syntropy still characterize the ecosystem with ordered structures, functions, and relationships (Guelpa & Verda, 2017).

We can consider another ecosystem example: plant-climate-soil as a model of complex and ordered system (Fig. 6), whose component interactions produce the major humus forms that we know as Mor, Moder, Mull and Amphi (Wilson et al., 2001; Ponge, 2003; 2013; De Nicola et al., 2014).

The picture can be an example of ecosystem complexity where a network of relationships and correspondences among soil-humus-vegetation has been identified by the study on humus and vegetation in Castelporziano Presidential Estate (Rome). The woodland is represented by *Fraxinus oxycarpa* humid subcoastal forest (FRO) and Mesomull humus form was found in correspondence of this forest type. Water fluctuations explain the natural disturbance recognizable in the undergrowth in Fig. 6.

Plant evolution would proceed generating many subsystems, each within another and all connected among them: *f.i.*, humus forms represent a subsystem into the soil system, in spatial and temporal contiguity with vegetation system. Bacteria and mychorrhiza with the plant roots create another subsystem into the soil. Each subsystem has syntropic structures and functions, according to the theory of entropy decrease in relationship with complexity and order increase (Di Corpo & Vannini,



DIAGNOSTIC HORIZONS Trans: O-A		MULL			
HYDRO	(typical)	Oligomull	Eumull	Mesomull	Dysmull
gOL, gOF posble not sufficient, gOH sufficient for Hydro prefix	nOL		disc pock (a)		
	vOL			disc pock	
	nozOF				
	zoOF	disc pock			
	szoOH				
	zoOH				
Transition O-A (mm)		< 3 (d)			
gAE, gnozA, gzoA (gmaA, gmeA, gmiA) sufficient for Hydro prefix	AE, EA				
	nozA				
	miA				
	meA	OR			OR
	maA				

Figure 6. The woodland is represented by *Fraxinus oxycarpa* humid subcoastal forest (FRO) and Mesomull humus form was found in correspondence of this forest type. This humus form is characterized by a continuous OL – Organic Litter horizon and absence of OL and OF- organic Fragmentation horizons. Water fluctuations explain the natural disturbance recognizable in the undergrowth. (The arrows combine the horizons recognizable in the photo with those reported in the table (key of classification of the humus forms of the Mull humus system). The small arrow in the forest shows the location of the profile in the area (De Nicola et al., 2018).

2011). Also, the carbon storage is an expression of order and entropy decrease. The carbon stock stored in the humus and soil layer shows a wide range among the forest types and in general a high concentration; however, the tendency is to increment with the increase of water availability, as in the humid *Fraxinus oxycarpa* forest (Cicuzza et al., 2015).

When natural (water in the case of Castelporziano), or anthropogenic (boars or fire *f.i.*) disturbance affects a community or ecosystem, the tendency toward order and syntropy it reverses pushing the ecosystem in a new chaotic condition of entropy increase. The process of order recovery starts again restoring the same species composition or, if disturbance time is too long and the impact too much strong, generating another species assemblage and consequently a different plant association.

In fact, every disturbance event, whether natural or anthropogenic, generates within a community or ecosystem, a chaotic, but time-limited, disarranging in the composition and distribution of species. By measuring these changes, for example, through Boltzmann's entropy equation* (1872), taken up by Shannon's diversity index (1949), an increase in values is observed: this means that entropy, the quantitative expression of species disorder, increased affecting vegetation structure (Guelpa & Verda, 2017).

*[$S= k \log W$ shows the relationship between entropy and the number of ways the atoms molecules of a certain kind thermodynamic system can be arranged]

According to Boltzmann and Shannon, after a fire event, *f.i.*, or soil inundation due to rain regime changes, entropy increases in relation to the highest probability of finding in burned or flooded areas, many species from surrounding environments that are no longer specific to the previous community: high Shannon diversity-entropy values are, in fact, recorded (Fig. 5). In physical transformations this corresponds to the equilibrium *state* characterized by maximum entropy, but in the LS the tendency toward restoration of order returns, also when the former community is replaced by another more suited to the new environmental conditions generated by repeated and intense disturbance events (Potter et al., 2003). Successions represent, indeed, good examples of the entropy variations: it increases in the pioneer stages when a chaotic species movement occurs and decreases in the last ones when the community reaches a stability in balance with environmental factors. The temporarily lost of order pushes ecosystem towards a new process of self-organization and order generation.

