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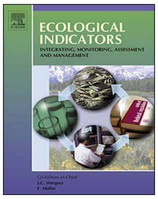

A functional approach to Hill's numbers for assessing changes in species variety of ecological communities over time

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ABSTRACT

Humans are dependent on a large number of species of animals, plants, fungi, and microbes that provide indispensable ecosystem functions and produce essential goods. Apart from the economic valuation of the direct and indirect benefits of biodiversity, people place existence values on biodiversity, i.e. they consider the existence of particular species, regardless of the services they provide. There is also a general recognition that species diversity indicates the status of the ecosystem or community, and thus the quality of the living environment; hence, both at academic and institutional level, there is a lively discussion about how to properly measure and monitor biodiversity. Although many candidates have been proposed, nowadays, no scientific consensus measure exists, and this is mainly due to three motivations: the large number of properties that an indicator of biodiversity should meet, the definition of biodiversity, and the specific interests of policymakers or stakeholders that indicators should satisfy. Because most existing indices neglect the multivariate nature of biodiversity, we address this drawback by proposing a functional approach to Hill's numbers for assessing changes in species variety of ecological communities over time. New functional tools are developed, both analytical and graphical: we present "the biodiversity surface", "the volume under the biodiversity surface", and some indicators which have been derived from them. This functional multivariate approach provides additional tools to the existing biodiversity monitoring techniques, and allows us to address biodiversity by considering both richness and evenness, and all of their possible shades. The goal of this research is to provide policymakers, stakeholders, and scholars with additional tools for improving the understanding of biodiversity dynamics within ecological communities.

1. Introduction

Humans are completely dependent on a large number of species of animals, plants, fungi, and microbes that provide indispensable ecosystem functions and produce our food, substances that are essential for health care, and materials for clothing, manufacturing, construction and other purposes. Apart from the economic valuation of these direct and indirect benefits of biodiversity, people place existence values on biodiversity, i.e. they consider the existence of particular species, regardless of the services they provide; hence, when a species disappears there is a general feeling of irreversible loss (EASAC, 2005). Therefore, biodiversity is globally recognised as one of the corner-stones of healthy ecosystems, and its conservation is increasingly becoming one of the most important aims of environmental management (Laurila-Pant et al., 2015; Worm et al., 2006; Kremen, 2005). Moreover, there is a general recognition that species diversity indicates the status of an ecosystem or community, and thus the quality of the living environment; hence, a high species diversity may contribute to the stability of the ecosystem (Diserud and Aagaard, 2002; Gaston and Spicer, 2004; Sankaran and McNaughton, 1999). Nevertheless, Ecologists also agree that humans are degrading the earth's ecosystems and leading biodiversity to extinction (Balmford and Bond, 2005; Cardinale, 2014; Ceballos et al., 2015). Indeed, we directly affect biodiversity through our actions, e.g. cutting trees, hunting, and fishing, and besides we indirectly influence living organisms, e.g. through our effects on global climate.

The importance of protecting biodiversity is receiving also growing political attention since the convention of biological diversity (UNEP, 2002), which is the first treaty in international law to stress the key role of biodiversity conservation. In 2002, parties to the Convention on Biological Diversity (CBD) decided to achieve by 2010 a significant decrease of the current rate of biodiversity loss. Afterwards, at the Conference of the Parties of the CBD in Nagoya (Japan), in 2010, the target was renewed for 2020 (UNEP, 2010). The EU adopted a similar target to halt the loss of biodiversity and restore habitats and natural

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systems by 2010 (European Community, 2001). To meet this target, the CBD has proposed the use of a set of indicators; however, the increasing interest of institutions on this topic has strongly stimulated the attention of Ecologists and Statisticians in developing new indices (e.g. Balmford and Bond, 2005; van Strien et al., 2009; Vačkář et al., 2012). Although several candidates have been proposed, nowadays, no scientific consensus measure exists (Royal Society, 2003), and this is mainly due to three motivations: the numerous properties that an indicator of biodiversity should meet, the definition of biodiversity, and the specific interests of people dealing with this information.

First, an acknowledged monitoring program should adopt statistically rigorous methods to evaluate changes in biodiversity over time (Lamb et al., 2009); moreover, to be effective, biodiversity indicators need to meet various scientific and practical requirements, some of which are not easy to fulfil (van Strien et al., 2009). For example, they must be quantitative, responsive to changes at policy relevant spatial and temporal scales, representative of biodiversity more generally, useable in models of future projections, linked to causes of trends, and practical in terms of data collection (van Strien et al., 2009; Scholes and Biggs, 2005; UNEP, 2002; Norm et al., 2012). Moreover, they should allow for comparison with a baseline situation and policy target, and satisfy numerous mathematical properties, e.g. monotonicity, proportionality, identity, base year invariance, oversensitivity to appearing and disappearing species, and spatial scale invariance (van Strien et al., 2012). In addition, they must be amenable to aggregation and disaggregation at ecosystem, national and international levels, broadly accepted and measurable with sufficient accuracy at affordable cost, and also simple and easy to understood. To meet all these requirements at the same time, in our opinion, is simply impossible for a single indicator. Due to the complexity of the concept of biodiversity, no single indicator can be devised. Hence, each aspect of biodiversity requires its own indicator, and, to have a complete picture of biodiversity, different indicators must be used together. Hence, the difficulties for reaching a consensus on the use of biodiversity indicators are manifold (Duelli and Obrist, 2003).

