**Does nature learn? Information integration and rare events in systems of increasing complexity**

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### ABSTRACT

The environment is a continuous source of matter and energy, which dynamizes the adaptive processes of biological systems, so that these systems emerge, persist or are extinguished as a consequence of their reactions to the environment. This perspective, forged from classical physics, gives way to multiple ecological theories, with evolution being the most prominent one. In all these cases, *information* would be both dependent and subsequent to *matter* and *energy*. Thus, the emergence and dynamics of genetic material or ecological attributes such as abundance, richness or diversity depend mainly on the interaction of these two fundamental states. However, recent approaches from quantum physics and complexity views put forward the notion that *information* can be independent and *prior* to matter and energy, which allows us to see ecological processes from another perspective, i.e., as including complex biological systems as capable of showing emergent properties such as *cognition*. We proposed here a set of postulates and ideas that suggests how the ability to *manipulate* (internalize, integrate, store and generate) information can be developed by those systems, which would directly and non-randomly influence ecological attributes and their dynamics; i.e., how this property can possibly help replacing the notion of the environment as the ultimate cause of changes. Besides fully detailing the sources of knowledge and our rationale in this sense, we have also discussed how these thoughts and possibilities can be employed in devising better and more comprehensive approaches for biological conservation strategies.

**Keywords**: *Ecological traits, informational attributes, complex systems, emergent properties, unusual events, environmental changes.*

### Introduction

Generally, the environment and its factors are considered the underlying cause of behaviors, patterns, and phenotypes observed in biological systems, at various scales. Thus, persistence, diversity, and evolution are dependent and continually influenced by the environment. Other approaches, though, that explain why biological systems persist; e.g., Flack (2014), Ramstead et al. (2019) and Krakauer et al. (2020) mention that living systems are attracted and selected by the best *known* conditions and, based on their past *experience*, the systems develop the ability to *predict*, and thus, define what to do and where to go. This view represents an externalist dynamic that would explain the persistence and accommodation of biological systems (BS) to changing conditions of increasingly complex environments (Godfrey-Smith 1996). This line of reasoning highlights an ability of complex systems to *manipulate* *information*, (i.e., internalize, integrate, store, and generate new information); from such an internalist perspective, what happens *inside* seems to be more important than what happens *outside* (e.g., Chomsky 1988; Tononi 2008; Varela et al. (1974); Edlund et al. 2011; Hohwy 2014; Fisher 2015; Busáky et al. 2014). From this view, there appear questions related to the connection between unique intrinsic conditions possibly present in BSs e.g., *empathy*; *autonomy* or *cognition* and the probabilities of persistence, extinction and other ecological attributes. From this informational perspective, further questions can be raised: how *surprised* a BS can be in relation to its immediate environment? How can this condition relate to the risk of death or extinction (Maldonado and Cruz 2012; Maldonado 2016a)? What mechanisms/functions operate when the system is in a *known* or an *unknown* environment.

According to Tononi (2008) and Edlund et al. (2011), the property of *cognition* emerges from the integration of information (I.I.) generated by a new event. This process, thus, generates novel information that is introduced into the immediate environment (the system’s surrounding), as suggested by Maldonado and Cruz (2012). In this dynamic, the system exhibits a *guided trajectory*, different from a simple reaction to the stochasticity of the environment. From this view, a *non*-*random* path to increasing complexity of the system and the environment occurs. In this context and circumstances, emergent properties such as *cognition* can generate *autonomy* and *decision-making* power, thereby generating a more *proactive* condition for the complex systems, which can thus be seen as more than simple reacting entities. This line of thoughts suggests that, initially, the challenges and the variable environmental conditions that affect a BS would explain the appearance of those attributes mentioned just above, which can drive BSs to develop new behaviors that could allow them to become independent from the stochasticity of the environment and, therefore, to *solve problems*, and so, to persist (e.g., Sol et al.2010; Sayol et al.2018; Ashton et al.2018). Such an interesting approach has been called *cognitive ecology* (Sol 2009). Those properties can also offer *intentionality* and *prediction* abilities, which would allow the system to show a certain *independence* from the environment. We think that these underlying properties of information processing and incorporation (cognition) can be fundamental for the persistence of every BS, which can *intentionally* interfere with ecological events.

Two key initial definitions are required to be put forward, in order to allow the reader to follow our line of reasoning in this paper. The first is how we consider the fundamental concept of 'information'. For the scope of our proposal (as we will discuss in detail below), we understand information as a fundamental component both in classical and non-classical worlds. In the former, information is to be seen as any change in the status of matter or energy (i.e., structure and/or function), of whatever magnitude, at a given moment. In the classical world, information is *determined*, that is, occupies a place in space-time, *materializing* itself. Thus, information can have different states and behaviors. On the other hand, in the non-classical world/environment, *uncertainty* dominates, i.e., the information is everywhere and at the same time (an environment that Schrödinger described as probabilistic). In either case, for information to *exist* (in practical terms), it should be possible to be somehow *perceived* as such by any *system*. In other words, if nothing perceives a change, there is no information generated. One might think that it would be possible to think on changes that are not necessarily perceived by any system; however, in this case, we ought to provide an additional view of *latent* *information* (a change not perceived) as opposed to *functional* *information* (a change perceived). Nevertheless, a key aspect in this scenario is that it is highly unlikely the *total absence of systems* in any circumstances (due to the nature of the cosmos, in all possible scales), so that we can depart from the assumption that all changes in matter or energy (or the various 'probabilistic states') can be always perceived somehow, and so, generate information. Hence, biological systems (BS), at any compatible scale and as complex systems, are intrinsically able to perceive (and so, process) information. We think that BS emerge from the accumulation of information in the classical environment, and so *persist* as a result of it (see detailed description discussed further below).

The second definition deals with 'cognition' and how biological systems of less complexity (but not absence of it), such as invertebrates, microbes and groups/populations of them would cognitively perceive/process information. Examples of evidence in the literature provide clues for the view we want to convey (e.g., biofilm succession – Stoodley et al. 2002; Lawes et al. 2016; or infrared perception/processing by insects – Klocke et al. 2011; etc.). As described by Tononi (2008), cognition can be understood as an emergent property of any BS, which can be expressed by a mensurable variable *phi* (‘’). A key issue in this approach is that, as a fully abstract concept, there is no specific terminology to appropriately describe it. Therefore, considering that *human* *consciousness* is an example of an emergent property of a (very) complex BS, we can borrow the idea of *cognition* to refer to such a general emergent property of a BS that perceive, incorporate and process information. However, we consider it would not be necessary (or adequate) to advance further with this association of cognition with other human-related characteristics and terminology; in other words, we should not think that BS necessarily have *minds*, or that is *conscious*: we can leave this concept only to humans, or at most, to other vertebrates that share commonalities of mechanisms, architecture and functioning of their brains (the delimitation of which is out of the scope of this manuscript). In this context, the use of the term *cognition* can be simply applied to describe any capability of any system (at molecular, cellular, organ, or population levels) to *perceive*, *process* and *react* to changes (i.e. information) in the surrounding environment, based on the inherent interactive characteristics among its parts; again, these should not be understood as strictly related to the human senses, such as hearing, vision, touch, etc. (although sometimes these properties, when present *stricto* *sensu*, can also serve to information perception, processing and reacting. In fact, the physical and chemical (molecular) aspects of a BS and its surrounding environment offer plenty of mechanisms and opportunities for an array of “senseless” information exchange. Hence, the line of thoughts presented in this paper were built upon these views of *information* (data) and *cognition* (variable). It is worth mentioning, though, that in many circumstances in the text, in our effort to provide sensible and meaningful descriptions, we had to borrow human-related expressions and concepts to provide a simpler, clearer and right-to-the-point view of the ideas we want to convey; for those cases, we used quotation marks.

