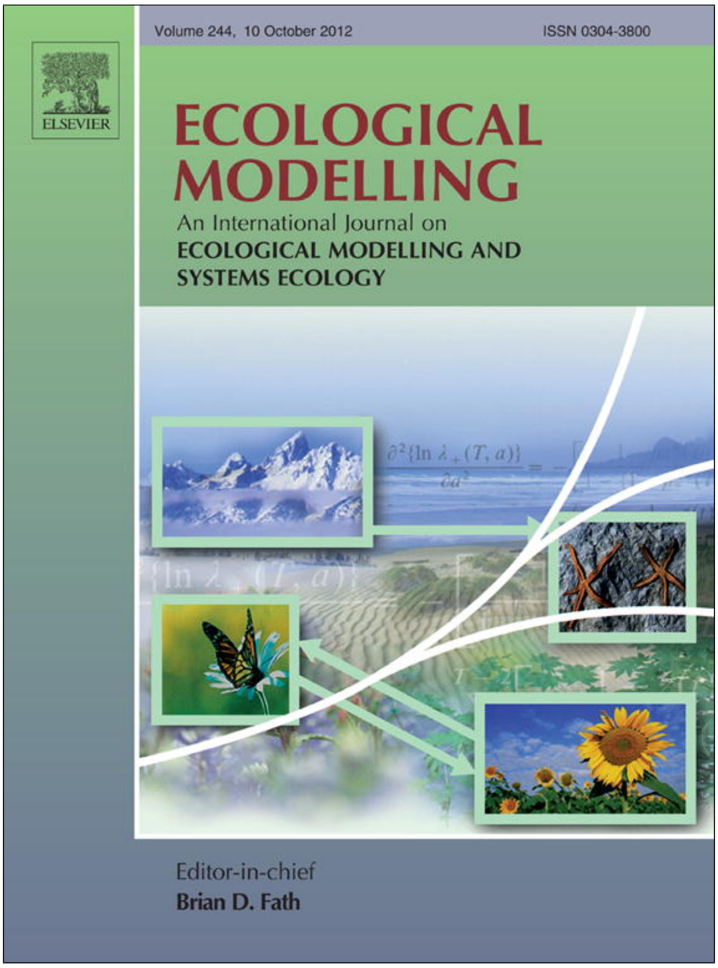
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Letter to the Editor

Can emergy sustainability index be improved? Complementary insights for extending the vision

Professor Harizaj (2011) and Professors Brown and Ulgiati (2011) have established a stimulating dialogue about the possibility of improving the emergy sustainability index (ESI): the ratio between the EYR (emergy yield ratio) and the ELR (environmental loading ratio). ESI, EYR and ELR are defined by ratios among R (renewable inputs), N (non-renewable inputs) and F (feedback of inputs from the economy). For further details, please see Odum (1996).

Harizaj (2011) triggered the discussion based on the idea that a higher EYR does not always lead to a higher ESI (Raugei et al., 2005). Harizaj proposes a criterion based on the inequality $R \gg F \gg N$ as a "modest contribution as a quick macroscopic snapshot of natural processes and human activities which might help us to check whether human activities are (approximately) in conformity with nature's capacity for recovery". Harizaj states that sustainability is achieved when R is much higher than N and F, and that "this 'sustainability inequality' deviates from the ESI analysis given in Brown and Ulgiati (1997)" especially when one try to calculate the long term sustainability of nations.

The letter of Brown and Ulgiati (2011) is a model of elegant and inspiring response. This letter made us think more deeply about the ESI and find a new interpretation based on the emergy ternary diagram. More details on theoretical aspects and the use of the emergy ternary diagram can be found in the literature (Agostinho et al., 2008, 2010; Almeida et al., 2007, 2010; Bonilla et al., 2010; Cai et al., 2008; Giannetti et al., 2006, 2007, 2011). Three excerpts from the answer given by Brown and Ulgiati to Harizaj are highlighted:

> "The infinite number of potential combinations of R, F and N generates as a consequence, many more combinations of EYR and ELR yielding a very large number of possible ESIs. These numbers may or may not correspond to real systems somewhere on the planet, that is, that Professor Harizaj's sustainability inequality is only partially true".

Insight 1: We distinguish two approaches to sustainability. One favors the maximization of R in the inequality of coordinates R, N and F and the other optimizes the yield/load relationship. Are these sustainability criteria complementary or opposites?

> "When trying to maximize ESI our Monte Carlo simulations show that ESI is maximized with three combinations of the inequality ($R > N > F$, $N > R > F$, $R > F > N$)".

Insight 2: The Monte Carlo simulations are used to describe the frequency of occurrences of different sustainability conditions. It is a powerful mathematical tool to evaluate non-deterministic models. Could we assess the frequencies of occurrence in the emergy ternary diagram?

> "We recognized then, as we do now, the complexities involved in advocating criteria for sustainability, which can hardly be captured by a single inequality".

Insight 3: Complexity is a key word in this sentence. Sustainability is an emergent property of complex systems. Therefore, the sustainability criteria should capture this property. The nations are complex systems; the biosphere is a complex system. Could we capture the complex nature of these systems using the criteria for sustainability in the emergy ternary diagram?

Based on the insights generated by the Letters to the Editor an assessment of the sustainability criteria of Harizaj and Brown and Ulgiati was carried out employing the emergy ternary diagram. Fig. 1(A) shows the coordinates R, N and F, depicting the areas corresponding to the inequality criterion. In Fig. 1(B), areas are defined based on the criterion of the EYR/ELR ratio. Values were defined using the ELR and EYR intervals proposed by Brown and Ulgiati (1997).

In Fig. 1(A) and (B), it is possible to verify two proportionalities (insights 1 and 2): (1) the areas are proportional to the probability that would be obtained by Monte Carlo simulation; (2) the criteria are complementary in the same proportion that predominance areas are complementary.

When the sustainability lines are drawn in the ternary diagrams (Giannetti et al., 2006; Almeida et al., 2007), it is clear that the probability of a certain sustainability condition changes significantly (Fig. 1(C)). Comparing Fig. 1(C) with 1(A) and (B), it can be noted that area for $ESI > 100$ covers only three inequalities ($N > R > F$, $R > N > F$ and $R > F > N$) and three conditions of EYR/ELR (high EYR combined with low, medium and high ELR). This observation may also be made at the table presented in Brown and Ulgiati's letter. The emergy ternary diagram offers a rapid assessment of the frequency of occurrence when the systems have pre-established minimum values for the ESI sustainability index.

A full overlapping of Fig. 1(A) and (C) helps to conclude that complementarities between ESI and $R > F > N$ exists only over the space defined by $R > F > N$ (Fig. 1(D), light/dark gray). In such a case, the inequality $R > F > N$ serves as a selection criteria for all EYR/ELR values throughout the ternary diagram that also present $ESI > 10$ ($R > N > F$ and $N > R > F$), ESI values within $R > F > N$ space should be further considered in terms of long-term sustainability. If one considers that only the extreme value of $ESI > 100$ satisfy the $R \gg F \gg N$ criteria can guarantee the long-term sustainability, the probability to find such system will fall to 0.4% (dark gray area). In fact, as it may be seen later in this paper, the Ternary Diagram Methodology may be complementary to sustainability inequality ($R \gg F \gg N$) by visualizing the limits of long-term sustainability imposed by the mathematical expression established by the inequality. The dark gray selection represents the space where the best sustainability options might be found ($R \gg F > N$). Non-renewable resources (N)

