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COMMUNICATION

A joint call for actions to advance taxonomy in China

Chaodong Zhu[1, 38 *], Arong Luo[1], Ming Bai[1, 38], Michael C. Orr[1], Zhonge Hou[1], Siqin Ge[1, 38], Jun Chen[1], Yibo Hu[2], Xuming Zhou[2], Gexia Qiao[1, 38 *], Hongzhi Kong[3], Limin Lu[3], Xiaohua Jin[3], Lei Cai[4], Xinli Wei[4], Ruilin Zhao[4, 38], Wei Miao[5], Qingfeng Wang[6], Zhongli Sha[7], Qiang Lin[8], Meng Qu[8], Jianping Jiang[9, 38], Jiatang Li[9, 38], Jing Che[10], Xuelong Jiang[10], Xiaoyong Chen[10], Lianming Gao[11, 38], Zongxin Ren[11, 38], Chunlei Xiang[11], Shixiao Luo[12], Donghui Wu[13], Dong Liu[13, 37], Yanqiong Peng[14], Tao Su[14, 38], Chenyang Cai[15], Tianqi Zhu[16], Wanzhi Cai[17], Xingyue Liu[17], Hu Li[17], Huaijun Xue[18], Zhen Ye[18], Xuexin Chen[19], Pu Tang[19], Shujun Wei[20], Hong Pang[21], Qiang Xie[22], Feng Zhang[23], Feng Zhang[24], Xianjin Peng[25], Aibing Zhang[26], Taiping Gao[26], Changfa Zhou[27], Chen Shao[28], Libin Ma[28], Zhaoming Wei[28], Yunxia Luan[29], Ziwei Yin[30], Wu Dai[31], Cong Wei[31], Xiaolei Huang[32], Jingxian Liu[33], Xiangsheng Chen[34], Tianci Yi[34], Zhisheng Zhang[35], Zhulidezi Aishan[36], Qin Li[36], Hongying Hu[36]

[1]*CAS Key Laboratory of Zoological Systematics and Evolution, Institute of Zoology, Chinese Academy of Sciences, Beijing 100101, China*
[2]*CAS Key Laboratory of Animal Ecology and Conservation Biology, Institute of Zoology, Chinese Academy of Sciences, Beijing 100101, China*
[3]*State Key Laboratory of Systematic and Evolutionary Botany, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China*
[4]*State Key Laboratory of Mycology (SKLM), Institute of Microbiology, Chinese Academy of Sciences, Beijing 100101, China*
[5]*CAS Key Laboratory of Aquatic Biodiversity and Conservation, Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan 430072, China*
[6]*Wuhan Botanical Garden, Chinese Academy of Sciences, Wuhan 430074, China*
[7]*Department of Marine Organism Taxonomy & Phylogeny, Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China*
[8]*CAS Key Laboratory of Tropical Marine Bio-resources and Ecology, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China*
[9]*CAS Key Laboratory of Mountain Ecological Restoration and Bioresource Utilization & Ecological Restoration and Biodiversity Conservation Key Laboratory of Sichuan Province, Chengdu Institute of Biology, Chinese Academy of Sciences, Chengdu 610041, China*
[10]*State Key Laboratory of Genetic Resources and Evolution & Yunnan Key Laboratory of Biodiversity and Ecological Security of Gaoligong Mountain, Kunming Institute of Zoology, Chinese Academy of Sciences, Kunming 650221, China*
[11]*CAS Key Laboratory for Plant Diversity and Biogeography of East Asia, Kunming Institute of Botany, Chinese Academy of Sciences, Kunming 650201, China*
[12]*CAS Key Laboratory of Plant Resource Conservation and Sustainable Utilization, South China Botanical Garden, Chinese Academy of Sciences, Guangzhou 510650, China*
[13]*CAS Key Laboratory of Wetland Ecology and Environment, Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun 130102, China*
[14]*CAS Key Laboratory of Tropical Forest Ecology, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Menglun, Mengla, Yunnan 666303, China*
[15]*State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Palaeontology, and Center for Excellence in Life and Paleoenvironment, Chinese Academy of Sciences, Nanjing 210008, China*
[16]*National Center for Mathematics and Interdisciplinary Sciences, Key Laboratory of Random Complex Structures and Data Science, Academy of Mathematics and Systems Science，Chinese Academy of Sciences, Beijing 100190, China*
[17]*Department of Entomology, College of Plant Protection, China Agricultural University, Beijing 100193, China*
[18]*Institute of Entomology, College of Life Sciences, Nankai University, Tianjin 300071, China*
[19]*Institute of Insect Sciences, College of Agriculture and Biotechnology, Zhejiang University, Hangzhou 310058, China*
[20]*Institute of Plant Protection, Beijing Academy of Agriculture and Forestry Sciences, Beijing 100097, China*
[21]*School of Ecology, Sun Yat-sen University, Shenzhen 518000, China*
[22]*School of Life Sciences, Sun Yat-sen University, Guangzhou 510275, China*
[23]*College of Plant Protection, Nanjing Agricultural University, Nanjing 210095, China*