Taking into account that any living system (BS) displays intrinsic characteristics and should be observed and understood in its own physical and biological scale, hence, it is worth asking: can this cognitive potential of a BS (capacity to integrate information) that allow it to project, organize and intentionally modify its environment, do so in such a way as to additionaly help with its persistence? Furthermore, to the extent that living things can internalize the environment and, thereby, progresses towards autonomy in different levels, can the BSs deliberately affect the physical environment surrounding them, and so, contribute *non-randomly* to its variation? From an ecological perspective, in the present work we approach *persistence* of a BS, independently from the scale, as a "problem" that must be constantly and permanently "solved". Our discussed hypothesis proposes that the intrinsic capacity to *manipulate* and *generate* information reduces a BS’s perception of *uncertainty* in its immediate environment (IE) and, at the same time, introduces new information to this same environment. This way, both the environmental uncertainty to other systems and the complexity of the environment increase. Under this view, variables/abilities such as *interpretation*, *prediction* and *intentionality* are seen as informative attributes of BSs that can, for example, reduce risks of extinction and generate *possibilities* as well.

To address this main hypothesis, we divided this paper into three core sections: the first serves as a background and describes current views on the causal environment–system relationships, and their impact on some ecological attributes. In the next section we discuss how common and rare events would relate to the degree of a BS’s perception of uncertainty about its IE, and how the prediction of these events is related to the cognitive potential of BSs; and finally, we address the importance of informational attributes of complex systems and their relevance in ecological processes. Our approach attempted to provide an extra complementary layer for explanatory frameworks that could assist in the development of environmental management strategies and biological conservation.

***Environment* as an underlying force shaping complex biological systems**

On an ecosystem scale, the environment is seen as the major player. Odum (1969) highlights that the flow of *matter* and *energy* is what configures the food web and gives stability to an ecosystem. Thus, this resulting configuration enables its components to react properly to environmental conditions, allowing them to spread and diversify as much as possible. May (1972) further explores this view and highlights that ecological systems that are rich in strong connections would be more susceptible to instability; in other words, strong interactions in few species and/or weak interactions in many species would reflect more stable ecosystems, which is a similar approach to that developed from network sciences (Hawoong and Barabási 2000) The main idea is that such configurations generate patterns that regulate the average interactive forces (matter and energy exchange), which would support stability in face of environmental variation. Other research has also highlighted the impact of the environment, for example, in ecological successions whose dynamics are evidenced at different scales and in different conditions (Santos et al., 2014; Smith et al. 2015; Buma et al. 2017). A similar position that attempts to explain how the environment affects biodiversity is the hypothesis of *intermediate disturbances* (Connell 1978), which is a subject currently under debate (Fox 2013; Sheil and Burslemm 2013). In these examples, it is suggested that the stability and persistence of complex systems such as ecosystems are governed by particularities of the environment that shape their structure and dynamics, under conditions that direct these systems towards *homeostasis*; Bertalanffy (1976) has defined it as *equifinality*.

Holling (1973) has originally proposed that the structure and function of an ecosystem or a population can be correlated with the *probability of extinction* of their shaping elements, which he called *persistence*; i.e., the presence of fewer elements (individuals / species) will lead to a lower probability that a given system will persist. Holling argued that, under varying climatic conditions, wide fluctuations in the systems structures can be observed, but not enough to extinguish them. In his view, it would be the variable *environment* that would forge the degrees of flexibility in a population or community, so that an unstable population showing large fluctuations in the number of its members (a high flexibility), will be more *resistant* to large environmental variations. In contrast, less structural flexibility would offer a lower potential to face extreme variations in the environment. In the end, from this point of view, the ability of a system to vary its structure is an *adaptive response* forged by the environment. Dynamics such as those shown by metapopulations (Hanski 1998; Grilli et al. 2015), metacommunities (Wilson 1992; Leibold et al. 2004) or metacycle of bacterial dispersion (Troussellier et al. 2017; Mester and Hofer 2020; Pedrós-Alió 2021) would be examples of high organizational plasticity. Interestingly, Zilber-Rosemberg and Rosemberg (2008) brought up such a view of plasticity to the *holobionts* as one generalization of their hologenomic theory of evolution (Rosenberg et al. 2009; Theis et al. 2016; Catania et al. 2017), with a structural dynamic that we can find in plants, cnidarians, sponges, insects etc. (Ramanan et al. 2015, Grajale & Sánchez 2016, Pita et al., 2018, Hassani et al., 2018, Guégan et al., 2018). We understand that such a view of structural plasticity would allow a complex system to configure its “best possible” structure ("the most suitable" one), at any organizational scale. In other words, there is a capacity that living systems possess to assemble a structure in conformity with local conditions.

Scheffer and Carpenter (2003) suggest that a system can behave structurally in a variety of ways, and yet, remain identifiable as such; that is, it can maintain its identity even displaying alternate stable states. However, a change in this dynamic without prior “warning” (without a ”previousexperience” of it) can occur, causing some descriptive/related variables to alter their behavior in such a magnitude/direction that result in a total modification in the trajectory or behavior of the system (structure and function). In this line of research, some authors such as Sugihara et al. (2012), Zhang et al. (2015) and Moore (2018) have used non-linear models to predict under what circumstances these unexpected changes may occur and detect their causes in complex ecosystems. Ideas such as those of Barbier et al (2018) suggest that *stability* comes from the variability / complexity of the parts that make up ecological communities. They also highlight that the mechanisms that structure the diversity, functionality, and stability of a system are related to individual behaviors. In other words, stability is evidenced by collectively dynamic patterns based on individual behaviors that respond particularly to environmental challenges. Such dynamics seems to be evident in communities, populations and even at the level of individual holobionts.

Beyond these examples, there is extensive documentation addressing the problem of the stability and persistence of BSs at different scales and under an array of different views, such as studies related to networks (Jiang et al. 2018; Valverde et al. 2009; Zamborain-Mason et al. 2017), connectivity (Terml et al. 2008; Treml and Kool, 2017), fragmentation (Fletcher et al. 2018; Betts et al. 2019; Fahrig et al. 2019), anthropogenic activity (Evans et al. 2016), climate change and management (Brodie et al. 2016; Tujo et al 2017), succession processes in tropical forests (Norden et al. 2015; Arroyo-Rodríguez et al. 2017), deep ocean communities (Marcus et al. 2009; Sylvan et al. 2012), reef systems (Done 1999; Wilson et al. 2006) or formation of microbial biofilms (Stoodley et al. 2002; Lawes et al. 2016). In all these studies, a stochastic environmental framework is established as the main effector of BSs structure and function.

In ecology, therefore, the predominant views are based on the premise that the causal forces that drive the progressive dynamics of complex systems are found *only* in the disturbances and variability of the environment, which furnish events to which organisms tend to respond mechanically, i.e., they are viewed as simply *reacting*. Classical ecology accepts an externalist view as a premise and most of the explanatory and predictive models of BSs are a reflection of/driven by the environment. Although they do not deny internal issues in the systems dynamics (for example, mutations), they are not seen as relevant for the models. There is only the *causal principle of environment* as what determines whether a BS persists or not. In synthesis, in all these approaches, the degree of *autonomy* or a *“self” causal principle* considered in the theoretical framework of analysis is not sufficient to overcome the causality power of the environment. Therefore, an array of *informational attributes* such as the abilities of *reducing uncertainty*, *solving unexpected problems,* *predicting outcomes*, and *manipulating* andgenerating information are all underestimated as underlying and modifying forces capable of triggering ecological processes. In fact, some ecological research work done on niche construction and ecosystem engineering suggest there is a dynamic feedback between BS and environment, so that the organism(s) adapt to the environment but the environment is also changed by the organism(s) (Laland et al., 2016); in this view, information processing is not considered as a fundamental, necessary variable. In the next sections, we aim at discussing the addition of this layer of information-related standpoints over such a matter and energy conventional framework.

**Common *vs* rare (unusual) events**

In ecology, an *observable phenomenon* (something that can be perceivable, so as it bears information) is an event occurring in the environment (e.g., winters, glaciations, droughts, warming or anoxia of the oceans, continental displacement, earthquakes, volcanism, etc.) and/or related to the BS itself (e.g., germination, flowering, reproduction, migration, settlement, etc.), both under an externalist view standpoint. Environmental events can be dangerous, disastrous or catastrophic and depending on their type, extent, intensity and frequency they can have consequences in evolutionary processes such as *natural selection* (Begon et al. 2006). From another perspective, depending on the *frequency of detection* by BSs, events can be classified as *periodic* (common or that happens more than once in a BS’s lifetime) or *non-periodic* (unusual or rare, happening once or for the first time in a BS lifetime) (Maldonado 2016a). Thus, *common* events can be those such as day-night cycles, lunar periods, hurricane periods, seasons of the year or ice ages, while *unusual* or *rare* events (not yet detected or “*felt”* by the BS) can be changes of abrupt and high-intensity nature in the environment caused by a single or a combination of factors (e.g., an emerging disease never “*experienced”* before by the BS parts/components). This type of event, in fact, can lead the system to a *change of identity* (e.g., an area of forest that changes to a savannah-like environment), which thereby modify its trajectory. Depending on these characteristics, unusual events can have a greater or lesser impact. From a BS perspective, Godfrey-Smith (1996) proposes that, informationally, the surrounding environment can be perceived as immediate environment (IE), which is made up of common (or very frequent) events, and the distant environment (DE) composed of rare or not yet *felt* events.

