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Error Cascades in the Biological Sciences: The Unwanted Consequences of Using Bad Taxonomy in Ecology

Why do ecologists seem to underestimate the consequences of using bad taxonomy? Is it because the consequences of doing so have not been yet scrutinized well enough? Is it because these consequences are irrelevant? In this paper I examine and discuss these questions, focusing on the fact that because ecological works provide baseline information for many other biological disciplines, they play a key role in spreading and magnifying the abundance of a variety of conceptual and methodological errors. Although overlooked and underestimated, this cascade-like process originates from trivial taxonomical problems that affect hypotheses and ideas, but it soon shifts into a profound practical problem affecting our knowledge about nature, as well as the ecosystem structure and functioning and the efficiency of human health care programs. In order to improve the intercommunication among disciplines, I propose a set of specific requirements that peer reviewed journals should request from all authors, and I also advocate for urgent institutional and financial support directed at reinvigorating the formation of scientific collections that integrate taxonomy and ecology.

INTRODUCTION

In the early 1900s, ecologists started splitting away from traditional descriptive biology and ecology by developing an increasingly experimental approach to nature. The gradual success of a manipulative experimental approach (1) gained popularity because descriptive observations and data correlation alone could not explain causal processes. As experimental ecology optimized searching for causation by offering a number of appropriate methods and perspectives, most ecologists rapidly devoted themselves to experimental research. Shortly thereafter, other descriptive disciplines, such as α-taxonomy, began to be progressively uncommon (2) to the point that even the word "descriptive" attached to any scientific discipline and/or work was considered to have pejorative implications (3). This unbalanced tendency strongly affected the structure of the international scientific community, generating *i)* a decline in the number of jobs in taxonomy over time (4, 5), *ii)* a decrease in the proportion of taxonomic papers appearing in journals with a high impact factor (6), and *iii)* an infrequent citation of these works in ecological studies (7–10). Although most ecologists are not able to classify all the different taxa involved in an average study (11), they seem to show no interest in other disciplines apart from ecology (2, 3). In addition, the overwhelming and long-lasting lack of resources devoted to taxonomy (12, 13) will likely decrease the impact that taxonomic studies have on other disciplines.

Within this context, there is a key question of major concern: how do ecologists get the correct scientific names of all the taxa they study? Figure 1 refers to a sample of 80 ecological papers published from 2005 to 2007 in top international peer-reviewed journals in ecological disciplines (*Ecology, Ecological Monographs, Journal of Ecology, Oikos, Oecologia, Frontiers in Ecology, Journal of Experimental Marine Biology and Ecology,* and *Marine Ecology Progress Series*). From each journal I only analyzed those papers (10 per journal) explicitly referring to community ecology studies that involved more than one species of any kind of organism from bacteria to vertebrates and flowered plants and specifically looked at the tools or procedures used to support/guarantee the correct taxonomic identification of the organisms involved in the study. For each paper I also checked for the participation of one or more taxonomists in the Methods and Acknowledgments sections or among the authors. I found that 62.5% of these modern studies are devoid of any supporting information justifying or guaranteeing the correct identification of the organisms studied or manipulated. In other words, the 62.5% of the analyzed papers did not mention or acknowledge the participation of taxonomists or the use of taxonomic literature or ecological literature or any other source of information from which the author might have found the scientific names of the organisms in the study. I also discovered that only 2.5% of the analyzed papers reported that specimen vouchers were deposited in a scientific institution, which terminates all prospects for conducting further taxonomic confirmations in the other 97.5%. Logically, the 2.5% reporting the deposit of vouchers came from those few works involving taxonomists. Figure 1 also shows that the participation of taxonomists in ecological research scored the same as the use of previous ecological papers and personal observations (made by ecologists). Moreover, the use of gray literature (including ecological theses and technical reports) is more common than the use of specialized taxonomic literature. The results shown in this figure agree in a complementary way with the relatively high number of misidentifications recently found in different taxa of marine ecosystems, among others (14). In addition, nearly half of all the papers surveyed report the experimental manipulation of several taxa involved in the study, suggesting that manipulative experiments are performed independently of the quality of taxonomic identifications. This analysis exposes the fact that scientific names are commonly transferred from one ecological work to another. However, usually only well-trained taxonomists are able to find and correct taxonomic errors. Consequently, taxonomic mistakes are likely to remain unnoticed in ecological works until a well-trained taxonomist amends it. Unfortunately, the impact generated by taxonomical mistakes usually transcends the limits of ecology and environmental management, while the opposite is less frequent. Medicine, biochemistry, paleontology, and geomorphology are some of the disciplines in which misidentifications could generate great loss of time, knowledge, money, and even human lives.

