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## RESEARCH IN ECONOMICS AND RURAL SOCIOLOGY

### Criteria for assessment of biodiversity: properties and difficulties of use

*Knowing the value of biodiversity would enable more efficient preservation choices. For this purpose it is useful to have quantitative and/or qualitative information on the object "biodiversity". We sum up here several literatures (ecology, biology, political sciences and economics) which attempt to define and measure biodiversity. The originality of this note is that it clarifies the axiomatic bases of the indicators. While theoretical bases are sometimes fragile and need to be confirmed, practical issues are also a challenge for research.*

#### Purpose of the research

Biodiversity is a complex notion. First made up by natural sciences and popularized by the Rio Earth summit in 1992, it has been echoed by other scientific disciplines but also by citizens, NGOs, economic agents and public decision-makers....

For economists, the problem is first of all to give a value to biodiversity in order to give substance to the decision-making rules regarding public preservation policies. As these may be more or less ambitious and therefore costly, public decision-makers must have quantitative elements to help them in their choices in a context of limited budgetary resources. So it is useful to take the time to have a critical look over the efforts that have been made to define and measure biodiversity. We explore and sum up here several literatures (ecology, biology, political sciences and economics) guided by four main questions: what does biodiversity mean? Have we mastered the properties of its measurement tools? In a certain way, are such tools "equivalent"? In practice, are they easy to use?

This exploration elicits four main messages: 1) knowledge of the properties of biodiversity indicators is quite often partial; we do not know how to relate the equivalence between a whole set of properties and a single criterion of measurement, *i.e.* we do not have an *axiomatic characterization*, 2) even when it works, the axiomatic approach may have limits of an interpretative nature, 3) indicators are not equivalent: They are not different measurements of a same thing but different measurements for different things;

consequently, a given policy can increase biodiversity for one indicator and bring it down for another one, 4) and last, the use of indicators is limited by difficulties of a practical nature.

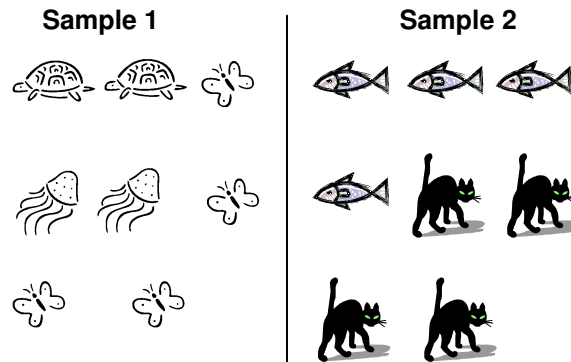
Section 2 presents an illustration, which, without losing its generality, will help develop thinking about biodiversity indicators, in section 3. Section 4 draws the conclusions of this exercise.

#### A simple example

The neologism "biodiversity" does not indicate a general and unique concept, but instead a set of concepts all the more difficult to understand in that they can be comprehended at different levels of life (genes, species, habitats, ecosystems), at various geographical scales or at different times...It does not lend itself to a general and standardized presentation. For example, as an illustration, let us consider the assessment of biodiversity of two samples of species in order to determine which one must be preserved. We may imagine that their survival is threatened and that budgetary limitations can only save one, hence the interest in ranking them. So the question asked is: "which sample offers the greatest biodiversity?"

Both samples are represented in figure 1, each one formed of eight elements and sharing a total of five species (butterflies, tortoises, jellyfish, sardines, cats).

**Figure 1: Samples of species**



For most of them, the ranking approaches that we will review consist in shortening the information contained in the samples to end up with a biodiversity index and then rank the samples in accordance with the values of this index. Since such an operation implies favouring only certain aspects of the information, there are several indices stemming from thinking in several disciplines (biology, ecology, economy...). They do not all produce the same ranking of our two samples and this is an important point. Where possible, it is thus essential to clarify the principles or axioms which underlie the way each one of them will use the information.

