

1 **Title:** *Degrees of freedom: definitions and their minimum and most meaningful combination for the*
2 *modelling of ecosystem dynamics with the help of physical principles.*

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15
16 **Abstract**

17 There is a neglected old schism in ecosystem ecology (EE): the foundations of crucial concepts and
18 principles of EE lie in thermodynamics, but the current mainstream of ecological thought is significantly
19 biased towards contingent mathematical models disconnected from physics. Frequently, these models
20 have weak theoretical support in ecology itself, as well as a limited empirical validation. This situation
21 emerged when some ecologists became aware that, seemingly, thermodynamics (devoted to study the
22 dynamics of closed systems in equilibrium) should be useless to understand ecosystems (far-from-
23 equilibrium open systems). The solution was, either developing a sort of “new physics” weakly linked to
24 the principles and methods of conventional physics, or a direction change towards an astonishing
25 diversification of analytical ways. In practice, both things have happened simultaneously. One of the
26 many expressions of this controversial decision was a sort of rigmorole in the use of the concept of
27 “degrees of freedom”. This article, based on a recent proposal (organic biophysics of ecosystems,
28 OBEC): (i) contributes to the resolution of the dilemma physics vs. non-physics in EE in the particular
29 case of the concept of “degrees of freedom”; (ii) proposes a plausible and empirically-backed solution to
30 the meaning, interaction and use of the concept of “degrees of freedom” in EE by reducing them to an
31 inseparable and all-encompassing triad of indicators (species diversity, dispersal intensity, and fresh
32 biomass or body weight per individual) valid for any kind of ecosystem (non-contingency) and backed by
33 six essential traits (simplicity, universality, evolvability, empirical manageability, inter-model inclusivity,
34 and interdisciplinary scope); and (iii) explores the aftermath of the aforementioned solution to propose a
35 complementary explanation to the metabolic theory of ecology, as well as the cornerstone of an analytical
36 framework commonly shared by economics and EE, in order to develop a new way of getting reliable and
37 empirically verifiable results in regard to the interaction between society and nature. In summary, the
38 results included in these three analytical axes (from i to iii) are based on previous publications including

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39 empirical field data from 12 different kinds of taxocenes involving a total of 1649 plots and 8.874×10^7
40 individuals belonging to 1280 species. Besides, this article includes in itself additional data from 638
41 species of mammals, 97 samples of ruderal vegetation, 26 samples of zooplankton, as well as data in
42 reference to a significant fraction of the US population as a whole ($\bar{x} = 2.973 \times 10^8 \pm 8.657 \times 10^6$ –S.D.–
43 individuals per year) in combination with abiotic environmental data (mean temperature and emission of
44 greenhouse gases at the country level) over 12 consecutive years.

45
46 **Keywords:** biodiversity; interdisciplinary modelling; metabolic theory of ecology (MTE); organic
47 biophysics of ecosystems (OBEC); society-nature interaction; statistical mechanics.

48

49 1. Introduction

50 There are five main domains within the realm of ecological research: (a) proposal of untested but
51 engaging hypotheses; (b) development of holistic theoretical approach solidly supported by empirical
52 field data; (c) development of pure mathematical models with the help of software and computing
53 devices; (d) techno-methodological issues; (e) empirical applications in order to reduce our impact either
54 on natural systems or on metastable man-made systems, including cities and their surroundings. The
55 concept of “degrees of freedom” (*df*) plays an essential, although subtle role, in all these domains.

56 In its *less strict meaning*, the number of *df* is an indicator of complexity (e.g.: “*the atmosphere is a*
57 *complex dynamical system with many degrees of freedom*”; Buizza, 2015). From a *statistical* point of
58 view, mainly linked to domains (b) and (c), the number of *df* reflects the amount of observations which
59 are free to vary after certain restrictions have been placed on the data. For example, if the data for 50
60 cases are classified into two categories, then as soon as we know that, say, 35 cases fall into one category,
61 we also know that 15 must fall into the other. For this example, $df = 1$, because with two categories and
62 any fixed value of N , as soon as the number of cases in one category is ascertained, then the number of
63 cases in the other category is determined (Siegel and Castellan, 1988).

64 In *classical mechanics*, a rigid physical body without ties deploys six degrees of freedom since it: 1st)
65 moves up and down; 2nd) moves left and right; 3th) moves forward and backward; 4th) swivels left and
66 right; 5th) tilts forward and backward; and 6th) pivots side to side (Tipler and Mosca, 2004). In *physical*
67 *chemistry*, the *df* of a system are the number of intensive state variables (e.g., pressure, temperature,
68 concentration) of the components that can be arbitrarily and independently varied without altering the
69 number of phases in the system (Fegley, 2012).

70 In statistical mechanics or *thermostatistics* (the statistical understanding of classical thermodynamics),
71 the number of *df* is the number of ways in which a molecule retains aliquots from a given total input of
72 energy. For example, a linear diatomic molecule has six *df* (Halliday et al., 2011): 3 degrees of
73 translational motion (x, y, z axes) + 2 degrees of rotational motion (y, z axes) + 1 degree of vibrational
74 motion of the atoms to each other (x axis), since molecules are not rigid physical bodies. Absolute
75 temperature (T) only depends on translational motion, and the kinetic energy (E) per each translational
76 degree of freedom is $E = \frac{1}{2} \cdot k_B \cdot T$, where k_B is the Boltzmann’s constant $= (m \cdot v_x^2) / T = 1.38064852 \text{ J} \cdot \text{K}^{-1}$ per
77 molecule; being m : molecular mass (constant for a given kind of gas), and v_x : mean molecular velocity on
78 the x axis. So, since there are 3 degrees of freedom of translational motion (x, y, z), and by assuming the

79 equipartition theorem (i.e.: that in thermal equilibrium energy is, on the average, shared equally among all
80 of the degrees of freedom), the total translational kinetic energy (E_T) of a mass of gas with N molecules is,
81 at the macroscopic scale, $E_T = 3 \cdot \frac{1}{2} \cdot k_B \cdot T \cdot N$.

82 One of the main problems about this issue is that, very frequently, it is not explicitly stated which one
83 of the previous concepts of df has been used in a given article, although the interdisciplinary nature of
84 ecology (Naiman, 1999) allows the use of any of them depending on the context. Given the foundation of
85 classical ecosystem ecology in thermodynamics (Lindeman, 1942; Patten, 1959; Margalef, 1963; Odum,
86 1968), the concept of df linked to statistical mechanics should be the most relevant within the above-
87 explored spectrum of concepts. However, there is a shortcoming in this regard: the foundational approach
88 to ecosystem ecology based on conventional physics is outside the mainstream of current thinking in
89 ecology because of the presumptive incapability of conventional statistical mechanics (devoted to study
90 closed equilibrium systems) to study far-from-equilibrium open ecological systems (Margalef, 1991;
91 Månsson and McGlade, 1993; Ulanowicz, 2004). This conclusion has yield a situation of semi-stagnation
92 which, despite the criticism by many authors (e.g., Simberloff, 1981; Belovsky et al., 2004; Rodríguez et
93 al., 2017a), has kept its ruling epistemological influence for decades. Therefore, the crucial analytical role
94 of the concept of ecological df based on statistical mechanics is in danger.