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[24]*The Key Laboratory of Zoological Systematics and Application, College of Life Sciences, Hebei University, Baoding 071002, China*
[25]*College of Life Sciences, Hunan Normal University, Changsha 410081, China*
[26]*College of Life Sciences, Capital Normal University, Beijing 100048, China*
[27]*School of Life Sciences, Nanjing Normal University, Nanjing 210046, China*
[28]*Department of Zoology, College of Life Sciences, Shaanxi Normal University, Xi'an 710119, China*
[29]*Institute of Insect Science and Technology, School of Life Sciences, South China Normal University, Guangzhou 510631, China*
[30]*College of Life Sciences, Shanghai Normal University, Shanghai 200234, China*
[31]*Key Laboratory of Plant Protection Resources and Pest Management, Ministry of Education, College of Plant Protection, Northwest A&F University, Yangling 712100, China*
[32]*State Key Laboratory of Ecological Pest Control for Fujian and Taiwan Crops, College of Plant Protection, Fujian Agriculture and Forestry University, Fuzhou 350002, China*
[33]*Department of Entomology, College of Plant Protection, South China Agricultural University, Guangzhou 510642, China*
[34]*Institute of Entomology, Guizhou University, Guiyang 550025, China*
[35]*School of Life Sciences, Southwest University, Chongqing 400715, China*
[36]*College of Life Science and Technology, Xinjiang University, Urumqi 830017, China*
[37]*College of Advanced Agricultural Sciences, University of Chinese Academy of Sciences, Beijing 100049, China*
[38]*College of Life Sciences, University of Chinese Academy of Sciences, Beijing 100049, China*
[*]*Corresponding authors, E-mails: zhucd@ioz.ac.cn; qiaogx@ioz.ac.cn*

Abstract Taxonomy plays an important role in understanding the origin, evolution, and ecological functionality of biodiversity. There are large number of unknown species yet to be described by taxonomists, which together with their ecosystem services cannot be effectively protected prior to description. Despite this, taxonomy has been increasingly underrated insufficient funds and permanent positions to retain young talents. Further, the impact factor-driven evaluation systems in China exacerbate this downward trend, so alternative evaluation metrics are urgently necessary. When the current generation of outstanding taxonomists retires, there will be too few remaining taxonomists left to train the next generation. In light of these challenges, all co-authors worked together on this paper to analyze the current situation of taxonomy and put out a joint call for immediate actions to advance taxonomy in China.

Key words Endangered taxonomists, morphology-based taxonomy, integrative taxonomy, capacity building, systematics.