### Conceptualisations for the measurement of biodiversity

#### Additive criteria

A first method consists in counting the number of the different species contained in each sample. It is the *cardinal criterion*, which, on the basis of the *richness* of the species, considers that sample 1 is more diversified (it includes 3 species against two in the second sample). This criterion plays a central role, because of the relationship which links the natural (space) with the number of various species; such a relationship, called the *Arrhenius relationship*, is used to assess the number of species in a given area, as an exhaustive count is impossible to carry out in practice, or to estimate the damage caused by the destruction of their habitats.<sup>1</sup>

<sup>1</sup> This diversity-space relationship is also in keeping with the alpha ( $\alpha$ ), beta ( $\beta$ ) and gamma ( $\gamma$ ) diversities suggested by Whittaker (1972) to comprehend biodiversity in its relationship with space.

The richness of species for a fixed area corresponds to the  $\alpha$  diversity. We may also wonder about the variation in space of the species composition of the habitats. One possibility is to calculate the replacement ratio of the species from one area to the other, that is to say the ratio (number of vanished species / total number of species in the area of departure); It is the  $\beta$  diversity which results from the specialisation of the habitats. So a greater diversity  $\beta$  means a greater richness in the habitats in the geographical area considered. Last, at a larger scale the  $\gamma$  diversity describes the richness in species of a bioclimatic region.

Pattanaik and Xu (2000) showed that the cardinal criterion is the only reflexive and transitive criterion that satisfies the following three axioms: A1) *indifference between singletons*, A2) *monotony towards the addition of a species to a singleton* and last, A3) *independency*.

According to axiom A1, the samples made up of a sole species (any one) are said to be equivalent from the viewpoint of biodiversity. For example, accepting that axiom means giving the same diversity index to a protozoon and a cheetah! The generalization of the cardinal criterion suggested by Klemish-Alhert (1993) helps overcome the problem by numerically weighting every species in order to reflect its importance to the decision-maker.

In accordance with the second axiom, biodiversity strictly increases if we add a species to a singleton. It is a weakened form of the principle of monotony in relation to inclusion, which means that biodiversity does not drop when we add species to a sample. Intuitive though this principle may appear, in the next section we discover reasons not to respect it.

Last, a ranking in accordance with the third axiom is not affected by the addition or the withdrawal of a common species. The contribution of a new species to diversity does not depend on the composition of the sample to which it is added (the contribution of a cheetah to global diversity would be identical, whether it was added to a sample of felines, insects, plants...) This property, clearly questionable, is violated by the indices based on the notion of genetic dissimilarity (or distance) that we shall see later.

#### The efficient number of species in an ecosystem

We can easily see that, with the additive criteria, all the species contribute to the biodiversity assessment in an equal way, whatever their proportion in the sample (with 10,000 cats more, sample 2 still counts only two different species). This property would not satisfy an ecologist who

is aware that in an ecosystem the functional role of a species varies in accordance with its *relative abundance*.

The relative abundance gives an indication of the viability of each species, which may vary according to species as their “efficacy” varies in the running of their ecosystems. For instance, “keystone” species are essential. According to their functional place in the ecosystem, we may consider a “threshold” measurement for each species, beyond which a deterioration of the health of the ecosystem is to be feared.

Sticking solely to the considerations above would lead to good health indicators in a whole set of species rather than to diversity indexes. The notion of *richness* should be added to the notion of *relative abundance*, to end up with the notion of an “efficient” number of species in an ecosystem. More precisely, indices must combine the notion of richness with the notion of *evenness*, which means that an ecosystem, the efficient species of which are well distributed, shows guarantees of viability. Formally, this “efficient” number depends on the number of species in the sample and on the vector of relative abundances. We have a family of indices - Berker-Parker index, Simpson index, Shannon-Wiener index - which are non decreasing functions of richness and evenness. If we write  $p_h$  as the relative abundance of the species  $h$  and  $\alpha$  as a positive parameter, we can give a general expression for that family:

$$D_E = \left[ \sum_h p_h^\alpha \right]^{1/1-\alpha}$$

the logarithm of which is called *generalized entropy* (for a synthesis, see Hill, 1973).

This family of measurements respects the axiom of indifference to the singletons but may violate the monotony axiom. Adding a new species to an evenly distributed sample could have two opposite effects, one of positive richness and one of negative evenness. In the example, the richness effect prevails for most of these family indicators: the first sample is considered as more diversified except for the Berger-Parker index, which declares them equivalent. This family may also violate the independence axiom because the weight of a species on one of these indices depends on its relative abundance which itself is a function of the whole set to which it is added.

