Endorheic currents in ecology: an example of the effects from scientific specialization and interdisciplinary isolation

Rodrigo Riera, Ricardo A. Rodríguez, Ada M. Herrera, Juan D. Delgado & Brian D. Fath

To cite this article: Rodrigo Riera, Ricardo A. Rodríguez, Ada M. Herrera, Juan D. Delgado & Brian D. Fath (2017): Endorheic currents in ecology: an example of the effects from scientific specialization and interdisciplinary isolation, Interdisciplinary Science Reviews, DOI: 10.1080/03080188.2017.1371480

To link to this article: http://dx.doi.org/10.1080/03080188.2017.1371480

Published online: 12 Nov 2017.
Endorheic currents in ecology: an example of the effects from scientific specialization and interdisciplinary isolation

Rodrigo Riera a, Ricardo A. Rodríguez b, Ada M. Herrera b, Juan D. Delgado c and Brian D. Fath d,e

aCentro de Investigaciones Medioambientales del Atlántico C.I.M.A., Tenerife, Spain; bIndependent researcher, Tampa, FL, USA; cDepartment of Physical, Chemical and Natural Systems. Faculty of Experimental Sciences, University Pablo de Olavide, Sevilla, Spain; dDepartment of Biological Sciences, Towson University, Towson, MD, USA; eAdvanced Systems Analysis, International Institute for Applied Systems Analysis, Laxenburg, Austria

ABSTRACT

Mainstream ecological thought is explored in three sections: (i) Epistemological traits. Given the typical scientific development and the necessity of preserving our intellectual heritage, the conservatism outlined in (i) is cyclical, so its stages are graphically summarized. (ii) Methodological benchmarks antithetically derived from (i), in order to get faster advancement consistent with the growing environmental challenges which spur ecological development. (iii) The renaissance of an old paradigm. This section exposes the misunderstanding of the physical concept of equilibrium by the mainstream ecological thought; this explains its current state. Consequently, section (iii) also summarizes the evolution of a recent set of proposals (organic biophysics of ecosystems) that rescues the foundational paradigm of ecosystem ecology based on physics, neglected by the mainstream thought before producing its most valuable results. We highlight that the main problems emerge from the weakness of integration between ecology, physics and epistemology, and spurious links between ecology and neoclassical economics.

ARTICLE HISTORY

Received 26 September 2016
Accepted 4 June 2017

KEYWORDS

Ecology; ecological state equation; organic biophysics of ecosystems; epistemology; evolution of science; interdisciplinary research; physics; scientific specialization

Introduction

The advancement of basic science is spasmodic instead of continuous. Long periods of intellectual calm, similar to water flows without a defined net direction trapped within the mouth (basin) of an endorheic river, are connected to each other by episodes with a relatively rapid succession of spectacular discoveries. Our illusion of continuity is mainly based on the tide of technological achievements derived even from a single basic scientific discovery. Teaching also has a paradoxical influence on science evolution. On the one hand, it trains young people’s minds to be more productive within an established paradigm. On the other hand, learning channelizes our mind within a dominant paradigm by stifling some potentially successful alternative routes. This dark side of academic training has already been pointed out (‘Education … is transmission of traditional doctrines
and valuations; it is by necessity conservative … Innovators … are precisely the men who defy what the school has taught them’, Von Mises 1996, 314). As a result, the development of science is an alternation between courses with a definite direction, and endorheic basins with slower streams of knowledge between marshy areas and small epistemological islands in which a miscellaneous empiricism rules. Thus, science can remain trapped in an endorheic basin for decades. Ecology is no exception. However, there are extant and emerging environmental problems that perhaps could be better addressed with new, innovative ecological sciences.

In addition, if there is a bias towards specialization, every scientific paradigm is the main reference point of itself. So, it is difficult to be aware that we are within an endorheic basin looking from the interior of it, because we lack external reference points. Thus, opening a basin to flow into new research domains can depend on influences from other scientific fields. This article is aimed to show that the current epistemological situation of mainstream ecological thought is an example in this regard.

Accordingly, the aims of this study are (i) to survey and diagnose the current state of ecology as a discipline; (ii) to obtain a set of useful methodological benchmarks, derived from item (i), in order to forecast the traits of an alternative general solution based on the most probable reason of the current condition in ecology; (iii) to offer a summary of the evolution of a very recent set of proposals (organic biophysics of ecosystems, OBEC) that embodies the general traits included in (ii) by rescuing the foundational paradigm of ecosystem ecology based on physics.

**General epistemological traits of the current state of mainstream ecology**

**A survey of probable endorheic currents**

‘Many papers in ecology do not even reference their theoretical context, while only a small minority are engaged in what is supposed to be the heart of the scientific enterprise: theory testing’ (Scheiner 2013, 1421). As mentioned above, this situation promotes stagnation, because the hegemony of empiricism indicates either (a) disconnection from an already known theoretical framework or (b) lack of a new theoretical framework able to selectively embrace all the variety of what we have called the endorheic currents of ecology. All in all, ‘there is no such thing as theory-free science. All observations presuppose a theoretical context’ (Scheiner op. cit.). Furthermore, any scientific proposal also presupposes a philosophical context, even if its author is unaware of it.

