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Life and the five biological laws. Lessons for global change models and sustainability.

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Life on Earth is the result of a continuous accumulation of information by combination and innovation using endo- (inside the organism) and exosomatic (outside the organism) energy. Sustenance occurs through cycles of life and death. We here define five life laws for these vital processes. These processes cannot exceed natural limits of size and rates because they are constrained by space, matter and energy; biology builds on what is possible within these physicochemical limits. Learning from the way nature deals with the accumulation of information, the limits of size and the rates at which life can acquire and expend energy and resources for maintenance, growth and competition will help us to model and manage our environmental future and sustainability.

Key words: Physical ecology, information, combination, innovation, endosomatic energy, exosomatic energy, discontinuous destruction, energy flow, natural limits, learning from nature, environmental management.

Life is a ride on matter and energy through space subject to selective pressure

Earth's life is complex and diverse. Life on Earth consists of discontinuous individuals belonging to millions of species. Life is the result of evolutionary processes acting on a continuous accumulation of structural and functional information by combination and innovation in the use of matter and endo- and exosomatic energy and on discontinuous processes of death and destruction that recycle the materials that form structure, information and energy compounds, such as proteins, DNA and ATP, respectively.

Combination builds atoms from elementary particles, molecules from atoms, polymers from monomers, tissues from polymers, organs from tissues, organisms from organs, populations from organisms and communities from populations. Pre-existing pieces in the environment or even other organisms are thus assembled into larger structures[1]. Enormous complexity and diversity can be attained from a relatively small number of elements by assembling them in different ways, e.g. at the molecular level alone, a few chemical elements such as C, N, P, S, H, O, K or Ca can combine to form ensembles that, ordered or interacting in different ways, produce unimaginable numbers of possibilities[2], or at the polymeric level, around 20 amino acids provide building blocks for multiple proteins, enzymes and other structures.

Living organisms store and cheaply copy and combine these pieces together with the implicit information they carry. The copied pieces are modified by mutation and other genetic mechanisms in an additional process of innovation. DNA and RNA have this ability. Interestingly, life is over 3 billion years old and has produced a large diversity of forms, shapes and species, but DNA remains the only form of information transfer within the history of life on Earth. Dawkins[3], in a particularly extreme but appealing point of view, argues that life is just the competition among genes, a dynamic change of genetic structure favoring the most adequate information for the continuous improvement of the interactions of organisms with the environment. 'Life is nothing but the maximization of DNA survival' a merciless contest among genes where DNA neither cares nor knows. DNA just is.

The living individuals produced by combination and innovation are open systems that import energy and materials to be used by their cells. They use chemical compounds such as ATP and NADPH to transfer energy and use RUBP to fix carbon. Photosynthesis by autotrophs, self-feeders such as plants and cyanobacteria, dominates the biosphere. They absorb solar energy (photons) leading to (1) photo-oxidation of water and production of oxygen, and (2) formation of electrochemical potential on biological membranes, ATP and NADPH, and finally CO_2 assimilation and biosynthesis of carbohydrates. This is an amazing feature of biological membranes enabling the transformation of solar energy to chemical energy. The chemical energy stored in carbohydrates is the prime energy source, or food, for the majority of life on Earth. The subsequent extraction of chemical energy from carbohydrates is associated with a variety of heterotrophic or chemo-autotrophic metabolisms that use a hierarchy of biogeochemical redox reactions. This energy is used to fuel various forms of work (chemical, osmotic, mechanical) that sustain life. The redox ladder determines the amount of energy extracted, which depends on the terminal electron acceptor. If there is energy to extract along the redox ladder, there is always a distinct microbial group that has evolved to extract that energy. Organisms must work to acquire matter to grow, acquire additional resources, out-compete their neighbors, move, avoid predators and ultimately reproduce, thereby passing their genes to the next generation.

Life thus depends on the flow of energy to sustain metabolism: plants use solar energy, animals and fungi use organic matter and bacteria and archaea can use a variety of chemical energy sources. Ecosystems consist of very complex networks of interacting species (at different levels of space and time) and a physicochemical environment. These networks are hierarchical, organized under the flow of energy, in a stepwise process, as it is dissipated to heat. Because of this link between life and the dissipation of energy, life can be seen as a manifestation of the second law of thermodynamics [4–7].