The IE of a BS can be perceived as a set of properties or variables that change over time (e.g., temperature, salinity, luminosity, pressure, concentration levels of some substance, etc.). Under such circumstances, detection of internal small variations would yet give to BSs the “*feeling*” (this quoted term here and next, again borrowed from human-related properties, refers to an internal state of perceiving/processing specific information by a BS) that they are part of a single, bigger and running event that is occurring (e.g., fall season, high tide, full moon, seawater outcrops, etc., all with internal small variations of their various components, elements and factors). On the other hand, when a BS detects more “*significant*” variations, this will allow the system to perceive a sequence of different events (e.g., all seasons of the year, seasonal dynamics of ocean currents, phases of the moon, etc.). It is important to highlight that all those perceivable variations fully depend on the system scale and components. With all this in mind, we think that such a “*feeling”* of temporality is what constantly update the *predictive* abilities of the BSs. Both cases described above are examples of *common* events that constitute the IE, where the *feeling* of uncertainty is low for the system. This is an idea analogous to the non-linear models of Lorenz (1976), whose dynamics generate *strange attractors*. In short, they are elements in fluid dynamics that relates three (or more) parameters and are sensitively dependent on initial conditions, being the core of the Chaos theory (details of this issue will be addressed and published elsewhere).

Differently from above, in a so-called *distant environment* (DE), new environmental conditions that have never been witnessed or priorly detected can be thus considered as *rare* events, i.e., they are not part of the *history of events* that have occurred in or around a system, so that it has no *previous experience* of them. In this sense, these events end up generating a greater degree of *uncertainty* to the system, which characterize this attribute as having a high impact on complex systems (Maldonado 2016a, 2018b). Hence, a DE emerges as typically loaded with uncertainty. For a better definition and comparative purposes, those *rare events*, under the theoretical framework discussed in the previous section, are considered as only *values* for one or more variables of the descriptive models that have not been previously recorded by a BS. Contrariwise, under the view of complex systems being capable of handling informational attributes, let us bear in mind that events happening around a BS do contain *information* (beyond the flow of matter and energy), which may or may not be new; thus, depending on this condition, the event may or may not be *predictable*. The whole rationale would be that, when there is more sense of uncertainty about the environment, less predictive power the system has, so that it is such an ability to *predict the unpredictable* that gives rise to the *cognitive* potential. We believe that particularities of *unusual* (or *new*) information can potentiate the *stability* and *persistence* capacity of systems who had survived and had the chance to internalize such unusual information. Obviously, if the system is “*caught by any surprise”*, it always run the risk to be extinct. The point here is that when such a rare event of great magnitude happensagain, the *survivor* system would now “know” what to do. In this case, it is important to realize that what may happen for the first time to an *individual* BS, can have *already* happened to a *populational* BS.

As a conceptual framework, BSs that have been sensitive to certain information may have also been evolutionarily selected, when such information appears as the driving selective force. Traits such as magnetic fields detection in lobsters or turtles (Boles and Lohmann 2003; Lohmann and Lohmann 2006), electric fields detection in sharks (Kalmijn (1971); Gauthier et al., 2018), or different frequencies of sound or electromagnetic waves sensing in bats or insects (Redgwell et al. 2009; Klocke et al. 2011) would be appropriate examples. Therefore, it is logical to think that the perception of *common* or *rare* events depends on (i) identity (e.g., species, lineage), (ii) condition (e.g., ontogenetic states or physiological status), and (iii) scale (e.g., individual, population, community) of a given BS. Hence, the cognitive potential of BSs will be certainly quali- and quantitatively different among them.

From an ontogenetic standpoint (an intergenerational dynamic), we can state that the *frequency* of *new* information tends to be reduced as a function of the system’s development; thus, such dynamics increases the predictive power and the potential to define what to do and where to go, with an increasingly lower risk of death (Fig. 1). In simpler terms, a system’s *experience* increases with the ontogenetic stages moving forward. In this case, the events (or informational patterns) of IE, in which the system has been selected for, are more easily internalized with time. For example, the periodic variation in the intensity of night light on the ocean’s surface, caused by the different lunar phases, leads to a specifically sensitive pattern of responsive larval behavior of palinurids (lobsters), which have been selected for. Thus, the negative phototropism that is shown throughout this period allows the lobster systems (BSs) to mechanically and more easily *solve problems* related to that particularly *known* sequence of events. This way, it becomes *easier* for them to evade predators, find food resources, stay in particularly “comfortable” conditions, or follow a known trail to areas of post-larval settlement. That is, the lobster systems activate evolutionarily selected mechanisms that allow them to solve problems more easily, in a manner that would be similar to what have occurred in their longest past. Under this ontogenetic trajectory, initially unusual events become recurrently perceived, which allows them to be less surprised by the environment and consequently improve predictability over time. A consequent conclusion from this line of reasoning is that the more frequent an event occurs, the information it provides will be less relevant, so that with fewer details the BS would more easily and quickly predict the most likely sequence of events. Therefore, we reason that, through the evolutionary force of natural selection, BSs establish mechanisms that allow them to *feel* that certain information from their IE are *familiar*, so they react faster and try to stay under those recognizable conditions. The system would tend insistently to seek the least degree of uncertainty.

Under this view, the expression of *survival instincts*, for example (Jung 1919; Sun and Wilson 2013; Blumberg 2017), would reflect the evolutionary accumulation of *monotonous information*, to the point that physiological responses to given stimuli (driven by selection) become inherently mechanical, automated, and fast. Gould and Marler (1987) suggest that organisms are differentially prepared (genetically? hologenomically?) to *learn* certain things more easily than others, and that they are limited by the information they receive, store, and use. Jung (1919) have already indicated that the origin of the *instincts* in vertebrate animals, for instance, could not be explained only by mere genetic expression and inheritance; it must be *learned* at some point, which is an idea that could be applicable to *any system capable of integrate information during its lifespan*. Blumberg (2017) interestingly proposes that *instinct* is a behavior that *develops individually* under the guidance of *typical experiences accumulated by the species*. This would happen in ecological contexts, so that the instincts would be not only genetically programmed or determined, but also that they would arise (or improve?) in each generation, through a cascade of physical stimuli and biological influence that *generate information to be incorporated* (I.I.). In other words, the evolutionarily acquired mechanisms must be triggered by environment and, from there, information is incorporated, leading to automatic responsive behaviors. The I.I. emerges evolutionarily, with an externalist dynamic that all BS experience in their initial phase.

Here, we are considering that any event will be unusual or not, depending upon whether it occurs for the first time for an individual, a population, a lineage or a community. In this sense, rare events can be a function of the scale of the observer. On a populational scale, a rare event will be one not experienced by *any* of its members; there will be no antecedent that would allow a predictable reaction by the system, so such an event will generate a problem or situation that must be solved in a new and different manner. Under these circumstances, environmental uncertainty is high, as it is the risk of extinction. As examples, alterations of one or more variables to levels not previously experienced could be those generated by increase in atmospheric O2 levels, strike of a meteorite, increase in atmospheric CO2, decrease in oxygen levels in the oceans, or unprecedented actions of anthropogenic nature. Under an informational approach, we postulate that BSs become *experts* in reacting to common events, and therefore tend to abound in those conditions of *lower uncertainty*. In contrast they tend to be more restricted where/when prediction is more difficult, i.e., when *uncertainty is higher*. Therefore, we assume that it is a *net exposure* to both common and rare events that will maintain and/or incorporate new information. In this sense, in a meta-population structure, sub-populations subjected to unusual events may be providing new information that turn it possible to the metapopulation to increase their chances of persisting under different conditions. From this point of view, it has been proposed that *extinction filters* generated by such a prior experience tend to foster species that are relatively more resistant to extinction in a given area (Balmford 1996; Betts et al. 2019).