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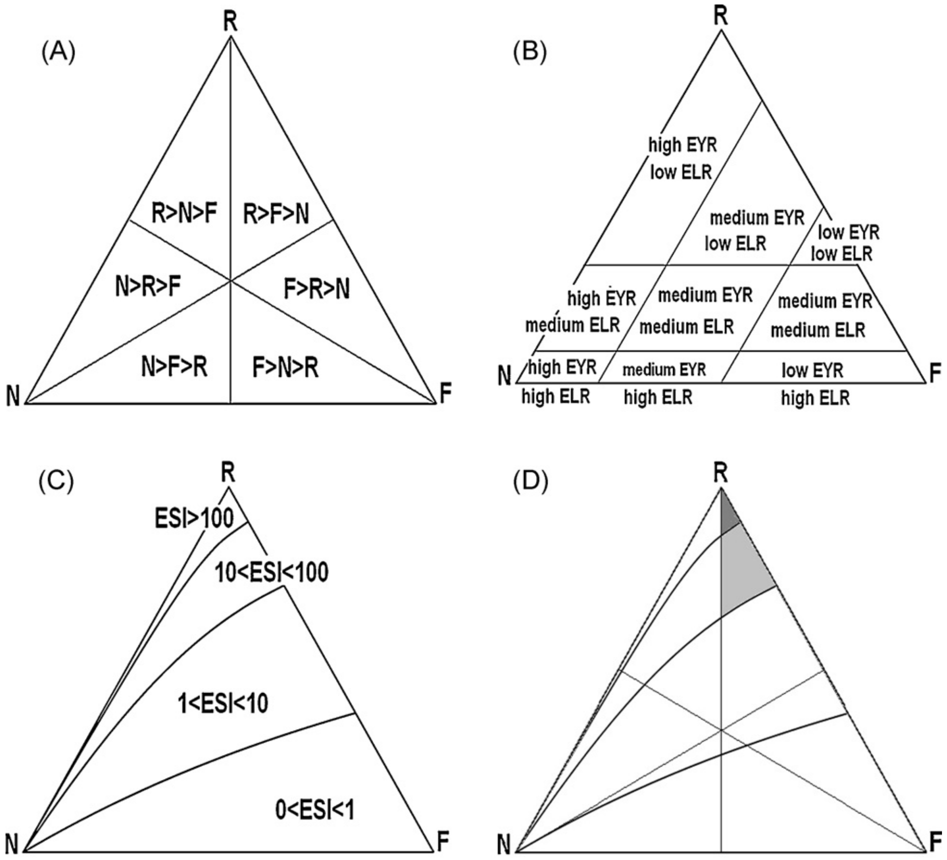

Fig. 1. (A) Areas corresponding to the inequality criterion; (B) areas defined by the criterion of EYR/ELR ratio; (C) areas defined by the ESI value; and (D) area of long-term sustainability according to both criteria: dark gray corresponds to $R \gg N \gg F$ and ESI > 100; and light gray to $R > F > N$ and ESI > 10.

should be the last to be used, as nature regenerates them at a very low rate compared to their rate of consumption by humans.

The lower part of $R > F > N$ space (Fig. 1(D), white) represents intermediary cases, were the long-term sustainability of natural processes and human activities are not guaranteed, but show the positive trend towards it. Countries in these positions have the opportunity to accentuate the positive trend towards long-term sustainability ($R \gg F > N$) or overturn the positive tendency they might have ($R > F > N$) for achieving short and medium term goals expressed primarily through Economic Growth paradigm.

As mentioned by Brown and Ulgiati (2011), there are an infinite number of combinations of R, N and F, and just some of them correspond to real systems on the planet. Taking as an example the study of the sustainability of nations, it can be said that the number of countries assessed by emergy (NEAD, 2000) is significant, in statistics terms. Thus, it is possible to determine whether countries occupy areas of the ternary diagram at random or not. Tables 1 and 2 compare the percentage of countries that occupy the areas corresponding to both sustainability conditions (Harizaj, 2011; Brown and Ulgiati, 2011) with the percentages of purely random behavior (insight 2). The comparison is made by the value of *A* in Tables 1 and 2.

Values of *A* (Tables 1 and 2) suggest a new interpretation for the emergy ternary diagram (insight 3). The diagram coordinates R, N and F, in the light of the theory of complex systems, define a phase space. The phase space is understood as the total number of combinations available to the system. Therefore, the diagram can be seen as a space in which all possible states of a system are represented. With this new interpretation, it is possible to move forward in the understanding of sustainability and its indicators.

Developing this idea, we can think of another important definition of the complex systems theory, the attractor. The attractor is a preferred position of the system in phase space. If the system evolves from an initial condition, it is directed toward an attractor.

Table 1
Values of *A* related to the attractors of each phase defined by the coordinates R, N and F.

Phase space	Percentage of countries (% *P*)	Frequency of occurrence (% *f*)	*A* (*A* = % *P*/% *f*)
$R > N > F$	26.3	16.7	1.6 ± 0.1
$R > F > N$	13.5	16.7	0.8 ± 0.1
$F > R > N$	7.5	16.7	0.4 ± 0.1
$F > N > R$	22.6	16.7	1.4 ± 0.1
$N > F > R$	14.3	16.7	0.9 ± 0.1
$N > R > F$	15.8	16.7	0.9 ± 0.1

Table 2
Values of *A* related to the attractors of each phase defined by the EYR/ELR ratio. The value of *A* is higher than 1.0 for approximately 60% of the countries.