For instance, from the very beginning of modern ecosystem ecology (e.g. Margalef 1963; Odum 1969), there is a consensus that ecosystems tend to maximize species diversity along natural ecological successions undisturbed by the influence of humans. As a consequence, the $H$-index of Shannon (1948) has become the main measure of species diversity. $H$ is known either as ecological information (if the internal structure of the system is already well-known by the observer), or as ecological entropy (if such a structure is unknown). Tribus and McIrvine (1971) explain the correlative and opposite relationship

---

1Conventional ecosystem biophysics deals with the influence of inanimate or lifeless physical factors (e.g. light, temperature, ionizing radiation, movement of isotopes in food webs) on ecological systems. Contrastingly, OBEC does not take into account either of these factors, but only the dynamics of living (organic) creatures that are analysed as if they would be indivisible physical particles in constant movement at the population scale within the ecosystem space. This explains the necessity of introducing the adjective ‘organic’ at the beginning of the term.
between these two concepts because of the necessity of external energy degradation to get internal information (additional comments below). Margalef (1991, 367) explains the equivalence between the product $N \cdot H$ and the statistical dimension of Boltzmann’s entropy ($S = \log \frac{N!}{\prod n_i!}$) in statistical mechanics when the mean number of individuals per species $n_i \gg 100$, being $N = \sum n_i$. Ayres (1994, 36) establishes the equivalence between entropy and uncertainty understood as the lack of information ($H$).

As a result of the insights in the previous paragraph, the maximum entropy formalism (MaxEnt: in brief, that the trend of natural ecosystems to maximize species diversity can be used as a central analytical guide to understand and forecast the ecosystem structure and functioning) is ‘in fashion’ in some ecological thinking schools nowadays (e.g. Dewar and Porté 2008; Banavar, Maritan, and Volkov 2010; Williams 2010; Renner and Warton 2013). But, at the same time, MaxEnt has been criticized (e.g. Marks and Muller-Landau 2007; Haegeman and Loreau 2008; Royle et al. 2012; Kramer-Schadt et al. 2013; Syfert, Smith, and Coomes 2013; Yackulic et al. 2013) due to a variety of reasons that can restrict its validity.

This paradox is normal in developing proposals. On the contrary, our main concern about MaxEnt should be addressed to the lack of an explicit philosophical percolation regarding its extrapolation to ecology. Such a percolation is essential because MaxEnt was initially proposed to develop a ‘subjective statistical mechanics (...) independently of any physical argument and in particular independently of experimental verification’ (Jaynes 1957, 620). First, ecology is not a subjective science, whatever this term could mean in this context and, second, the foundational approach to ecosystem ecology lies in a fully objective thermodynamics (e.g. Lindeman 1942; Odum 1968; Gallucci 1973; Jørgensen and Fath 2004). These issues match with the criterion of Haegeman and Loreau (2008) about MaxEnt: ‘we point out that a blind application of this formalism can easily lead to wrong conclusions’. Third, a classic article (Odum 1969, 265) clearly states that the level of internal entropy decreases along the development of any ecosystem at the same time that species diversity ($H$) increases. So, what is the objective foundation for selecting the maximization of entropy as a reference point for statistical inference, as in the case of MaxEnt? The response is the concept of negentropy (or negative entropy, Brillouin 1953). Negentropy is the entropy that a living system exports to the outside world at the same time that it increases its internal value of $H$ to keep its own internal entropy as low as possible by reducing the amount of net energy consumed to sustain every kg of biomass (Margalef 1992, 232–240; Banavar et al. 2002, 10506; Rodríguez et al. 2013a, Fig. 3b). But the whole of living systems is nested. That is to say, there is a system A within another system B, and so on ... So the entropy that a given system exports in order to keep a high level of internal order (low entropy or high information: $H$) is the internal entropy of another system at a higher hierarchical level, instead of the entropy of the considered system itself. Thus, the application of MaxEnt as if it were an objective, instead of a subjective approach (see Jaynes’ comment above), is equivalent to devoting more importance to the blood that is already outside the body during a haemorrhage, rather than to control the blood that is still inside the body: that is to say, a mismatch of the appropriate reference point.

The points noted in the previous paragraphs are connected with two frequent traits of ecologists: (a) our naive enthusiasm for really new or seemingly new ideas (a sort of scientific snobbery that may promote a ‘hot’ idea over a better less visible one) and, (b) the
performance of our labour neglecting the epistemological experience of other sciences, mainly from physics. One of the most outstanding examples of (a) is the analytical role of species diversity and, specifically, the use of $H$ (see above) as a measure of species diversity. From the initial propositions by MacArthur (1955) and Margalef (1957), the empirical evidence in favour of $H$ is so overwhelming (e.g. Magurran 2004; Ptacnik et al. 2008; Rodríguez et al. 2012, 2013a, 2013b) that it would not be rational to reject its usefulness. Nevertheless, if the concept of diversity is demystified, it lies in a naive empirical rule about nature: any ecosystem free of human interference tends to maximize the variety of functional options (plants, herbivores, carnivores, scavengers, detritivores, and decomposers) within its own physical and chemical limits and thus the species diversity to fill said functional options. The empiricism that governs $H$ was theoretically analyzed by Hurlbert (1971), who pointed out several problems about the ‘non-concept’ of species diversity. There is not any special signal that this situation has been overcome by mainstream ecology (Rossberg 2008). Thus, we have a myriad of unconnected signals in this regard, but we continue looking for a solid theoretical framework (Spellerberg and Fedor 2003) able to confirm if an empirically relevant concept really is an essential state variable in ecosystem ecology. The final section of this article includes a consistent response to this issue.