95 This article is addressed to offer a brief synopsis about how the Organic Biophysics of Ecosystems
96 (OBEC) has been able to dodge the above-mentioned paradox, with the goal of establishing what is the
97 minimum and most meaningful set of ecological df of any living creature, as well as their meaning from
98 the interdisciplinary point of view in the large scale. The minimum and most meaningful combination of
99 ecological df proposed in this paper: (i) contributes to the resolution of the dilemma physics vs. non-
100 physics in EE in the particular case of the concept of df ; (ii) proposes a plausible and empirically-backed
101 solution to the meaning, interaction and use of the concept of df in EE by reducing them to an inseparable
102 and all-encompassing triad of indicators (species diversity, dispersal intensity, and fresh biomass or body
103 weight per individual) valid for any kind of ecosystem (non-contingency) and backed by six essential
104 traits (simplicity, universality, evolvability, empirical manageability, inter-model inclusivity in the
105 ecological realm, and interdisciplinary scope beyond the ecological realm) and; (iii) explores the
106 aftermaths of the above-mentioned solution to establish the cornerstone of an analytical framework
107 commonly shared by economics and EE, in order to develop a new way of getting reliable and
108 empirically verifiable results in regard to the interaction between society and nature.

109 In summary, the results included in the above-mentioned items (from *i* to *iii*) are based on previous
110 publications including empirical field data from 12 different kinds of taxocenes (marine microalgae;
111 marine interstitial meiofauna of sandy beaches; massive –non-branching– corals; litter invertebrates in
112 laurisilva and pine forest; tropical rocky shore snails; coral reef fishes; ruderal vegetation; Mediterranean
113 shrub vegetation; mixed shrub vegetation; pine forest vegetation; and coastal succulent shrub vegetation)
114 involving a total of 1649 plots and 8.874×10^7 individuals belonging to 1280 species. Besides, this article
115 includes in itself additional data from 638 species of mammals, 97 samples of ruderal vegetation, and 26
116 samples of zooplankton. The proposal is completed by an example based on human population data
117 retrieved from official institutions of the U.S. government ($\bar{x} = 2.973 \times 10^8 \pm 8.657 \times 10^6$ –S.D.– individuals
118 per year, in combination with data of mean temperature and emission of greenhouse gases at the country

119 level over 12 consecutive years) that offers a preliminary assessment of the extrapolation of OBEC to the
120 analysis of society and its interaction with nature. This example is a sprout of a non-cosmological TOE
121 whose further development should stimulate our thought on a controversial topic, at the same time that
122 suggests new ideas for the research areas herein involved (i.e.: ecosystem ecology, physics, and
123 economics).

124

125 **2. Brief summary of OBEC**

126 *G 2.1 Definition and main results*

127 The OBEC, as a denomination to embrace a large set of non-contingent models connected to each
128 other, has been defined (Rodríguez et al., 2017b) as a proposal based on the extrapolation of the
129 principles of classical thermodynamics, statistical mechanics and quantum mechanics to the analysis of
130 the living fraction of ecosystems in accordance with well-known principles of conventional ecology and
131 evolutionary biology. The conventional biophysics of ecosystems deals with the influence of several
132 typical abiotic factors, e.g.: isotope movement in food webs, light, temperature, ionizing radiation, all of
133 them of physical nature in their origin, even though modified by their interaction with biotic factors. In
134 contrast, the OBEC, in development since the initial proposal of an ecological state equation by
135 Rodríguez et al. (2012), does not take into account any abiotic factor, but analyzes the dynamics of living
136 (organic) creatures assumed as if they were indivisible physical particles in movement and interacting
137 with each other within ecosystems. In a similar way to the case of statistical mechanical *df*, all the
138 essential traits of every organism in ecosystems depend on transforming solar energy into ecological
139 parameters, this explains the necessity of finding the ecological equivalents of statistical mechanical *df* in
140 ecosystems. Fig. 1 summarizes in a very simplified way the main results from OBEC so far. A careful
141 review of these achievements indicates that OBEC seems to be on the right path to rescue the classical
142 paradigm of ecosystem ecology based on links between physics and biology in order to put it back in the
143 mainstream of ecological thinking.

144

145 *2.2 The single root of all the models included in OBEC, and its link with the minimum and most 146 meaningful combination of ecological df*

147 There are two general ways to do science: (1) starting from a broad set of details in order to achieve a
148 single result; (2) starting from a single essential detail in order to achieve a broad set of results. OBEC is a
149 typical example of the second way because the single foundation to sustain all the results summarized in
150 Fig. 1 is the biomass ↔ dispersal trade-off in function of the gradient of species diversity per plot
151 (Rodríguez et al., 2013a). This statement requires to explain some details linked to the analytical
152 equivalence between the concepts of *static physical equilibrium* and *dynamic biological stationarity* in
153 ecology.

154 The increase of species diversity per plot (H_p ; Shannon, 1948; see also Eq. (A.1) in the text box of
155 spreadsheet “rv1” in Appendix A, online) has an anti-kinetic influence (Odum, 1972, pp. 37–41;
156 Margalef, 1991), and so an anti-thermic effect at the ecosystem level (see the positive association between
157 kinetic energy and temperature in Section 1). Thus, the relationship between H_p and the ergodic statistical
158 indicator of dispersal intensity (I_e ; expressed in dispersal units: δ) is of the form $H_p \propto 1/I_e$, where \propto means

159 “proportional to” (for additional details about I_e see Rodríguez et al., 2013a, and/or Eq. (A.2) in the text
160 box of spreadsheet “rv1” in Appendix A, online).

161 There is a concurrency between r - K selection theory and $H_p \propto 1/I_e$. That is to say, K -strategy large-
162 body organisms predominate under conditions of high species diversity, and their I_e values are low;
163 meanwhile r -strategy small-body organisms predominate under conditions of low species diversity, and
164 their I_e values are high (Reznick et al., 2002). Thus, there is a biomass \leftrightarrow dispersal ($m_{ep} \leftrightarrow I_e^2$) trade-off
165 in function of the gradient of species diversity per plot (ΔH_p) with a pro-stationary influence **if and only if**
166 the system is under stationary ecological conditions (SEC). In statistical terms, there is a significant
167 positive correlation H_p vs. m_{ep} concurrently with a significant negative correlation H_p, I_e^2 . As a result, the
168 dynamics of any ecosystem under SEC can be roughly divided in three contiguous **functional segments**
169 in which \uparrow means high variable values, and \downarrow means low variable values: **(i)**: ($m_{ep}\downarrow, I_e^2\uparrow, H_p\downarrow$). **(ii)**:
170 ($\overline{m}_{ep}, \overline{I}_e^2, \overline{H}_p$). **(iii)**: ($m_{ep}\uparrow, I_e^2\downarrow, H_p\uparrow$). Therefore, $m_{ep} \times I_e^2 \times H_p = k_e \rightarrow \text{constant} = 1.38064852E\pm\varphi$
171 ecoJoule \times nat/individual, or $J_e \times \text{nat/individual}$ ($J_e = \text{kg} \cdot \text{d}^2$, see Eq. (1), below), and $\varphi = \dots, -3, -2, -1, 0,$
172 $1, 2, 3, \dots$; always an integer number typical of a given taxocene. So, k_e (i.e., the ecological equivalent of
173 k_B , that is one of the most important universal constants in physics; see Section 1) assesses the magnitude
174 of the exchange between eco-kinetic energy (E_{ep} , a proxy for trophic energy, see Eq. (1)) and H_p per
175 individual under SEC, in a similar way in which k_B assesses the rate of conversion between Newtonian
176 kinetic energy and absolute temperature per molecule under conditions of physical equilibrium.

$$177 E_{ep} = \frac{1}{2} m_{ep} \cdot I_e^2 \quad (1)$$

178 where m_{ep} : mean fresh biomass or body weight per individual per plot (p) expressed in kg, and I_e : a
179 statistical index of dispersal activity per individual per plot with similar traits to those of v in order to
180 replace v by I_e without failures in the extrapolation of concepts and methods from statistical mechanics to
181 ecosystem ecology. This proposal mimics in ecology the same manner in which kinetic energy (Eq. (2)) is
182 calculated in classical mechanics, but by replacing physical variables by their ecological equivalents.

$$183 E = \frac{1}{2} m \cdot v^2 \quad (2)$$

184 where m : physical mass, and v : physical velocity. The analytical equivalence between Eq. (1) and Eq. (2)
185 is grounded in the universal fulfillment of first law of thermodynamics (i.e., that energy never disappears,
186 but only changes from one form to another). Thus, OBEC assumes that Eq. (1) is the most appropriate
187 proxy to empirically assess trophic energy in the simplest way possible.