From this, we propose that the *power* of a BS to “decide” how to solve something under exceptional conditions *is what would be selected for*. Moreover, such a power can play a fundamental role in the BS functional results, which has consequences to the IE by adding new information to it, and so, *increasing environmental uncertainty to other systems*. By incorporating the theory of information to the process of evolution, Adami (2012) emphasizes that the greater the capacity to predict the environment (less uncertainty), the greater are the functional abilities of a BS. From a non-human-centered view, this could be seen as a measure of a system’s “*intelligence”*. Under an externalist and mechanistic dynamic, Maldonado (2018) states that *learning* and *adaptation* are required for the persistence of a system, such that proper decisions based on experience are ultimately an issue of life or death. The ability of a BS to be *less surprised* will depend on *how complexly* it is organized, and consequently, how *informed* it is. In this context, the temporal and/or spatial scale in which events are perceived and recorded by BSs is relevant for their own definition as a BS.

**Emerging Properties of Complex Systems**

*Information* is the underpinning concept that is essential for the generation of emergent properties in a complex system, such as *cognition*. Tononi (2008), in his ‘*manifesto’*, has developed a mathematical method based on causal networks that makes it possible to measure/gauge the cognition as an *emergent property of a system*, which is, in other words, a variable that expresses the capacity of the system to *integrate information* (I.I.). Since BSs (on their various scales) can be regarded as complex systems, we then ponder that their intrinsic capacity of I.I. can affect ecological attributes. In this sense, not all the functions, actions and activities of a BS result *exclusively* from mechanical reactions to periodic and non-periodic environmental stimuli. Although this idea has already been proposed 50 years ago (Anderson 1972), it is yet difficult to quantify this emergent property in a complex system and to assess its impact on the environment, mainly if one considers the different types and levels of complexity. However, we suggest that the ability to I.I. is an *informational trait*, and its possible relationship with ecological attributes should also be considered in the studies on ecology and conservation. Tononi (2008), Maldonado and Gómez (2014) and Maldonado (2018) have focused their attention on *information processing*, and have treated it as a fundamental entity that can generate changes in the structure and function of a system. From this view, it is suggested that, as life manifests itself, when the ability to I.I. increases, then the uncertainty about the environment concomitantly decreases. The ability of a system to I.I. (i.e., to reduce uncertainty) would be thus related to a set of intangible and inexorably “*subjective*” properties (another human-related term, again borrowed for appropriate semantic purposes), such as *decision making*, *intentionality*, risk *calculation*, new problems *solving*, destination *proposing*, *inventing*, etc.; such a set of properties help increasing the flexibility of a BS to face changes in its surroundings, and consequently, to improve *stability* and *persistence* of BSs. In the end, all would comprise *non-random* informational attributes that can interfere with ecological processes. This can be viewed as an *internalist* dynamic that detaches the system to some degree from the *causes* of the environment and makes it more and more *independent* from this same environment. In this scenario, from an internalist point of view, environmental complexity must be tracked by a BS, which is presumably achieved by appropriate internal states capable of storing and processing information (Odenbaugh, J., personal comm.). What are these internal states and how do they operate? Yet subjected to scrutiny and empirical research, we can suggest these internal states may be related to an array of biological properties, such as molecular sensing of free energy variation (ΔG), redox states, substances' concentration gradients, cellular pH, temperature and water levels, gravitational, electric and magnetic fields, reception/emission of quantum signals, gene expression responses (including epigenetics), physiological, biochemical and metabolic outputs, etc., all operating simultaneously, in interactive manners yet to be more in-depth dissected.

From this perspective, we propose that the evolutionary and ontogenetic developments of BSs go from conditions of more uncertainty to less uncertainty; from full environmental dependence to *autonomy*; from stochastic to finalistic, non-random actions. With respect to this idea, a schematic view is presented (Fig. 1), where, for instance, bacterial communities’ succession, the ontogenetic development of crustaceans, or the evolution of hominids, all move forward according to this approach. Biologically, the informational acquisition, processing and incorporation (I.I.) makes it possible for a system to delimit possible life trajectories, make better predictions about the IE, build a *power of choice*, project a destination or modify its environment at “its own convenience”; in other words, and from a large timeframe standpoint, a system can develop greater autonomy and, consequently, increase its persistence by reducing uncertainty in a non-random manner. Therefore, this proposed view suggests that a better abilityto“interpret” the IE (i.e., *cognition*) would be *a key evolutionary feature* that is selected for. Within pairwise informational frameworks that shape complex systems, i.e., structure and function, mechanical and cognitive, predictable and unpredictable, common and rare, facts and possibilities, is how the *biological plasticity* would be forged. The ability to persist in the daily living of BSs moves between these pairwise informational conditions taken altogether; this idea is analogous to that of Godfrey-Smith (1996), which is schematized in Fig 2. Therefore, the differences among BSs lie in the proportional and combined relationship of all those informational conditions that make up each one of them, which allow the BSs to move flexibly along an ever-changing informational environment.



**Fig. 1** Graphical scheme representing the progression of complexity in biological systems. Individual/collective empirical experience by biological systems (BS), e.g., ‘A’ or ‘B’, increases with time (*t1* – *tn*). The ability to integrate information (I.I. = *cognition*) by a BS would increase its *autonomy*, improve the quality and scope of its prediction power (certainty), and decrease *uncertainty* regarding its immediate environment. Rare events (RE) would be related to stressing conditions of the environment upon the system. As time flows (and I.I./cognition develops), systems move from stochastic to *intentional* dynamics; the *causal power* of the environment reduces relevance in relation to that of the systems; systems’ complexity tends to be higher; systems’ uncertainty tends to be lower. Biofilms succession, lobster’s ontogeny or human evolution are shown as examples.



**Fig. 2.** Graphical scheme representing the ‘informational world’ where BSs live. **A**: Representation of the immediate environment (IE) that the BS physically detects, and the distant environment (DE) which shapes its cognitive potential. **B**: Particularities of the environments and the structural and functional composition of the BS. **C**: Proportional composition of the structure and function of BS and their tendency to be more complex. Scheme based on the ideas of Godfrey-Smith (1996).

At this point, a very important idea can be set forth. Analogous to Tononi's theory (2008), and on a *holobiont* scale (Zilber-Rosenberg and Rosenberg 2008; Rosenberg and Zilber-Rosenberg 2009; Bordenstein and Theis 2015; Theis et al. 2016), an *individual* multicellular organism (e.g., plants and animals) can be considered as a *network* that can *manage* both the information obtained from the IE, as well as those generated by itself. Viewed either as evolutionary (Catania et al. 2017; Haag 2018) or as cooperation (Stencel and Wloch‑Salamon 2018) units, those individuals would be sets of *nested* elements (microorganisms and host cells, with their genetic material, biochemistry, physiology and reproductive modes) that interact with each other in a collectively complex manner. Their connections and dynamics can be causally correlated (Ugarelli et al. 2017; Cregger et al. 2018; Pita et al. 2018), although with variable levels of restrictions, according to the types, intensities and duration of the interactions (Moran and Sloan 2015; Catania et al. 2017; Stencel and Wloch‑Salamon 2018). In other words, when the conceptual requirements are met, a *hologenome* would be a very large set of genes displaying a *nested structure* (way beyond those from the host or microbes separately), which could allow such a complex system to functionally operate both mechanically and cognitively at different levels. Thus, both the structure (components and their links) and the cognitive ability (an emergent property) furnish complexity to a BS and establish its *plasticity* and *persistence* capacity.

Systems that do not adequately process new information and do not adequately solve problems, both structurally and functionally, would show a greater chance of extinction (Maldonado and Gómez 2014; Maldonado 2016a, 2018). From its evolutionary nature, cognitive reality is thereby a concept/variable that must not be seen, neither conceptually nor semantically, as exclusive to the human species, having evolved in multiple ways and levels in different living systems (Trevaguas 2005; Ben-Jacob 2009; Boly et al. 2013; Tononi and Koch 2015; Calvo 2016; Owen et al. 2016). However, as initially explained, this reality does not imply the use of ‘*mind’* as a synonym for *cognition*; one can postulate the notion that a *mind* is a very complex human property that lies in a level beyond that of *cognition* here employed. I.I./cognition can be seen as an emergent biological property that arises from the dynamics between *matter*, *energy* and *information*, which would allow a complex system to “invent” solutions to problems or “plan” destinations, in a non-stochastic way. The quality and scope of these informational properties depend upon the individual and/or collective complexity of the BS (Fig.1, 2). In this informational framework, it is interesting to highlight that complexity would not only be related to BSs, *but also to the environment*, which would also become more complex as a result of the BSs introducing novel/additional information.