We can assert that entropy variations follow two ways: at general level it increases also in the LS, like in the inanimate matter, but locally it decreases when we consider living organisms as self-organizing systems creating "order out of randomness", always far from thermal equilibrium.

As some researchers stressed, "self-organization is a property of dissipative nonlinear processes that are governed by a global driving force and a local positive feedback mechanism, which creates regular geometric and/or temporal patterns, and decreases the entropy locally, in contrast to random processes" (Aschwanden et al., 2018; Capra, 2021).

Entropy and Syntropy at cultural/scientific level

According to the second thermodynamic law, the Universe and Life evolution is the story of the progressive establishment of increasingly energy-intensive and entropic dissipative structures, where the human societies show the highest values (Fig. 7).

It is very interesting to note that man occupies the final position of an exponential curve representing the energy spreading out along the time arrow (Roddier, 2021).

From another point of view, instead, we must consider that "whatever the human mind finds itself having to understand, order is an indispensable condition"(Arnheim, 2001) and that "in each science, depending on the purpose and topic, man tells himself" (Spengler, 1925).

This assumption is intended to be the basis on which to develop the question of entropy also in the way in which man approaches the study of any level and topic.

In recent times some scientists in vegetation science and plant ecology asked themselves the following question: "May ecoindicators be a way to reduce in the vegetation analysis long time effort with consequent energy spreading out and consequent entropy increase"?

Traditional approach in vegetation science

The best naturalists of the last century had a knowledge of the nature at 360°; a list of plant species sampled and classified, already at that time, was not a simple list of names but rather a scan of an area with information on climate, soil….Even if the concept of "species as indicators" was not yet developed and codified, that kind of scientist already had a holistic outlook (Montelucci, 1953-54; 1976-77; 1980; Pignatti, 1995; 2011). Traditionally, from the floristic composition of a site, Raunkiaer's forms spectrum or the percentage of different geographical distribution of chorotypes were well established in botanical literature, as simple ecological indicators derived (Fanelli et al., 2006).

The development of the vegetation science produced a lot of important results concerning the community classification and consequent realization of an European database (European Vegetation Archive; Chytrý et al., 2016), very useful for the more recent research on habitat classification and its quality evaluation; the limit of this approach is due to analysis exclusively based on a floristic assemblage, which may lead to redundancy in syntaxonomical framework emphasizing small floristic variation that may only be due to local conditions (Crosti et al., 2010).

Application of ecoindicators system

Pignatti (1988) build up the topic of bioindication on the beginning of phytosociology, when Braun-Blanquet

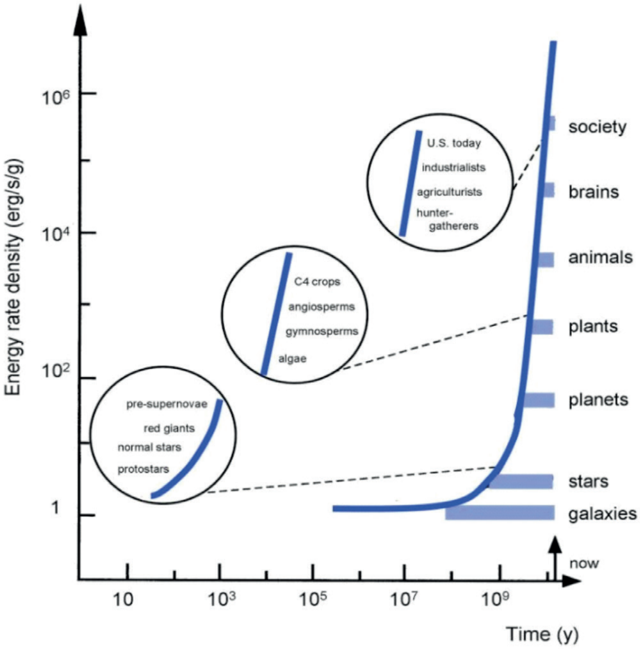


Figure 7. Dissipated energy by unit mass in watt/Kg of different systems as a function of time.