188 The above-described situation, in combination with the physical necessity of either gain or loss energy
189 to gain or loss information (Tribus and McIrvine, 1971) in the form of species diversity (H_p), indicates
190 that an ecosystem under SEC, **despite its open nature**, behaves like a strongbox without tangible walls:
191 $I_e^2\uparrow$ but $m_{ep}\downarrow$ when $H_p\downarrow$; and $m_{ep}\uparrow$ but $I_e^2\downarrow$ when $H_p\uparrow$; in contrast with the fact that m_{ep} and I_e^2 must change
192 in the same sense to promote a net variation of E_{ep} able to support a corresponding net variation of H_p at
193 the aggregate scale, either forward or backward. Consequently, there is no justification to hinder the
194 application of conventional physics to ecology, given that the single requirement for physical equilibrium
195 is that state variable values do not change over time (Callen, 1985, pp. 6, 13). Since the values of state
196 variables do not change over time in the large scale either under physical equilibrium or under open SEC
197 (energy input \cong energy output, and intensity of competition relationships \cong intensity of mutualistic

198 relationships), then the stationary state is for the analysis of ecological systems what equilibrium state is
199 for the analysis of physical systems in equilibrium (Montero and Morán, 1992, pp. 48-49; Rodríguez et
200 al., 2012).¹

201

202 **3. The minimum and most meaningful set of ecological df**

203 *3.1 Theoretical and empirical reasons to assume the triad of fresh biomass per individual (m_{ep}), dispersal*
204 *intensity (I_e) and species diversity (H_p) as a non-contingent set of ecological df*

205

206 *3.1.1 Simplicity*

207 On the one hand, from the point of view of modelling, we could suppose that a given ecosystem has
208 hundreds or even thousands of df . So, we are unable to understand its functioning because it is too much
209 complex. On the other hand, even assuming that this criterion is not valid and we would be able to
210 introduce all these df in a computing device handled by a suitable software, then we would get an
211 analytical output so complex and unintelligible as the real system itself. This means that any successful
212 modelling needs to simplify the seemingly complex nature of a system until its most essential and less
213 numerous traits, instead of getting models which are more and more complex by exactly mimicking the
214 complexity and incomprehensibility of the real system itself. So, a basic set of only three indicators
215 accomplishes one of the main requirements for a good combination of ecological df : ***simplicity***, either
216 from the abstract or from the graphical point of view (i.e., the most complex graphic that keeps a suitable
217 level of comprehensibility for any reader has three dimensions: x , y , z ; see empirical examples below,
218 Section 3.1.3).

219

220 *3.1.2 Universality*

221 Any kind of organism (either vegetal or animal, either sessile or mobile, either large or small, either
222 aquatic or terrestrial, and either able of rational thinking or not) needs to transform either physical or
223 chemical energy into body weight (biomass), needs to deploy a given level of dispersal activity, and
224 needs to live in concurrency with other species (diversity), there is no exception to this combination.
225 Therefore, the triad m_{ep} , I_e , and H_p accomplishes a second requirement for a good combination of
226 ecological df : ***universality***.

227

228 *3.1.3 Empirical evaluability*

229 A third trait that deserves special attention is the possibility of ***empirically assessing*** the differential
230 behavior of these df in regard to each other depending on if the ecological system is under SEC or under
231 non-SEC. Fig. 2 shows the correlative behavior between H_p , I_e^2 and m_{ep} in these alternative situations by
232 means of examples based on empirical field data of ruderal vegetation (rv, see data and sampling method

¹ Human metabolism is a quite simple but very illustrative example in this regard: any kind of living structure –at any scale– implies a far-from-physical-equilibrium position. But our body weight in the adult stage can remain, in the average, constant over time. This means that the energy input to output ratio is near to 1, fulfilling in such a way the above-mentioned premise stated by Callen (1985) in spite of... or thanks to... our living nature.

233 in spreadsheets “rv1” and “rv2”, Appendix A, online) and freshwater planktonic crustaceans (crust., see
234 data and sampling method in spreadsheet “crust”, Appendix A, online).

235 In agreement with the above-commented biomass-dispersal trade-off under SEC, the 3D ($x: H_p$; $y: I_e^2$;
236 $z: m_{ep}$) surface adjustment by means of distance-weighted least squares fitting under SEC (Fig. 2a) shows
237 that the set of plots is associated to a basin-shaped surface very similar to a horse-riding saddle. So, this
238 figure supports the idea that, under SEC, the system is trapped into a pro-stationary basin, in spite of its
239 open nature. In summary, the scatter plot in Fig. 2a avoids extreme values, either very low or very high,
240 of any of the three df (i.e., prevalence of functional segment **(ii)** in Section 2.2)

241 The correlative behavior of df under **oligotrophic** non-SEC (see cells J3:J5 in spreadsheet “rv5”,
242 Appendix A, online) is shown in Fig. 2b. In this case, the main fraction of the scatter plot is associated to
243 a dome-like surface instead to a horse-riding saddle surface, like in Fig. 2a. The dome surface is deflected
244 by an ascending slope towards low H_p values in a shape that suggests that the highest probability of plot
245 presence is biased towards relatively low values of H_p and m_{ep} , and relatively high values of I_e^2 . This is an
246 example of a system that follows an anti-successional drift (predominance of functional segment **(i)** in
247 Section 2.2).

248 The correlative behavior of df under **eutrophic** non-SEC (see cells J3:J5 in spreadsheet “crust”,
249 Appendix A, online) is shown in Fig. 2c. This situation is, from the graphical point of view, similar to the
250 situation described in the previous paragraph (i.e., there is also a dome-like surface in Fig. 2c). However,
251 the dome surface in Fig. 2c is deflected by an ascending slope towards high H_p values, and the highest
252 probability of plot presence is biased towards a combination of high values of H_p and m_{ep} , and low values
253 of I_e^2 (predominance of functional segment **(iii)** in Section 2.2).

254

255 3.1.4 Evolvability

256 A fourth desirable trait to support H_p , I_e and m_{ep} as reliable df in ecology is **their link to evolutionary**
257 **processes** in the deep time. That is to say, instead of a simultaneous emergence, there have been a
258 sequential emergence of ecological df : **(i)** The evolutionary dawn of life on Earth was presumably
259 characterized by the initial emergence of a single and very small cell belonging to one initial unicellular
260 species. So, only 1 df (I_e) had a key role for life development in the earliest evolutionary stage; because
261 m_{ep} had a very low value, and that founding species was spread by every nook capable of sustaining life
262 all over the planet. Simultaneously, since species number = 1, then $H_p = 0$. **(ii)** Later on, a state in which
263 $H_p > 1$ meant the emergence of a second df concurrently with the process of species diversification of
264 primitive prokaryotic and eukaryotic unicellular organisms. **(iii)** Finally, millions of years later, the
265 macroevolutionary transition of species toward new adaptive zones with a higher availability of external
266 energy was able to support the emergence of multicellular organisms with a significant increase of body
267 weight (m_{ep}).