By “memorizing” repetitive (*monotonous*) environmental conditions and propose new targeted actions during or after unusual events, a BS can generate *predictive* *models*, *project* possible individual and/or collective future, solve problems more easily or in different ways, generate novel functional/structural outputs, prepare for some unusual event, etc.; all these traits can thus progressively and *intentionally* enter new information into the IE, which makes the whole environment more complex. Such a view reinforces the impact of a system’s *autonomy* itself as a *relevant causal agent of ecological phenomena*, a scenario that considers both the *internal* and *external* aspects of the systems, as well as the intricated structural and functional networks that results from them. Nevertheless, other opposing views have also been developed concerning the duality *system–environment*; for instance, Sol et al. (2005, 2010) and Sayol et al. (2018) suggest that the decision-making ability necessary to deal with challenges has its ultimate cause in the environment. From their view, *intention* would emerge as a mere *reaction* to the environment, i.e., it should not be seen as a system’s possibly *based-on*-*independence* trait. In this view, the *causal power* of the environment would remain preponderant, so that evolutionarily acquired attributes by the systems could not become causal principles in themselves. This position is shared, for instance by H. Spencer and J. Dewey, among others (Godfrey-Smith 1996).

Tononi (2008) has proposed a variable called *phi* (ɸ) to quantify the emergent property of *cognition* in the systems. As seen in Fig. 3, we suggest that this emergent property is expressed in different ways, covering a wide and complete spectrum of life that can range from hyperconnected collective organizations, with lower individual complexities and greater dependence on the environment (Prokaryotes), to organizations with higher individual complexities, each with increasing levels of *autonomy* (Eukaryotes). From this standpoint, *intention* would have a fundamental role in the organization of the living, and its reality can be conformed to some principles suggested by Aliev et al. (2015), which can be adjusted to an ecological framework. Under these circumstances, *decision-making* would abide by (i) the possible options offered by the environment, (ii) the sensitivity of the system to its IE, i.e., the type and quality of *information* that it can integrate, (iii) the physical-mechanical capacity of the system to “*assume”* some of the options, (iv) information processing and *risk calculation*, which depend on the accumulated *experience* by the system and their cognitive potential, and (v) a certain degree of *opportunity* related to the stochasticity of the environment.



**Fig.3.** Progression in the systems and environment’s complexity. This graphical scheme is representing a hypothetical progression of the flow and incorporation of new information by BSs. The emergent property of *cognition* is represented by ‘*phi*’ (ɸ), which can be expressed in BSs in different ways, covering a wide spectrum that goes from hyperconnected collective organizations, with less complex individuals (e.g., Archeae, Bacteria), to organizations with greater complexity of its individuals (Eukaryotic). The horizontal axis represents the progression of *time* from an *origin*, and it is the central axis of a ‘cone’ (the base of which is indicated by the semitransparent grey ellipse surrounding the vertical axis), whose lateral area is representing phylogenetic irradiation, which has led to an increase in environmental complexity, and so, an increase in the ‘*phi’* values, i.e., *cognition* of the BSs. [This graphic scheme can show different configurations, an issue that will not be treated in this current theoretical approach].

**Conclusions and outlook on biological conservation**

From what we have discussed above, the fundamental rationale we wish to convey would state that the various possible evolutionary paths of BSs would range from undirected trajectories that would correspond to a strong dependence of the system to its environment, to being directed towards *intention* and system *independence*, which would free itself from environmental stochasticity. Considering that *ecological* attributes such as distribution, connectivity, abundance or persistence can likely be affected by *informational* attributes, we thus suggest that the different abilities of complex biological systems (BSs) to integrate information (I.I.) can influence the possible trajectories of ecological processes, *not being* a matter *entirely dominated solely by the environment*. The bottom line would be that the greater the ability of complex systems, at any scale, to modify the environment and to *know it better*, the lesser the risk of extinction for the system and the greater the complexity of the environment around. The approach of recognizing informational attributes such as *intention* for the living things would provide an additional and alternative perspective that can be studied at a variety of different systems and scales in ecology (i.e., microbes, individuals, populations, lineages, communities, holobionts, ecosystems, biomes, etc.).

However, a great challenge that remains is to ask relevant questions within this framework of complexity and designing appropriate methods, so that this approach can frame and test novel, complementary and innovative hypotheses. Thinking on *systems of increasing complexity* (which generate varying degrees of *independence* over the environment) can allow us to incorporate and integrate novel ideas developed in other areas of knowledge, such as physics, neuroscience, psychology, philosophy, as well as those from complexity sciences, as described by Maldonado (2016b, 2018). Such a multi- and interdisciplinary approach turns it possible to more fully understand (from a *systemic* view of life) how the ability to *manipulate* information can lead a system to overcome the *causal* *power* of its surrounding and generative environment. This way, issues such as persistence or diversification of life in the planet can be more comprehensively addressed and explained; a broader understanding of the ability of a BS to reduce uncertainty about the environment in a non-random, *intentional* way highlights the importance of *information* beyond/besides *matter* and *energy* as fundamental elements.

From this view, and depending on the particularities of the events and/or the systems under assessment, *information* would tend to always *increase* and *accumulate*. For example, geologic/phylogenetic lineages directly derived from ancient entities, older individual organisms, or populations with broader ranges of dispersal would tend to be *less surprised* by the environment. It is reasonable to suspect that global events with potential for higher impacts, such as anoxia, acidification, and ocean warming, might likely select those beings that have already experienced similar events, thus being those with a greater probability of persisting. Likewise, depending on their particularities, rare events allow *new information* to be incorporated into the system, which can progressively modify *informational attributes* such as *autonomy*, *intention*, *invention*, *prediction*, or the *ability to modify* their environment at will.

Under this perspective, we propose a situation as follows: a meta-population structure would be composed by some populations able to persist and abound in informationally monotonous environments, and by others that move and are less abundant in less monotonous, more variable (more *unusual*) environments. This situation tends to give rise to an array of challenges and responses among these populations and their individuals, which can affect both *ecological* and *informational* attributes, such as richness, abundance and composition (structural diversity), and the ability to generate *possibilities*. In conservational terms, we suggest that those populations located at the limits of its usual physical distribution, thereby facing greater environmental challenges in such an ecotone-like condition, could internalize different information than those located in more monotonous environments, such as those that typically describes/delimits the population structure under scrutiny. We ponder this condition likely provides an important conservation value to those marginal or peripheral systems/areas, whose components *know more different things* (structurally and functionally) of *that particular environment* and, therefore, can express *different actions*, which allow them to *reduce uncertainties* (for its species) and/or *make the environment more complex.* Then, after ‘*intergenerational links’*, the *species as a whole* will have a greater opportunity to persist. Under these conditions, greater structural and functional plasticities can be forged, thereby increasing ecosystem’s potential and conservational value. In our view, those ‘marginal’, ecotone-like populational/environmental targets for conservation (including those directly facing human-related activities) would have as much value as those based strictly on typical appropriate conditions, abundance, distribution or connectivity. Although functional aspects like seeds dispersal, pollination, shelter finding, parental care, etc. are key for conservation strategies, these mechanisms do not necessarily cover intrinsic abilities of *making choices* of destinations, or modifying behaviors and/or the immediate environment (IE); in other words, they would not *know what to do* under infrequent conditions. These would be a series of attributes that should not be fully explained *solely* by genetics (heredity), since, at some point, they had *emerged* as a result of the systems’ increase in complexity, which, in turn, comes from continuous *information* incorporation and processing. We do not know, at this point, whether such I.I. would or not, somehow, be incorporated (“recorded”) into the genetic make-up of a holobiont; this is certainly a very interesting scientific (e.g., epigenetics) and philosophical quest to pursue.