Regarding point (b), we should take into account the contradictions that shocked classical physics with the arising of relativity theory and quantum physics. However, the validity of Newtonian physics was undeniable. Hence, the founders of modern physics enunciated the principle of correspondence (Bohr 1976). This principle states that a new theory should reproduce the results of older well-established theories in those domains where the old theories work. Contrastingly, there are reports about our trend either to downplay or to forget some of the most solid foundations of ecology for the sake of promoting a seemingly new and impacting approach (e.g. ‘there is a lack of appreciation of past literature; this, in part, leads to ecology’s fickleness toward central issues’, Belovsky et al. 2004, 346). For instance, there are ecosystems everywhere, and even our health depends on a suitable combination of microbial ecosystems (Petrof et al. 2013). But, paradoxically, a groundless doubt about the usefulness of the ecosystem concept have been stated (O’Neill 2001). Similarly, with exceptions (e.g. Ballantyne 2004), our orthodox understanding of food chains has been regarded as the central theory of ecology (Fretwell 1987) and it is based on conventional thermodynamics. Meanwhile, some relatively recent proposals to explain ecosystem functioning starting from physics are based on non-conventional and subjective approaches (see comments above). Thus a simple question arises, is conventional physics applicable or not to obtain a consistent description of ecosystem performance?

Regarding the issue about the paradoxical coexistence of closely related species in a single ecosystem [aka: biodiversity paradox; about a recent debate in this field see Kalmykov and Kalmykov (2016) vs. Rodríguez et al. (2016a)] there is also a confused coexistence between: (a) the competitive exclusion principle [CEP: one species ↔ one ecological function or ‘niche’; e.g. Hardin (1960); Gordon (2000); Wang, Zhang, and Wang (2005)] and (b) the hypothesis of functional redundancy [HFR: several species ↔ one niche; e.g. Walker (1992); Hubbell (2006); Mayfield and Levine (2010)]. The spurious interdisciplinary connection here is that the most general insight from HFR applied to natural resource management is perfectly equivalent to the concept of ‘elasticity of substitution’ developed by neoclassical economics (Samuelson and Nordhaus 1986). By applying this analytical
equivalence, the relationship between two species (A′ and A″) within a functional group that supposedly perform a commonly shared ecological niche is analogous to the alternative demand relationship between to equivalent commodities, such as tea and coffee. If coffee prices rise (if the conservation of species A′ is expensive), but those of tea remain stable (if the conservation of species A″ is cheap), then we simply opt to buy less coffee and buy more tea (we give priority to the conservation of A″). Thus, our total utility in the consumption of stimulating beverages (redundant species) remains constant regardless of whether coffee (species A′) disappears from the market (the ecosystem) or not.

HRF is also connected with economic concepts such as ‘goods and services’ (Naeem 1998) and ‘cost-benefit’ (Walker 1992). This is paradoxical with respect to conservation efforts, because supply and demand assigns incidental prices to goods, but not value, since neoclassical economics does not have a theory of value but only a theory of price formation. On the contrary, since wild species are not products of human activity, one cannot assign market prices to wild species under natural conditions, but they all have value. The main problem is that any commodity can be replaced by a better one, but human beings do not hold enough information to replace species in ecosystems without unpredictable consequences. Thus, this kind of application of economic concepts implies a conceptual distortion of species diversity based on pro-economic reductionism, which is neither scientifically justified nor ethically acceptable.

As it can be inferred from the dilemma HFR vs. CEP, the contemporary first reaction to improve our comprehension of ecosystem functioning was not to explore if there is a given detail that had been neglected in our primary understanding of the CEP, to rectify it, but to abolish the CEP as a whole despite its undeniable analytical role in ecology and evolution: ‘issues come in and out of fashion in ecology (…) without scientific resolution’ (Belovsky et al. 2004, 346).

When mathematics becomes a pernicious analytical influence

The either pro-endorheic or anti-endorheic role of mathematics, depending on the circumstance, is another problem in ecology. For example, correlational research is very common in ecology. However, if we do it without a solid theoretical framework, then we will frequently confront a serious problem: a correlation of $r = 0.976$, $p < 0.0001$ could have a deep meaning or no meaning at all depending on two factors: (a) the premises used to select the variables (e.g. if one calculates correlations between ten variables –45 different correlation coefficients–, then it is possible to find, by chance, that at least two –5%– correlation coefficients are significant at the $p < 0.05$ level even if the values of the variables were totally random); and (b) the availability of a theory useful to understand the real meaning of that result, since the mathematical procedure to calculate correlations is not under debate in this case.

Given the advancement in computer technology applied to statistical packages, it is possible to shuffle variables ad infinitum until obtaining a multiple regression model with $R = 0.9999$ and $p = 0.000001$. But even in this case there may be no underlying theoretical principles to explain the black-box-like model obtained, whose reproducibility could be null. Contrarily, since a consistent model is a good reflection of natural laws which cannot be changed, the model cannot be altered at will either. It only admits the
introduction of a limited amount of certain improvements providing that they are also in agreement with the laws of nature.