The term *bad taxonomy* is an expression that in Biology implies the identification, classification, and nomenclature of organisms without following the appropriate procedures and rules that specialist taxonomists define (15). These rules are specified in the different international codes of nomenclature and have the ultimate function of unifying the way we name organisms worldwide. Why do ecologists seem to underestimate

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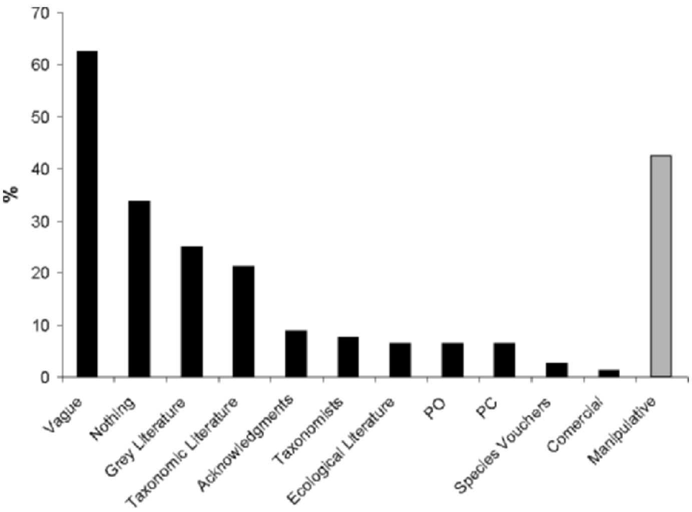

Figure 1. Percentages from a total of 80 selected ecological papers published between 2005 and 2007 in high-impact peer-reviewed ecological journals supporting their taxonomic identifications with the following: vaguely related ecological papers from which the authors may have obtained the scientific names they used (Vague); nothing at all (Nothing); thesis, technical reports, and field guides (Grey Literature); specialized taxonomic keys or papers (Taxonomic Literature); authors acknowledge the taxonomic assistance on one or more species (Acknowledgments); the participation of taxonomists is explicitly reported (Taxonomists); previous ecological papers mentioning the scientific names used (Ecological Literature); personal observations (PO) and communications (PC); standard supplied by a commercial laboratory (Commercial). Manipulative refers to the proportion of these papers reporting experimental manipulation of one or more taxa, and Species Vouchers refers to the papers reporting the deposit of specimen vouchers in scientific institutions.

the consequences of using bad taxonomy? Is it because the consequences of doing so have not been yet scrutinized well enough? Is it because these consequences are irrelevant? By discussing specific examples in this paper, I evaluate the hypothesis that different failures in the communication among biological sciences evolve into a cascade of errors with negative consequences for the development of scientific knowledge, as well as for biodiversity and human welfare. In order to improve the intercommunication among disciplines, I propose a set of specific requirements that peer reviewed journals should request from all authors, and I also advocate for urgent institutional and financial support directed at reinvigorating the formation of scientific collections that integrate taxonomy and ecology. Although many cases of taxonomic misidentification are favored, deliberately generated, and/or masked by scientists and nonscientists without ethic or moral bounds, I do not address this topic here.