268 As a result, this latter df (biomass or body weight per individual per plot) is responsible for evolution
269 irreversibility. This needs a brief explanation: I_e is an *intensive* variable because it does not depend on the
270 system size. For example, it is possible to calculate a value of, let us say, $I_e = 61$ d, either from data of the
271 microbiota in the oral cavity of a dog or from data of rainforest vegetation; in a similar way in which a
272 physical velocity of 110 m/s can be measured either for a gas molecule or for a sport car. H_p is an

273 *intensive* variable too and, in practice, H oscillates over a narrow range between a minimum of 0 and a
274 maximum of ≈ 5 nat/individual. On the contrary, m_{ep} has an *extensive* nature. In other words, a given
275 ornithocenosis (bird community) with $H_p = 3.25$ nat/individual and $I_e = 45$ d does not fit inside a dog's
276 oral cavity inhabited by a given microbiota with exactly the same values of H_p and I_e . Therefore, the eco-
277 evolutionary process is a biomass-dependent expansive process addressed toward reaching greater mean
278 body weights by every taxocene (Cope's rule; see Hone et al., 2005).

279 Simultaneously, the general trend is that, within every taxocene, those organisms that are the largest
280 ones are also the smartest ones because of their ontogenetic capability of managing a greater amount of
281 information (H at the individual level) due to their longer life expectancy (Margalef 1992, pp. 221-223).
282 This capability seems to be impossible to achieve without a reduction of biotic potential and dispersal (I_e).
283 The key issue is that, in front of an always limited amount of sunlight energy, a dilemma between energy
284 investment in I_e , on the one hand, and in $m_{ep} + H_p$, on the other hand, emerges. Natural selection in favor
285 of I_e is a choice in favor of very large populations with small individuals of short life cycles and few
286 opportunities to acquire knowledge (information) about their environment. The opposite combination (in
287 favor of $m_{ep} + H_p$) is a choice in favor of individualism, because a longer life cycle allows that each
288 individual learns about its environment, producing a scarcer but more capable offspring (e.g.: the
289 capability of killer whales –learned by means of a long lasting training between relatives belonging to
290 small families– for hunting seals just on or even beyond the seashore cannot have an equivalent behavior
291 in mosquitoes and cockroaches).

292 Nevertheless, on the one hand, it would be an error to forget that trillions of very small organisms
293 with maximum I_e values, as planktonic creatures and soil bacteria, sustain with their metabolism the rest
294 of the assemblage of life on Earth. On the other hand, the economic anthropomorphization of the above-
295 commented evolutionary drift should also be avoided (i.e., that collectivism is a disadvantage in
296 comparison with individualism –a point established as a methodological paradigm by neoclassical
297 economics– even in plants and animals). Simply and plainly, the second option means a drift of the
298 ultimate goal of evolutionary process (adaptability) from the population level to the individual level and,
299 therefore, a statistical acceleration of the process due to an overwhelming increase of the amount of
300 selection units.

301 At the intra-taxocene scale, this sacrifice of the first df for the sake of achieving higher values of m_{ep}
302 and H_p seems to reach its paroxysm in the case of human beings, in which a single biological species is
303 able to perform thousands of productive functions in urban ecosystems (occupations are the equivalents in
304 society of ecological niches in nature –Margalef, 1991–, and r - K selection theory is also valid in human
305 populations –Chisholm, 1993), accumulating in such a way an overwhelming information amount, and
306 being able to manage huge volumes of biomass even at the exo-somatic level. After all, it is quite possible
307 that Marshall (2013, p. xxv) was right when asserted that “*the Mecca of the economist lies in economic*
308 *biology rather than in economic dynamics*”.

309 Rodríguez et al. (2013b) explain why I_e can be regarded as an indicator of the *talandic temperature*
310 (Kerner, 1959; Goodwin, 1963; the term “*talandic*” derives from a word that, in Greek, means
311 “*oscillation*”: *ταλάντωση*) of ecosystems. Low I_e values per plot indicate low average fluctuation levels
312 of ecological niches. So, this condition allows that organisms deploy oscillations of lower amplitude and

313 frequency around a center in space taken as a figurative point that grasps the dynamics of a given plot of
314 non-null area or volume. Meanwhile, with high I_e values just the opposite occurs (oscillations of higher
315 amplitude and frequency). Consequently, the higher the values of I_e , the higher the intensity of ecological
316 interference between species, an unfavorable condition for coexistence. As a result, the above-commented
317 biomass-dispersal trade-off (Section 2.2) indicates that the increase of H_p stimulates coexistence via I_e
318 reduction: an ecosystem involved in a non-SEC pro-successional process is equivalent to a refrigerator
319 that increasingly cushions the amplitude and frequency of species oscillations in the ecological phase
320 space (see Rodríguez et al., 2013b).

321 This phenomenon is ecologically equivalent to the well-known process of bremsstrahlung (braking
322 radiation: radiation release produced by the deceleration of a charged particle when deflected by another
323 charged particle, typically an electron by an atomic nucleus; Haug and Nakel, 2004). The particularity in
324 the ecological context is that there is no observable net release of free radiation at all, but a rapid
325 assimilation of the new amount of available sunlight to be converted into eco-kinetic energy (Eq. (1)) and
326 information by new species added to the ecosystem, by increasing, in turn, the average value of H_p .

327 This is in agreement with the statement from Margalef (1963, p. 363) about the intrinsic capability of
328 ecosystems to dampen the random oscillations of ecological factors. A seemingly valid objection to this
329 approach is that the original physical bremsstrahlung requires interaction between charged particles, and
330 species have no charge from the physical point of view. But the fact that species coexistence, trophic
331 energy flows and functional exchanges between biological communities are possible *if and only if* there
332 is an underlying gradient of species diversity (Margalef, 1963; Odum, 1968), indicates that this gradient
333 plays a resulting role in the ecosystem similar to that of the electromagnetic field in physics. Additionally,
334 interspecific relationships (like mutualism and competition) imply attraction and repulsion between
335 species, in a similar way in which attraction and repulsion between physical particles depend on the
336 relationship between their respective electric charges.

337

338 3.1.5 Inter-model inclusivity

339 During the period under the influence of natural history rationalism in ecosystem ecology (between 50
340 and 70 years ago), mainstream ecology, in a similar way to the case of evolutionary biology with
341 Darwinism, had a large active central paradigm (the foundation of ecosystem ecology based on physics,
342 specifically on thermodynamics) able to unify a wide spectrum of empirical observations and theoretical
343 proposals. But this situation drastically changed in the last decades (e.g.: *"I think that traditional ecology
344 is breaking down into a mosaic of hypotheses, some interesting, others less, some contradictory and even
345 frivolous. While most of the sciences have tried to delve into their foundations, ecology has been
346 populated with concepts, hypotheses, rarely theories, which tend to remain disconnected from each other.
347 An old-fashioned ecologist regrets both the lack of common superstructure, and the progressive
348 devaluation of the naturalistic point of view"*; Margalef, 1991b, p. 17), and the current mainstream
349 ecology is a cluster of many micro-paradigms in frequent contradiction with each other. In such a way,
350 we could say that, instead of *"a great ecology"*, there are *"many small ecologies"*.

