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Contributions to biodiversity theory: the importance of formal rigor

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Abstract. In this short paper, some consideration is given to the term *biodiversity*. We stress the need for a strong formal rigor in using this term in order to maintain the credibility by non-ecologists and environmental agencies over the scientific community involved in biodiversity studies. After a historical introduction to the use and concept of the term *biodiversity*, this paper presents some theoretical aspects, concrete methodological proposal, and discussion for the further scientific and consistent use of the term *biodiversity*.

1 Historical introduction

Authors of ecological papers have used the term *biodiversity* with various meanings over the decades. The phenomenon of biodiversity has been analytically described in practice, without any exact conceptualization, since the classical authors (see, e.g., Lucretius, 54 BC) up to the origin of ecology as a science, in the second half of AD 800. According to Pignatti (2006), the word *biodiversity* probably took its origin from the Italian scientist Federico Cesi (1651), who coined *diversitas plantarum* (Latin: i.e., the diversity of plants), the "diversity of the elementary units of the whole set of the plants". It is remarkable that Cesi (1651) wrote explicitly about *diversitas* (diversity) rather than *differentia* (difference), because the term *differentia* would refer to a comparison between different sets (Pignatti, 2006).

For the expression *biological diversity* (see Dasmann, 1968) and the derived term *biodiversity* (Rosen, 1985; Wilson, 1988), several definitions were proposed:

1. Each kind of variability among living organisms and its ecological complex, as established by the Rio Conference on Sustainable Development in 1992, apparently cumulate discrete and continuous variability.

2. The totality of genes, species, and ecosystems of a region (Larsson, 2001) is quite restricted to some territorial abundance.

3. The variation of life at all levels of biological organization (Spicer, 2004) cumulates variance and diversity.

In the first half of the twentieth century, a better theoretical approach to the concept of biodiversity arose through the use of mathematical tools (Gini, 1912; Shannon and Weaver, 1948; Simpson, 1949) along the way of the science of multiplicity–complexity, at least partly arising from the roots of thermodynamics. However, the physical meaning of biodiversity, linked to the statistical multiplicity and complexity, was rarely underlined by authors.

Some further quantitative research, theoretically very promising and valuable (e.g., Patil and Taillie, 1976; Pielou, 1975; Hill, 1973; Magurran, 1988, 2004; Magurran and McGill, 2011), was a bit overlooked, while there was a illusory race towards discovering the *best index* (see also the critiques presented by, e.g., Margalef, 1957, 1986; Barbault et al., 1991; Colwell, 1979; and in general Dhand and Howlett, 2000). During the increasing environmental crisis of the last century, there was a pressing impetus towards operative and pragmatic solutions (especially after the Rio Conference in

Table 1. Google Scholar analysis of the occurrence of the following terms in the ecological literature: B – biodiversity; **B** – biodiversity, abundance, numerosity, richness, evenness, and profiles. The abbreviation o.o.m indicates order of magnitude.

Year	B	**B**	**B**/B	**B**/B (o.o.m.)
1940	5	5	1	1
1945	22	7	0.3	0
1950	6	6	1	1
1955	5	5	1	1
1960	8	8	1	1
1965	3	3	1	1
1970	69	54	0.8	1
1975	5	5	1	1
1980	124	55	0.4	0.5
1985	384	52	0.1	0.5
1990	522	57	0.1	0.5
1995	4310	54	0.01	0.3
2000	8160	9	0.001	0
2005	9570	7	0.001	0
2010	54 3000	5	0.00001	0

1992), and as a consequence the theoretical grounds of biodiversity were disregarded, even in the few acclaimed contributions (e.g., Eldredge, 2004; Wilson, 1999). Biodiversity and its protection were increasingly intended in a relatively static and non-evolutive sense. A quick analysis of Google Scholar shows that the term *biodiversity* increased exponentially from 1940 to 2010 (Table 1), whereas the entries for the more specific words such as *abundance*, *numerosity*, *richness*, *evenness*, and *profiles* declined, thus meaning that a more technical approach to the matter seems to have been becoming less common in recent years (Table 1) likely due to a declining interest in the conceptual aspects of such problems with respect to the emotional ones.

Nowadays, in the various definitions of biodiversity there is usually no emphasis on its functional aspects, and the term is even non-technically used as a synonym for *nature* or *wilderness*. Even studies allegedly more interested in the formal aspects aim at expressing diversity intuitively (Sherwin, 2010). So, it seems that some dubious use of the word *biodiversity* is present not only in non-scientific media but also within the scientific community.