Organisms and ecosystems depend in many ways on high amounts of exosomatic energy (outside the organism) jointly with this relatively weak endosomatic (inside the organism) flow of energy that permits metabolism[7]. Evapotranspiration lifts water and nutrients from soil to the leaves in plants while also providing turgidity for cell growth. This transport is possible thanks to solar radiation. Many species benefit from wind or water transport to disperse, hunt or find reproductive partners. Some are especially effective in using exosomatic energies for their own benefit. In aquatic ecosystems, movements of water are subsidies of energy for organisms. In the case of mankind, this trend has been much promoted by the advantage of cultural transmission of knowledge and rapid communication. The enormous cultural development of the use of exosomatic energy by mankind is an extreme case of a more general trend in the evolution of life. This cultural development allows a continuously increasing use and control of space and resources that have never been exploited before and feeds back cultural evolution and population growth, but it also involves an increasing danger of climatic disturbance, loss of biodiversity and exhaustion of resources.

In this biological ride on energy and matter: 1) reproductive success passes on genes for successful organismic traits to those who ride the best, given the available resources and the organisms' ability to extract and use them, 2) species differentiation (via evolution, competition and selective winnowing) produces the traits that define the structure and function of microbes, plants and animals, 3) structure and function provide the mechanisms for competing for and capturing light energy, acquiring water and nutrients, modulating the diffusion of gases in and out of plant stomata, plant feeding by herbivores and herbivore hunting by carnivores, and 4) bacteria, fungi and other microorganisms recycle material by exploiting differences in redox potential associated with the chemical energy in carbohydrates and the available electron acceptor, whether it is oxygen, nitrate, sulfate, ferric iron (Fe^{3+}) or carbon dioxide.

Schrödinger (1944)[8] proposed the idea that life implies less entropy, which comes from the ability of life to extract energy from the environment. The second law of thermodynamics establishes that the total entropy of any system cannot decrease unless by increasing the entropy of some other system ("drawing energy from the environment"). Organisms can only stay alive by continually drawing energy from their environment, avoiding decay by eating, drinking, breathing and, in the case of plants, assimilating[8]. The technical term is metabolism. Without this ability to acquire energy, organisms die. Death is therefore the result of not acquiring energy and resources but is useful and necessary when thinking about life as an interconnected system. When organisms die and cease assimilating the products of photosynthesis, the transition toward greater entropy is inevitable, leading to bodily decay, decomposition and the recycling of matter for the next generation of life.

…but life is also a continuous asymmetric accumulation of information

Ecology has been especially interested in these flows and budgets of energy and matter since the late nineteenth century[8–11], understanding ecology as the study of flows of energy and matter, which is why "physics sets the limits on life but biology is how it is done". Some researchers such as Margalef (1997)[7], however, highlighted in the 1960s the importance of the third Aristotelian principle: form, or structure, reinterpreted as information. This information not only regulates the building of structure but also function and metabolism. Information content thus increases faster than the material size of its store, i.e. information content is not simply proportional to the material size of its store, but rather a power with an exponent larger than one:

$$Information = f(Store\ size^{>1})$$

The result of most events in life is a gradual increase in the complexity of nature. This increase, though, cannot continue forever. Changes leading to simplification occasionally occur discontinuously and apparently randomly, erasing large stores of information. The acquisition of information is historical and cannot be run in reverse; it cannot be played back to dismantle each block of added information in an inversely valid way.

Asymmetry thus rules this acquisition of information by life relative to individual birth, growth and death, ecosystem succession and its catastrophic destruction and even the deployment and collapse of human cultures: there is hysteresis from the fact that construction is slow, whereas destruction can be very fast. Changes toward simplification occur discontinuously, apparently distributed at random, similar to punctuated equilibrium and evolution[13], but it is impossible to orderly extract the pieces that came with successive inputs and interactions in biological evolution, one after another. The inclusion of death as a normal event in life's program is very efficient and cheap, because the mechanisms of genetic copying and reproduction of the organisms work so well and are thermodynamically cheap.