351 However, it would be a flagrant mistake to deny that there must be a certain fraction of truth in every
352 one of these micro-paradigm. If we aspire to achieve a large paradigm again, then it must include, instead

353 of excluding, these aliquots of truth. For example, it is plausible to assume that the metabolic theory of
 354 ecology (MTE; see Brown et al., 2004; Sibly et al., 2012; Hirst et al., 2014) includes a fraction of the total
 355 landscape of ecological dynamics, at the same time that OBEC also includes a fraction of this landscape.
 356 Therefore, an inclusive attempt to achieve a more general image of ecosystem dynamics by using the
 357 degrees of freedom proposed in this paper should allow the reproduction of some results of MTE by
 358 means of the central principle of OBEC explained in Section 2.2. As it can be directly deduced from
 359 Sections 2.2 and 3.1.4, body size (mass: M) has a deep effect on ecological dynamics due to the
 360 regulatory linking relationship of metabolism in between the internal medium of organisms and their
 361 trophodynamic environment. The most extended criterion about the quantitative relationship between M
 362 (in kg) and the consumption of energy at rest (basal metabolic rate: BMR , in kJ/h) is of the form:

$$363 \quad BMR = a \cdot M^b \quad (3)$$

364 Eq. (3) is, essentially, an empirically inferred relationship (several theoretical explanations have been
 365 proposed *post hoc*, see below) in which a is a dimensionless normalization constant independent of M and
 366 derived from the statistical treatment of data, and b is an exponent whose magnitude generally impose an
 367 allometric (Greek: *allos*, other; *metron*, measure) relationship (i.e., $b \neq 1$) between M and BMR , and its
 368 observed value fluctuates between 0.565 and 1.179 (White, 2011, p. 348, Table 1). The relationship
 369 reflected in Eq. (3) is well-known, and many authors have devoted a lot of effort to its study from many
 370 years ago (e.g.: Rubner, 1883; Krogh, 1916; Huxley, 1932; Brody and Proctor, 1932; Kleiber 1932; 1947;
 371 Reynolds, 1997).

372 Starting from the excellent review performed by White (2011), it is easy to be aware about the large
 373 number of authors interested in this subject, and the variety of collateral traits connected to Eq. (3) in
 374 regard to methods of measurement; suitability of statistical approaches to assess either the relationship
 375 between M and BMR or the degree of fitting between predicted and observed values of BMR ; inter-
 376 taxocene variation of the spectrum of values of b ; and probable theoretical explanations. The most
 377 frequent values of b are around two main figures: $\frac{2}{3} = 0.66$, and $\frac{3}{4} = 0.75$. Besides, it is possible to
 378 summarize the most frequent theoretical explanations about Eq. (3) in the following way: (i) **Geometric**
 379 **hypothesis**: If we reduce the shape of a given organism to a warm solid sphere e of radius r_e , its energy
 380 exchange surface (area: A_e) is proportional to r_e^2 (because $A_e = 4\pi \cdot r_e^2$), meanwhile its volume (and
 381 therefore its mass) is proportional to r_e^3 (because $V_e = (4\pi \cdot r_e^3)/3$). So, with the increase in body size, there
 382 is an allometric increase of the surface of energy exchange with the environment in a relative way to the
 383 amount of mass proportional to $b = \frac{2}{3} = 0.66$. (ii) **Hypothesis of the branched design of the inner**
 384 **networks of distribution of energy and substances**: Firstly, reducing an organism to a simple sphere is to
 385 push things too hard; and secondly, in practice, the observed value of b for many species was found to be
 386 a little far away of 0.66. So, the internal systems of distribution of energy and substance should
 387 significantly improve the surface/volume ratio to a higher allometric scaling exponent of $b = \frac{3}{4} = 0.75$.
 388 (iii) **Hypothesis of the influence of external ecological factors and the corresponding adaption of**
 389 **organisms**: For example, McNab (2008), starting from data of 638 species of mammals encompassing a
 390 rank of mass values between 0.0022 kg and 3221 kg, obtained a correlation of $r = 0.989$, $r^2 = 0.979$, $p <$
 391 0.0001 from a \log_{10} vs. \log_{10} scaling of observed vs. predicted values of BMR according to the regression
 392 equation:

393 BMR (kJ/h) = 0.062($M \cdot I \cdot S \cdot T \cdot C \cdot H \cdot E \cdot F$) $g^{0.694 \pm 0.005}$ (4)

394 where non-dimensional coefficients describe the response of BMR to various conditions, including M for
 395 mountains or lowlands; I for islands or continents; S for substrate; T for torpor; C for climate; H for
 396 habitat; E for infraclasses; and F for food habits.

397 Even if we neglect the aforementioned hypotheses, the resulting fact of ecological importance is that,
 398 given the allometric relationship in Eq. (3), the larger the organism the lower the amount of energy to
 399 sustain every kg of standing biomass. Thus, larger organisms (K -strategists), despite the total amount of
 400 food they are able to eat is larger, are ecologically more efficient than smaller organisms, because they
 401 consume less energy per unit of biomass (Margalef's principle; see Matsuno, 1978; Barragán and
 402 Sánchez, 2012). For example, the correlation between $\log_{10}(BMR/M)$ vs. $\log_{10}(M)$ starting from the very
 403 data of McNab (2008; data in spreadsheet "mammals BMR", Appendix A of this article, online) yields r
 404 = -0.8812, $p < 0.000001$ (see also Fig. A1, spreadsheet "mammals BMR" in Appendix A of this article,
 405 online). This eco-evolutionary drift in favor of energy saving promotes coexistence under conditions of
 406 high values of total species diversity (H_T), because more and more standing biomass can be sustained by a
 407 constant input of solar energy if there is an opposite correlation between the amount of energy per kg and
 408 H_T . Such a trend has been empirically tested before in a very large scale by Rodríguez et al. (2013a. p. 16,
 409 Fig. 3b: 24 samplings, 1274 plots, 1257 species and 87964545 individuals).

410 In regard to the value of a in Eq. (3), there is neither preferred values nor any theoretical framework
 411 capable to propose a reliable way of assessing them within the conventional analytical framework of
 412 mainstream ecology, in which a is a simple statistical "goop".

413 Now we will propose a fourth hypothesis (iv) based on those issues commented in Sections 2.2 and
 414 3.1.4 in order to explore if the allometric relationship between BMR and M in Eq. (3) can be explained
 415 from the eco-evolutionary point of view developed by OBEC, and by using the three ecological df
 416 proposed in this article. Within the theoretical framework of OBEC, it is possible to assume that, given
 417 that all the placental mammals have a common ancestor (A), the BMR of the current evolutionary
 418 descendants from this primitive ancestor is a product of the primitive value of k_e of the taxocene to which
 419 that ancestor belonged (k_{eA}), multiplied by the body weight per individual (M) of every current mammal
 420 species, raised either to the power of 0.75 or $h_e^{ev} = 0.662607004 J_e \cdot J_e \cdot \text{nat}/\text{individual} \approx 0.66$. h_e^{ev} is the
 421 evolutionary equivalent of Planck constant (see Rodríguez et al., 2015b). h_e^{ev} indicates the magnitude in
 422 which eco-kinetic energy per individual (see Eq. (1), above) increases at the inter-taxocene scale per each
 423 unit in which k_e increases in the deep -evolutionary- time. That is to say, according to OBEC, the
 424 theoretically expected (exp.) value of BMR could be assessed either as:

425 $BMR_{(exp.)} = k_{eA} \times (M^{0.75})$, (5)

426 or as:

427 $BMR_{(exp.)} = k_{eA} \times (M^{h_e^{ev}})$ (6)

428 The only unknown parameter in Eq. (5) and Eq. (6) is a plausible value of k_{eA} . The intensive nature of
 429 H_p and I_e , the extensive nature of mass (m_{ep}), and therefore the biomass-dependent expansive nature of
 430 evolutionary process has been established in Section 3.1.4. Besides, at the very beginning of adaptive
 431 radiations (either in mammals or in any other kind of taxocene), the "evolutionary clocks" of H_p and I_e^2 at
 432 the intra-taxocene scale are set to zero (i.e.: species number = 1, so $H_p = 0$, and $I_e^2 = 0$ too, because the few

433 original organisms of the founding species have not had time to conquer a large area). But the biomass-
 434 dependent extensive nature of evolutionary process and its net cumulative effect across adaptive
 435 radiations (starting from *r*-strategists founding species to *K*-strategists climaxing species) means that the
 436 “evolutionary clock” of body mass (m_{ep} in Eq. (1) and M in Eq. (3)) can never be set to zero.