THE HIERARCHY OF ERRORS AND ITS EFFECT ON NATURE

The objectives of the biological sciences are essentially related to the identification of patterns and processes in nature in a variety of temporal and spatial scales, with the ultimate intention of manipulating natural resources in a beneficial/optimal way. Different biological disciplines share and assimilate their results in a way that establishes a quite vertical structure among them, in which, under normal conditions, management studies are based on the results of ecological works (2, 16, 17). In a similar vein, manipulative ecological studies are supported by mensurative ecological studies, which are in turn supported by descriptive biological studies and taxonomic studies. In essence, environmental management would not be possible without ecological studies, and ecology would not be possible without taxonomy (the opposite direction in this interdisciplinary relationship is possible but not pertinent here), and this structure is what seems to make biological sciences robust (18). However, as I will explain, this same structure is what often facilitates the propagation of errors among disciplines. This is because a single incorrect taxonomic identification has a great potential to be assimilated into many different biological and ecological studies and then in several environmental management studies and programs, multiplying its impact synergistically. Such an error cascade is likely to have a variety of negative consequences.

Errors in taxonomic studies are commonly fixed before they are transmitted to other disciplines. For example, the classification of the Argentinean snails of the genus *Littoridina* (Hydrobiidae) had been reviewed and their nomenclature changed to *Heleobia* (19, 20). Parodi (21) determined grass plants from Patagonian to be the native sterile hybrid *Spartina towsendii,* when in fact they were *S. anglica* plants, as Nicora (22) corrected 6 decades later (23). When errors in taxonomic studies are not detected, they may be assimilated in descriptive biological/ecological studies without causing major consequences. For example, Scott et al. (24) conducted a survey to increase the knowledge of foraminifers in North and South America. In this survey, the authors based the description of the vegetation associated with the foraminifera on an incorrect taxonomic identification of what they called *S. patens* instead of *S. densiflora,* a species with a similar phenotype (25). I noticed this overlooked mistake while surveying the same site while working on a *S. densiflora* review (26). However, this misidentification did not affect the quality of the authors' conclusion that "foraminifera do respond to latitudinal gradients in both hemispheres of the Americas" (24). The succulent halophyte *Sarcocornia perennis* (Mill.) A.J. Scott was experimentally manipulated in salt marshes of the Mar Chiquita coastal lagoon (Argentina) under the name of *Salicornia ambigua* to test if plant cover facilitates the colonization and survival of invertebrates in the high-marsh level by buffering major critical harsh environmental conditions, such as temperature and humidity (27). Although this nomenclatural problem was detected later, the error did not affect nature at all and did not affect the conclusions of Bortolus et al. Examples like this, in which an organism is not identified correctly with negligible consequences, are relatively common in the scientific literature (26, 28). In these cases, an *erratum* is usually enough to amend the problem.

A different situation would be if errors in taxonomic studies remain undetected by ecologists and a misidentified species gets involved in manipulative experiments, resulting in the alteration of natural patterns of distribution of species assemblages. Given that the number and size of the experimental plots used in most field works are relatively small (due to logistic and economical constrains), the ecological consequences of this kind of error are usually not very important. However, in some ecological scenarios, the detection of this kind of error may cause a population believed to be homogeneous and monospecific to be recognized as a complex assemblage with unexpected origin and spatial distributional patterns. For instance, the mussels *Mytilus galloprovincialis*, *M. trossulus,* and *M. edulis* have been often referred to by scientists as one single species because they make up a complex of morphologically similar species (29). This confusion caused the decline of the native *M. trossulus* in the US to be masked by the introduction of one of its sibling species until molecular studies confirmed it recently (29). The different members of this species complex commonly appear in the rocky shores of many regions worldwide (29), where they currently are or may be involved in experimental ecology works. Although morphologically identical, these species have different ecological and behavioral characteristics, including competitive abilities, resistance to parasite infections, attachment strategies, and mortality rates (29). Therefore, an error in the identification of the manipulated species may seriously compromise the interpretations of the experimental results and also have negative consequences on the communities in which the experiments are to be deployed by affecting the relative abundance and geographical distribution of native and nonnative organisms. This situation originates with an error in taxonomy that evolved into an error in manipulative ecology.