Informational attributes/traits are considered fundamental to explain the *emergence* of mechanisms and the necessary *experience* of complex systems to face common and unusual events. Therefore, we consider it important to generate studies that allow us to understand the scope, value, and impact of these attributes and their relevance in the biological dynamics. From the whole perspective presented and discussed in this assay, we suggest that conservation strategies based essentially upon monotonous (though typical) environments may not be a total guarantee of species persistence, since any unexpected or unavoidable remarkable change in the IE can *surprise* a system to an extent that it can be eventually extinct. Our claim is that life persists and extends itself to being prepared physically, functionally and *cognitively* to face expected or unusual, small or large changes. Biological conservation strategies that take this framework into account could likely be more successful than the current paradigm of simply keeping *what is there* intact, in a vain attempt to avoid the *inevitable* anthropogenic interference.

At the end, we leave some questions derived from the core ideas here presented and discussed, which we are currently addressing, and believe they should be tackled and further explored in the *milieu* of biological conservation: (i) evolutionarily, is the *information* obtained from the immediate environment (IE) evident in the physical/functional structure of a biological system (BS)? (ii) Would this characteristic allow the BS to acquire the *ability to predict*? (iii) Can a supposed raise in predictive power of a BS increase its *intentionality* potential? (iv) Can such intentionality (translated as *deliberate actions*) by a BS introduce new information into IE and possibly change entropy values? (v) Is there a direct relationship between the *levels of diversification in a lineage* and *the ability to manipulate information*? (vi) Does the capacity of *deciding* (as a result of *cognition*), together with rare (unusual) events in the environment, show the potential to trigger and drive diversification? (vii) Is it possible to correlate the level of *autonomy* reached by a BS, with the *architecture* and *dynamics* of their IE? (viii) Is the ability to incorporate/integrate information (I.I.) capable of generate different levels of *independence* of a BS to its IE? (ix) Do higher *structural complexity* in BSs correlate with more complex *decision abilities*? (x) Evolutionarily, can highly complex systems be causative sources of environmental variation that affect other systems? (xi) In its respective scales, proportions and levels of cognitive expression, does the *intention* influence the organization and persistence of the living in an ecosystem? (xii) Can the domination and control of information by a BS cause a destabilization in the environment that surrounds it? (xiii) Is *information* the causal source that concentrates, disperses and distributes *matter* and *energy* in space and time?

### REFERENCES

Adami C (2012) The use of information theory in evolutionary biology. Ann. N.Y. Acad. Sci 1256(1):49–65. https://doi.org/10.1111/j.1749-6632.2011.06422.x

Aliev RA, Pedrycz W, Kreinovich V, Huseynov OH (2015) The general theory of decisions. Information Sciences. https://doi.org/10.1016/j.ins.2015.07.055

Anderson PW (1972) More is different. Science 177(4047):393–396. https://doi.org/10.1126/science.177.4047.393

Arroyo-Rodríguez V, Melo FPL, Martínez-Ramos M, Bongers F, Chazdon RL, Meave JA, Norden N, Santos BA, Leal IR, Tabarelli M (2017) Multiple successional pathways in human-modified tropical landscapes: new insights from forest succession, forest fragmentation and landscape ecology research. Biological Reviews, 92(1):326–340. https://doi.org/10.1111/brv.12231

Ashton BJ, Thornton A, Ridley AR (2018) An intraspecific appraisal of the social intelligence hypothesis. Philosophical Transactions of the Royal Society B: Biological Sciences 373(1756). <https://doi.org/10.1098/rstb.2017.0288>

Barbier M, Arnoldi J, Bunin G, Loreau M (2018) Generic assembly patterns in complex ecological communities. PNAS 115(9):1–14. <https://doi.org/10.1073/pnas.1710352115>

Begon M, Tuwnsend CR, Harper JL (2006) Ecology from individuals to ecosystems. Blackwell, Oxford

Ben-Jacob E (2009) Learning from bacteria about natural information processing. Academy of Sciences 1178:78–90. https://doi.org/10.1111/j.1749-6632.2009.05022.x

Bertalanffy LV (1976) Teoría General de los sistemas: Fundamentos, desarrollo, aplicaciones. Fondo de Cultura Económica, México.

Balmford A (1996) Extinction filters and current resilience: the significance of past selection pressures for conservation biology. Trends Ecol Evol 11(5):193-6. https://doi.org/ 10.1016/0169-5347(96)10026-4. PMID: 21237807.

Boly M, Seth AK, Wilke M, Ingmundson P, Baars B, Laureys S, et al (2013) Consciousness in humans and non-human animals: recent advances and future directions. Frontiers in Psychology 4:1–20. https://doi.org/10.3389/fpsyg.2013.00625

Borde**n**stein SR, Theis KR (2015) Host Biology in Light of the Microbiome: Ten Principles of Holobionts and Hologenomes. Plos Biology 13(8):1–23. https://doi.org/10.1371/journal.pbio.1002226

Betts M, Wolf C, Pfeife M, Banks-Leite C, Arroyo-rodríguez V, Ribeiro DB, Faria D, et al (2019) Extinction filters mediate the global effects of habitat fragmentation on animals. Science 366:1236–1239. [http://science.sciencemag.org/content/sci/366/6470/1196.full. Accessed 02 January 2021](http://science.sciencemag.org/content/sci/366/6470/1196.full.%20Accessed%2002%20January%202021).

Blumberg MS (2017) Development evolving: the origins and meanings of instinct. Wiley Interdisciplinary Reviews: Cognitive Science. (8):1-12. <https://doi.org/10.1002/wcs.1371>

Boles LC, Lohmann KJ (2003) True navigation and magnetic maps in spiny lobsters. Nature 421:60-63. https://doi.org/10.1038/nature01333.1.

Brodie JF, Mohd-Azlan J, Schnell JK (2016) How individual links affect network stability in a large-scale, heterogeneous metacommunity. Ecology 97(7):1658–1667. <https://doi.org/10.1890/15-1613.1>

Buma B, Bisbing S, Krapek J, Wright G (2017) A foundation of ecology rediscovered: 100 years of succession on the William S. Cooper plots in Glacier Bay, Alaska. Ecology 98(6):1513–1523. https://doi.org/10.1002/ecy.1848

Calvo P (2016) The philosophy of plant neurobiology: a manifesto. Synthese 193(5):1323–1343. https://doi.org/10.1007/s11229-016-1040-1

Catania F, Krohs U, Chittò M, Ferro D, Ferro K, Lepennetier G, Görtz HD, Schreiber, RS, Kurtz J, Gadau J (2017) The hologenome concept: we need to incorporate function. Theory in Biosciences 136(3-4):89-98. <https://doi.org/10.1007/s12064-016-0240-z>

Connell JH (1978) Diversity in Tropical Rain Forests and Coral Reefs. Science, 199:1302–1310. https://www.jstor.org/stable/1745369

Cregger MA, Veach AM, Yang ZK, Crouch MJ, Vilgalys R, Tuskan GA, Schadt CW (2018) The Populus holobiont: Dissecting the effects of plant niches and genotype on the microbiome. Microbiome 6(31):1–14. https://doi.org/10.1186/s40168-018-0413-8

Done T (1999) Coral community adaptability to environmental changes at the scales of regions, reefs and reef zones. American Zoologist 39:66–79. <https://doi.org/10.1093/icb/39.1.66>

Edlund JA, Chaumont N, Hintze A, Koch C, Tononi G, Adami C (2011) Integrated Information Increases with Fitness in the Evolution of Animats. PLos Computational Biology 7(10):1–13. https://doi.org/10.1371/journal.pcbi.1002236

Evans EW (2016) Biodiversity, ecosystem functioning, and classical biological control. Applied Entomology and Zoology 51(2):173–184. https://doi.org/10.1007/s13355-016-0401-z

Fahrig L, Arroyo-Rodríguez V, Bennett JR, Boucher-Lalonde V, Cazetta E, Currie DJ et al (2019) Is habitat fragmentation bad for biodiversity? Biological Conservation 230:179–186. <https://doi.org/10.1016/j.biocon.2018.12.026>

Flack JC (2019) Life’s information hierarchy. In: Worlds Hidden in Plain Sight: Thirty Years of Complexity Thinking at the Santa Fe Institute. SFI Press, México.

