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Mapping the biosphere: exploring species to understand the origin, organization and sustainability of biodiversity

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Perspective

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*The vision, ideas, observations and recommendations presented in this report are summarized from discussions by the participants during the 'Sustain What?' workshop held in New York in November 2010. The atmosphere was an example of creative collaboration at its best and the intellectual property herein belongs to the participants as a whole. Agreement with everything in the report by any single author should not be assumed as there was lively debate and disagreements over details. That said, most major points including, importantly, the feasibility of a 50-year species inventory were agreed to by all. The participants willingly set aside minor divergences of opinion in the interest of community-building and the creation of a powerful general vision for what can be.

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The time is ripe for a comprehensive mission to explore and document Earth's species. This calls for a campaign to educate and inspire the next generation of professional and citizen species explorers, investments in cyber-infrastructure and collections to meet the unique needs of the producers and consumers of taxonomic information, and the formation and coordination of a multi-institutional, international, transdisciplinary community of researchers, scholars and engineers with the shared objective of creating a comprehensive inventory of species and detailed map of the biosphere. We conclude that an ambitious goal to describe 10 million species in less than 50 years is attainable based on the strength of 250 years of progress, worldwide collections, existing experts, technological innovation and collaborative teamwork. Existing digitization projects are overcoming obstacles of the past, facilitating collaboration and mobilizing literature, data, images and specimens through cyber technologies. Charting the biosphere is enormously complex, yet necessary expertise can be found through partnerships with engineers, information scientists, sociologists, ecologists, climate scientists, conservation biologists, industrial project managers and taxon specialists, from agrostologists to zoophytologists. Benefits to society of the proposed mission would be profound, immediate and enduring, from detection of early responses of flora and fauna to climate change to opening access to evolutionary designs for solutions to countless practical problems. The impacts on the biodiversity, environmental and evolutionary sciences would be transformative, from ecosystem models calibrated in detail to comprehensive understanding of the origin and evolution of life over its 3.8 billion year history. The resultant cyber-enabled taxonomy, or cybertaxonomy, would open access to biodiversity data to developing nations, assure access to reliable data about species, and change how scientists and citizens alike access, use and think about biological diversity information.

Key words: biodiversity, bioinformatics, biomimicry, biosphere, conservation, cyberinfrastructure, ecology, evolution, international collaboration, organization of science, origins, species, sustainability, systematics, taxonomy, team work

Introduction

Dynamic, constantly evolving and awesome in complexity, Earth's biosphere has proven to be a vast frontier that, even after centuries of exploration, remains largely uncharted. Its intricate webs of interacting organisms have created resilient sources of ecological services. In its diversity of species and their attributes are told the story of the origin and evolutionary history of life, reflecting billions of ways in which organisms have adapted, again and again, to a constantly changing planet. So beautiful, its flora and fauna have inspired poems, songs and great works of art. So creative, natural selection has successfully solved, many times over, challenges analogous to those facing human society today. In knowledge of biodiversity lie both clues to our past and our best hopes for the future.

Exploring the biosphere is much like exploring the Universe. The more we learn, the more complex and surprising the biosphere and its story turn out to be. We have made, and are making, spectacularly impressive progress. Nearly 2 000 000 species are known and another 18 000 new plants and animals are discovered each year (Chapman, 2009; IISE, 2012). One recent study calculated the number of eukaryotic species at 8.7 million (Mora *et al.*, 2011), a number close to but somewhat smaller than the often-cited 10 million species estimated by Chapman (2009). Assuming that these numbers are close to the actual number, and recognizing that the challenge includes both description of new species and redescription of existing species, the magnitude of the challenge is in the range of 10 to 12 million species treatments. Recognizing that there are mitigating factors (e.g. some species descriptions are in relatively good shape; many undescribed species are already present in collections), we have used the round number of 10 million as a goal for initial planning purposes. In any case, the number of species will remain controversial until we have gained significantly more knowledge. Molecular sequencing is revealing unsuspected microbial diversity and adding critically important data for both species identifications and phylogenetic reconstructions. Ecologists continue to reveal the function of dynamic and massively complex living networks. The accumulated knowledge of biodiversity, more than 250 years of published literature and field observations, associated with several billion specimens in herbaria and natural history museums around the globe, is becoming accessible and analysable in digital form, enabling questions new in kind and scale about the ecology, biogeography and evolution of life. By adapting existing technologies and organizing a transdisciplinary workforce, we have the opportunity to make much faster progress exploring species and, in turn, enable society to make better-informed decisions about the environment.