In this paper, we try to reaffirm the need for applying methodological rigor in the field, presenting and discussing the conceptual unifying aspects of biodiversity, their names and definitions, because even an uncritical approach may favor the introduction of involuntary artifacts.

2 Theoretical aspects, concrete methodological proposal, and discussion

- *Definition*: biodiversity, the diversity of life, is the multiplicity, variety and interaction of each set of living systems (e.g., communities, guilds).
- *Application field*: a single, distinct set of living systems.

In several instances, the idea of biodiversity seems to be more relative to intuitive feeling rather than to perception, and even less to the field of the rational understanding. All our conceptions about biodiversity seem to refer essentially to our own spatial and temporal environmental context. Thus, at the end of the day, we have an intuitive idea of the word *biodiversity*, referring to biotic complexity. We are hence confronted with a *personal concept* that is intrinsically unique, exactly like the concept of *environment*. Therefore, we could provocatively combine the two terms into a single, further, subjective definition of *biodiversity*, a set inclusive of all the biotic interactions of each living system in a perceptive environment. Hence, each of us as living organisms would have a different perception of the exact meaning of the word *biodiversity*, and because of this we may end up with vague, ambiguous, and partly controversial definitions of this word. This may be linked to the well-known and never forgotten critique by Hurlbert (1971), who considered species diversity as a non-concept: at the very least biodiversity is not a mono-concept, but a multi-concept. This is understandable if we think that each mathematical index of biodiversity may correspond to a particular mathematical idea, although it is necessary to still respect the formal and unifying aspects of the concept clusters. This is necessary to guarantee that biodiversity will keep a purely scientific meaning, predominating over the social or political ones.

Moving from a more subjective to a more objective meaning of the term *biodiversity*, one goes from extrinsic to intrinsic approaches to it, ranging from aspects exclusively descriptive (extrinsic biodiversity) to those aspects that are functional and therefore intrinsic to the considered set. In most cases, studies deal with extrinsic properties of biodiversity (for instance, most of the current field studies on biodiversity), but the number of studies dealing with intrinsic properties of biodiversity is increasing year by year (see studies with mathematical modeling, like *rarefaction*, *geometric*, *log-normal*, *logarithmic*, and *broken stick*: see Magurran, 1988; Ganis, 1991).

Extrinsic biodiversity may be therefore only subjective and descriptive, thus avoiding concept systematizations. In general, biodiversity, unlike *variance*, is a quali-quantitative concept, apart from the particular case of a set composed by only one *group*. Biodiversity is different from *difference* in that biodiversity applies to a single set of typically discrete and distinct elements (Hamilton, 2005).

Biodiversity may have a meaning relative to the biological complexity (see, Paine, 1966; Odum, 1973; Pimm, 1982;

Margalef, 1989; Contoli, 1992). Especially in this field and before any further speculation/analysis, it is always necessary to test the homogeneity of the samples as a mathematical set. This approach has already been performed (e.g., Contoli, 1998; Akani et al., 1999), but in too many cases this is regularly forgotten by experimenters (e.g., see Contoli, 1998, for a discussion).

On the other hand, intrinsic biodiversity must be characterized by a objective typological systematization, according to the various elements, levels, scales, and components. Elements of biodiversity are the quali-quantitative *set* of application, the discrete and distinct subsets of the *set*, and the discrete and distinct elements of the subsets. We recommend that one not use terms with a previous particular meaning (e.g., in taxonomy). So, *group* for the subsets and *unity* for an element of the *set* seems to meet such a requirement.

– *Set of application*: all and only the *groups* and *unities* of the biological systems under study. The individuation of the *set* is fundamental, especially in the choice between a formalistic or relational approach. Namely, in comparisons among biodiversities of the same biotope in time, a stress can "open" a quite functionally isolated set towards some others that are much larger (Contoli, 1992), making the two sets noncomparable.

– *Group*: a discrete and separate part of the *set*, composed of one or more *unities*.

Linking biodiversity to a discrete quantitative concept and its definition, the *group* concept gives a quali-quantitative meaning to biodiversity. Nevertheless, even a series of continue values can be subject to diversity indices through, for example, a multivariate tool, like principal component analysis.

– *Unity*: a discrete element of a *group*. The *unity* defines the level of the biodiversity.

– *Numerical components*: essential tools for each quantitative evaluation of biodiversity, the numerical components can be compared, for example, through diagrams called *profiles* (Reyni, 1961; Patil and Taillie, 1976) or in the frame of a *evenness/richness graphic analysis of biodiversity* (see, e.g., Contoli, 1986). Indeed, a large number of graphical analyses of diversity are available (Whittaker plots and diversity/dominance diagrams, ABC curves, k-dominance plots, richness/evenness diagrams; see Ukmar et al., 2007; Battisti et al., 2008).