Phase space	Percentage of countries (% P)	Frequency of occurrence (% f)	*A* (*A*=% P/% f)	
High EYR / Low ELR	32.3	22.9	**1.4 ± 0.1**	
Medium EYR / Low ELR	15.0	18.8	0.8 ± 0.1	
Low EYR / Low ELR	0.8	2.7	0.3 ± 0.1	
High EYR / Medium ELR	6.0	9.8	0.6 ± 0.1	
Medium EYR / Medium ELR	9.8	14.6	0.7 ± 0.1	
Low EYR / Medium ELR	9.0	14.1	0.6 ± 0.1	
High EYR / High ELR	2.3	3.6	0.6 ± 0.1	
Medium EYR / High ELR	8.3	5.2	**1.6 ± 0.1**	**1.8 ± 0.1 ***
Low EYR / High ELR	16.5	8.3	**2.0 ± 0.1**	

[a] The value of *A* corresponds to the contiguous phase spaces with medium/low EYR combined with high ELR.
Bold values denote situations where *A* > 1

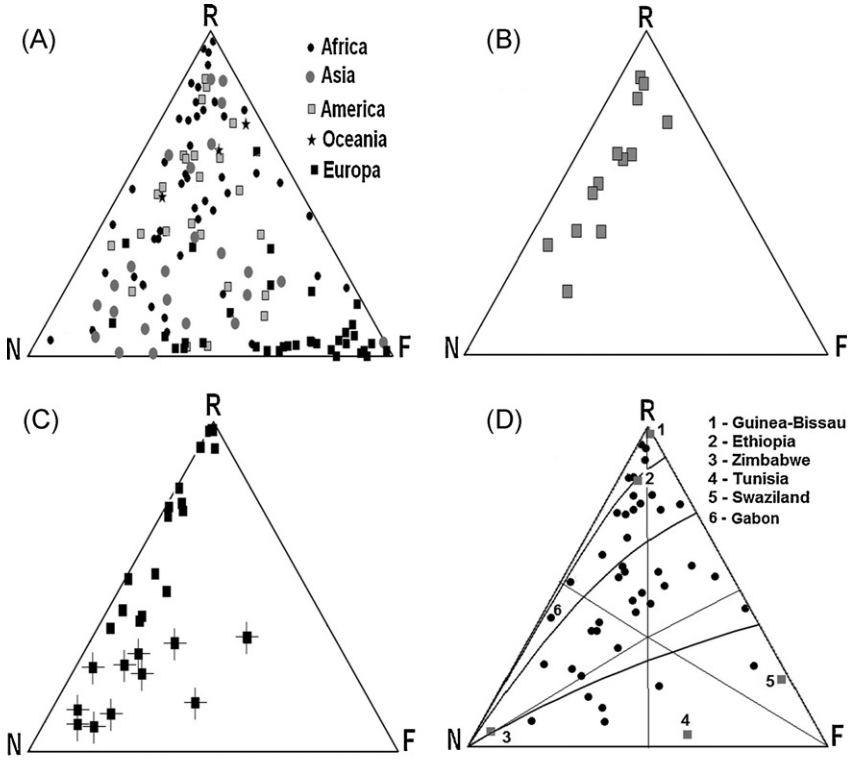

Fig. 2. Emergy ternary diagrams: (A) World (NEAD, 2000); (B) South America (NEAD, 2000) and (C) Brazilian states (Demétrio, 2011). States marked with a cross have economic development above Brazilian average. Each point in the diagrams corresponds to a country (A) and (B) or to a Brazilian state (C). (D) shows the countries distribution of the African continent (NEAD, 2000).

Therefore, the values of A calculated in Tables 1 and 2 are related to the attractors of each phase defined by the inequality R, N and F (Table 1) or the relationship EYR/ELR (Table 2).

The evolution of a complex system is conceived as being regulated by a relationship between 'need' (deterministic response of the systems) and 'chaos' (fluctuations that are measured by the frequency of occurrence). Thus, when $A = 1$ in a given phase space, the behavior is purely probabilistic. In this case, the various possible influences, internal and external, are canceled, and the system has random behavior. When $A \neq 1$, the system converges ($A > 1$) or diverges ($0 < A < 1$) to a given phase space (Tables 1 and 2). In the case that $A \neq 1$, the behavior is probably influenced by causes which divert the system from the purely probabilistic behavior. Among these causes, there are the local resources availability and the decisions of a given society, which are influenced by cultural, historical and other aspects of human nature.