For the first time in human history, the rate of species extinction may exceed that of species discovery (Wilson, 1992; Raven, 1997) and foretell a mass extinction event (He & Hubbell, 2011). The consequences of losing so much biodiversity are neither known nor knowable without significantly greater understanding of the biosphere's structure, status and function. We stand to lose things of both great intrinsic and instrumental value (Vane-Wright, 2009). Increased knowledge of what species exist and where they live would prepare us to detect, monitor, measure and predict increases or decreases in biological diversity as well as the impacts of these changes on the functions of ecosystems. Beyond direct environmental benefits, an inventory of species taps a wellspring of living diversity from which we may seek new materials, processes, designs, inspirations and ideas to confront environmental, medical and engineering challenges in a rapidly changing world. Nature has had the benefit of billions of years of countless trial-and-error

experiments to find creative and sustainable solutions to survival challenges. For the most serious issues facing humanity, we do not have the luxury of a nearly indefinite period of time to stumble upon effective solutions. The next best thing is to emulate the creativity of the natural world (e.g. Benyus, 1998), even when model does not map directly to solution (Reed *et al*., 2009).

Technological advances mean that it is now possible to envision an exploration of Earth's species on an unprecedented scale and tempo (Wheeler, 2010). The benefits of knowing our planet's species are innumerable. We can learn what species exist and in what combinations, so that we are prepared to detect responses to environmental change and introductions of invasive species. We can analyse and understand the function of ecosystems, and delivery of ecological services, at a level of detail never before possible. And we can gather comprehensive evidence of phylogeny.

Our goal is no less than a full knowledge-base of the biological diversity on our planet, by which we mean: knowledge of all Earth's species, and how they resemble and differ from each other (i.e. all their characters from detailed morphology to as much genomic information as is feasible to collect); a predictive classification of all these species, based on their interrelationships as inferred from all these characters; knowledge of all the places at which each of these species has been found with as much ecological data as are available from specimens in the world's collections (e.g. host data, microhabitat data, phenology, etc.); and cyberinfrastructure to enable the identification of newly found specimens (including automated identification systems based on images and genomic information), the efficient description of species, and open access to data, information and knowledge of all species by anyone, amateur or professional, anywhere, any time.

To achieve this goal, we propose an intensive internationally collaborative mission aimed at discovering as many plant and animal species on earth as possible and mapping their distributions in its biosphere. Inconceivable a generation ago, we conclude that theoretical and technological advances make attainable a campaign to describe 10 million species in less than 50 years, virtually completing an inventory of 'higher' organisms and complementing the accelerating exploration of microbes. The mission would utilize the input and participation of many disciplines and partners to generate outputs that would advance evolutionary biology, environmental biology and sustainable problem-solving (Fig. 1).

Sustain what?: the workshop

A workshop entitled 'Sustain What? Mission to Explore Earth's Species and Conserve Biodiversity' was held at the