Ecosystems are also cyclically destroyed by fire, wind throw, flooding, landslides or other disturbances, although in cases with components that are less integrated, some manipulation and restoration are possible. After a large collapse (e.g. a wildfire), the system is rebuilt mostly from the remaining pieces, such as seeds and spores that were protected or buried. Space and resources in Earth's history were conquered by the survivors that quickly evolved and diversified (adaptive radiations) to use the empty niches after the mass extinctions, i.e. to form a new hierarchical network of energy paths; mammals diversified from surviving species and filled the gap after dinosaurs became extinct. Life amazingly fills all gaps nearly everywhere on Earth: below the ice in Antarctica, in the deep ocean vents, in the driest deserts, …

All life and ecological processes are thus built in a thermodynamic continuum where joining an existing store of information is more effective (the winning strategy in a selective game) than starting a new one. Maybe this is why DNA formed only once. Information accumulates easily and faster when there is already a large core. Information growth is allometric, as are most processes concerning life. Saint Matthew's principle, that those who already have more get more due to the advantage of previous organization, applies here. The compound-interest effect also applies here. Time thus offers the possibility for life systems to enlarge and produce complicated structures, but keeping them functionally coherent, up to a limit imposed by the distance between potential reactants. More complex systems may appear as time flows and history accumulates. Basic mechanisms such as natural selection, self-organization and random processes not driven by selection are particularly useful for understanding this huge complexity of organisms and ecosystems and this huge accumulation of evolutionary biological information through combination, innovation and death while cycling matter and energy. Natural selection and random processes not driven by selection operate on individuals (genotypes), governing the traits that influence fitness and how they vary with the environment. Although still under debate[14], self-organization operates on communities and ecosystems, governing the interactions of system components. These mechanisms explain how life on Earth generates its huge complexity, a complexity and heterogeneity that can be seen as noise in physics or as the magic of life in ecology, a complexity that we humans are intentionally or unintentionally affecting in the most recent history of Earth. The more complex and diverse a system is, the more information it contains. This principle applies to biological systems as well as physical or cultural systems. Understanding and modeling the accumulation of information in organisms and ecosystems are the main challenges for biology and ecology.

Life laws

Physics has universal laws. Biology is envious because it is perceived not to have universal laws. They just seem to be overlooked. Very few laws may in fact explain life on Earth. The five most prominent laws pertinent to life and ecology (Fig. 1) are:

1-the law of mass conservation (introduced by Lomonosov and Lavoisier)

2-the first law of thermodynamics, energy cannot be created or destroyed in an isolated system

3-the second law of thermodynamics, the entropy of any isolated system always increases.

4-information content is a power of the material size of its store with an exponent larger than one and

5-basic mechanisms such as natural selection, self-organization and random processes not driven by selection drive evolution, generating the huge complexity of organisms and ecosystems.

These five laws of nature translate into mostly “principles of limits”, e.g. two things cannot be present simultaneously in the same place, or the same energy cannot be used twice in continuity and in the same way. Life needs to acquire energy to do work and matter to work with in a region of space. The amounts of solar energy and matter per square meter of soil or cubic meter of water are limited, so the number and size of plants, animals and microbes, and the metabolism of an ecosystem have an upper limit. These five laws thus also lead to particular, more focused field laws, e.g. a forest can sustain many small trees or a few big trees but not many big trees.

Life is a space-filling system, so power-law exponents characterize the relationship between energy and mass. The metabolic energy of an organism, ME, needed to sustain metabolism scales with the mass of the organism, M, to the ¾ power (Kleiber’s Law):

$$\mathrm{ME} \approx \mathrm{M}^{3/4}$$

This law has been challenged by studies of plants showing that this law works only if plant nitrogen mass is used instead of the total plant mass[15,16]. This can have some important consequences. For example, if the CO_2 fertilization of the future world will lead to nitrogen dilution in plant tissues it can have an important consequence for modelling of future ecosystems[16].

The number of individuals scales with mass to the -¾ power (modified Yoda’s Law):

$$N \approx \frac{M^{-3/4}}{a}$$

The energy/metabolism of the system is thus scale-invariant with mass; the exponent equals zero:

$$\mathrm{E} = \mathrm{N\ ME} \approx \mathrm{M}^{-3/4}\,\mathrm{M}^{3/4} \sim \mathrm{M}^{0}$$

Physical laws set the limits, and biology adapts to what is available, recycles material and extracts energy from the environment while evolving to develop structures and functions optimized for their environment. Due to the accumulation of information in organisms and ecosystems, joining an existing store of information is more effective (the winning strategy in a selective game) than starting a new store. The physical laws and limits make some forms and functions inviable. A 100-m tree does not grow in the desert, nor can ecosystems evaporate more water than is available from rainfall or groundwater, nor can a CO_2 fertilization period like the one Earth has lived in the past decades be expected to last long since other resources take over the limits[7].