Looking at Tables 1 and 2 it is evident that the countries in the planet have two major attractors. Using the criterion of inequality (Table 1), a high concentration of countries (above the probabilistic value) in the phase spaces R > N > F and F > N> R is observed. Interestingly, these two attractors concentrate approximately 49% of the countries, and half of them has mirror-type coordinates: R > N > F versus F > N > R. Using the criterion of the relationship EYR/ELR (Table 2) countries, above the frequency of occurrence, are identified with high EYR and low ELR, or in the contiguous phase spaces with medium/low EYR combined with high ELR ($A = 1.8$). These attractors concentrate approximately 60% of the countries, and there is also a mirror effect of the low versus high ELR.

Another interesting observation can be made when one observes the phase space occupied by the countries of South America and the Brazilian states (Fig. 2(B) and (C)). The similarity suggests a fractality, a pattern repetition at different scales. Fractals are used to describe self-similarity in complex systems. Most Brazilian states are placed in the high EYR/low ELR phase space ($A = 3.8$ for South American countries and $A = 2.7$ for Brazilian states). It is noteworthy that the Brazilian states that occupy other attractors are the most developed in the economic aspect. The Brazilian states out of high EYR/low ELR phase space (Fig. 2(C), indicated by crossed squares) can be divided into two groups: those which are 'attracted' by an N vector, and others under 'attraction' of an F vector. The majority of South American countries and Brazilian states belong either to R > N > F or N > R > F spaces (Figs. 1(A)–(C) and 2(B) and (C)). These two spaces coincide with high EYR/low ELR or high EYR/medium ELR spaces (ESI > 100 or 10 < ESI < 100). According to ESI criterion these countries or states may be considered sustainable in the medium or long run, although they consume their native nonrenewable resources at a rate faster than Nature's rate of their recovery. This means that high ESI values serve to hide the unsustainable economic development of these countries. The Sustainability Inequality considers the economic development of these countries unsustainable as long as multiple criteria of long term sustainability are not satisfied ($R \gg F \gg N$). This influence is clear when one realizes that public policies understand "progress" by mimicking the developed countries policies (mostly located in the high ELR phase space, Figs. 2(A) and 1(B)).

Comparing the emergy ternary diagrams of Figs. 1(A) and 2(A), it appears that the R > N > F phase space is mainly occupied by African countries, and the F > N > R phase space is preferentially occupied by European ones. Fig. 2(D) shows the distribution of the African countries (NEAD, 2000). Contrary to what is observed in the American continent, where countries occupy defined regions in the ternary diagram, the distribution of African countries is quite heterogeneous. There are the countries as Ethiopia (ESI = 96, R > N > F), Zimbabwe (ESI = 1.4, N > R > F, Tunisia (ESI = 0.07, F > N > R) and Swaziland (ESI = 0.35, F > R > N). Guinea-Bissau (ESI = 1534, $R \gg N \gg F$) is the only country in the extreme long-term sustainability area defined by both approaches (Harizaj, 2011; Brown and Ulgiati, 2011). This country has one of the lowest GDP per capita in the World, with also low Human Development Index (0.289). In the region $N > R > F$ and $10 < ESI < 100$ (Fig. 2(D)), Gabon ($ESI = 23$, $N > R > F$) is the only country. This country is one of the most prosperous countries in Sub-Saharan Africa, with the Human Development Index of 0.648 and the third highest African GDP per capita, but its economy is based on oil exportation, which corresponds to 43% of its gross domestic product.

The global system, humanity and nature, is intimately connected by commerce, treaties, finances, military alliances and shared information. In a first glance, Africa and Asia have shown heterogeneous distribution on the ternary diagram, and further studies are needed to evaluate their complex nature. For all three Americas, Europe and Oceania, countries distribution in the emergy ternary diagram suggests attractors and fractals, but also leads us to think about the concept of Odum's macroscope (Odum, 2007). The complex systems theory and Odum's macroscope are systemic and advanced views of Nature. Perceptions of sustainability and indicators that arise from these theories increase our understanding of the World. However, one has to accept the difficulty to deal with all aspects of this complex reality, especially when we are part of it.

These insights were only possible after the encouraging exchange of letters by Harizaj and Brown and Ulgiati. We appreciated the opportunity to discuss the ESI under the complex systems theory point of view.

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