1 Introduction

May 22 is the International Day of Biodiversity (IDB). China's commitment to biodiversity is ever increasing, demonstrated by the first phase of the 15th meeting of the Parties to the United Nations Convention on Biological Diversity (COP15) held in Kunming, China in October, 2021. The theme of COP15 is "Ecological Civilization: Building a Community of Life on Earth". The importance of biodiversity and ecological security issues cannot be overemphasized (Díaz *et al.*, 2006). This is acknowledged in the concept of ecological civilization, a central tenet of Chinese society recently enshrined within the constitution, covering "co-ordinating the relationship between man and nature" as well as "green transformation to promote global sustainable People's well-being, social fairness and justice".

Biodiversity conservation is a national key policy focus in China, in which taxonomy plays an important role. Simply put, if we cannot identify species then we cannot know how they are impacted by management practices, ultimately impeding our ability to effectively protect or control them. Recently, Deyuan Hong, Wenying Zhuang, and Min Zhu, academicians of the Chinese Academy of Sciences, addressed the significance and importance of taxonomy in video speeches. These esteemed researchers and several leading taxonomists, along with a number of experts in the field, jointly called for a better understanding of the value of taxonomy and to pay due attention and lend support to this basic discipline.

With the development of human production, life science and technology, taxonomy itself has advanced with the times. Today, with the rapid development of life science theories and technologies, it has gradually become a modern discipline in the form of integrative taxonomy (Dayrat, 2005; Will *et al.*, 2005; Padial *et al.*, 2010; Schlick-Steiner *et al.*, 2010, 2014). With this integrative approach, morphology-based species can be re-tested by other lines of evidences and then become better supported (Luo & Zhu, 2022).

As taxonomists, we are grateful to our predecessors for their kind care and support, not to mention their training and knowledge. Based on what we have learned, and the present circumstances in the Chinese academic community and abroad, we put forward several ways in which we can advance taxonomy and ensure its persistence as a vital, basic scientific discipline well into the future. Comments or suggestions are welcome to refine and promote what we present here.

2 Taxonomy at the frontiers of basic science

It's one of the fundamental scientific questions to know how many life forms there are on this planet (May, 1992, 2010). Taxonomic discovery, description, naming, and identification of species are how taxonomists have delimited the central units of biological research, species, for hundreds of years. Taxonomy establishes a fundamental framework for human beings to identify and understand all kinds of organisms (Wilson, 2004). Moro *et al.* (2011) statistically analyzed current valid species (Bisby *et al.*, 2010; WoRMS, 2022) via the higher taxa approach. Their results suggest that the large number of unknown species remain to be described by taxonomists, including 86% of species on Earth and 91% of them in the oceans. In China, there are around 250,000 species catalogued, with an average increase of 6,500 species per year over the last 20 years (Liu *et al.*, 2022).

First, the biodiversity of the earth is an important basis for human survival and development (Díaz *et al.*, 2006). A comprehensive knowledge of the biodiversity status and evolutionary dynamics in the modern and, beyond this, the entire evolutionary history of the earth, requires effective and accurate identification of biological species. Taxonomy is the cornerstone of conservation (Li & Quan, 2017). However, the synergistic documentation, storage and extraction of nomenclatural and biodiversity information remain major challenges (Orr *et al.*, 2020a, 2021). At present, there is still a large gap in our understanding of global species diversity and its drivers. Adding to this challenge, many species have yet to be discovered and named (Costello *et al.*, 2013; Stork, 2018). The classification systems for many groups need improvement and revision in light of phylogenetic relationships, and this task can only be achieved through in-depth taxonomic studies (Borkent, 2020) alongside carefully recording the status of described species and what we know about them (Garnett *et al.*, 2020; Orr *et al.*, 2021).

Second, taxonomy is a central pillar of systematics, key to understanding the origin and evolution of life as well as building the tree of life (Agnarsson & Kuntner, 2007; Hinchliff *et al.*, 2015). By investigating the evolutionary patterns and causes of various behaviors or the distribution of species, we can answer the basic scientific questions: "where do biological species, including humans, come from and where do they go?" This helps us build our knowledge and understanding of adaptability at all levels.

Third, taxonomy is integral to the sustainable development of biological industries (such as agriculture, forestry, *etc*.), biosecurity, and other areas important for human beings. The inability to identify and recognize organisms will not only negatively influence human understanding of biodiversity, but will even mislead human development. Taxonomy is essential for biodiversity conservation and sustainable resource utilization globally (Scott *et al.*, 2018). Efficient monitoring and the accurate identification of both native and new invasive species, if effectively implemented, will help to eliminate significant biological hazards in agriculture and forestry (Smith *et al.*, 2008). Native pests and invasive species need specific integrated control measures according to the habits and behaviors of different groups. In the context of global climate change and increased human movement, with many goods shipped worldwide, it is not possible to accurately predict the distribution and dynamics of species without expert taxonomic support (Hellmann *et al.*, 2008). In an era of dauntingly serious biodiversity loss and increasingly prominent biosecurity issues (Cardinale *et al.*, 2012), taxonomy has important applications in not only accurately assessing dynamic changes of biological patterns and proposing targeted scientific protection plans, but also quickly identifying harmful organisms and invasive species (Smith *et al.*, 2008). Moreover, on the basis of taxonomic research, the in-depth determination and utilization of biological functional traits, and the integration and intersection with other disciplines, have important prospects for bionic applications in fields like biophysics, not to mention the vast field of chemical and geological prospecting. From this perspective, taxonomy not only increases our understanding of nature, but also provides new problem-solving ideas for improving the quality of human well-being.

Fourth, taxonomy is the basis for understanding of biodiversity and ecological functionality. Global issues arising from human activities, including global climate change and biodiversity loss, are often intertwined. For example, in the context of global climate change, the spread of pests is accelerating, and the patterns of pest outbreaks are becoming increasingly complex (Manika & Howard, 2010). Just as worrying, the diversity of functional biological groups such as pollinators has declined (Dicks *et al.*, 2021), which may lead to cascading impacts on ecosystems. This could create an unprecedented crisis for humans, impacting many aspects of our daily lives, yet we have little idea of which species are lost (Kim & Byrne, 2006; Pereira *et al.*, 2012; Costello, 2015). At the same time, we have little idea of what species we have protected, other than the flagship or star species, which cannot always effectively act as protective umbrellas for other species (Carlisle *et al.*, 2018; Henry *et al.*, 2019). We cannot be fooled by overreaching global studies that claim undue knowledge of biodiversity (Wyborn *et al.*, 2021), as countless species are virtually unknown in all aspects. Hundreds of thousands of invertebrates, and even some vertebrates, are threatened or could go extinct before they are formally described. Although some have been discovered, or are noted as distinct in museum collections, many more species remain entirely unknown. The ecosystem services that these organisms can provide, including decomposition, carbon sequestration, pollination, pest control, medicinal or other product services (Cardoso *et al.*, 2011; Díaz *et al.*, 2018), are all vital and should not be underestimated. If we cannot identify the species involved in these services and discern their contributions, it will be difficult for us to develop science-based effective conservation responses (Mace, 2004).

Therefore, taxonomy is the basis for our understanding of nature and its harmonious coexistence. Its importance is self-evident.

3 The current state of taxonomy in China

China is one of the countries with most biodiversity in the world, but taxonomists here face many challenges. The taxonomy in China did not begin until the late 19th century, with prior work done in limited capacities largely by researchers from other countries (Donovan, 1798a, b). China is not only rich in species, but also houses many rare, endangered and endemic species, which are of great significance to the conservation of germplasm resources and evolutionary uniqueness (Gu, 1998; Long *et al.*, 2003), which can make their detection more difficult. A large number of new species are still being discovered every year, and sorting and classification of the discovered species are progressing (Costello *et al.*, 2013; Stork, 2018; Wang *et al.*, 2021). These underlying data are the cornerstone of biodiversity research in this country and many others. Therefore, the taxonomy in China still has a large space for development in various aspects.