Second, the obstacles in finding a suitable measure of biodiversity are also due to its definition because, under the term "biodiversity", different concepts are enclosed together. The term "bio-diversity" has been used for decades for indicating the "*variety of living organisms in a delineated study area*" (Patil and Taillie, 1982; Pielou, 1975); however, the CBD (UNEP, 1992) defines biodiversity as "*the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems*". Hence, according to this statement, biological diversity describes the variety, quantity, and distribution of the components of life whether they are species, ecosystems or genes. In summary, biodiversity conveys the biological richness of planet Earth because it relies on the number of different types (variety), number or total biomass of any type (quantity), and extent and nature of geographic spread of different types (distribution) (EASAC, 2005). Scholars have highlighted various drawbacks in this definition; for example, genes often require specific technical equipment and expertise to be analysed because several variations of genes exist and can reasonably be studied. Moreover, at what arbitrary scale should we measure ecosystem biodiversity, and why? At landscape scale, locally, or microscopically? (Feest et al., 2010). Common practice is studying biodiversity at the species level but even the word variability is ambiguous; indeed, many concepts are questionable: Are all species equally important? Is species richness an acceptable indicator? If we are interested in the abundance of species, what weight should we give to the calculation of rare species? Furthermore, in the last few decades, the term "biodiversity" has gained a much wider meaning than before, and scholars agree that it has become a multi-dimensional concept. Besides the broad definition which has been given by the CBD, other scientists distinguished among "*compositional*", "*structural*" and "*functional*" biodiversity (Noss, 1990). Recently, also many other facets of the concept of biodiversity have been illustrated (e.g. see Duelli and Obrist, 2003). Even if considering only species diversity of an ecological community, scientists' interest does not only focus on "variety" but also on the total and mean of the abundances of living organisms. Hence, from a strictly statistical perspective, it seems quite difficult that a single index could synthesize every aspect. For example, monitoring biodiversity with the arithmetic or geometric mean of abundances could appear inappropriate because they do not contain any information on variability; however, also variations over time of the classical diversity indices (i.e. richness, Simpson's or Shannon's index) seem to be unsuitable for monitoring biodiversity because they are very few sensitive to changes in the total amount of living organisms in an ecological community (e.g. we could obtain a high value of these indices in case of low number of individuals but high number of different species and evenness).

Third, another major obstacle in finding a universal accepted measure of biodiversity is that indicators must supply significant and meaningful information to policymakers and stakeholders. In effect, who is involved in developing or using biodiversity indicators is inevitably influenced by its personal and/or professional goals, which depend on the motivation for dealing with biodiversity and determine the specific aspect of biodiversity to take into account (Duelli and Obrist, 2003). Policymakers need a broad indication of the level of overall biodiversity or evidence of how effective policy is a lever for taking measures; moreover, they demand information which are able to indicate cause-effect relationships and provide a reliable trigger for action (EASAC, 2005). Regarding a general stakeholder, e.g. in the agricultural context of industrialised countries, there are three most important motivations for him to enhance biodiversity, and each of these requires its own indicators: "*species conservation*" needs focusing on rare and endangered species, "*ecological resilience*" requires analyzing genetic or species diversity, "*biological control of potential pest organisms*" necessitates information on predatory and parasitoid arthropods (Duelli and Obrist, 2003).

For these reasons, the search for the "perfect" index has led to the development of a large number of diversity metrics which are available to monitor biodiversity; however, their responses to biodiversity changes are not necessarily coherent with each other (Santini et al., 2016), and different indicators may even do not correlate with each other or show a negative correlation (Duelli and Obrist, 2003). Therefore, according the above mentioned requirements, all metrics are questionable because no single index could synthesize a concept such as biodiversity, which is intrinsically multidimensional and multivariate (Chao et al., 2014; Hill, 1973). Hence, Ecologists should be aware that the choice of biodiversity indicators may strongly influence their interpretation of biodiversity variations, and thus it is crucial to understand which metrics respond to certain changes, are the most sensitive to change, and detect early signals of species decline (Santini et al., 2016).

In the field of Ecology, researchers distinguish between α-diversity, β-diversity, and γ-diversity: α-diversity refers to biodiversity within a particular sample (within-habitat biodiversity), β-diversity refers to biodiversity associated with changes in sample composition along an environmental gradient (between-habitat biodiversity), and γ-diversity refers to differences across samples when they are combined into a single (landscape biodiversity) (Whittaker, 1972; Magurran, 2004; Villéger and Brosse, 2012). Despite the notion of beta diversity may be exploited to monitor biodiversity over time, few studies have used it for this purpose; indeed, for decades, most ecological research has focused on trends of total abundance of species (Norm et al., 2012; Harrison et al., 2014), arithmetic and geometric means of abundance (Loh et al., 2005; Gregory et al., 2005), changes in proportions, and indices of α-diversity such as species richness, changes in Shannon–Wiener (Shannon, 1948) or Simpson indices (Simpson, 1949). However, in addition to these, a plethora of indices exists for summarizing either separately or in combination the key components of biodiversity: