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Opinion

Is the demise of plant taxonomy in sight? Maybe yes, maybe no…

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> *Taxonomy – the scientific discipline that explores, discovers, interprets, represents, names, and organizes organic beings – is an integral component of biogeography, evolutionary biology, ecology, conservation and other biodiversity studies* (Ebach et al. 2011: 550).

The wide and significant spectrum of taxonomy in our society is clearly stated in the above quote by Ebach et al. (2011). As taxonomists who have embraced the amalgamation of traditional and modern research techniques, we have witnessed dramatic changes and the gradual disappearance of one of the oldest disciplines in biological science, that is, taxonomy and the associated application of nomenclature. In this note we address some of the causes and effects behind reductionism and the ensuing curricular changes affecting research, education and training in taxonomy in major academic institutions.

Over the last few years scientific specialization has had an unprecedent impact in society enabling biological research progress primarily due to the implementation of technological innovation, raising employment and economic development. As a result, the resolutions in scientific and educational institutions have been adjusted accordingly. The field of botany, in particular, has undergone significant changes. Botany has been influenced by shifts in the approach to the scientific method, to the extent that this traditional field of studies has been increasingly replaced in universities and research institutes by broader meaning labels, such as of "Plant Biology" and "Integrative Biology." In fact, several claims regarding the vanishing of taxonomic research have been made, from the lack of funding (Ebach and Holdrege 2005; Guerra García et al. 2008), training of new personnel (Drew 2011; Britz et al. 2020), denying recognition (Dar et al. 2012; Wheeler 2014), and reductionism (Crisci 2008; Crisci et al. 2020).

According to Dar et al. (2012), taxonomic impediment in education is based in part on the deficiency in institutional and financial support, lack of appreciation, job opportunities, turn-around in research output, and relative lower impact factor for taxonomic journals, among other causes. Furthermore, in an era of genomics and applied science, the taxonomist has become an endangered species (Ali et al. 2014). All these adverse factors are overwhelming and difficult to overcome by the community of taxonomists, to the extent that potential new positions emerging from retirement of senior taxonomists are being modified in scope or lost from the academic program.

Among the previous indicators, reductionism has impacted taxonomy in programs and institutions throughout the world. The changes are evident in numerous major universities that used to have old traditional and prestigious botany and zoology departments and graduate programs with strong taxonomic training but are now integrated into more widely contemporary named departments and units dominated by non-organismal professionals (Woodland 2007). These changes have enabled modern approaches intersecting evolutionary biology and technological applications putting aside a curriculum embracing aspects of classical taxonomy. The increasing practice of reductionism with concomitant decrease of organismal biology is directed to applied sciences and more profitable programs that have driven the way for the neglect of taxonomy (Dar et al. 2012).

In a recent provocative and somewhat alarmist commentary entitled the "*End of Botany*," Crisci et al. (2020, but see also Crisci 2006, 2008), reflected on the modern meaning of botany in light of the influence of methodological reductionism. It is clear, even to the most distracted researcher, that over the last three decades or so there has been an erosion in the conceptual perception of botany as a typical multidimensional discipline. This decline is associated to the use of new, more inclusive techniques that often disconnect our understanding and objectivity from the surrounding natural world. Within this context, plant taxonomy and nomenclature, two core components in the botanical and zoological sciences, have been directly and adversely affected by reductionism, an ongoing issue for most teachers responsible for the training in plant taxonomy (Crisci et al. 2019, 2020). The limited training has produced numerous plant biologists lacking basic training, hence unable to morphologically recognize some of the most common plant species, i.e., the loss of the operational and predictive value of botany. This problem has also been addressed in a paper discussing the "*One-dimensional Systematist*," (Crisci 2006), a topic worthwhile exploring in conjunction with the aspects addressed below, which may be needed to understand this discussion.

THE EFFECT OF REDUCTIONISM ON PLANT TAXONOMY

Reductionism encompasses a set of ontology-based, epistemic, and methodological opinions about the relations between different scientific domains (Brigandt and Love 2019). In science, reductionism leads to marketable inventions that may have detrimental effect on the outcomes of quality and planning in order to attain a fabricated metric evaluation dictated by corporations and personal needs (Muller 2018). For instance, Crisci et al. (2020: 1173) stated: "*…molecular biology cannot dispense with the reference systems of biology as a whole provided by Botany, among other disciplines..., it is impossible to complete a biological project at any level of hierarchy in nature without any scientific names associated with the observations or experimentations.*" Thus, because of their multidimensional approach, the research core components of botany and plant taxonomy cannot be reduced to a few modules of investigation (Crisci 2006; Crisci et al. 2020). Reductionism alone cannot express the complexity of nature. Taxonomy, as opposed to reductionism, is based on critical and practical analyses with several layers and contextual factors leading to specific outcomes (Mingers 2014, reviewed in Fox and Alptekin 2018).

CLASSIFICATION AND IDENTIFICATION AS MULTIDIMENSIONAL METHODOLOGICAL PROCESSES

In the broad sense, classification and identification are intimately connected and are cognitive and basic aspects of botany. Their dissemination synthesis is reflected in a correct and stable procedure of scientific names according to the nomenclatural rules established by the International Code of Nomenclature (Turland et al. 2018). Because of classification and identification are complex processes based on a multidimensional knowledge, they cannot be the result of a single method focused solely on one source of information. For instance, identification cannot be based only on DNA barcodes (Hebert et al. 2002), a method that is not easy to access or that cannot replace morphology (Will and Rubinoff 2004; Will et al. 2005) and presents either promises or serious pitfalls (cf. Moritz and Cicero 2004).

On the other hand, it is likely that a good number of sequencing DNA accessions with misidentified (or lacking vouchers) has been deposited in DNA sequencing data repositories. Therefore, the reconstruction of a phylogenetic hypothesis based only on molecular information extracted from a GeneBank source without supporting reliable herbarium vouchers and accurate morphological identification of the species investigated (taxonomic sampling), is not admissible. In addition, issues of hybridization and lineage sorting are not easily resolved in a single-gene phylogeny and multiple datasets from different genomic regions are desirable to generate a more accurate phylogenetic scheme. According to Rouhan and Gaudeul (2021) molecular taxonomy is at disadvantage because of the potential lack of genetic divergence in sister-species sharing recent origins, i.e., they will share alleles due to recent ancestry. Thus, the amalgamation of different datasets, e.g., morphology and molecular, is desirable to more accurately infer evolutionary process (Hillis 1987; Humphries 1988; Patterson et al. 1993; Pennington 1996; Scotland et al. 2003; Martynov 2012; Zanini et al. 2018). In addition, the conflict emerging from combining the data sets should be considered in the outcomes (Bremer 1996; Petersen and Seberg 1998; Wiens 2004).

NAMING TAXA AND THE TYPIFICATION PROTOCOL AT A TURNING POINT

In addition to the excessive reductionism exemplified by the exclusion of formal classification and identification practices based on morphology, another aspect that seriously threatens botany is the superficial approach to botanical nomenclature including the limited knowledge and application of the rules included in the International Code of Nomenclature (Turland et al. 2018). Typification is the merging point between two basic components of botany: taxonomy and nomenclature (Witteveen 2014; Rao 2017; Thompson et al. 2018). Typification is, in fact, a very delicate and often complex process at the base of which lies the stability of scientific names, their application not only in taxonomy, but also in the evaluation of biological diversity and numerous conservation efforts (Thompson et al. 2018; O'Connell et al. 2020).

Type specimens and their names are often formalized automatically. A major responsibility in terms of issues of synonymy and faulty described species falls on journals that easily accept papers with taxonomic mistakes due to superficial and somewhat poorly researched nomenclatural decisions. Behind this issue often lies the lack of a strict peer review evaluation of original voucher materials supporting the typification and nomenclatural content. Nowadays, new species descriptions rely on digital images available on the Internet. Digitalization and natural history virtual collections are certainly important in research and classroom (Cota-Sánchez 2020a), but publishers and authors should be aware about published online digital images with unverified data and/or erroneous information that can be misleading and unrelated to the biological entity in discussion.

Naming of species, as epistemological process, is a basic step in any scientific discipline (Valdecasas et al. 2014; Holstein and Luebert 2017). In biology, and botany in particular, seven characteristics can be associated to formal scientific names including: individuation, hypothesis of relationship, retrieval information, explanatory power, testable predictions, conceptual power, and language (Valdecasas et al. 2014). All these attributes support the stability of each scientific name through the correct process of typification that permits to reproduce and scientifically verify the application of each name.

The process of naming plant species includes uniform and internationally acceptable principles (Haider 2018), but it is often considered a superfluous exercise and a sort of aristocratic waste of time because it can be a tedious and prolonged process (Riedel et al. 2013). Linking a name to an organism (a plant for example), is not a specious exercise but implies an epistemological process that makes any name verifiable anytime allowing to standardize the assessment of biodiversity. Taxonomic plant checklists, floras and monographs are produced with verified names and associated vouchers supporting species' identity by experts in the field (Grace et al. 2021). In other words, taxonomy (and nomenclature) are key components of biology (Costello 2020) and species are the currency of biodiversity (Sigwart et al. 2018), which and in conjunction with monographs disseminate scientific information to accelerate research (Grace et al. 2021).

It is often the case that in numerous university courses when students are asked what the "name" or the components of a scientific name in a plant or animal means, an extensive unawareness about taxonomy and nomenclature is revealed. We believe that students in natural sciences cannot leave university after graduation without mastering the basic principles of scientific names and communication as universal language on which the natural order of the biological knowledge is founded. Furthermore, an integration between descriptive general morphology, ecological and molecular data in the diagnostic and analytical description of a new taxon must be embraced, appreciated and improved (Tautz et al. 2003; Hassemer et al. 2020; Hütter et al. 2020). Training in taxonomy and nomenclature should encompass a holistic equilibrium between morphology and molecular data and other information available (Dunn 2003).

NATURAL COLLECTIONS AND THEIR DESTINY

The decline and reduction of botany is not only due to the extreme effect of scientific reductionism. For years, herbaria, including natural history museums with their vast richness of historical artifacts and natural biological collections, which constitute the foundation of the knowledge of biological diversity, have been gradually losing institutional and governmental support for funding, infrastructure, and professional and technical personnel. In fact, many institutions remain active thanks to various forms of volunteering and citizen science programs. In many cases, these facilities are in a serious danger of permanent shutdown. Problems due to the lack of funding including basic house-keeping budget, potential employment of new taxonomists, and bureaucracy in the processing of collecting permits are well discussed by Britz et al. (2020), whereas planning, usage, datamining and organization future specimen collections is found in Krell and Wheeler (2014).

It is unfortunate that in a world in which the loss of biodiversity has increased to alarming levels with limited mitigation proactive efforts, the value of biological collections has also been underestimated and their scientific meaning for understanding biodiversity undermined (Meineke et al. 2018). However, several endeavors have been focused on the management, use and exploitation of the vast data stored in biological collections (Baldini and Guglielmone 2012; Rønsted et al. 2020), including preserved specimens in herbaria and living material in botanical gardens, with ensuing digitalization and big data captured in online cyber portals and databases available on the Internet (Heberling and Isaac 2017; Soltis 2017; James et al. 2018; Alba et al. 2020; Miralles et al. 2020; Paton et al. 2020).

CAN JOURNAL METRICS BE USED TO EVALUATE PLANT TAXONOMY?

The journal metric evaluation, based on the number of bibliographic citations of a research article by a journal or a researcher, influences the quality and often the originality and value of a scientific production, including botany (cf. Alberts 2013; Crisci 2006; Muller 2018; Crisci and Katinas 2020). Nowadays all aspects that establish the scientific production are often related to economic profit, in which social and human interactions are pure marketing relationships. Thus, we question is whether this metric assessment is a trustworthy parameter to assess the value of botany-related publications. Furthermore, the rigid metrics and impact factor method to taxonomic research are inapplicable as stated by Krell (2000: 507) "… *is impossible to classify taxonomic or ecology journals as more or less important. They can only be classified as of high or low quality, which does not affect the number of citations.*"

Taxonomy, as one of the oldest biological disciplines, cannot be evaluated as other subjects, such as molecular genetics, bacteriology, virology, neuroscience or cancer research. The fact that these other fields have more practical applications in technology explains how impact factors adversely affect taxonomic research with a decrease in funding opportunities, number of taxonomists and limited appreciation (Ebach et al. 2011; Britz et al. 2020).