Taxonomy is considered as one of the macrobiology, and the current trend is to focus on the micro than the macro aspects. Therefore, taxonomy is also underestimated. At the same time, the main problems in China is that the obvious lack of supports for taxonomist, which were not only reflected in improper programs, funding, research laboratory *etc*., but also on the biased evaluation system. Taxonomists are working with high workload and long research time. As a result, it is not easy to produce significant products at the same time. That is why more and more young scholars abandon taxonomy and move to other research fields.

Challenges and dilemmas are not only faced by Chinese taxonomists, but also the entire global taxonomic community, largely following the 1980s. Taxonomy is increasingly underrated, with insufficient funds and too few long-term positions to attract and retain outstanding young talent (Schrock, 1989; Wheeler, 1995, 2004, 2008, 2014; Bebber *et al.*, 2014; Britz *et al.*, 2020; Orr *et al.*, 2020a). Although some report that the rate of species description is not dropping, it is difficult to investigate how often these individuals keep describing new species rather than focusing on phylogenomics or other fields to achieve their career goals. Since then, both professional and amateur taxonomists around the world have made recommendations to cope with the long decline of researchers in this discipline (Wheeler, 1995; Costello *et al.*, 2013; Orr *et al.*, 2020a; Engel *et al.*, 2021). The impact factor-driven evaluation systems in China and other countries have further exacerbated this downward trend (Krell, 2002). It is estimated that more than 80% of the graduate students majoring in taxonomy are unable to continue engaging in their research, resulting in a continual loss of such talents.

A group of leading taxonomy experts including Deyuan Hong, Wenying Zhuang, and Min Zhu, academicians of the Chinese Academy of Sciences, appealed: "Taxonomists themselves have become endangered species. Saving taxonomy is urgent." In order to bend the curve of biodiversity loss, China needs to show courage in establishing a new type of evaluation system and take the lead in proposing an action plan to reverse the declining trend of "endangered" taxonomists. Such a system must place more emphasis on not just species descriptions but also data generation, as without sufficient and accurate data, biodiversity declines cannot be reverted due to immense biases in existing data sources (Hughes *et al.*, 2021).

The development of taxonomy in China obviously began later than that in Europe, the United States, and other western countries. In the early days, a large number of Chinese species have been discovered and named by foreign scholars, and therefore many type specimens of named specimens are scattered abroad in different natural history museums, herbaria, or private collections, often on the other side of the world. This remoteness creates multiple degrees of obstacles for Chinese researchers attempting to work on taxonomy. They may need a large financial budget to access multiple type specimens that a researcher has deposited in different countries or regions, including expensive areas such as London, Washington D.C., and New York City (Orr *et al.*, 2020a). Each specimen kept in herbarium/museum documents species information about specific time, natural habit, and locality. It is critical to know these specimens, which have been collected, identified and grouped by taxonomists. Although some of these institutions have recently taken more efforts in digitizing and sharing their specimens, a direct examination remains necessary for many groups, especially those with micromorphology as diagnostic characteristics.

After more than 90 years of accumulation, modern taxonomic studies in China have developed to a great degree, incorporating many types of evidence in integrative contexts (Fang *et al.*, 2018; Yang *et al.*, 2022). However, in recent years, the development of taxonomy in this country has increasingly been constrained by the current one-size-fits-all evaluation system and limited attention from policy makers as well as some researchers from other disciplines. This has resulted in the inability of taxonomists to obtain fair views on their academic contributions, despite fundamental taxonomic knowledge and data, especially locality or trait data, being considerably applied in other fields. Many young taxonomists have been forced to abandon their expertise and change their research direction early in their careers, resulting in a monumental loss of young taxonomy talents. Training taxonomic talents to a professional level takes a much longer time than many other disciplines because of group-specific knowledge, lacking online training materials, and the number of museums one must visit and the number of specimens that must be examined to reach an accurate identification. When the current generation of outstanding taxonomists retires, there may be too few remaining taxonomists with truly sustainable positions left to train the next generation to become professional taxonomists. How can taxonomists, who are in an endangered situation, sit on the cold bench peacefully, while maintaining their rich productivity? This challenge deserves our attention and vigilance.