437 The hypothetical ancestor (*A*) of all the current placental mammals (most of the species included in
 438 spreadsheet “mammals BMR”, Appendix A, online) weighed between 0.006 kg and 0.245 kg (O’Leary et
 439 al. 2013). Therefore, it had a body weight median of $(0.006 + 0.245)/2 = 0.1255$ kg. However, according
 440 to OBEC, this ancestor must have been a sort of “giant” species in a relative way to the rest of species of
 441 its taxocene, because it must have belonged to a degenerate ecological state (see Rodríguez et al., 2015d;
 442 Figs. 6d, 6e, 6f, 7 and 8, and comments about them) with a level of eco-kinetic energy per individual (Eq.
 443 (1)) of tenfold the energy level of the general ecological background occupied by the remaining species of
 444 its taxocene. So, a suitable assessment of the mean body weight per individual of the primitive taxocene
 445 to which *A* belonged is: $((0.006 + 0.245)/2) \times (1/10) = 0.01255$ kg. This body weight is, approximated, in
 446 between the mean body weight of tropical rocky shore snails ($m_{ep} = 0.0011$ kg; with $k_e =$
 447 $1.38064852E+00$ $J_e \cdot \text{nat}/\text{individual}$) and coral reef fishes ($m_{ep} = 0.042044$ kg; with $k_e = 1.38064852E+02$
 448 $J_e \cdot \text{nat}/\text{individual}$), explored by Rodríguez et al. (2013a). As a result, a plausible value of the ecological
 449 equivalent of Boltzman’s constant for the taxocene that was the “evolutionary cradle” of *A* could be: k_{eA}
 450 $= 1.38064852E+01$ $J_e \cdot \text{nat}/\text{individual}$. Thus, Eq. (5) and Eq. (6) become, respectively:

$$451 \quad BMR_{(\text{exp.})} = 13.8064852 \text{ } J_e \cdot \text{nat}/\text{individual} \times (M \text{ kg}^{0.75}) \quad (7)$$

$$452 \quad BMR_{(\text{exp.})} = 13.8064852 \text{ } J_e \cdot \text{nat}/\text{individual} \times (M \text{ kg}^{0.662607004} \text{ } J_e \cdot \text{nat}/\text{individual}) \quad (8)$$

453 There is a positive and highly significant correlation between the \log_{10} basal rate of metabolism
 454 observed by McNab (2008) and the \log_{10} basal rate of metabolism expected either from Eq. (7) or from
 455 Eq. (8); see Fig. 3a and Fig. 3b, respectively. In addition, there is no significant difference between the
 456 mean values of the aforementioned parameters (Fig. 3c). This result is very important due to its analytical
 457 meaning: **(1)** It reinforces the usefulness of H_p , m_{ep} , and I_e as ecological *df*. **(2)** The statistical equivalence
 458 of means in Fig. 3c indicates that the replacement of v (expressed in m/s) in Eq. (2) by I_e (expressed in \dot{d})
 459 in Eq. (1) does not produce a significant change between the resulting derivate unit of expressions of
 460 energy in both equations. In other words, J_e and J are two units quite equivalent to each other, in such a
 461 way that kinetic energy and eco-kinetic energy as well. **(3)** It seems that by means of the theoretical
 462 framework of OBEC is possible to assess a non-empirical an *ante hoc* value of a in Eq. (3), an
 463 unprecedented result so far. **(4)** The noticeable similarity between the allometric exponent $\frac{2}{3}$ and the
 464 evolutionary equivalent of Planck constant² highlights the paradoxical possibility of the emergence of
 465 similar indicators despite they are seemingly disconnected from each other. So, this paradox could be
 466 explained either as a typical case of statistical spuriousness due to an implicitly omitted-variable bias
 467 from the theoretical point of view (DeMaris, 2004, p. 98-100) and/or because the influence of h_e^{ev} is so
 468 pervasive that it spontaneously arises even when the model under development does not include any
 469 previous notion of its objective existence. Fig. 3c indicates that an allometric exponent of 0.75 yields a
 470 better one, but not significantly different adjustment between expected and observed data, than h_e^{ev} .

² h_e^{ev} was empirically assessed by means of a different methodology, and it is based on a different theoretical framework in comparison with hypotheses *i*, *ii*, and *iii* exposed in the fourth paragraph of this section.

471 However, h_e^{ev} has several advantages in comparison with 0.75. That is to say: it is very frequent in many
472 other approaches to this issue, even for non-mammalian species (see White, 2011, p. 348, Table 1); it is
473 supported by a theoretical framework (OBEC). It is also possible that the measurements of metabolic rate,
474 either at rest or under active conditions, need to increase their accuracy level including other collateral
475 indicators besides body mass values (see White and Seymour, 2005; White, 2011), and taking into
476 account the result commented in item (3) of this paragraph.

477

478 *3.1.6 A sixth suitable trait of m_{ep} , I_e , and H as df : their potentiality to support approaches linking society*
479 *and nature by means of a commonly shared analytical framework*

480 The lack of a theoretical and methodological framework commonly shared by social sciences and
481 natural sciences is one of the most frequently neglected topics in the study of the human impact on nature.
482 Despite commendable heterodox efforts in this field (e.g.: Costanza, 1996; Jacobs, 2000), economics and
483 ecology remain conventionally seen as two immiscible “substances” from the analytical point of view: the
484 former of them is based on neoclassical theory, meanwhile the latter one is based on a diffuse analytical
485 cloud of ephemeral and/or contingent approaches (Lawton, 1999, p. 178; Scheiner, 2013), included as a
486 whole under the economic term “externalities”. Hence, there is a lack of equivalence between impact
487 indicators (nature also impacts on society, despite ecologists are in general more interested in the opposite
488 direction of this interaction), and a better correspondence of analytical tools between these two disciplines
489 would be suitable. The set of df analyzed in this paper can offer a plausible approach in order to get better
490 the above-mentioned condition by means of a connection between social science and ecology throughout
491 physics.

492 As it has been previously commented, there is an equivalence of meaning between occupations or
493 socioeconomic functions in society, and species or ecological niches in ecosystems. In fact, the diversity
494 of socioeconomic functions (let us call it H_s to differentiate it from the ecological context) has been
495 proposed as a reliable economic indicator (e.g., Marcuzzi and Camuffo, 1968; Hackbart and Anderson,
496 1975; Matutinovic, 2001; Frenken, 2007). Additionally, the calculation of I_e has no analytical or
497 methodological restrictions to be applied to society (let us call it I_s , to distinguish it from the ecological
498 context), being in this context a good indicator of the talandic temperature (see comments about this
499 concept in Section 3.1) of socioeconomic systems.