A common limit of these indices is that they are absolutely insensitive to the larger or smaller dissimilarities which may exist between species. This objection points out that two species are all the more likely to provide redundant genetic information when they are close. Furthermore, with the same view to capturing the functional role of a species, the proximity notion is essential in specifying certain processes generating biodiversity, such as natural selection which results from interactions between genes and the environment.

### ***Taking into account the dissimilarities between species***

Three approaches attempt to give content to dissimilarity. The first one is based on the notion of distance and

assesses the diversity of a sample by means of a particular kind of cardinal aggregation of dissimilarities. The second one appears as an aggregation of ordinal dissimilarities built from a quaternary relationship between pairs of species, by ranking pairs of elements, taken four by four. Finally, the last approach relies on a vision of biodiversity as a value of fulfilled attributes.

### **The aggregation of cardinal dissimilarities**

Let us suppose that the cardinal measurements of dissimilarities between pairs of individuals are given; these could be for instance the genetic distances measured by an AND-ADN hybridization method. From such information, several indicators aggregate the cardinal dissimilarities.

The only of these indicators for which we have an axiomatic characterization is that of Weitzman (1992). Relying on a procedure of iterative calculation, its principle is, at every iteration, to build the set to be valued by addition of the species that will offer the highest measurement. By writing  $X$  as a set of species and

$$\delta(i, X) \equiv \min_{h \in X} d(i, h)$$

the dissimilarity between a species  $i$  and its nearest neighbour in the set  $X$ , the Weitzman procedure is given by:

$$D_W(X) \equiv \max_{i \in X} D_W(X - i) + \delta(i, X - i)$$

When the sample is considered as rich enough, this procedure is in a one-to-one relationship with three axioms: A4) *Monotony in relation to dissimilarity*, A5) *restrictive independence*, A6) *indifference to the link*.

Axiom A4 says that for a whole set of species  $i, i', i''$  and  $i'''$ , the subset  $\{i, i'''\}$  is at least as diversified as the subset  $\{i', i''\}$  if and only if the dissimilarity between  $i$  and  $i'''$  is at least as large as that between  $i'$  and  $i''$ .

The restrictive independence axiom says that the addition of species increasing the maximum proximity, in the same way, in the samples where they are inserted, does not affect the ranking of samples.

The exact terms of axiom 6 were not taken up here (we find it in Aulong *et alii*, 2005); their opaqueness and to a lesser extent that of the previous one calls into question the normative content of the Weitzman procedure.

There are two other observations of importance. First, that measurement can reverse the ranking of our two samples obtained with the cardinal criterion or with any generalized entropy criterion. If needs be, this reversal underlines the interest of good knowledge of the principles which characterize the various indices before using them to guide conservation choices.

So in practice, the functions of numerical distances which are considered as given are only known for a limited number of species. Beyond these particular situations, this

approach probably requires more biological information than we will ever possess.

### The aggregation of ordinal dissimilarities

Faced with this difficulty, Bervoets and Gravel (2004) suggested apprehending diversity as an aggregation of ordinal dissimilarities. We suppose as a given the ability to formulate wordings of the type “the dissimilarity between the *sardine* and *cat* species is greater than that between the *tortoise* and *butterfly* species”. The informational requirement is obviously smaller than that of the wording needed for the cardinal approach.

With only this ordinal information, the *maxi max* criterion, based on the relative dissimilarity of their two most dissimilar species, is the sole criterion which verifies the three following axioms: A7) *Weak monotony in relation to inclusion*, A8) *Ordinal monotony in relation to dissimilarity*, A9) *Robustness in relation to the addition of dominated sets*. The first two axioms are similar to the ordinal translations of axioms A2 and A4. The last axiom translates the principle that the domination of one sample by another is preserved if, to the dominated sample, we add a set of individuals, the diversity of which is lower than that of the dominating sample.

Let us imagine that the tortoise and the butterfly offer the greatest dissimilarity in the first sample and, additionally, let us suppose that this pair is less dissimilar than the sardine and cat in the second sample 2: sample 2 is then said to be more diversified according to the *maxi max* criterion. Let us observe that this prevalence would be preserved if sample 1 were enriched by dragonflies, ants, and so on, provided that the dissimilarities per pairs remain lower than that between the sardine and the cat. By ignoring the contribution to the diversity of a set of individuals which offer a lesser dissimilarity, the approach leads to a very debatable arbitration between samples.

Here we understand one of the interests of the cardinal approach, the informational requirement of which was indeed underlined but which, by aggregation of dissimilarities, helps avoid the systematic dictatorship of the most dissimilar pairs.<sup>2</sup>

### Biodiversity as a value of fulfilled attributes

The consequence of the sacrifice of the second sample would be the disappearance of the only species with the characteristic of being felines, and that of the first sample would be the loss of the only species which can fly and of the unique species representative of molluscs. So could the choice result from an explicit arbitration between these attributes? Clearly, an answer cannot come from a one-dimensional vision at the end of which biodiversity would only rely on genetic dissimilarities (cardinal or ordinal ones) between species.

Nehring and Puppe (2002) clearly offer a multi-dimensional vision. Their approach supposes that the decision-maker has pinpointed a set of attributes to which

he attaches importance.<sup>3</sup> For instance, as regards the species in sample 1 and 2, these attributes could be: ability to fly, being a vertebrate, a feline, etc...

Pinpointing attributes proceeds from the subjectivity of the decision-maker who must list the ones he values: we suppose that for the decision-maker the importance of each pertinent attribute of the sample is indicated by a numerical value. Nehring and Puppe suggest measuring the diversity of a sample by adding the values of the fulfilled attributes.

This theory may find an “ex post” rationality to each safeguard choice. Moreover, diversity will remain insensitive to the number of times when an attribute is fulfilled. As with the Weitzman criterion, the notion of relative abundance, which is central to the indices based on uniformity, will remain ignored.

### Conclusions

Even if we do not always have the axiomatic characterization of diversity indicators, some of their properties are known and a few regularities appear. Some of the criteria do not respect the axioms of monotony (in relation to the addition of species, to dissimilarities), but respect the principle of indifference to singletons, while others respect the principle of monotony in relation to inclusion and that of monotony in relation to dissimilarity, but neither the axiom of independence nor the principle of robustness to the addition of dominated sets.

These criteria are not all equivalent and may lead to divergent preservation policies. The first two families of indicators (additive and of entropy) are very widely used by the Life sciences, while the others are better known in the Human and Social Sciences (chiefly economics). Should we see a disciplinary explanation to the adhesion to a particular axiomatic? Some say that the Life sciences see diversity with a view to conservation. Their study purpose would lead them to promote the integrity and functionality of the ecosystems, properties which are closely linked to their composition, especially the abundance of species which conditions the probabilities of survival and the dynamics of populations. On the other hand, as a rule, for economists, the objective to be reached is the maximisation of social (human) well-being. From this viewpoint, diversity has a value for the variety of choices it offers. This explanation is not very convincing because ecologists and economists are both at the origin of the first measurements of aggregation of cardinal dissimilarities.

Several times, practical obstacles have been mentioned, most often regarding the acquisition and processing of the information necessary for the calculation of indicators (for the Weitzman procedure, with more than 30 species, the capacity of ordinary computers would be exceeded). In the face of this difficulty, Thaon d’Arnoldi *et alii* (1998) imagined a procedure which is approximate yet less demanding in calculations (around  $2^n$  to be compared with  $n!$  calculations of the Weitzman criterion). On a sample of 29 cattle breeds, their procedure required 20 minutes. More recently, some INRA researchers in the SAE2

<sup>2</sup> The prevalence of sample 2 in the cardinal approach only lasts if the genetic distance between the sardine and the cat is sufficiently bigger than the aggregation of the distances in sample 1.

<sup>3</sup> Their approach is inspired by Lancaster’s theory of multi-attribute utility (1966).

Department developed a technique allowing even quicker calculations to supply the exact value of the Weitzman indicator. For the sample of 29 cows, the calculation is

immediate. Trials on fictive samples have helped go up to 800 species after 48 hours of non-stop calculations.

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#### For further information

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