The worst kind of error originates when an error in taxonomy becomes an error in manipulative ecology and is incorporated in a large-scale experimental study or in an environmental managing program. An error in environmental management is easy to detect *a posteriori* because of the visual impact that it usually causes, but it is difficult to amend because it compromises the integrity of ecological and physical aspects of the environment. A clear example of this error comes from the West Coast of the US (25). During the late 1970s, a team of geneticists, managers, architects, politicians, biologists, and landscapers got involved in the transplant of propagules of the cordgrass *Spartina foliosa* from Humboldt Bay to Creekside Park in San Francisco, California, as part of a restoration project involving the only *Spartina* species native to the West Coast. Using an esthetic criterion, they selected gray clumped mats of *S. densiflora,* believing they were a good-looking growth form of the native *S. foliosa*, and they did not question the species identification (after all, it was the only *Spartina* species described for the region by then). In fact, biologists had mentioned that the plants "on Humboldt Bay looked different from the San Francisco native, but no significant attempt was made to further identify it" (which would have amended the error) "until after it had been introduced into Creekside Park" (30). It was not before a number of phenological and ecological differences became highly evident between the transplants and local specimens that botanists realized they were probably working with a different species than presently thought. About 30 years later, the transplanted specimens were correctly recognized as *S. densiflora* (31). By then, the repeated transplant of this species seamed to have triggered a latent invasive ability in *S. densiflora*, which after decades of apparent inactivity expanded its original distributional range, massively displacing native organisms and changing the entire physiognomy of regional landscapes along the West Coast (32). At this stage (after the error in environmental management was originated), eradicating *S. densiflora* from the US may be possible but uncertain and expensive. Although the boundary between errors in taxonomy and the other errors may seem unclear, it must be noted that an errors in taxonomy imply a theoretical problem, whereas errors in manipulative ecology and errors in environmental management are practical problems. Therefore, whereas the former (errors in taxonomy) affect our knowledge of nature, the latter (errors in manipulative ecology, errors in environmental management) directly affect nature.

EFFECTS OF THE ERROR CASCADE ON OUR KNOWLEDGE OF NATURE

The following discussion presents examples of how the quality of a taxonomic study may affect the way we interpret nature while reconstructing paleoenvironmental conditions, evaluating the integrity of a given ecosystem, or describing ecological patterns and processes. The classification of paleospecimens is particularly susceptible to taxonomic confusion, given that the number of morphological characteristics usually available is limited and that molecular procedures are not always possible. For example, an analysis of the taxonomy of Triassic and Early Jurassic cytheracean Ostracoda revealed that the validity of many genera is questionable (33). Given that these organisms are used in palaeoenvironmental interpretations of many of the Triassic deposits, their misidentification is likely to have led to failures in the formulation of retrospective predictions in paleobiological disciplines. A similar case is found in malacology. Fossil shells of the South American hydrobiid snails *Heleobia australis* and *H. parchappii* are also used as paleobiological and palaeoenvironmental indicators to reconstruct the evolutionary geomorphology of Holocene coastal environments of Argentina. The differences shown in the fossil concentrations of both species seem to be related to the energy conditions of the environments in which they lived (34). Although *H. australis* inhabits brackish environments, *H. parchapii* is restricted to freshwater environments (35). However, living *H. australis* frequently coexists with living *H. conexa,* a third species extremely hard to differentiate from the other two. The shell morphology of these three species is variable, and the occurrence of convergent forms is common (35). Nevertheless, although specific discrimination is possible from the observation of its penian morphology (36), this character is not preserved in the fossil record (35), which originated a number of misidentifications of fossil records. The living populations of these three species commonly overlap in distribution along gradients of salinity. However, whereas *H. australis* is restricted to estuarine zones, *H. conexa* is more abundant in shallower brackish-water areas, suggesting that the presence of each one of these species may be related to different environmental conditions (34, 35). Consequently, the quality of the taxonomic determination will determine if the resulting paleoenvironmental reconstruction is right or wrong (37).

The misinterpretation of environmental conditions caused by taxonomic errors occurs more often than we think. Many misinterpretations of the bioindicators of environmental pollution are currently originated in taxonomic failures involving sibling species. Knowlton (38) argued that sibling species are common in marine environments and failure to recognize them affects our evolutionary and ecological understanding of marine communities and the environmental factors affecting them. For example, three species of the coral *Montastraea annularis,* which have different growth rates and oxygen isotopic ratios, have been commonly measured (indistinctly) as indicators of environmental degradation and global climate variation, ignoring the fact that they have different metabolisms (39, 40). Consequently, the presumed environmental signal is confounded when the sibling species are not recognized and their biology is not well understood (39, 40).