Conventionally speaking, when mathematics is used as an argumentative or analytical demonstration tool in applied sciences, the most common way is to start from one or more axioms (i.e. some so self-evident or unquestionable statements that they do not need demonstration at a certain scale) used as qualitative starting points to achieve quantitative results later on. The so common rhetorical phrase ‘so let us to assume that …’ is the typical linking phrase between the initial qualitative axioms and its quantitative outcomes. Euclidian geometry, Copernican celestial mechanics, Newtonian mechanics and statistical mechanics are typical examples in this regard. Initial axioms are sometimes so buried under many layers of subsequent equations and derived deductions that, sometimes, modern researchers are not aware of their existence, but axioms remain there anyway, immutable in the dark basements of sciences. Contrastingly, it is becoming more frequent nowadays in ecology that any article fragment directly begins with ‘let us to assume that …’ following with an abstruse equation without clear connections with solid ecological principles and, very frequently, without subsequent empirical testing. That is to say, that the proposal could be either true or false, nobody knows, including the authors themselves; they only assume that, perhaps, it could be true. In this regard, the opinion of Leon-tief (1982, 104) about neoclassical economics is gradually becoming more and more real for some fields of ecological research:

‘Page after page of professional journals are filled with mathematical formulas leading the reader from sets of more or less plausible but entirely arbitrary assumptions to precisely stated but irrelevant conclusions.’ Coincidentally: ‘Pretty mathematics by itself is not an adequate reason for nature to have made use of a theory. We still have much to learn in seeking for the basic principles of nature’ (Dirac 1982, 604).

In general, those qualitative features that remain as marginal non-computable traits of a given reality constrain the validity of any mathematical algorithm. This is more valid in the same measure in which the hierarchical level of the topic is nearer to complex philosophical subjects. For example, Newtonian mechanics is marvellous within its very wide field of validity, but the absolute nature of time was one of the foundational qualitative assumptions for Newtonian mechanics; and Einstein proved later on that this had been an analytical mistake by Newton. Paradoxically, the final stage of Einstein’s life itself seems to have also been an expression of the pro-endorheic effect because of the disconnection between mathematics and qualitative thinking:

‘Where were the comparable guiding principles that could lead to the construction of a unified field theory? No one knew. Not even Einstein. Thus the search was not so much a search as a groping in the gloom of a mathematical jungle inadequately lit by physical intuition’ (Hoffmann and Dukas 1972, 227); ‘… like an all but random shuffling of mathematical formulas with no physics in view’. (Bernstein 1991, 157)

There are opposite examples to the former one to support the validity of the same statement: Darwin himself was not an outstanding mathematician, and ecology did not exist at all in the time of his most important publication. But his analytical allegory about the role of natural selection was so powerful that the absence of complex mathematics in ‘On the Origin of Species’ did not limit the impact of this book. The main problem with the use of mathematics in ecology is that, in addition to its exact nature, it is also an abstract science.
What this means from a philosophical viewpoint is that large sections of mathematics can be introspectively developed regardless any connection with quotidian world phenomena, and vice versa:

The investigator in another department of science would not need to envy the mathematician if the laws of mathematics referred to objects of our mere imagination, and not to objects of reality … As far as the laws of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality. (Einstein 1922, 27–28)

The ecological use of mathematics is exciting and useful in the same measure in which its abuse (May 2004; Pilkey and Pilkey-Jarvis 2006) is detrimental: a smoke screen frequently used to mask the underlying triviality of some results with the goal of convincing editors and reviewers about the suitability of a given publication; a variant of the propagandistic use of mathematics (Koblitz 1981). In such a manner, it is more and more frequent in current ecology that some people think, tautologically, that those speculations purely derived from mathematics are true, by force, simply because they have been derived from mathematics.

It must be said that mathematicians and those ecologists skilled in the application of mathematics as a deductive tool cannot be blamed by this controversial usage of mathematics. They are simply very creative people looking for a general pattern by using that tool that they know (i.e. to a person who has a hammer, everything can start to look like a nail). So, they are able to produce an exploration of the whole spectrum of probable solutions, instead of the exact solution that is coherent with reality. As a result there would exist, we might say, 120 mathematical models regarding a particular scale and research context. If this were the case in physics, then the best conclusion would be perfectly clear, at least for a physicist: either all these models are wrong, or there are 119 models wrong. But, as it is explored in sections below, this uncomfortable situation derives from the inability of mainstream ecology to produce a consensual and reliable theoretical framework capable of sieving mathematical proposals to sort the wheat from the chaff.

**Miscellany of epistemological problems in mainstream ecology**

The main role of a good theory is to provide a trustworthy framework of qualitative limits. Without theoretical limits, the myriad of observed facts and collected data only produce a confused mixture of loose evidence: ‘If we do not develop a strong theoretical core that will bring all parts of ecology back together we shall all be washed out to sea in an immense tide of unrelated information’ (Watt 1971, 569). Mathematics is especially fruitful after this theoretical framework has been established. In such a way, it is possible to grasp the relationship between mathematics and qualitative thinking (i.e. the underlying set of principles related with a topic in order to develop ideas and hypotheses previously to the quantitative research) by summarizing the advancement of ecology as it is shown in Figure 1. Therefore, if ecology is trapped inside an endorheic basin, then we need to obtain a new qualitative sprout to overcome successfully the current situation.

Another typical mismatch of the mainstream ecology is to use dry weight, instead of fresh weight, as the main measure of biomass per individual, an essential indicator in ecosystem ecology. But, ecology studies the spontaneous dynamics of complex systems in
which living creatures evolve and interact with each other under natural conditions. These creatures are alive precisely because their tissues are ‘watery’. If there is no water, then there is no life at all: getting and keeping such water inside the body implies a consumption of energy. Then, a question arises, what is the aim of mainstream ecological thought, to study a ‘real biosphere’ or to study a ‘methodological necrosphere’?