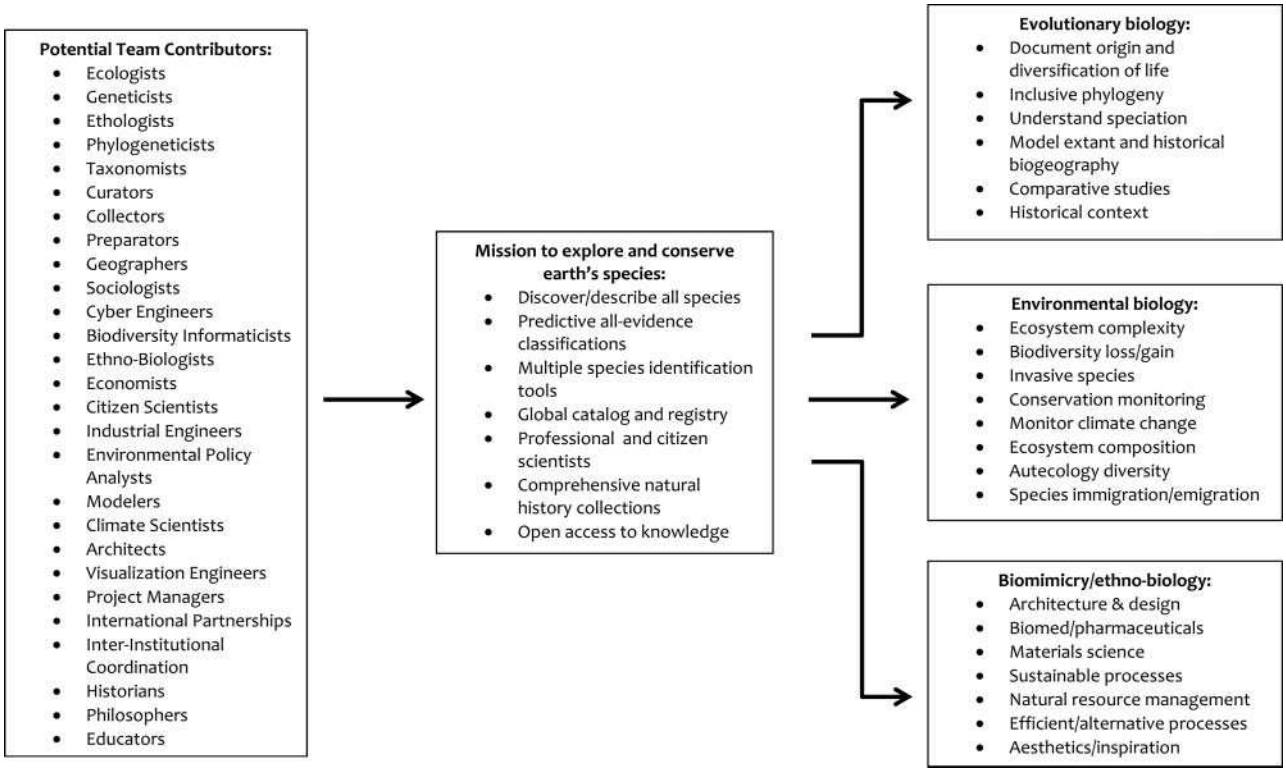

Fig. 1. A partial list of the trans-disciplinary expertise required to plan, undertake and complete an inventory and mapping of Earth's flora and fauna and three examples of scientific and engineering domains advanced by the resulting knowledge of the biosphere's species and their properties, relationships and distributions.

Table 1. Challenges confronted by "Sustain What?" workshop at New York Botanical Garden, 7–8 November 2010.

Challenge	Interpretation of Focus
A: What immediate actions might avoid compounding constraints on taxonomic progress?	a: Digitization of data associated with 3 billion specimens and accumulated over 250 years is progressing. What practices could avoid adding to this backlog?
B: How can the annual rate of species discovery be accelerated by one order of magnitude?	b: The stated challenge of describing 10 million species in 50 years or less can be met if rates of species description are increased from 20,000 to 200,000 species per year. How might this rate be realized?
C: Envision a mission to discover, describe, and map the species of the biosphere.	c: Identify the workforce, infrastructure, priorities, collections, cyber tools, etc. that would be needed to describe or re-describe 10 million species in 50 years or less.
D: How can the taxonomic and museum communities be organized to set a rolling agenda of top priorities to complete the mission?	d: Envision a plan for decadal assessment of needs and opportunities much like that successfully used to drive the astronomy and astrophysics agenda forward.
E: Assessment of need to know.	e: From the perspective of various disciplines, how much knowledge of species and their attributes, relationships, interactions, and distributions is necessary and appropriate?
F: What are scientific benefits of knowing all species?	f: Were an all-out mission to discover and map all species completed, evaluate the impacts on science.
G: What are impacts on society of knowing all species?	g: Were an all-out mission to discover and map all species completed, evaluate the impacts on society.
H: What can be done to improve public awareness and appreciation of biodiversity and species exploration?	h: A successful mission should go beyond the creation of reliable information and knowledge to also make the public aware of the importance of biodiversity and of the exploration of species. What kinds of outreach are likely to be successful?

New York Botanical Garden on 7–8 November 2010. An overarching question put to our group of about 40 scientists, engineers and scholars was whether a comprehensive mission to discover, describe and map the species of the biosphere is feasible. Our answer was an unequivocal 'yes'. In short, there are no scientific obstacles to such a mission that cannot be overcome by a combination of technology and collaboration. The purpose of this paper is to summarize our recommendations for what can and should be done. We came away from the meeting inspired by the possibilities and with a sense that the stunning advances in the exploration and understanding of the biosphere possible during the next half-century can match or surpass those made by astronomers mapping the heavens over the past half-century.

Participants were confronted by eight broad challenges (Table 1). The first day, participants were asked to temporarily suspend any reservations about *whether* a mission to discover and describe all species of our planet was possible, necessary or desirable, and focus specifically on *how* it could be approached. The second day, scepticism was welcomed and participants were asked how much knowledge of species is necessary or appropriate to meet the needs of science and society. Additionally, participants were asked to think about the likely impacts of such a mission on science and society. What follows are observations and recommendations from the workshop.

The workshop concluded that strategic investments in infrastructure and workforce, combined with innovative inter-institutional, international, professional–public collaborations and transdisciplinary partnerships, could quickly create the research capacity to successfully undertake such a mission.

Benefits envisioned

Environment

We seek to understand and sustain a dynamic, responsive biosphere comprised of ecosystems with the kind of flexibility and adaptability that is uniquely conferred by species diversity. A diversified economy is more resilient to unexpected financial stresses than a simple one; diverse living systems are more resilient than less diverse ones to unforeseen change. We seek to enhance the precision with which ecologists may study ecosystem functions and increase the detail and accuracy with which models may be used to predict the future of those systems. We propose to establish empirical baseline information about species and to continue to expand and improve our knowledge and measurement of the status of biodiversity (Magurran & McGill, 2011) and its economic implications (TEEB, 2010).

Evolutionary biology

We aim to gather material evidence of the results of evolutionary history in order to better understand the origin, diversification and history of species, what makes each species unique, and how they are evolutionarily related. Our goal is the integration and synthesis of all available evidence, morphological, molecular, developmental and fossil, into a predictive phylogenetic classification and to answer long-standing fundamental questions about biological diversity (Cracraft, 2002). Beyond biodiversity in general,

improved knowledge of species and their history will contextualize our understanding and appreciation for the origins of humans, cultures and civilizations.

Sustainable problem-solving

We seek to make all species identifiable and to facilitate advances in sustainability by opening access to the inventiveness of natural selection to engineers, designers and other problem-solvers. Ethno-biologists have estimated that, worldwide, tens of thousands of species are used by humans and biodiversity has profound importance to human well-being and economic prosperity (Jeffries, 1997; Raven, 1997; Cracraft & Grifo, 1999; Alonso *et al*., 2001; Gaston & Spicer, 2004; Millennium Ecosystem Assessment, 2005; Lovejoy *et al*., 2010; TEEB, 2010). Biodiversity remains the basis for resources we depend upon in daily life, from fuel to food, medicines, fibre and feed. In spite of their central role in human civilization and commerce, the full diversity and richness of living resources are yet to be explored and understood. As we discover species, millions of products, processes, materials and design models will become newly available to humanity (Benyus, 1998; Turner, 2007) that will be of incalculable value to problem-solving and economic prosperity. For examples, see Ask Nature (http://asknature.org) and Map of Life (http://mapoflife.org).

Intellectual curiosity, aesthetics and recreation

Making it possible for anyone to identify any species, any time, from anywhere will reignite awareness of the innate connections between humans and Nature (Wilson, 1984), inspire creations in art, poetry, literature and music, and fuel already strong interests in hunting, fishing, gardening, birding, natural history collecting, ecotourism and the myriad other ways in which people indulge their curiosity, awe, fascination and love of the natural world. Put simply, it is difficult to highly value things that are unknown or inaccessible to us. An inventory and mapping of the species of the biosphere makes species identifiable and places them within our reach. Just as we are driven to explore the unknown in outer space, we have an innate drive to explore the diversity and origins of the biosphere and our place in it.

Assumptions

Several general assumptions and guiding principles underlie our vision, recommendations and observations.

More than a name

The ultimate goal of the proposed mission is to know every species; to learn what makes each unique, from its anatomy to its genome, behaviour, ecological associations, geographic and seasonal distributions and phylogenetic relationships. While scientific names are essential, they are the beginning of knowledge, not its end. In the context of biological classifications, names uniquely reference species and are the foundation for biodiversity informatics. Because species are based on hypotheses, they must be periodically tested and improved or replaced. Thus, the long-term aim goes beyond an intensive first pass to make something known of all species to learning as much as possible about each species, limited only by curiosity, opportunity, resources and needs. To that end, it is our aim to establish the conceptual foundation and infrastructure within which knowledge of species will continue to be expanded and refined indefinitely by both scientists and the public.

Describe and predict

Reliable descriptions of species and their diverse attributes and distributions are also a beginning. Documented characters and attributes, integrated with genomic and fossil evidence, become integral to phylogenetic classifications and a historical evolutionary frame of reference for biology. Distribution data reassembled in a GIS environment become a powerful ecological research and conservation tool. Species sorted on the basis of some structural or physiological property of interest become open books to engineers and designers seeking sustainable alternatives. Trends in geographic and phenological data become early warnings of climate change or environmental degradation. Empirical knowledge informs effective policy.

Collaboration and coordination

The challenge is so great that the expertise of a wide range of professionals is necessary for success: computer and information engineers, anatomists, conservation biologists, ecologists, geneticists, molecular biologists, project managers, sociologists and taxonomists representing the hundreds of specializations in biology, to name some. Partnerships must include botanical gardens, natural history museums, universities, scientific societies, government agencies and NGOs. Because the species and ecosystems of the biosphere are related and interact in many ways, this is a global enterprise by definition and will require a level of internationalization achieved in few fields of science. Avoiding redundancy, using resources wisely, and assuring efficient progress toward measurable goals will all require a highly coordinated set of priorities and objectives. Networked in cyberspace, the world's natural history collections will function as a single, albeit geographically distributed, research resource. All of this supposes a clearly articulated vision and ambitious milestones, something that will require organizing bodies both within nations and internationally.

Collections

Growth and development of natural history collections is central to the success of a mission to explore species diversity and its most enduring legacy (Blackmore, 1996). Specimens, tissues, sequences, observational data and recordings will be among the valuable results of a species inventory. Museums and herbaria will collectively house a comprehensive and permanent record of biodiversity in the early Anthropocene (Crutzen, 2002; Steffen *et al*., 2009). Type specimens will serve as the objective basis of stable systems of scientific names. And voucher specimens will provide evidence of species soon to be extinct as well as changes in geographic distributions in historic time. There is ample evidence that clever scientists and advances in technology will continue to find new uses for museum specimens (e.g. Miller & Rossman, 1995; NSTC, 2009).

Innovation

While success will depend heavily on innovative practices and newly adapted technologies and infrastructure, it is equally critical that the fundamentals of the best of 250 years of taxonomy be recognized, modernized and leveraged. Moreover, it is critical that clear, explicit goals and mileposts be established in order to keep the overall enterprise focused on deliverable knowledge of species and demonstrable progress toward those ends. The enterprise must be attentive to both the needs of knowledge creators and consumers so that the results are maximally reliable and useful.

Start rules. Mapping the species of the biosphere is so ambitious and engages so many competing interests that deciding which projects to fund first and in what sequence is far from trivial. Paradoxically, funding the mission as a whole will require univocal support from the community while success in its various parts will require meeting a diversity of needs.

Perhaps the easiest priorities are those that benefit everyone and for which there ought to be broad agreement. Strategic investment in cyberinfrastructure is a prime example. Everyone undertaking taxonomic work will require access to certain research resources including digitized literature, museum data, specimens (especially types), teleconferencing and software for e-monography, and everyone will benefit from expanded capacities of herbaria and museums.

Such common infrastructure helps address the question of which taxa to tackle first since all taxa can advance in parallel, although at different rates. Specialists will have to assess and prioritize the next level of needs in their community. For some it may involve filling gaps in expertise or engineering instrumentation to overcome some obstacle to progress. For others the pressing issue may be criteria for which taxa or ecosystems to emphasize first.

There are objective criteria for prioritizing taxa, but ranking them is a decision that belongs to the community. We could tackle relatively well-known taxa first because a concerted effort could complete an inventory in the shortest time, or we could prioritize the least-well-known taxa under the argument that we would discover the largest number of new species in the shortest time. Either way, we could also prioritize taxa for which there is an urgent need among consumers of taxonomic information. Plants are a good example of a taxon with a strong infrastructure and workforce, a solid foundation of knowledge on which to build, and species critical to the characterization of terrestrial ecosystems (Paton *et al*., 2008). The completion of The Plant List in 2010 (http://www.theplantlist.org) in response to target 1 of the Global Strategy for Plant Conservation (UNEP, 2002) is a good example of a community coming together to reach a goal.

Moore's law. We recognize that, while an order of magnitude or more acceleration in taxonomy is immediately achievable given existing technology, a great deal of progress in coming decades will in fact be the result of advances in technology itself. Adapting current cyberinfrastructure is merely a first step. As our mission progresses, so too will the technology enabling it. This suggests to us that our estimates are *conservative* and that as technology continues to advance, and as we have more taxonomic information to guide future targeted goals, overall progress may be substantially faster than that which we can demonstrate today. Thus, we advise the community to frequently reassess and recalibrate its goals and aim for progress as rapidly as resources, data and technology will permit.

Building on strength

A mission to inventory our planet's species can build on several sources of great strength. Far from beginning from scratch, the project would draw from more than 250 years of species exploration, accumulated collections, and wisdom based on experience as well as an international standing army of experts.

A capable workforce

A capable workforce exists (Joppa *et al*., 2011). Each year, taxon experts name and describe about 18 000 new species in addition to improving our understanding of already known species. The theories and methods of modern revisionary taxonomy are sound and efficient within existing constraints, yet a number of resources and improvements are clearly needed. Existing gaps in expertise, particularly among ecologically, phylogenetically or economically important groups or cases where pending retirements threaten

community access to knowledge, should be filled (Rodman & Cody, 2003). Institutional and funding agency support of revisionary work is encouraged to take full advantage of existing expertise. Employers should maximize the availability of time for established taxon experts to contribute to taxonomic progress, and amateur taxon experts, already major contributors to progress, should be given guidance in working to the highest levels of excellence possible.

Open access to research resources

Taxonomy, more than any other life science, depends upon access to past work and is visibly built on the steady accumulation and improvement of descriptive work. Acceptable taxonomic scholarship requires access to all relevant publications beginning in 1758 for most animals, 1757 for spiders and 1753 for plants, and access to relevant collections of specimens. The Global Biodiversity Information Facility paved the way toward creating open access to data by linking millions of digitized specimen-associated data records. The Biodiversity Heritage Library is in the process of digitizing 250 years of legacy literature. Wilson's (1993) vision for a Web page for every species is being realized by the Encyclopedia of Life. Digitization is beginning to reach the most important research resource of all: specimens. For example, in the USA, the National Science Foundation has launched a major effort to digitize museum specimens held in U.S. institutions (Advancing the Digitization of Biological Collections, see http://www.idigbio.org). In France more than 10 million plant specimens of the Museum National d'Histoire Naturelle are being scanned. The latter, combined with the Global Plants Initiative (http://gpi.myspecies.info), is transforming how herbaria are used in research.

Collections

Thousands of botanical gardens, natural history museums and universities hold an estimated 3 000 000 000 specimens worldwide. This is a profoundly powerful scientific research resource (National Science and Technology Council, 2009) that would take hundreds of years and billions of dollars to duplicate. No outcome of an intensive campaign to inventory species will be more important than the growth and development of collections. International planning and cooperation among natural history museums is essential in order to avoid unwanted redundancy in effort and to assure that collections in aggregate ultimately reflect species diversity as completely as possible. As a museum-specific cyberinfrastructure is envisioned and engineered, it is reasonable to predict a time in the not-too-distant future when all collections become nodes in a global network that functions as if it were one vast, distributed 'museum' accessible to all.

Phylogeny

Since Darwin's (1859) prediction that classifications would one day reflect the evolutionary affinities among species, and Hennig's (1966) presentation of an integrated theoretical foundation for phylogenetic classifications, great progress has been made in increasing our understanding of phylogeny (Cracraft & Donoghue, 2004). Broad sampling has both confirmed and challenged long-standing ideas about relationships (Palmer *et al*., 2004; Dunn *et al*., 2008). Although the availability of abundant, affordable molecular sequence data has complemented fossil, morphological and developmental data in resolving phylogenies, challenges persist (Delsuc *et al*., 2005). With as many as 90% of species unrepresented in reconstructed phylogenies, we cannot yet appreciate what newly discovered species and characters may ultimately contribute to our understanding of evolutionary history. Aggressive expansion of collections, from whole specimens to DNA and tissue samples, is the best insurance against phylogenetic ignorance.

Teamwork

The US National Science Foundation Planetary Biodiversity Inventory projects have demonstrated that species discovery can be dramatically accelerated through coordinated teamwork among taxon experts and institutions (Knapp, 2008; Page, 2008). PBI projects described or redescribed thousands of species over five-year funding periods, even while working with limitations of existing tools, software and access to specimens. European taxonomists have adopted a series of bold efforts to modernize descriptive taxonomy including Platform Cybergate (http://wp5.e-taxonomy.eu/platform/), part of the ambitious European Distributed Institute of Taxonomy, or EDIT (Clark *et al*., 2009), and the Virtual Biodiversity Research and Access Network for Taxonomy (ViBRANT: www.vbrant.eu; see Smith & Penev, 2011). A combination of such teamwork and innovative cyber tools will continue to accelerate the processes of taxonomy.

Digital publication

Electronic journals are adding efficiency to the process of writing and disseminating descriptions (e.g. Bénichou *et al*., 2010; Berendsohn, 2010; Blagoderov *et al*., 2010). Examples include the Census of Marine Life, *Zootaxa*, *Phytotaxa*, *Zookeys* and *Phytokeys* (Penev *et al*., 2010*a*, 2010*b*, 2010*c*) and tools that expedite preparation of components of descriptive work such as 'scratchpads' (Smith *et al*., 2008) and anatomical ontologies (Yoder *et al*., 2010). The decision taken at the International Botanical Congress in Melbourne, Australia (see Knapp *et al*., 2011) to allow electronic publication of new names and typifications for algae, fungi and plants from 1 January, 2012, has already

begun to accelerate the rate of species description. The capture, analysis and distribution of knowledge will continue to accelerate as further improvements are made in how descriptions are written, peer reviewed and published. Digital publications are also extending the impact of and uses for scientific names (e.g. Patterson *et al*., 2006). Beyond formal species descriptions, software can simultaneously populate registries (e.g. ZooBank), catalogues (e.g. ITIS) and general information portals, such as the Encyclopedia of Life. These are the beginnings of the emergence of a cybertaxonomy that will ultimately mature into cyber-mediated taxon knowledge communities that combine the efficiencies of comprehensively comparative revisions with the immediacy of access to research resources, communication among experts and rapid information dissemination and update.

Meet basic needs

- Expand and develop natural history museums as permanent record of biodiversity.
- Invest in cyberinfrastructure that modernizes and makes efficient both production and access to taxonomic information.
- Create revisionary taxonomy communities that link distributed experts and research resources in cyber-enabled collaboratories.
- Enlist industrial engineers to complete time-and-motion studies to maximize efficiency of work from collection and preparation of specimens to data collection and analysis to its publication and visualization.
- Taxonomic and museum communities undertake strategic and tactical planning with end goals in mind.

What is needed?

With only two days to tackle an enormous set of issues at the New York workshop, we did not pretend to be able to specify fully what is needed to plan, organize and successfully carry out the mission. That said, we did identify an (admittedly incomplete) list of ingredients essential to the process. We urge the community to flesh out a more detailed and comprehensive list of needs from which costs can be more precisely estimated.

Museums and herbaria

Assuming we overcome the rate-limiting issue of collecting (May, 2004), the mission will require substantial growth and development of natural history collections. If the existing ratio of museum specimens to known species is about right (i.e. 3 billion specimens representing 2 million species), and if we assume 10 million additional species, we can anticipate museum collections about six times the size of those at present, say 18 billion specimens worldwide. These estimates may be slightly inflated if recent calculations prove correct (i.e. Mora *et al*., 2011), but serve to emphasize the importance of planning for collection growth. While planning for that expansion, it is an appropriate time to modernize existing physical plants to assure optimal conditions for the long-term conservation of specimens and frozen tissues, and to re-examine the efficiency of storage systems themselves that have changed little in more than a century. Attention should also be paid to efficiency in the processing of large volumes of material, perhaps in some cases in regional sorting and preparation centres. As new material is accessioned, it should be done in a fashion that does not add to existing backlogs and that makes specimens and associated data immediately accessible.

Cyberinfrastructure

Many components of the general cyberinfrastructure needed to do descriptive taxonomy exist, can be adapted from current technology or are being built (Wheeler, 2008; see also the digital hub for the NSF's ADBC program, http://www.idigbio.org). Other functionality can be specified by consultation with experts on various taxa with specialized needs. Memory, communication and data transmission speed and volume challenges are being addressed for science and engineering in general (Nentwich, 2003; Atkins *et al*., 2004; National Science Foundation, 2008) and need not be duplicated. What urgently requires attention are specialized cyber tools for doing revisionary taxonomy in a digital environment and tools that continue and expand upon ongoing efforts to assure open access to research resources including literature, specimen-associated data, a global species catalogue, specimens (above all, type specimens), molecular sequence data, images of specimens and their characters, electronic publication tools and real-time video conferencing among experts.

Revisionary taxonomy collaborators' network

Taxonomy must mature from a cottage industry to a highly efficient, cyber-enabled, high-throughput, modern science. This requires a new level of collaboration and international and inter-institutional coordination (Parker *et al*., 2010; Vermeulen *et al*., 2010). Importantly, it requires also a fundamental cultural change as well as modifications of the incentives and rewards associated with taxonomic work, including the equivalent of an impact factor for taxonomy based on use of scientific names. More than most areas of science, it shall also require a thorough integration of amateur and professional science practitioners. Cybertaxonomy, from databases to advanced instrumentation and communications, will provide the research platform on which to

reform how taxonomic information is created, maintained, accessed and used.

Time and motion studies

Opportunities exist at nearly every step in the process of doing taxonomy to add efficiencies. From collecting to mounting, sorting, labelling, storing, accessing, imaging and databasing specimens, new technologies and methods of work hold promise to maintain or increase quality while increasing speed (but see Bebber *et al*., 2012, for an example of expertise enabling discovery). The same can be said for data acquisition, analysis and dissemination. A critical, detailed time-and-motion study by professionals in industrial processes would identify many areas for improvement.

Strategic and tactical planning

While it is crucial to maintain the intellectual freedom of individual researchers to pursue curiosity-driven projects as well as the flexibility of various institutions, programmes and nation states to meet their unique self-interests, it is also essential that the community as a whole develops a clearly articulated and sufficiently detailed overarching vision for the mission so that steady and measurable progress is being made at all times toward the ultimate goal. The uneven progress across major taxa over the past decade (International Institute for Species Exploration, 2012), indeed over the whole 250-year history of modern taxonomy, reflects the lack of community planning. Support for inspired individual studies is necessary to enable excellent work, but a comprehensive inventory is more than the sum of a limited number of randomly selected revisions. An overall strategy is necessary and a process to prioritize campaigns that chart steady progress toward the end goal.