(1926) and Ellenberg (1963) foresaw the development of a multi-methodological analysis overcoming the approach exclusively based on floristic assemblages, advancing the use of ecoindicators. So, following Pignatti (1988; 1995; Pignatti et al., 2001), the life forms as well as the chorological types firstly represent good bioindicators of climate and geographical plant distribution. Ellenberg (1974-1979) marks a shift from a qualitative to numerical approach with his consolidated bioindication model. So, when the Ellenberg ecoindicators for climate (L-Light, T-Temperature, K-Continentality) and soil (pH-Reaction, F-Moisture, N-Nutrients), *f.i.*, started to be applied in different European countries (Zarzycky, 1984; Hill et al., 2000; Borhidi, 1995; Pignatti et al., 2005) and in many ecological studies (Schaffers & Sýkora, 2000; Pignatti et al., 2001, Testi et al., 2006; Fanelli et al., 2007), shortcutting the long-time measurement of chemical and physical parameters, many important results were obtained and new criteria for habitat evaluation and environmental monitoring were given to scientific community (Ellenberg et al., 1992; Körner, 1994), such as to territory managers. The demand of monitoring of species, communities and landscapes becomes ever more pressing at different scale levels: Ellenberg Indicator Values-EIV and ecological maps are a powerful tool in this respect. Ecomaps allow to translate the results of punctual observations into a dynamical and spatial model that can be used as a powerful tool to monitor the coenological shift of species and communities and identify the main ecological factor responsible for the changes (Testi et al., 2006).

The traditional approach changed: mapping EIV instead species or communities is a sort of quantum jumping which would show the states of ecological factors of the species or plant communities in each time (Testi et al., 2021).

A dip from vegetation to soil through soil/humus ecoindicators

To reduce the long-term effort of soil/humus and vegetation sampling and analysis, such as measurements of physical-chemical soil parameters and species/communities' classification, two composite indicators coming from EIV as proposed by Rogister (1978): RxN (Reaction x Nutrient) and R/N (ratio between Reaction and Nutrient) were applied with success to vegetation forestry in Italy. Forest associations and humus forms resulted in agreement each other, described by only two indices (Testi et al., 2021). "So, reducing redundancy to few ecoindicators, two mains in this case, we provided a measure of complexity detecting syntropic structures and functions of the living organisms, through processes of self-organization, dynamic of network and complexity increase, always keeping away from thermodynamic equilibrium (Pignatti, 2003; Varela et al., 1974; Aschwanden et al., 2018). In this way we think to have taken up the initial challenge of Ellenberg and Pignatti and develop their pioneer thought" (Testi et al., 2021). Furthermore, since the two humus indexes resulted highly predictive, we can also overturn the steps of vegetation and humus sampling and analysis: basing on the knowledge and classification of the humus forms in a site, we can predict the vegetation that is expected in correspondence, shortcutting the long-time traditional soil and vegetation analysis.

CONCLUSION

The processes affecting the order with consequent syntropy decrease, occur at global such as local scale, but are time-limited, since the LS always tends, locally, toward a state of syntropy. More specifically dynamics of populations, communities, ecosystems generate changes in the state of order namely of syntropy of a system or subsystem; structures and functions may be considered as "ordered islands in a physical-chemical matrix", which is subjected to the transformations proper of an isolated system going toward entropy increase.
According to Arcidiacono & Arcidiacono (1991),

- In Nature, entropic and syntropic phenomena are closely overlapping and intertwined
- Syntropic phonemena are anti-dissipative
- In syntropic phenomena, we observe a decrease in entropy with the course of time, because the degree of mixing and uniformity of the system decreases with consequent differentiation processes and complexity increase
- In syntropic phenomena a continuous exchange of matter and energy occurs.

A following synthetic scheme summarizes the main characters and differences between isolated and open systems:
Entropy > in isolated systems with dissipation of energy not reusable; increasing of freedom degrees.
Entropy < in open systems (LS) with high available energy; decreasing of freedom degrees.
Structures and functions supporting the inverse entropy direction toward syntropy:

- Leaf shape – laminar surface to optimize the capture of radiation
- Stomata distribution and dimension optimizing O_2 and CO_2 conductance
- Efficiency in water and nutrients absorption by roots
- Transpiration
- Hydraulic mechanism in the trunk

According to the second thermodynamic law, at general scale, Universe such as living organisms spread out energy causing the entropy increase (Fig. 7), but at local scale we observe biological evolution as the story of a progressive establishment of syntropic-ordered structures and functions characterized by complexity.

As concerns the cultural-scientific point of view, we can dare a similar trend of syntropy increase or entropy decrease when we shift from traditional methods in vegetation analysis into methods relying on ecoindicators, resulted more performing by many studies. So, we can give an answer to the initial question about ecoindicators and complexity: in studying ecosystem complexity the ecoindicators approach and application are comparable to a mind process which reduces "entropy" of the traditional vegetation analysis integrating it in a more suitable and efficient – syntropic- way.

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