While facing challenges, young taxonomists also have opportunities:

First, after more than 90 years of disciplinary development, China has established an international-level taxonomic framework and capability. The new century promises many more advances.

Second, species diversity in China is still unclear although it is known to be high, which provides many opportunities for research. Many groups lack taxonomic studies, especially hyper-diverse groups like insects, fungi, and bacteria (Hawksworth *et al.*, 2018; Stork, 2018).

Third, prevention and control of wild infectious diseases and invasive organisms puts forward great demands for the classification of wild organisms, because spillover risk is highly dependent on taxa and traits (Olival *et al.*, 2017). The increasing demands for sustainable development in agriculture, forestry, livestock, and food also raise new requirements for the identification of new functional organisms, such as functional artificial microbiota from plant rhizosphere or animal guts. Experts in various industries also expect taxonomists to provide more useful information such as ecological information, DNA sequences, and species and environment interactions, as well as accurate species identification and professional descriptions of new species.

Fourth, the government should increase the investment on biodiversity conservation in line with the Kunming Declaration and other recent efforts, as well as increase the number and size of nature reserves, especially national parks. But fundamental questions, such as “what to protect?” and “where to protect?” certainly require the basic species and distributional information provided by the taxonomists, making their knowledge critical to support scientific assessments, planning, and decision-making.

Fifth, continuous application of big data, deep learning and artificial intelligence to all aspects of the life sciences will surely promote the development of taxonomy, and should be central to future innovations.

Sixth, taxonomic knowledge are still in very early stages in many developing countries. Chinese taxonomists can start to work together with young scholars in neighboring countries and Belt and Road areas, to build capacity for biodiversity assessment and conservation, to build a community with a shared future for sustainable development (Aung *et al.*, 2020).

4 Prospective areas for improvement

Only by having a fundamental understanding of the composition of regional species and their population structure, and studying them in their complex ecosystems, can we answer frontier scientific questions about biodiversity science and support national needs for resource security, biosecurity, and ecological security. An unclear background on species composition cannot support a correct response to increasingly sudden and complex situations involving pest outbreaks, for instance (Rosen, 1986, Huber *et al.*, 2021). Consequently, long-term, standardized monitoring of the diversity of different taxa should be strengthened and supported (Schmeller *et al.*, 2017). The essence of the stability of ecosystem function is the relationship between species, so it is natural that taxonomy should play an increasing role in ecology, via host associations and other data generated. It is necessary to expand and stabilize a group of specialized talents in the classification of biological systems, and to develop integrative taxonomy based on multi-technical means, multi-data types, to more capably build best practices for integrative taxonomy (Schlick-Steiner *et al.*, 2010).

First of all, taxonomic researchers should strengthen their understanding of the development of the discipline and improve their research ideas and levels in an all-around way (Agnarsson & Kuntner, 2007; Orr *et al.*, 2021). With the development of science and technology, many new methods have emerged, and their interdisciplinary integration is increasingly prevalent. Although taxonomists have long tried to introduce new ideas and new technologies, at present most of them are still working in the traditional way for 260 years to show their progresses. Therefore, taxonomy is regarded as an outdated discipline by some experimental biologists (Godfray, 2002). Unfortunately, to address this, some others have sought to cut corners and streamline taxonomic work in a minimalist fashion (Sharkey *et al.*, 2021), which is clearly improper on multiple fronts as it limits diagnosability and often relies on proprietary methods (Meier *et al.*, 2022). While learning these new methods, taxonomists should also pay attention to appropriate screening and integration to determine which ones could be more suitable for their own research. For example, DNA barcoding and paleontological fossil data cannot be used alone. They need to be combined with the morphological classification or as an auxiliary verification method. We need to expand the meaning of taxonomy on the basis of traditional taxonomic research rather than insist on replacing it with something inferior and of limited usefulness, and this can be done through new frameworks such as the Large-Scale Integrative Taxonomy (LIT) approach (Hartop *et al.*, 2022). Taxonomists should further apply ecology, genomics, paleontology, information science, machine learning and artificial intelligence and other theories and methods, on the basis of multi-technical means and multi-data types, and strive to forge ahead and become integrative taxonomic researchers (Orr *et al.*, 2020a).