As indicated, Crisci et al. (2020), affirm that in recent times the term "botany" has been increasingly replaced with "plant sciences," as if it had a derailing connotation. The authors add that this practice should be avoided, stating that "*Part of this image problem is based on misconceptions of how some botanical subdisciplines work*" (Crisci et al. 2020: 1174). The view that plant taxonomy and nomenclature are purely formal aspects of plant knowledge based solely on description and its nominal understanding, is an evident misunderstanding and adverse notion of these foundational scientific concepts. We agree with Crisci et al. (2020: 1174) that plant taxonomy must be considered a scientific discipline that requires "*theoretical, empirical and epistemological rigor, a hypothesis-driven approach, and field and lab expertise.*" As such, emphasis must be made to reinstate this discipline in major biological academic programs throughout the world, especially in tropical countries where the largest spots with plant animal diversity remain.

A DECLINE OF INTEREST AND SUPPORT IN TAXONOMY OR SOMETHING ELSE?

In this regard, it is important to reflect how we, as botanists, place ourselves with respect to the study of plants. While we admit and welcome the impressive impact of new research technologies for human development, we advocate that plant taxonomy should be maintained at the center of the imminent destiny of the biosphere. With an evolving economy and strong trend towards applied science, the debate is still open and challenging (Wheeler and Meier 2000; Schuh 2003; Will et al. 2005; Garnet and Christidis 2017; Funk et al. 2017), but most importantly, it is worth considering that botany deserves the right of citizenship as a multidisciplinary science rather than a downgraded subject as part of reductionism.

It is also essential to recognize that botany, in particular plant taxonomy, has an integral role as discipline in the understanding of reality. The excessive reductionism prevailing in contemporary educational systems may disregard and ultimately eliminate its cognitive centrality needed to understand nature. A good starting point towards the resurgence of organismal taxonomy is found in a recent stimulating and promising paper by Wheeler (2020). However, as stated by Tancoigne and Dubois (2013), it is not a matter of declining but of inertia that affects taxonomy. We argue that the existing crisis of "*inertia*" in taxonomy requires rapid action by the community of taxonomists around the world. As pointed out in Wheeler (2014) and Bebber et al. (2014), a sensitive aspect can be also traced in the relationship between the increase quantity of new species described and number of authors involved in the designation. This practice seems to reflect changes in the scientific practice rather than taxonomic expertise, quality and capacity in plant taxonomy. Increased number of authors in the species description of a new species doesn't necessary mean more taxonomic training and equal understanding of typification, taxonomic and nomenclatural rules among investigators.

A last, but not of lesser importance, in addition to reductionism, an issue for deliberation regarding the future of taxonomy is how the COVID-19 pandemic has been affecting the teaching and training of the future generations of plant taxonomists (Cota-Sánchez 2020a) and the world's botanical community (Baldini 2020; Cota-Sánchez 2020b). Current academic programs for instruction in plant systematics and training in taxonomy and nomenclature around the world involve remote teaching models in conjunction with numerous digital botanical archives and supporting digital and social media platform for plant identification. Nonetheless, current experiences by the authors of this commentary indicate while training in taxonomy may be successful, the effectiveness of the delivery and grasping and accurate use of terminology is hampered by the lack of direct face-to-face contact and live specimens for demonstration and training.

As a result of the challenges imposed by remote teaching, which was new for many, several organizations have made significant contributions to online instruction during the COVID-19 crisis. Worth mentioning is the dedication of the Education Committee of the Botanical Society of America (BSA). This organization has been offering remote peer support sessions for teaching, a great forum to share teaching ideas and resources and to discuss techniques that work well and those not working for the instructor and students. The BSA also has a fabulous resource section (https://cms.botany.org/home/resources/online_resources.html) with links to diverse and interesting creative teaching exercises that can be adapted for online undergraduate courses in biological sciences, including botany (BSA, 2021). We feel that all these resources, and many others available in the public domain, will be very handy for students and instructors to become more confident in the remote teaching world. Therefore, it should not be difficult for botany instructors to find creative and innovative ways to approach teaching and training in plant taxonomy and keep this basic discipline alive rather than extinguishing.

In summary, we should be mindful that in the light of climate change and unparalleled anthropogenic changes, the current biodiversity crisis needs urgent attention to classify, name, and identify the remaining biological diversity in order to cover with intellectual competence knowledge gaps, especially in plant taxonomy (Aedo et al. 2017). It is only with coordinated efforts among plant and animal taxonomists, academic institutions, industries and governments that this traditional but essential scientific field will reemerge as an ultimate resource, including the rediscovery of the value of botanical monographies (Grace et al. 2021), to catalogue those unknown species waiting to be described in the lingering pristine terrestrial and marine ecosystems of the Earth.

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