500 As it is expected according to our hypothetical premise in regard to the validity of ecological df also in
501 economics, the value of total socioeconomic diversity for the United States of America (H_{sT} , see Fig. 4)
502 collapsed just after 2008 (Wall Street meltdown and its subsequent expansion to the rest of the world,
503 mainly after October 2008). H_{sT} abruptly decline along 2009, hits bottom in the period between 2010 and
504 2011. Later on, H_{sT} increased its value from 2011 to 2016. Fig. 4 also shows that, according to the above-
505 mentioned anti-kinetic and, therefore, anti-thermic influence of H , the value of I_s deploys just the opposite
506 behavior in comparison with H_{sT} (i.e., the internal talandic temperature of economic systems has an
507 opposite behavior in comparison with socio-diversity). In fact, the noticeable positive slope of I_s in the
508 short stage between 2005 and 2007 supports the idea that the economy was in a process of “overheating”
509 even before the economic crisis.

510 Every dissipative system is able to keep a high level of order or low internal entropy (high H_{ST} and
511 low I_s , in this case) only by pumping entropy to its surroundings (“*each technology always creates a*
512 *temporary island of order at the expense of greater disorder in the surroundings*”; Rifkin 1980, p. 123),
513 environmental overheating is the expected a result. Consequently, the opposite association between the
514 five-year LOWESS smooth surface air temperature averaged over the contiguous 48 United States
515 relative to the 1951-1980 mean ($T(^{\circ}\text{C})$) and I_s in Fig. 4 is quite clear. However, even taking into account
516 this evident association, the suspicion of the underlying influence of a spurious correlation cannot be
517 ruled out.

518 The suspicion of spurious correlation is *suppressed* if we introduce a third anthropogenic indicator
519 directly connected to climate warming in the USA: the mean volume of greenhouse gas emissions due to
520 transportation in the USA between 2005 and 2016 was 26.748% of total emissions (see Appendix A,
521 spreadsheet “economics”, cell G16), only surpassed by the greenhouse gas emissions from electricity
522 generation (31.823% of total greenhouse gas emissions). Electricity generation is geographically
523 concentrated in certain points, but transportation activity is spread all over the country, linked to every
524 kind of human activity, associated to a huge amount and variety of industrial waste as well as to the high
525 capability of asphalt surfaces for transforming the incident solar radiation into heat. In addition, there is
526 reliable evidence that aircraft-produced contrail cirrus clouds contribute to anthropogenic climate change
527 (Minnis et al., 2004; Burkhardt and Kärcher, 2011; Kärcher, 2018), even in a notoriously sudden way
528 (Travis et al., 2002). Thus, the impact of greenhouse gas emissions due to transportation could be
529 regarded as more harmful than the impact of electricity production.

530 The cubic-polynomial-fitted values of greenhouse gas emissions by transportation expressed as a
531 percentage of total emissions in million metric tons of carbon dioxide equivalents ($\text{Gh}_{(\text{t.e.}\% \text{Total})}$) in Fig. 4
532 follow a trajectory that coincides quite well ($r = 0.917$, $p = 2.77\text{E-}05$) with $T(^{\circ}\text{C})$; even the correlation
533 between $T(^{\circ}\text{C})$ and the original (non-adjusted) values of $\text{Gh}_{(\text{t.e.}\% \text{Total})}$ is high and significant (see Appendix
534 A, spreadsheet “economics”, cell E20: $r = 0.805$, $p = 1.576\text{E-}3$). This result supports the consistency of
535 the above-mentioned relationships between $H_{ST}\downarrow$, $I_s\uparrow$, and $T(^{\circ}\text{C})\downarrow$, and vice versa. So, a very deep and
536 long-lasting economic crisis would be good news to reduce global warming. The most important outcome
537 from Fig. 4 is that the combination of df analyzed in this article can establish a fruitful analytical bridge
538 based on a reliable equivalence of meaning between ecological df and economic df .³

539 The complete analytical landscape is that the current combination of (a) intense economic competition
540 between countries + (b) high rates of technological development and economic growth (i.e., $H_{ST} \gg 3.732$
541 nat/individual^4 at the world scale) + (c) increasing scarcity of raw materials to sustain an ever-increasing
542 human population (“*anyone who believes exponential [economic] growth can go on forever in a finite*
543 *world is either a madman or an economist*”, Kenneth E. Boulding, 1966; cited by Cairns, 2004) is not
544 sustainable for long a time. The key point is that, meanwhile all the living systems on Earth are open
545 systems, the global village in which we are living nowadays is not and has never been an open system
546 from the socioeconomic point of view: it develops under a paradoxical regime of “*enclosed degrees of*

³ The amount of exosomatic biomass handled by man has been omitted due to the methodological difficulties associated to its exact measurement per U.S. state.

⁴ The highest value of total socio-diversity assessed for the U.S., in 2008 (see cell B7 in spreadsheet “economics”, Appendix A)

547 *freedom*". The main result is a conflict, at a so large scale, that it often overcomes the encompassing
548 capability of our scientific view, generally biased in favor of dissecting analysis rather than in favor of
549 holistic synthesis.

550 The essentially far-from-equilibrium and open nature of economic systems has been recently stated as
551 an inescapable requirement for the stability of economic dynamics according to the information theory of
552 intrinsic value (Rodríguez and Cáceres-Hernández, 2018). This new theory of economic value unifies the
553 two main previous theories so far in a reliable and self-evident way based on the principles of
554 thermodynamics. Thus, in a similar way in which the European exploration expeditions from the second
555 half of the 15th century until the beginning of the 17th century could be considered as a way to open a
556 closed and declining medieval Europe, the future exoplanetary expeditions could be regarded as an
557 emergency solution to open our global village from the socioeconomic point of view. The most
558 worrisome issue is that these kind of events, although seemingly depend on our will, are influenced by a
559 so complex combination of circumstances, that they seem to have their own objective internal dynamics:
560 they either will take place in the most suitable moment or they will not take place ever, and then our
561 species will vanish self-consumed by its socioeconomic voracity.

562

563 **4. Concluding remarks**

564 In summary, the results of our analysis show, either due to the easily understandable logic of its
565 theoretical foundations or due to its empirical support, that the dilemma physics vs. non-physics in
566 ecosystem ecology is nonsense: it is unavoidable to recover the lost connection between the early stage of
567 classical ecosystem ecology and several branches of physics. Astonishingly, as it has been exposed in
568 Section 2.2, the lack of understanding in ecology of a so simple concept as that of physical equilibrium
569 has delayed the development of this field over five decades. In addition, it is probable that any research
570 work that, either directly or indirectly, neglects the analytical influence of the triad of ecological *df* here
571 proposed will arrive to contingent conclusions. Finally, these *df* and their alternative combinations can
572 have a key role to establish a commonly shared language between ecology and economics; a goal that is
573 more and more imperative to reach in order to overcome the variety of urgent environmental challenges
574 impinging on humankind nowadays.

575

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583

584

585 **Compliance with ethical standards**

586 **Conflict of interest:** The authors declare no actual or potential conflict of interest in relation to this
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588

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725

726 **FIGURE CAPTIONS:**

727 **Fig. 1.** Summary of the main results from OBEC so far.