Second, taxonomic researchers should actively participate in administrative planning work, strive to change the evaluation system, and reduce the dominant role of solely high-impact journals in the evaluation system. We must develop a novel evaluation system to encourage categorical types of assessments for specific fields, including taxonomy, based on positional responsibilities and expectations. Through capacity building and the screening of candidates good at their specific fields, we will select and retain a Chinese taxonomy team that has reached the world-class research level and provide stable support to them. Taxonomists need to think carefully about "what they want to do", "what they can do", "what they should do", and balance their disciplinary interests and national demands at different stages of their career development, while being able to keep sight of their important duties in describing new species. Taxonomist should also assist decision makers in formulating stable support policies and programs to promote the sound development of taxonomy, and actively participate in major national projects such as national basic resource surveys, biodiversity assessments, and biography compilation and research, so as to maximize the unique value of taxonomic research.

Third, taxonomists should strengthen exchanges and cooperation with researchers in other disciplines, and promote the exchange of research advances, and the synergistic collision of research ideas. New ideas should be discussed and refined through academic conferences, training courses and other forms, so as to realize the interdisciplinary development of basic research on taxonomy (Orr *et al.*, 2020b). Thereby, we can naturally also improve integrative taxonomic methods. The development of taxonomy cannot be achieved by one person or two, but requires the joint efforts and struggles of many taxonomy scholars (Deng *et al.*, 2019). It is an inevitable trend after the discipline developed to a certain level, that new technologies and methods for taxonomy would be developed, which can in turn better inform us of what a species truly is (the species concept) (Kong, 2016; Liu, 2016). High-level results can take the development of taxonomy to the next level. At the same time, it is important to set up training programs and project plans to encourage young taxonomy talents, and strengthen the education of the next generation of taxonomic scholars (Orr *et al.*, 2020b).

Fourth, taxonomists should establish new ideas bolstering and building upon integrative taxonomy, speed up classification collaboration, and improve online products efficiently through high-resolution imaging technology, virtual taxonomy laboratories (VTL), and other measures. Beginning with the digitization and online accessibility of type specimens, we must build capacity to enable taxonomists to collaborate on a global scale to the greatest extent possible (Smith & Figueiredo, 2009). Also, it is also especially important to promote the connectivity among taxonomists between China and surrounding countries, as they share many species, through mutually beneficial partnerships involving training and specimen exchange, with special focus on joint capacity building as seen in initiatives elsewhere (Klopper *et al.*, 2002). In this way, China can become a leading core country in such a cooperative system, playing an important role in feature identification, taxa description, data archiving, and manuscript writing (Orr *et al.*, 2020b).

Fifth, taxonomic research teams that have studied certain groups in depth should be given continuous support to achieve the frontier of their disciplines, striving to be world-class. Meanwhile, taxonomists should also, in consideration of the national biodiversity conservation strategy, identify important taxa and regions that are in urgent need of taxonomic research, to take a leading role in the nation’s nature conservation (Dubois, 2003). At the same time, suiting needs from other disciplines, such as agriculture, forestry and grassland, ecology, conservation biology, *etc.*, taxonomists should actively seek collaborative opportunities and provide solutions extending from classification to evaluation. At the same time, scholars should follow certain principles to communicate with each other in terms of specimens and data sharing, in response to national demands and discipline development. A good example of this is the effort to build a complete list of species in China. On May 22 of this year, Chinese Academy of Sciences released the 2022 edition of the Catalogue of Biological Species in China online (The Biodiversity Committee of Chinese Academy of Sciences, 2022). The list of biological species answers the question "what is the diversity of species in China", demonstrating the huge value of taxonomic collaborations. Still, many species remain to be discovered (Costello *et al.*, 2013; Costello, 2015; Stork, 2018), and future updates to this initiative will be necessary.