– *Abundance*: number of *unities* in a *set*. The sample *abundance* is not only of numerical significance; it is also a necessary and fundamental, even if not sufficient, condition for biological diversification.

– *Numerosity*: number of *groups* in a *set*. It is the most widespread numerical approach to biodiversity. It must be mentioned that the concepts (and metrics) of *abundance* and *numerosity* have been often equivocated.

– *Richness*: a *numerosity* directly or indirectly weighted against *abundance*. The *richness* aims at making two or more numerosities comparable, through weighting (e.g., by rarefaction) if suitable (Contoli and Marenzi, 1982; Contoli, 1995).

– *Evenness* (e.g., equitability): degree of quantitative similarity of *unity* number among *groups*. Evenness is certainly the more important univariate metric of diversity that is sensitive to changes in species assemblages induced by anthropogenic and natural disturbances (Magurran and McGill, 2011). The *evenness* is often evaluated by detracting *richness* by a complex index of biodiversity. A relativization (Alatalo, 1981) or rarefaction (Contoli, 1995) procedure was adopted to purify *evenness* from other components of biodiversity, like *richness*.

– *Dominance*: prevalence numerical degree of one or few *groups* on the others of a *set*.

Biodiversity analysis can be applied to various dimensional and/or structural kinds of units, and indeed there are several typological levels:

1. molecular diversity (see Contoli, 1995; Campbell, 2003; e.g., different types of haemoglobin, chlorophyll, immuno-factors);

2. genetic diversity (e.g., allelic, genic, genomic; see Amori and Contoli, 1994; Mallet, 1996);

3. phenetic diversity (e.g., morphological or morphometrical characters; see, e.g., Amori and Contoli, 1994; Contoli, 1996);

4. biotic diversity in an ecological (i.e., ecospecies, sensu lato) or taxonomic meaning (through a number of sublevels; e.g., species richness, which is a very popular component of it);

5. community diversity (many measures – these metrics may be uni-, bi- and multivariate; see Magurran, 2004);

6. landscape diversity (many measures; e.g., ecosystem diversity);

7. Biodiversity analysis can be performed at different spatial (mainly, territorial) scales: this is clearly what has been shown by Whittaker (1977) and many later studies.

8. Punctual biodiversity; alpha-biodiversity; gamma-biodiversity; and so on, up to a limit like: (limit-to-) $\rightarrow$ omega-diversity (at the biosphere scale; Contoli, 2007). They are defined as follows:

a. alpha diversity: the diversity within a site, or quadrat, a.k.a. local diversity (Bacaro and Ricotta 2007);

b. beta diversity: the change in species composition from site to site, a.k.a. species turnover;

c. gamma diversity: the diversity of a landscape, or of all sites combined, a.k.a. regional diversity.

When we make comparisons among different levels of biodiversity (sensu Whittaker, 1977), it is always necessary to remember that odd ordinal numbers of the Greek alphabet (e.g., α, γ 1–3) correspond to true biodiversity, with the even letters (β, δ, etc.) representing differences among different aspects of diversity.

– *Indices of biodiversity*: numerical tools to quantifying biodiversity. Diversity indices are a range of not fully inter-changeable tools that represent overall measures of diversity. Often, their aim is to weigh together, but differently, the various components of biodiversity (complex indices).

Some authors combined aspects of richness and evenness, but in different proportions, as can be seen through the *diversity profiles* (sensu Hill, 1973; Reyni, 1961; Patil and Tailie, 1976). The indices including the π relative frequencies enable us to calculate the biodiversity of the principal components from continue measures. Note that the use of a widespread diversity index does not express at all, ipso facto, a biodiversity evaluation, if applied to inadequate data. So, the very popular Shannon–Wiener index (H'), of great international importance as it allows also some useful cumulative computations (e.g., in hierarchical biodiversity; see Feoli and Scimone, 1984), is unfortunately often used without adequate data sets.

3 Conclusions

In recent years, some instrumental critiques to the importance of defending biodiversity used as an argument the somewhat careless attitude in methods and analysis of most biodiversity research (e.g., see Lomborg, 2001). Apart from the instrumentality of these critiques, it would be necessary however in the future to avoid giving these weaknesses in the hands of those who act against environmental conservation as a whole.

If not correctly presented in both methodological and biological/functional terms, there is a real risk for the term *biodiversity* to be more deleterious than useful to the theoretical ecological knowledge and even to the more applied ecological science, with the ultimate result of being no more than a flatus vocis (Battisti and Contoli, 2011).

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