Lessons for life modeling and sustainability

These laws and principles suggest Bayesian priors and relationships for traits, structure and function of organisms and ecosystems, and thus put us closer to what model parameters may and may not be. Both Earth system and integrated assessment models (ESMs and IAMs) should take these general ecological laws into account, mostly as principles that set the limits of space, matter, and energy, and the evolution of the asymmetrical accumulation of information through "compound-interest" principles. Most models are already successful because they implicitly apply these laws. ESMs and IAMs must, moreover, consider that basic mechanisms such as natural and intended selection, but also random processes not driven by selection, drive the evolution of species, and self-organization drives the evolution of semi-natural and agricultural ecosystems, which together generate the highly complex feedback processes in organisms, communities and ecosystems.

These ecological principles also apply to human activities, including landscape architecture and design, economics or urban transport systems of water and vehicles. Even though our species has acquired increasing abilities to use matter, exosomatic energy and information, thanks to the industrial and technological revolutions, the limits of space, matter and energy and the asymmetric accumulation of information, which depends on the size of its storage, still hold, with multiple and complex feedbacks, often unexpected. For example, when we try to geo-engineer CO_2 uptake by plants, these limits and multiple feedbacks lead to ecosystem responses that may have counteracting effects on the original objective[17]. CO_2 uptake is accompanied by undesired changes in albedo and latent and sensible heat, and desiccation of streams, among other energetic and environmental costs to soil, water, air and land-use change and societal and ethical costs. The actual solution to avoid increasing atmospheric CO_2 concentrations is to reduce carbon emissions. Other examples involve the availability and use of water or the design and expansion of cities. As a city continues to grow, moving resources to the interior becomes increasingly congested. Additional examples can come even from the economical and societal worlds. These laws also apply to money to fund societal projects. One cannot expect success by spending huge or unlimited amounts of money on a problem. It takes time to build the infrastructure to use resources.

Life has adapted to these ecological laws and physical limits for billions of years, and if we humans want to develop a sustainable world, we would do well to not forget them in our use of space, matter and energy. In the end, we are only another biological species among millions on Earth and are living in a very short period of Earth's history. We must also subscribe to the same rules and limits as all other forms of life. Management strategies for sustainability must learn from living systems, such as trees or coral how to deal with the ecological laws and principles. They have become structures and functions optimized for their environments; they have learned how to adapt to what is available, to recycle material and to extract energy from the environment in a sustainable way. We should listen and learn lessons from nature that has had several billion years to evolve and get it as right as possible.

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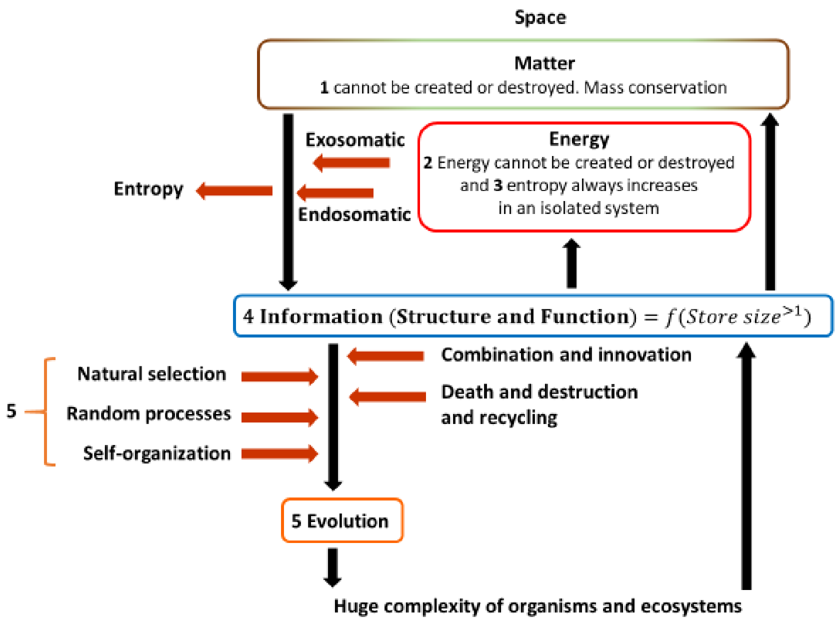

Figure 1. Five laws of life in Earth numbered from 1 to 5 and depicted on a schematics of life fluxes of matter, energy and information on space throughout evolutionary processes