Sixth, taxonomists should stay true to their taxonomic backgrounds and tell the story of biodiversity well. Taxonomists have been dedicated to field work, exploring unknown mysteries in nature, with many possessing unusual and interesting life experiences. The discovery of each new species is a manifestation of their scientific insight into the long-term history of adaptation and evolution. While describing these beautiful creatures within the framework of taxonomy, we can share the discovery process, scientific insights, and subtleties with the public in a readily understandable way, to garner appreciation for this research. By exploring species' life history in interesting and interdisciplinary ways, we can get more attention and recognition for taxonomic work.

Seventh, taxonomists should stick to the classic journals of their discipline and continuously improve the influence of these journals. We must develop better alternative metrics to judge these journals, either as complementary or as an alternative to the current scheme that heavily relies on high impact factor. The vast majority of species descriptions are not published in high-impact journals and may be overlooked under current assessments, considered inferior to many high-impact "flash in the pan" studies in other disciplines that are forgotten within a couple years. For example, in terms of animal taxonomy, one can consider *Zoological Systematics*, *Zootaxa*, and *ZooKeys* as the main target journals to publish their basic works including taxonomic revisions. At the same time, we should also encourage the younger generation to strengthen their academic discussions, collaborations, and exchanges via new concepts, new theories, new methods, and new data, so as to truly form a new taxonomic paradigm.

5 A brighter future for taxonomy

The development of integrative taxonomy, or the use of new, interdisciplinary evidence to identify and understand species, is at the heart of the taxonomic revolution (Padial *et al.*, 2010; Schlick-Steiner *et al.*, 2010; Orr *et al.*, 2021). Among various facets, the use of artificial intelligence image recognition technology and modern machine learning can identify and optimize the automatic classification of hyper-diverse taxa such as insects (Ärje *et al.*, 2020; Williams *et al.*, 2020; Spiesman *et al.*, 2021), and these methods can be further integrated with DNA species delimitation (Yang *et al.*, 2022). In this way, the development of new, technology-driven integrative taxonomic frameworks can be encouraged to ensure that future approaches maintain the best practices and rigorous underpinning offered by traditional taxonomy. Only by leading the ever-changing trend of cutting-edge research can the new generation of taxonomists make innovative discoveries that lead the development of the discipline.

Taxonomy scholars have the responsibility and obligation to improve the popularization of taxonomic knowledge and improve the understanding and appreciation of taxonomy among scientific research managers and young students. Taxonomy is, to a certain extent, close to the category of philosophy, and is a subject that actively changes how we see the world. The practitioners of taxonomy should be proud, both in this country and throughout the world.

The academic community should encourage the exploration of new directions, new paradigms, and new taxonomic models, and allow for failures. It is hoped that in the future, the very meaning of the term taxonomy can be reshaped, in line with the national demands, so that taxonomic practitioners can obtain the same development space and opportunities as in other disciplines. To achieve this, the academic community should provide more support to domestic taxonomic journals, and publish more excellent papers in their respective disciplines, thus forming a virtuous circle of positive feedback. Similarly, academic units at all levels should encourage more peer review in respective disciplines, to further strengthen these journals and better recognize various academic responsibilities and other contributions beyond just publications.

We hope that taxonomy in China can run parallel along the frontier of disciplines and national needs, and lead the development of international taxonomy. Through the establishment of a world-class platform, we will attract and educate a new generation of outstanding young taxonomy talents, and make breakthroughs and innovations in both theories and methods. If properly supported, taxonomists will make continuous and substantial contributions in supporting the China

Program of Biodiversity Conservation, otherwise the ongoing biodiversity crisis may claim many species before they are even discovered.

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