728

729 **Fig. 2.** Typical examples of the three possible trophodynamic states of an ecosystem according to the
730 correlative relationship between the variables of the minimum and most meaningful set of ecological *df*.
731 (a) 3D surface plots (distance weighted least square fitting) under SEC in order to highlight the pro-
732 stationary effect of the trade-off between biomass (m_{ep}) and dispersal activity (I_e) in function of species
733 diversity values per plot (H_p). (b) Graphical analysis, equivalent to (a), but under anti-successional non-
734 SEC. (c) Graphical analysis, equivalent to (b), but under pro-successional non-SEC. Panels (a) and (b)
735 were obtained from field data of ruderal vegetation (rv); panel (c) was obtained from field data of
736 planktonic crustaceans of inland waters (crust). Original data for these figures are included in Appendix
737 A.

738

739 **Fig. 3.** Relationship between the observed value of basal metabolic rate ($BMR(\text{obs.})$) of 638 species of
740 mammals (data from McNab, 2008) and the respective expected values according to the principles of the
741 Organic Biophysics of Ecosystem. (a) Correlation between log-transformed values of $BMR(\text{obs.})$ and
742 $BMR(\text{exp.})$ according to Eq. (7). (b) Correlation between log-transformed values of $BMR(\text{obs.})$ and
743 $BMR(\text{exp.})$ according to Eq. (8). (c) Results of the ANOVA applied to compare the mean values of

744 $BMR(\text{obs.})$, $BMR(\text{exp.})$ according to Eq. (7), and $BMR(\text{exp.})$ according to Eq. (8); non-log-transformed
745 original values.

746

747 **Fig. 4.** Results of the extrapolation of ecological df to analyze the USA socioeconomic system and its
748 interaction with global warming at the country scale over time. H_{st} : total socio-diversity at the country
749 scale including employed population, unemployed population, as well as inactive population divided in
750 two categories (< 16 years old, and > 16 years old) as socioeconomic niches. Original data sources (raw
751 spreadsheet includes 498168 cells) retrieved from: Bureau of Labor Statistics, Occupational Employment
752 Statistics (<https://www.bls.gov/oes/tables.htm>); Bureau of Labor Statistics, American Community Survey
753 (<https://www.bls.gov/lau/acsqa.htm>); Department of Defense Manpower Data Center
754 (https://www.dmdc.osd.mil/appj/dwp/dwp_reports.jsp); United States Census Bureau
755 (<https://factfinder.census.gov/faces/nav/jsf/pages/index.xhtml>). I_s : index of social dispersal intensity,
756 analytically equivalent to I_e in ecosystem ecology (original data source of central geographical
757 coordinates per state in UTM system: Rogerson, 2015). $T(^{\circ}\text{C})$: Five-year LOWESS smooth surface air
758 temperature averaged over the contiguous 48 United States relative to the 1951-1980 mean. Original data
759 source: National Aeronautics and Space Administration, Goddard Institute for Space Studies
760 (https://data.giss.nasa.gov/gistemp/graphs/graph_data/U.S._Temperature/graph.txt; retrieved June 21
761 2018). $Gh_{(\text{i.e.}\% \text{Total})}$: cubic-polynomial-fitted values of greenhouse gas emissions by transportation
762 expressed as a percentage of total emissions in million metric tons of carbon dioxide equivalents (EPA:
763 <https://www3.epa.gov/climatechange/ghgemissions/inventoryexplorer/#allsectors/allgas/econsect/all>;
764 retrieved June 22 2018).

Fig. 1

OBEC

1. Development and empirical testing of an ecological state equation (equivalent to the ideal gas state equation) aimed to describe stationary ecological conditions (SEC; see Rodríguez et al., 2012).
2. Fulfilment of Boyle-Mariotte's Law under SEC and its links to farming and livestock (Rodríguez et al., 2013b).
3. The ecological succession as a process of physical cooling (Rodríguez et al., 2013b).
4. Boltzmann negative exponential distribution of total eco-kinetic energy per plot to model ecological energy pyramids under SEC (Rodríguez et al., 2015a).
5. Empirical assessment of the evolutionary equivalent (h_e^{ev}) of Planck's constant (h) (Rodríguez et al., 2015b).
6. Maxwell-Boltzmann gamma distribution of H_p values under SEC and ecological equivalent (h_e^{ec}) of Planck's constant (h) (Rodríguez et al., 2015c).
7. Heisenberg's uncertainty principle under SEC as a solution to the old dilemma between competitive exclusion principle and functional redundancy (biodiversity paradox) (Rodríguez et al., 2015d; 2016a).
8. Ecological state equation under non-SEC (Rodríguez et al., 2016b).
9. Maxwell-Boltzmann gamma distribution of H_p values under non-SEC (Rodríguez et al., 2016b).
10. Equivalence between foundational principles of information theory and well-known eco-evolutionary principles (Rodríguez et al., 2016c).
11. The role of human beings as Maxwell demons in the interaction society \leftrightarrow nature, and its meaning for sustainable development (Rodríguez et al., 2017a).
12. Review of OBEC's results that complement and expand the meaning of Darwinism (Rodríguez et al., 2017b).
13. Boltzmann negative exponential distribution of total eco-kinetic energy per plot to model ecological energy pyramids under non-SEC (Rodríguez et al., 2017c).
14. A model to assess ecosystem trophodynamic power starting from the power equation for an oscillating string (Rodríguez et al., 2017d).

Fig. 2

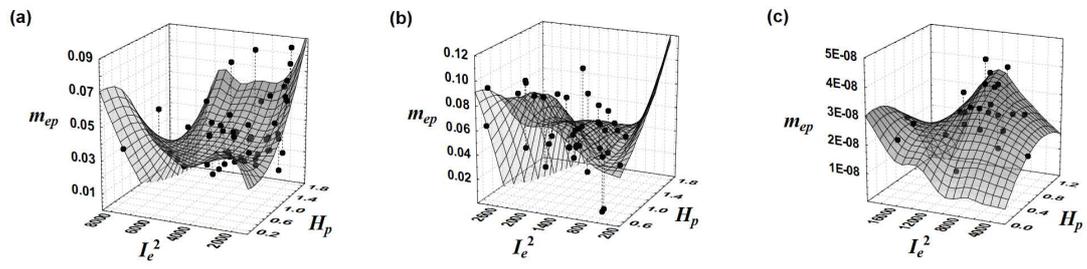


Fig. 3

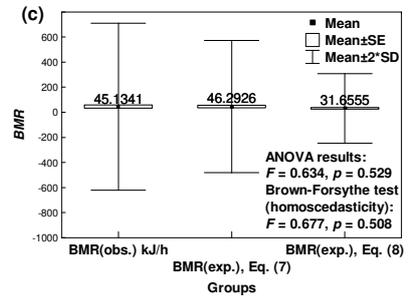
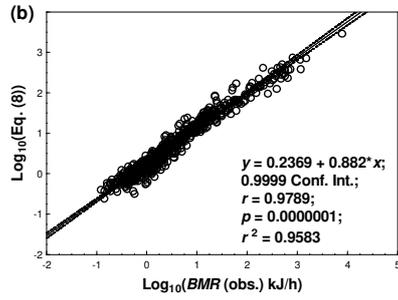
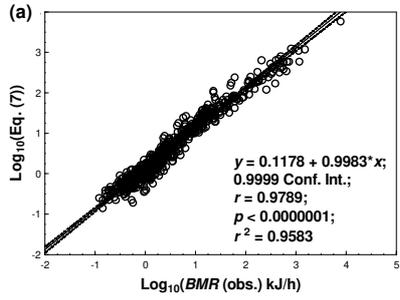


Fig. 4