Fletcher RJ, Didham RK, Banks-Leite C, Barlow J, Ewers RM, Rosindell Jet al (2018) Is habitat fragmentation good for biodiversity? Biological Conservation 226:9-15. https://doi.org/10.1016/j.biocon.2018.07.022

Fox JW (2013) The intermediate disturbance hypothesis should be abandoned. Trends in Ecology & Evolution 28(2):86–92. <https://doi.org/10.1016/j.tree.2012.08.014>

Gauthier A, Whitehead D, Tibbetts I, Bennett M (2019) Comparative morphology of the electrosensory system of the epaulette shark *Hemiscyllium ocellatum* and brown-banded bamboo shark *Chiloscyllium punctatum*. Journal of Fish Biology 92(2):313–319. https://doi.org/10.1111/jfb.13893

Gould JL, Marler P (198**7**) Learning by Instinct. Scientific American 256(1):74–85. <https://doi.org/10.1038/scientificamerican0187-74>

Grajales, A. and J. A. Sanchez. 2016. Holobiont Assemblages of Dominant Coral Species (Symbiodinium Types and Coral Species) Shape Caribbean Reef Community Structure. Natural Sciences, 40(115):300–311.

Grilli J, Barabás G, Allesina S (2015) Metapopulation Persistence in Random Fragmented Landscapes. PLos Computational Biology 11(5):1–13. <https://doi.org/10.1371/journal.pcbi.1004251>

Guégan M, Zouache K, Démichel C, Minard G, Tran V, Potier P, Mavingui P and Moro CV (2018) The mosquito holobiont: fresh insight into mosquito-microbiota interactions. Microbiome 6(49): 1-17. https://doi.org/10.1186/s40168-018-0435-2

Haag KL (2018) Holobionts and their hologenomes: evolution with mixed modes of inheritance. Genetics and Molecular Biology, 41(1, suppl): 189-197. http://dx.doi.org/10.1590/1678-4685-GMB-2017-0070.

Hanski I (1998) Metapopulation dynamics. Nature 396:41–49. <https://doi.org/10.1038/23876>

Hassani MA, Duran P and Hacquard S (2018) Microbial interactions within the plant holobiont. Microbiome. 6(58): 1-17. <https://doi.org/10.1186/s40168-018-0445-0>

Hawoong R, Barabási A (2000) Error and attack tolerance of complex networks. Nature 406:378–381. https://doi.org/https://doi.org/10.1038/35019019

Holling CS (1973) Resilience and stability of ecological systems. Annual Review of Ecology and Systematics, 4:1–23. <https://doi.org/10.1146/annurev.es.04.110173.000245>

Jiang J, Huang Z, Seager TP, Lin W, Grebogi C, Hastings A, Lai Y (2018) Predicting tipping points in mutualistic networks through dimension reduction. Proceedings of the National Academy of Sciences, 115(4):639–647. https://doi.org/10.1073/pnas.1714958115

Jung B (1919) Instinct and the unconscious. British Journal of Psychology 10(1):15–26. <https://doi.org/10.1111/j.2044-8295.1919.tb00006.x>

Kalmijn BYAJ (1971) The electric sense of sharks and rays. Journal of Experimental Biology 55:371–383. [https://jeb.biologists.org/content/55/2/371.article-info. Accessed 02 January 2021](https://jeb.biologists.org/content/55/2/371.article-info.%20Accessed%2002%20January%202021)

Klocke D, Schmitz A, Soltner H, Bousack H (2011) Infrared receptors in pyrophilous (“fire loving”) insects as model for new un-cooled infrared sensors. Beilstein Journal Nanotechno 2:186–197. https://doi.org/10.3762/bjnano.2.22

Krakauer D, Bertschinger N, Olbrich E, Flack JC, Ay N (2020) The information theory of individuality. Theory in Biosciences 139:209–223. https://doi.org/10.1007/s12064-020-00313-7

Lawes JC, Neilan BA, Brown MV, Clark, GF, Johnston, EL (2016) Elevated nutrients change bacterial community composition and connectivity: high throughput sequencing of young marine biofilms. Biofouling 32(1):57–69. <https://doi.org/10.1080/08927014.2015.1126581>

Laland K, Matthews B, Feldman M (2016). An introduction to niche construction theory. Evol Ecol 30:191-202. <https://doi.org/10.1007/s10682-016-9821-z>

Leibold MA, Holyoak M, Mouquet N, Amarasekare P, Chase M, Hoopes MF, et al (2004) The metacommunity concept: a framework for multi-scale community ecology. Ecology Letters 7:601–613. https://doi.org/10.1111/j.1461-0248.2004.00608.x

Lohmann KJ, Lohmann CMF (2006) Sea turtles, lobsters, and oceanic magnetic maps. Marine and Freshwater Behaviour and Physiology 39(1):49–64. https://doi.org/10.1080/10236240600563230

Lorenz N (1976) Nondeterministic Theories of Climatic Change. Quaternary Reseach 6:495–506. [https://doi.org/10.1016/0033-5894(76)90022-3](https://doi.org/10.1016/0033-5894%2876%2990022-3)

Maldonado CE, Cruz G (2012) El Mundo de las Ciencias de la Complejidad. Universidad del Rosario. Bogotá. https://doi.org/[10.13140/RG.2.1.4543.5286](https://www.researchgate.net/deref/http%3A//dx.doi.org/10.13140/RG.2.1.4543.5286)

Maldonado CE, Gómez N (2014) Biological Hypercomputation: A New Research Problem in Complexity Theory. Complexity Essays & Commentaries, 1–13. https://doi.org/10.1002/cplx

Maldonado CE (2016a) El evento raro: Epistemología y complejidad. Cinta de Moebio, 56:187–196. https://doi.org/10.4067/S0717-554X2016000200006

Maldonado CE (2016b) Metaheurísticas de investigación en complejidad In: Eschenhagen M, Vélez-Cuartas G, Maldonado C, Pino G (eds) Construcción de problemas de investigación: Diálogos entre el interior y el exterior. Medellín, Colombia. pp. 210-229

Maldonado CE (2018) Quantum physics and consciousness: a (strong) defense of panpsychism. Trans/Form/Ação 41:101–118. <http://dx.doi.org/10.1590/0101-3173.2018.v41esp.07.p101>

Marcus J, Tunnicliffe V, Butterfield DA (2009) Post-eruption succession of macrofaunal communities at diffuse flow hydrothermal vents on Axial Volcano, Juan de Fuca Ridge, Northeast Pacific. Deep Sea Research Part II, 56(19–20):1586–1598. https://doi.org/10.1016/j.dsr2.2009.05.004

May RM (1972) Will a large complex system be stable. Nature, 238:413–414. <https://doi.org/10.1038/238413a0>

Mester M, Hofer J (2020) The microbial conveyor belt: Connecting the globe trough dispersion and dormancy. Trends in microbiology 29(6):1-11. <https://doi.org/10.1016/j.tim.2020.10.007>

Moore JC (2018) Predicting tipping points in complex environmental systems. PNAS 115 (4):635-636. <https://doi.org/10.1073/pnas.1721206115>

Moran NA, Sloan DB (2015) The Hologenome Concept: Helpful or Hollow? PLoS Biology 13(12): e1002311. https://doi.org/10.1371/journal.pbio.1002311

Norden N, Angarita HA, Bongers F, Martínez-Ramos M, Granzow-de la Cerda I, et al (2015) Successional dynamics in Neotropical forests are as uncertain as they are predictable. Proceedings of the National Academy of Sciences 112(26): 8013–8018. <https://doi.org/10.1073/pnas.1500403112>

Odum PE (1969) The strategy of ecosystem development. Science 164: 262–270. DOI: 10.1126/science.164.3877.262

Owen MA, Swaisgood RR, Blumstein DT (201**6**) Contextual influences on animal decision-making: Significance for behavior-based wildlife conservation and management. Integrative Zoology 12(1):32–48. https://doi.org/10.1111/1749-4877.12235

Pita L, Rix L, Slaby BM, Franke A, Hentschel U (2018) The sponge holobiont in a changing ocean: from microbes to ecosystems. Microbiome 6(46):2–18. <https://doi.org/10.1186/s40168-018-0428-1>

Predós A (2021) Time travel in microorganisms. Systematic and Applied Microbiology 44(4):126227. https://doi.org/[10.1016/j.syapm.2021.126227](https://doi.org/10.1016/j.syapm.2021.126227)