The final point that we want to explore in this section is the ecological meaning of the hackneyed concept of ‘complexity’. Goldenfeld and Kadanoff (1999, 87) establish the key question about this subject:

‘Everything is simple and neat –except, of course, the world … Each situation is highly organized and distinctive, with biological systems forming a limiting case of exceptional complexity. So why, if the laws are so simple, is the world so complicated?’

Our understanding of complexity in ecology lies in two factors, one of them objective and the other one subjective. The objective one is linked to the level of our analytical cut off: in a similar way to a tree, a transversal slice at the central root level shows a very simple structure. On the contrary, a cut off at the branches level show a more complex structure full of anastomoses and divergences in many directions. Hence, complexity first depends on the degree of generalization of the model sought.
The subjective side of complexity can depend, paradoxically, on our inability to think in a way simple enough to understand the beauty of the natural world: in general, our lack of understanding is equated with the internal ‘complexity’ of the studied system. In such a sense, complexity is a subjective effect that could emerge from the distance between the epistemological level of our knowledge and the phenomenology of the system, rather than from the real complexity of the system itself. As a result, a frequent failure is that we add more and more variables to our model at the expense of its generality, predictability, and intelligibility (Rosindell et al. 2012). There is a general trade-off in this regard: the most exact models are completely irrelevant in the same measure in which an approximated model that is able to reflect the essential features of the system has an insurmountable analytical value. In fact, without this general trait the word ‘model’ loses all its meaning.

However, this way of building a model is a reflection of one of the most essential traits of life, rather than a sign of scientific subjectivity. Biological adaptation, as the supreme expression of life, precisely implies the capability of any kind of living system to modify some of its non-essential traits without sacrificing its essential features. Thus, the key question of any model is to include the essential characteristics that rule the functioning of the system, neither more nor less. If the main laws of science are quite simple, then it is because the essential functioning of nature it is also simple rather than complex. Those systems that are too complex tend to have a high frequency of failures, and Darwinian Theory is precisely based on the selective elimination of those biological units that tend to fail. Without general patterns independent of our will there is not science at all. If we had to accept a ‘dogma of faith’ in science, then it would be that, under the external complexity of a given system, there is always an underlying simple general pattern that is the main goal of any scientific search.

**Methodological benchmarks, derived from previous sections, in order to reduce the probability of endorheic basins in ecology**

The situation described in the previous sections favours a wide spectrum of schools of thought. However, in practice, such theoretical diversity also spreads a feeling of uncertainty and a lack of consensus among scientists ['community ecology is a mess, with so much contingency that useful generalizations are hard to find’, Lawton (1999, 178)]. Thus, it is appropriate to highlight some methodological benchmarks to respond to the question about how ecological epistemology should be (Campbell 2008) in order to reduce the probability of lasting endorheic states:

a) Ecology means a ‘distillation’ of ideas from other disciplines (e.g. Nekola and Brown 2007; Egerton 2012) to explain certain problems that those sciences, isolated, are unable to explain. Thus, the interdisciplinary nature of ecology should be kept as one of its most important methodological principles. Contrastingly, since the bias towards specialization prevails nowadays, those proposals addressing new questions with a broad intellectual scope have a higher risk of being rejected. A typical example: the earliest modern publication about the formal relationship between physics and ecosystem ecology (i.e. trophodynamics; Lindeman 1942) was rejected by Ecology because the reviewers felt that it was not supported by a sufficient
amount of data: a variant of Carl Sagan’s statement that ‘extraordinary claims require extraordinary evidence’, where ‘extraordinary’ is not equivalent to ‘abundant’.\footnote{After all, Newtonian mechanics was universally accepted when its primordial astronomical dimension was empirically based on observations from only 1 moon and 6 planets.} One of the reviewers proposed that ‘Dr. Lindeman could put this paper aside for ten years’. Only through Evelyn Hutchinson’s intercession, who considered the above-mentioned proposal as ‘ironical rather than practical’, the paper of Lindeman was posthumously published by Ecology (Cook 1977). After all, the main underlying human factor is that a big part of our personal collection of knowledge becomes immediately obsolete with every ‘paradigm shift’, in the Kuhnian sense of the word (Kuhn 1962). Additionally, it is quite hard to recover our previous level of scientific update by studying a new paradigm many years after our early postgraduate stage. But this is the price of all scientific progress (De Broglie 1962, 31). So, a certain degree of conservatism is suitable for preserving the rigour of our intellectual heritage. But this should not be an obstacle to spread challenging proposals, although it is certainly easier putting old wine in new bottles. McCarthy (2016, 70) describes this dilemma as a fight between our trend to novelty and our trend to a status quo which ensures continuity across time. This benchmark derives from the first subsection of the previous section.

b) Our qualitative ecological thought should constrain our mathematical constructions instead of the opposite (Ginzburg, Jensen, and Yule 2007). This methodological benchmark derives from the analysis performed in the second subsection of the previous section.

c) As a result of the narrowness of our analytical scope, noted in items (a) and (b), the weakest epistemological elements of ecology are: (i) the philosophical principles that are essential to grasp the great functional patterns of nature, and (ii) the bond between theoretical and empirical ecology (e.g. Belovsky et al. 2004; Moore et al. 2009; Angilletta and Sears 2011; Joseph et al. 2013). Strengthening such elements is essential to build a fruitful and reliable framework of knowledge in ecology: ‘Science is built up with facts, as a house is with stones. But a collection of facts is no more a science than a heap of stones is a house’ (Poincaré 1917, 168). Complementarily: ‘a theory which cannot be confronted with the facts or which has not been verified quantitatively by observed data is, in fact, devoid of any scientific value (Allais 1990, 5). This methodological benchmark is a general conclusion from the analysis performed in the third subsection of the previous section.