Populations of organisms with different genotypes but similar phenotypes may alter the ability of ecologists and environmental managers to recognize changes in different patterns and processes occurring in local landscapes. For example, the introduction and invasion of a non-native genotype of the common reed *Phragmites australis* in North America showed how cryptic a population can be to the scientist's eyes and the real relevance of recognizing it appropriately (41). Even though *P. australis* is cosmopolitan, molecular studies had recently reported a population with an exotic genotype that seems to be much more aggressive than the natives (41). Because native *Phragmites* populations commonly grew in coastal marshes with little or no morphological differences with the introduced one, the establishment of the latter was not noticed until now. The populations with this non-native genotype have dramatically increased their distribution and abundance over the past 150 years, and currently they are more common than the native haplotypes across North America. This example definitely shows how much organisms may differ in their biology, ecology, and evolution, even though they are considered to belong to the same species and/or look extremely similar. It also shows the real need for constant reliable taxonomic checking of the different taxa we work with through updated methods and perspectives. Ecologists usually have the feeling that taxonomic assistance may not be needed when working in areas that have been studied for decades (or centuries) by many other ecologists. In fact, this may be a major reason ecological papers are cited in support of the taxonomic identification in ecological articles (Fig. 1). However, it is clear that just because many other ecologists have been working in the exact same place we are now does not guarantee that the existing species assemblages are currently the same or prevent cryptic non-native species (e.g., *Spartina densiflora* in California) or genotypes (e.g., *Phragmites* in North America) from being introduced and unnoticed.

SOME SOCIOECONOMIC CONSEQUENCES OF THE ERROR CASCADE

Although the loss of native biodiversity by favoring the unnoticed introduction of invasive and noninvasive species is one of the most conspicuous consequences of the error cascade, the consequences can be much more diverse and have direct socioeconomic effects. For example, *Anopheles*' classification commonly relied on intuitive taxonomic interpretations of a limited number of morphological similarities (42). However, considering that about 20% of the *Anopheles*' species reviewed by Harbarch (42) were sibling species, "intuition" does not seem better than a pair of dice. In the Binh Thuan Province in Vietnam, what was thought to be an unusual morphotype of the mosquito *Anopheles minimus* (a known malaria vector) was shown to be *An. varuna* s.l. (a nonmalaria vector), and most specimens identified as the former species in the field proved to be the latter (43). Thus, for a long time a nonvector organism was incorrectly targeted as a malaria vector, while the primary target for vector control in the region was in fact *An. dirus* (43). This case shows that simple mistakes in identification may have a deep impact in biological, ecological, and sociological topics. These mistakes cause not only the waste of large amounts of money but also of the precious time of ill people waiting for a cure.

The efficiency of environmental management and conservation regulations commonly depends on the reliability of the taxonomic information available (14). The under- or overestimation of species richness in a given environment not only will present an unreal picture of its biodiversity, community structure, and landscape conformation but also will hamper the making of efficient policies and regulations directed to better protect natural resources and ecosystem services (44). A reliable taxonomy is among the major factors guaranteeing the accurate identification of biodiversity hot spots and wilderness areas on Earth (45). This issue becomes dramatic when it is negatively combined with the intensive and extensive exploitation of natural resources (44). How can we control or even measure the impact of fisheries, hunting, or land reclamation on biodiversity when the biodiversity itself is unreliably described? How can we even delimitate potential natural reservations or national parks? In sum, how can we protect our natural resources from being overexploited and/or destroyed? Or do ecological impact studies supply reliable/accurate conclusions when referring to biodiversity? All these genuine concerns arise from analyzing the error cascade problem.