Ramanan R, Kim BH, Cho DH, Oh HM, Kim HS (2015) Algae–bacteria interactions: Evolution, ecology and emerging applications. Biotechnology Advances 34(1):14-29. doi: 10.1016/j.biotechadv.2015.12.003

Ramstead M, Badcock P, Friston K (2019) Answering Schrödinger’s question: A free-energy formulation. Physics of Life Reviews 24:1–16. https://doi.org/https://doi.org/10.1016/j.plrev.2017.09.001

Redgwell RD, Szewczak JM, Jones G, Parsons S (2009) Classification of Echolocation Calls from 14 Species of Bat by Support Vector Machines and Ensembles of Neural Networks. Algorithms 2:907–924. https://doi.org/10.3390/a2030907

Rosenberg E, Sharon G, Zilber-Rosenberg I (2009) The hologenome theory of evolution contains Lamarckian aspects within a Darwinian framework. Environmental Microbiology 11(12):2959–2962. <https://doi.org/10.1111/j.1462-2920.2009.01995.x>

Santos A, Tabarelli M, Melo FPL, Camargo LC, Andrade A, Laurance S, Laurance WF (2014) Phylogenetic Impoverishment of Amazonian Tree Communities in an Experimentally Fragmented Forest Landscape. PLoS ONE 9(11):1–7. https://doi.org/10.1371/journal.pone.0113109

Sayol F, Downing PA, Iwaniuk AN, Maspons J, Sol D (2018) Predictable evolution towards larger brains in birds colonizing oceanic islands. Nature Communications 9:1-7. https://doi.org/10.1038/s41467-018-05280-8

Scheffer M, Carpenter SR (2003) Catastrophic regime shifts in ecosystems: linking theory to observation. TRENDS in Ecology and Evolution 18(12):648–656. https://doi.org/10.1016/j.tree.2003.09.002

Sheil D, Burslem DFRP (2013) Defining and defending Connell’s intermediate disturbance hypothesis: a response to Fox. Trends in Ecology & Evolution 28(10):571–572. https://doi.org/10.1016/j.tree.2013.07.006

Smith A, Martin-Spiotta E, Balser T (2015) Successional and seasonal variations in soil and litter microbial community structure and function during tropical postagricultural forest regeneration: a multiyear study. Global Change Biology 21:3532–3547. https://doi.org/10.1111/gcb.12947

Sol D (2009) Revisiting the cognitive buffer hypothesis for the evolution of large brains. Biology Letters 5(1):130–133. https://doi.org/10.1098/rsbl.2008.0621

Sol D, Lefebvre L, Rodríguez-Teijeiro JD (2005) Brain size, innovative propensity and migratory behaviour in temperate Palaearctic birds. Proceedings of the Royal Society B: Biological Sciences 272:1433–1441. https://doi.org/10.1098/rspb.2005.3099

Sol D, Garcia N, Iwaniuk A, Davis K, Meade A, Boyle WA, Székely T (2010) Evolutionary divergence in brain size between migratory and resident birds. PLoS ONE 5(3):1–8. https://doi.org/10.1371/journal.pone.0009617

Stencel A, Wloch‑Salamon DM (2018) Some theoretical insights into the hologenome theory of evolution and the role of microbes in speciation. Theory in Biosciences 137:197–206. https://doi.org/10.1007/s12064-018-0268-3.

Stoodley P, Sauer K, Davies DG, Costerton JW (2002) Biofilms as Complex Differentiated Communities. Annual Review of Microbiology 56(1):187–209. https://doi.org/10.1146/annurev.micro.56.012302.160705

Sugihara G, May R, Ye H, Hsieh C, Deyle E, Fogarty M, Munch S (2012) Detecting Causality in Complex Ecosystems. Science 338(6106):496–500. https://doi.org/10.1126/science.1227079

Sun R, Wilson N (201**3**) Roles of implicit processes: Instinct, intuition, and personality. Mind and Society 13(1):109–134. https://doi.org/10.1007/s11299-013-0134-4

Sylvan JB, Toner BM, Edwards KJ (2012) Life and Death of Deep-Sea Vents: Bacterial Diversity and Ecosystem Succession on Inactive Hydrothermal Sulfide. MBio 3(1):1–10. <https://doi.org/10.1128/mBio.00279-11>

Trewavas A (2005) Green plants as intelligent organisms. Trends in Plant Science 10(9):413–419. <https://doi.org/10.1016/j.tplants.2005.07.005>

Troussellier M, Escalas A, Bouvier T, Mouillot D (2017). Sustaining Rare Marine Microorganisms: Macroorganisms As Repositories and Dispersal Agents of Microbial Diversity. Front. Microbiol. 8:947. doi: 10.3389/fmicb.2017.00947

Theis KR, Dheilly NM, Klassen JL, Brucker RM, Baines JF, Bosch TC, Cryan JF, Gilbert SF, Goodnight CJ, Lloyd EA, Sapp J, Vandenkoornhuyse P, Zilber-Rosenberg I, Rosenberg E, Bordenstein SR (2016). Getting the Hologenome Concept Right: an Eco-Evolutionary Framework for Hosts and Their Microbiomes. mSystems, 1(2):28–16. https://doi.org/10.1128/mSystems.00028-16

Tononi G (2008) Consciousness as Integrated Information: a Provisional Manifesto. The Biological Bulletin 215(3):216–242. <https://doi.org/10.2307/25470707>

Tononi G, Koch C (2015) Consciousness: here, there and everywhere? Philosophical Transactions of the Royal Society B: Biological Sciences. http://dx.doi.org/10.1098/rstb.2014.0167.

Treml EA, Halpin PN, Urban DL, Pratson LF (2008) Modeling population connectivity by ocean currents, a graph-theoretic approach for marine conservation. Landscape Ecology 23(1):19–36. <https://doi.org/10.1007/s10980-007-9138-y>

Treml EA, Kool J (2017) Networks for Quantifying and Analysing Seascape Connectivity. In: Pittman SJ (ed) Seascape ecology, UK, Oxford, (pp. 293–318)

Toju H, Yamamichi M, Guimarães PR, Olesen JM, Mougi A, Yoshida T, Thompson JN (2017) Species-rich networks and eco-evolutionary synthesis at the metacommunity level. Nature Ecology & Evolution 24:1-24. https://doi.org/10.1038/s41559-016-0024

Ugarelli K, Chakrabarti S, Laas P, Stingl U (2017) The Seagrass Holobiont and Its Microbiome. Microorganisms 5(81):1–28. <https://doi.org/10.3390/microorganisms5040081>

Varela F, Maturana H, Uribe R (1974) Autopoiesis: The organitation of living system, its Characterization and model. BioSystem (5) 187-196.

Valverde S, Piñero J, Corominas-Murtra B, Montoya J, Joppa L, Solé R (20**09**) The architecture of mutualistic networks as an evolutionary spandrel. Nature Ecology & Evolution 2(1):94–99. <https://doi.org/10.1038/s41559-017-0383-4>

Wilson DS (1992) Complex Interactions in Metacommunities, with Implications for Biodiversity and Higher Levels of Selection. Ecology 73(6):1984–2000. <https://doi.org/10.2307/1941449>

Wilson SK, Graham NAJ, Pratchett MS, Jones GP, Polunin NVC (2006) Multiple disturbances and the global degradation of coral reefs: Are reef fishes at risk or resilient? Global Change Biology 12(11):2220–2234. https://doi.org/10.1111/j.1365-2486.2006.01252.x

Zamborain-Mason J, Russ GR, Abesamis RA, Bucol AA, Connolly SR (2017) Network theory and metapopulation persistence: incorporating node self-connections. Ecology Letters 20(7):815–831. <https://doi.org/10.1111/ele.12784>

Zhang Z, Yan C, Krebs CJ, Stenseth N (2015) Ecological non-monotonicity and its effects on complexity and stability of populations, communities and ecosystems. Ecological Modelling 312:374–384. <https://doi.org/10.1016/j.ecolmodel.2015.06.004>

Zilber-Rosenberg I, Rosenberg E (2008) Role of microorganisms in the evolution of animals and plants: the hologenome theory of evolution. FEMS Micr Rev 32: 723-35. <https://doi.org/10.1111/j.1574-6976.2008.00123.x>