The renaissance of a truncated old paradigm; could it be a solution or just an additional endorheic current?

Despite the thermodynamic roots of modern ecosystem ecology (Lindeman 1942; Patten 1959; Margalef 1963; Odum 1968, 1969), the link between ecology and conventional physics is not in the centre of mainstream ecological thought (e.g. Margalef 1991, 884, 894–895, 904–905; Månsson and McGlade 1993; Ulanowicz 2004, 341). The reason for this situation is the following: conventional thermodynamics deals with the study of systems under \textit{equilibrium conditions (EC)}. The typical example is a closed flask immersed
### Table 1: Summary of the analytical evolution of OBEC as a whole.

<table>
<thead>
<tr>
<th>Step</th>
<th>Essential proposal</th>
<th>Physics (Resnick, Halliday, and Krane 2001)</th>
<th>Ecosystem ecology</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>State equation for equilibrium or stationary conditions (SEC)</td>
<td>$2N\left(\frac{1}{2}m \cdot v^2\right) = N \cdot k_B \cdot T$</td>
<td>$2N_p \left(\frac{1}{2}m_{ep} \cdot v^2\right) = \frac{N_p \cdot k_{ee} \cdot v^2}{H_p}$ (Rodríguez et al. 2012)</td>
</tr>
<tr>
<td>2</td>
<td>Generalized nature of the ecological equivalent ($k_{ele}$) of Boltzmann constant ($k_B$)</td>
<td>$k_B = m \cdot \frac{v^2}{T}$</td>
<td>$k_{ele} = m_{ep} \cdot H_p \cdot \frac{v^2}{H_T}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$k_{ele}$ tends to be an expected constant value at the intra-taxocene level under SEC because: $m_{ep} \text{min.} \rightarrow H_p \text{min.}, \frac{v^2}{H_T} \text{min.} \rightarrow H_p \text{max.}$ ($m_{ep} \text{max.}$) Intermediate values of $H_p$ (i.e. there is a biomass-dispersal trade-off in function of species diversity which is equivalent to r-K selection theory). (Rodríguez et al. 2013a)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Fulfilment of Boyle-Mariotte’s Law under SEC</td>
<td>$P_1 \cdot V_1 = P_2 \cdot V_2 = P_3 \cdot V_3$ with $T_3 &gt; T_2 &gt; T_1$</td>
<td>$P_{e\delta_{\lambda_1}} \cdot V_{e\delta_{\lambda_1}} = P_{e\delta_{\lambda_2}} \cdot V_{e\delta_{\lambda_2}} = \ldots$ or: $I_{\lambda_1}^2 H_{\lambda_1} = I_{\lambda_2}^2 H_{\lambda_2} = I_{\lambda_3}^2 H_{\lambda_3}$ with $H_{\lambda_3} &gt; H_{\lambda_2} &gt; H_{\lambda_1}$ at the intra-taxocene scale. (Rodríguez et al. 2013b)</td>
</tr>
<tr>
<td>4</td>
<td>Boltzmann negative exponential distribution of energy values</td>
<td>$N_i = \left(\frac{N}{\sum_{j=1}^{N} e^{-\frac{j}{k_B T}}}\right) \cdot e^{-\frac{i}{k_B T}}$</td>
<td>$N_{\lambda ip} = \left(\frac{N_{\lambda ip}}{\sum_{j=1}^{N_{\lambda ip}} e^{-\frac{j}{k_B H_{\lambda ip} + k_B \phi v_j}}}\right) \cdot e^{-\frac{i}{k_B H_{\lambda ip} + k_B \phi v_i}}$ The product of this equation, transposed and with bars centred, models energy pyramids based on a ratio scale. (Rodríguez et al. 2015a)</td>
</tr>
<tr>
<td>5</td>
<td>Evolutionary equivalent ($h_e^{ev}$) of Planck’s constant ($h$)</td>
<td>It does not exist or it has not been detected</td>
<td>$h_e^{ev}$: empirically detectable at the inter-taxocene scale as the regression coefficient of $E_e$ vs. $k_{ele}(\delta)$ with intercept = 0. So the regression equation: $E_e = k_{ele}\lambda h_e^{ev}$. i.e. $h_e^{ev} = 6.62606957E-34 J \cdot s$ indicates the non-continuous or ‘granular’ variation of $E_e$ per each unit of $\lambda k_e = 1 J \cdot \text{nat/individual}$. (Rodríguez et al. 2015b)</td>
</tr>
<tr>
<td>6</td>
<td>Maxwell–Boltzmann gamma distribution under SEC</td>
<td>$dN_v = 4 \pi N_T \left[\frac{m}{2 \pi k_B T}\right]^{\frac{1}{2}} v^2 \cdot e^{-\frac{mv^2}{2 k_B T}} dv$</td>
<td>$dN_{H_p} = 4 \pi N_{H_p} \left[\frac{k_{ele} H_T}{2 \pi E_{em}}\right]^{\frac{1}{2}} H_p^2 \cdot e^{-\frac{k_{ele} H_T H_p^2}{2 E_{em}}} dH_p$ (Rodríguez et al. 2015c)</td>
</tr>
<tr>
<td>7</td>
<td>Planck’s constant under SEC</td>
<td>$h = m \cdot \lambda \cdot v = 6.62606957E-34 J \cdot s$</td>
<td>$h_p^{ec} = m_{ep} \cdot \lambda_e \cdot l_e = 6.62606957E9 \ J_e$ per unit of $\lambda k_e$. $h_p^{ec}$ is detectable under SEC at the intra-taxocene scale. (Rodríguez et al. 2015c)</td>
</tr>
</tbody>
</table>

(Continued)
Table 1 Continued.