REMARKS AND PERSPECTIVES

This paper is a reinforced call for researchers, journal editors, and reviewers to incorporate and advocate the idea of disciplinary interaction not as a utopia (46) but as an essential scientific tool that should be implemented with special emphasis in the fields that I discuss here. The spreading and magnification of errors have a variety of optional pathways, but all of them reveal the same practical importance of underestimating the use of bad taxonomy in biological, ecological, and environmental management projects. Special attention may be paid on those works not using scientific names but using values of specific richness indexes, biodiversity indexes, and all other indexes based on taxonomic identifications. This is because the species richness and biodiversity indexes may be unexpectedly under- or overestimated due to previous taxonomic misidentifications. Even more attention should be paid to those studies using parataxonomic methods because the kind of errors they may originate are not predictable (47). In my opinion, ecologists may have to assume a central role in this problem, for we constitute a key step in the error cascade process by assimilating, producing, magnifying, and distributing errors.

A main causal factor in the error cascade is that even though we recognize taxonomy as an important part of biology as a whole, during the last decades taxonomists have lost consideration from the rest of the scientists (6, 48). Even after screaming for help to the rest of the scientific community (49, 50), they received a *requiem* (6) instead of more attention. It is not well understood why good taxonomists and their work seem to have been so segregated (3, 51). However, they now have to play the emergent role of assisting other disciplines, not only in solving their nomenclature problems but also in improving their taxonomic skills (4), and helping them to mature and evolve. If ecologists disregard or underestimate the work of taxonomists, then they must show reliability and excellence in their taxonomic identifications, and this is not what presently seems to be occurring (Fig. 1). Like with any other aspect detailed in the Materials and Methods section of all scientific papers, ecological papers should state explicitly how authors performed a reliable taxonomic identification. It is clear that citing previous vaguely related ecological works is not enough to guarantee this, and it is also clear that ecologists are not affectionate to taxonomic literature probably because it usually requires hard specific training to be fully understood. Therefore, the ideal situation is that in which specialist taxonomists are directly involved or consulted about the different taxa in ecological studies. In this case, the participation of well-trained taxonomists must be explicitly acknowledged for all and every contribution, allowing any reader to check the reliability of every scientific name separately, if necessary. If this is not possible, then authors must specify which methods and/or materials were used (e.g., keys, species lists, catalogs, specimen vouchers, theses, technical reports, web pages), along with statements supporting their choice. If the applied methods did not involve taxonomists at all, then specimen vouchers of all species in the study (especially the species being manipulated, measured, compared, or integrating the core of the work) should be deposited in a scientific institution so that accurate taxonomic checking is possible. Ecological journals and related journals should have these minimum requirements for all authors submitting manuscripts. Such requirements will invigorate not only the appreciation for taxonomists but also the quality of ecological works. It also will encourage the establishment of new scientific collections worldwide, indirectly favoring the recruitment of taxonomists specialized in local taxa. The creation of local scientific collections is likely to alleviate the increasing tension in this scenario by providing ecologists with a place to enter specimens from the populations involved in their studies for further appropriate taxonomic checking. The creation of this kind of ecological scientific collections is in an experimental phase at the Centro Nacional Patagónico (Chubut, Argentina). There, the first ecological herbarium (Herbario Ecológico de Costas, HECO) is being organized as a part of an integrative project directed to understanding the ecological patterns and processes shaping the remote coastal environments of Patagonia in Argentina. The HECO's collections are formed by specimens coming from the different sites at which the ecological studies are being conducted. In addition to the objectives common to all herbaria, HECO also contains specimens collected inside the plots of field experimental trials in order to *i)* preserve the changes in plant structure derived from a given experimentation and *ii)* allow as much taxonomic checking of the manipulated organisms as needed by appropriate specialists and through updated techniques and perspectives over time.

There are many factual connections among environmental policy, ethics, biology, and social sciences, and for better or for worse, these connections are more than mere rational inquiries. Because each discipline has its own language, rules of analysis, and standards of validation, the passing of argumentations from one to another commonly results in confusion. The kind of scenario in which this confusion takes place will determine the kind of impact it will have (on ideas or on nature). If we accept the error cascade as something normal and inevitable, then we are violating the axial foundation of science by accepting the systematic formulation of argumentations based on wrong assumptions.

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