<table>
<thead>
<tr>
<th>Step</th>
<th>Essential proposal</th>
<th>Physics (Resnick, Halliday, and Krane 2001)</th>
<th>Ecosystem ecology</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Heisenberg’s uncertainty principle under SEC(^5)</td>
<td>(\sigma_\Theta \cdot \sigma_\Omega \geq \left(\frac{\hbar}{2\pi}\right)^2) (Rodríguez et al. 2015d)</td>
<td>(</td>
</tr>
<tr>
<td>9</td>
<td>State equations equivalent to those in panels A1 &amp; B1, but for non-stationary conditions(^6)</td>
<td>It has not been developed because of panel A5.</td>
<td>(</td>
</tr>
</tbody>
</table>

The results summarized in this table are supported by field data from 29 surveys, 1438 plots, 1586 species, and 8,873,312 individuals from 12 different taxocenes.*

* \(N\): total number of molecules; \(m\): molecular mass. \(v\): molecular velocity. \(T\): absolute temperature in Kelvin (K). \(k_{B}\): physical Boltzmann constant: 1.38054063 E-23 J/K. \(N_{p}\): total number of individuals per plot \((e)\). \(m_{p}\): mean fresh biomass per individual per plot. \(T_{p}\): ecological indicator of the intensity of dispersal activity with equivalent statistical and physical traits to those of physical temperature \((v)\). \(k_{selo}\): expected \((e)\) ecological equivalent of Boltzmann constant \(\approx 1.38054063 \phi\) ecoJoule \((e)\) · nat/individual, with \(\varphi = -\chi_{1}, \ldots, 0, \ldots, +\chi_{k}\), where \(\chi_{k}\) is an integer number that tends to be typical of each particular kind of ecological assemblage (taxocene); e.g. \(\chi_{k} = -10\) for marine microalgae; \(\chi_{k} = 00\) for tropical rocky shore snails, and \(\chi_{k} = +02\) in ruderal vegetation. \(H_{p}\): Shannon’s species diversity index at the plot level = \(-\sum_{i=1}^{S} \left(\frac{n_{i}}{N_{p}} \times \ln \frac{n_{i}}{N_{p}}\right)\), where \(S\) is the total number of species per plot and \(n_{i}\) is the number of individuals of species \(i\). \(P_{selo}\) and \(V_{selo}\): specific (per unit of biomass: kg) ecological pressure and volume, respectively. \(H_{p}\): total \((\varphi)\) species diversity at the survey level. \(N_{i}\): number of molecules at the energy level \(\sigma_{e}\); \(e\): Euler’s number (2.71828). \(N_{p}(e)\): expected number of plots at the intra-survey scale. \(dN_{p}(e)\): total number of plots per survey. \(N_{\text{mep}}\): mean number of individuals per plot at the survey level. \(dN_{\text{mep}}\): expected number of molecular velocity values for which the expected value of \(dN_{\text{mep}}\) is calculated. \(d_{v}\): amplitude of the categories of \(v\) values included in the distribution. \(d\): minimum of the category of molecular velocity values for which the expected value of \(dN_{\text{mep}}\) is calculated. \(E_{\text{em}}\): mean value of the individual eco-kinetic energy per plot at the survey level. \(H_{p}(e)\): minimum of the category of \(H_{p}\) for which the expected value of \(dN_{p}\) is estimated. \(dN_{p}\): expected number of \(H_{p}\) values from \(H_{p}\) to \(H_{p} + dH_{p}\), \(N_{\text{valp}}\): total number of \(H_{p}\) values included in the distribution (plots with a single species and \(H = 0\) are excluded from \(N_{\text{valp}}\). But all species are included in the calculation of \(E_{\text{em}}\). \(\sigma_{e}\): standard deviation of the observed values of \(\Theta\) (either position or time in physics) and standard deviation of the observed values of \(\Omega\) (either momentum or kinetic energy in physics), respectively. \(\sigma_{p}\) and \(\sigma_{\omega}\): standard deviations of the observed values of \(\Theta\) and \(\Omega\), across the categories of \(V_{p}\) and \(E_{\text{em}}\) across the categories of values of a continuous series of distribution of \(H_{p}\) values per taxocene, respectively. \(k_{selo}\): observed \((e)\) ecological equivalent of Boltzmann constant.

\(^5\)Panel B1 is the above-mentioned ‘epistemological sprout’ aimed to open the endorheic basin of ecology, by proving that a subjective approach to ecosystem thermodynamics (i.e. MaxEnt algorithm, see above) is not necessary at all. So panel B1 matches with position (d) in Figure 1, meanwhile panels from B2 to B9 match in Figure 1 with position (e) which is still growing.

\(^6\)Distribution of \(v\) values in panel A6, and its mirror distribution of \(H_{p}\) values in panel B6 starting from the statistical effect of axiom c in the last section of this article. Equation in panel B6 becomes an option also valid for non-stationary conditions by replacing \(k_{selo}\) by \(k_{selo} \cdot h_{p}^2\) when \(k_{selo} \neq k_{selo}\) (see Rodríguez et al. 2016b).

\(^7\)Panel B8 provides a win-win solution to the dilemma CEP ↔ HFR or ‘biodiversity paradox’ commented above: species coexistence is possible only because when the hypothesis of functional redundancy (HFR) is true in one dimension (either low values of \(\sigma_{p}\) or \(\sigma_{\omega}\)) the competitive exclusion principle (CEP) is influencing in the opposite one (either high values of \(\sigma_{p}\) or \(\sigma_{\omega}\)), and vice versa. In such a way, concurrent species avoid the lethal effects of extremely high levels of competition.

\(^8\)Panel B9 combines Newtonian mechanics and quantum mechanics in a way that is innovative even in comparison with physics itself.
in a thermal bath which keeps the temperature constant. However, an ecosystem is a far-from-EC open system. Thus, conventional physics is regarded as unsuitable to explain ecosystem functioning. This viewpoint lies in the inability of mainstream ecology to grasp the meaning of the term ‘equilibrium’ in physics. The understanding of equilibrium that is implicitly applied in ecology suggests the absence of tangible boundaries between the ecosystem and its surrounding, and therefore a sort of general equalization or ‘dilution’ of the internal properties of ecosystem that ends with its destruction.

But the physical concept of equilibrium is simpler than the former one: time-independence is the only solid requirement for equilibrium (Callen 1985, 13); and the values of state variables (temperature, pressure, volume, entropy, etc.) do not change with time either under equilibrium or under stationarity in far-from-equilibrium open systems. This implies that stationarity in open systems is analytically equivalent to equilibrium in isolated systems (Montero and Morán 1992, 48–49) given that, under stationarity, energy gains $\approx$ energy losses even in the absence of tangible physical walls. So, contrastingly to the mainstream viewpoint, there is no obstacle to describe the essential features of ecosystem functioning by means of conventional physics.

The above-mentioned definition (axiom $a$); the opposite relationship between information and entropy (axiom $b$, see comments above); the anti-kinetic effect of the increase of species diversity (Margalef 1991, 871–872, 875–876; Odum 1972, 37–41), that is to say, the reduction of dispersal activity and so the anti-thermic effect of species diversity (axiom $c$); and the well-known $r$–$K$ selection theory (axiom $d$; see Reznick, Bryant, and Bashey 2002) have been the four axioms ($a$; $b$; $c$ and $d$; see comment about the analytical meaning of axioms in science in previous section) to develop the OBEC (Table 1).

A comparison between the evolution of OBEC summarized in Table 1 (see also the respective six notes above) and the content of the previous sections, shows that OBEC is free of the epistemological drawbacks of mainstream ecology. This trait is possible because OBEC performs a complete rescue of the foundational paradigm about ecosystem ecology based on physics, which was prematurely neglected by the mainstream ecological thought due to a misunderstanding of the physical concept of equilibrium. We hope that OBEC can contribute to resolve this adverse situation in favour of the joint advancement of ecology, physics, and philosophy.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

**Notes on contributors**

Rodrigo Riera (PhD in marine invertebrate ecology), is the Head of Development and Research Dept. of C.I.M.A. S.L., in Sta. Cruz de Tenerife, Canary Islands, Spain. His interests are (i) the human perturbations on marine coastal ecosystems, and (ii) the study of global diversity of fish and invertebrates from coastal ecosystems, mainly temperate reefs.

Ricardo A. Rodríguez BSc in Biology; MSc in Didactic of Science; PhD in Ecosystem Ecology; PhD in Development Economics; 17 years of teaching experience in several disciplines. His interest is to develop reliable approaches to unify several fields of science that seem disconnected from each other at the first glance. Dr Rodríguez is the founder of organic biophysics of ecosystems (OBEC).
Juan D. Delgado (PhD): since 2008 he is associate professor of Ecology at the Physical, Chemical and Natural Systems, Universidad Pablo de Olavide, Seville, Spain. He has also done research and teaching activity in benthic ecology and zoology, biological invasions, and effects of human impacts (mainly road systems) on ecosystems, and was previously at the Applied Physics and Ecology areas at University of La Laguna, Tenerife, Canary Islands, Spain.

Ada Mª. Herrera (BSc in Biology, with specialization in ecosystem ecology; PhD in Biomedicine) has researched in the improvement of anti-inflammatory activity of non-steroidal drugs at the University Hospital of the Canary Islands. She has published in JCR journals in the above-mentioned issue, simultaneously to her activity as an independent researcher in ecosystem ecology.

Brian D. Fath (PhD): Professor, Department of Biological Sciences at Towson University (USA) and Research Scholar in the Advanced Systems Analysis Program, IIASA (Austria). Currently, Editor in Chief Ecological Modelling Journal, Chair of Ecosystem Dynamics Focus Research Group in CSDMS, and President, North American Chapter of the International Society for Ecological Modelling. The research goal of Dr Fath is to contribute to a science of sustainability, which he addresses by using thermodynamics, network analysis, information and complexity theory.

ORCID

Ricardo A. Rodríguez ☞ http://orcid.org/0000-0003-2752-005X
Ada Mª. Herrera ☞ http://orcid.org/0000-0002-5106-822X

References


Plants and Animals: A Statistical Mechanistic Approach to BIODIVERSITY.” *Science* 316: 1425c.