Mobilize and develop workforce

- Maximize impact of existing taxonomists with support staff.
- Create new master of taxonomy category of professionals.
- Engage and train citizen scientists.
- Engage diverse partners from life sciences, social sciences, humanities and engineering.
- Create or identify one or more objective oversight organization(s) to provide coordination and undertake periodic (minimally decadal) assessments of progress, needs and priorities.

Who is needed?

Taxonomic workforce

A successful mission will require a trans-disciplinary workforce including knowledge and talents drawn from many fields. Impacts of existing taxon experts should be maximized by providing support staff and rewarding descriptive work. Gaps in taxon expertise should be identified and filled. The workforce should be expanded through the creation of professionals at the MS level trained specially to undertake revisionary and curatorial activities, these being in addition to traditional doctoral researchers. These master taxonomists should be grounded in the theories relevant to species exploration and phylogenetics, and well versed in appropriate technologies, particularly those comprising the emerging cybertaxonomy. Further workforce development must include teams of specialized support staff led by taxon experts and including collectors, preparators, database specialists, illustrators/imagers and other technical staff as appropriate. Taxonomy should be reinvigorated in biological curricula at the high school and college levels, and advanced training in species identification should be made available through high-quality video courses and utilization of the full range of digital instrumentation and resources. A world expert working on an obscure taxon and living in Paris could instruct students in Bolivia and South Africa while viewing rare specimens remotely and in real time located in museums in Washington and London. As such online resources emerge, interfaces and auto-tutorial websites should be developed that welcome and encourage citizen scientist involvement in aspects of the mission (see Pearson *et al*., 2011).

Another important workforce issue involves international partnerships. It is critical that in-country expertise and collections be developed in areas of high biodiversity. Similarly, it is critical that the world's museums and herbaria communicate and coordinate activities and taxon expertise to avoid undesirable levels of redundancy and to assure that, in aggregate, the world's collections create a comprehensive representation of species, clade and ecological diversity. Natural history collections have traditionally been organized to optimize their use for the comparative studies by taxonomists and phylogeneticists. Biodiversity informatics means that specimens can be virtually reassembled for many other purposes. For example, with digital data ecologists can rapidly determine all taxa and life stages collected at a particular site during a specified period of time.

Partners

Much of the talent needed is best obtained through partnerships with existing experts and organizations. Success for the mission will require that the scientists, scholars and engineers involved learn new and effective ways to work together (Poteete *et al*., 2010). Some of the partners needed

are self-evident: engineers to conceive and construct specialized instrumentation, biodiversity informaticians, taxonomists, palaeontologists, molecular geneticists, ecologists, conservation biologists, etc. Others are equally important but represent radically new partnerships for biodiversity scientists. Sociologists are needed to assist in constructing cyber-networked communities of experts to assure that appropriate incentives and recognition of intellectual contributions exist. How are intellectual contributions of individuals acknowledged in a community-maintained knowledge base? What aspects of character comparisons and analysis might be automated (e.g. Lasalle *et al*., 2009)? Historians should assess why a strong acceleration of the rate of species discovery that existed prior to World War II did not resume following the war, in spite of investments in universities, advances in technology and obvious benefits to biology, and why phylogenetic systematics, successful by many measures, failed to perpetuate support for the formal descriptions and classifications for which it was conceived by Hennig (1966). Philosophers of science must be engaged to continue to refine and communicate the rigour of non-experimental homology, species and phylogenetic theories (Williams & Forey, 2004). And a close working relationship with the broad array of communities that use taxonomic information is crucial to assure that their needs are fully met in the process. Examples include agricultural pest management, detection of invasive species at ports of entry, conservation biology and natural resource management, and biomimicry, to name only a few.

Coordination

Setting priorities for the mission will require a level of coordination within and beyond the community that is unprecedented. It is critical that an organization or set of organizations be identified or created that is capable of speaking for the community as a whole and that can coordinate activities at a high level (see Boxshall & Self, 2011). From a political point of view, such an organization is needed also within funding domains. In the USA, for example, there is no existing mechanism by which the state or needs of taxonomy are assessed. Just as the National Research Council of the US National Academies of Science appoints a panel on a decadal basis to survey the astronomy and astrophysics communities to determine the highest priorities and greatest needs for the following ten years (Committee for a Decadal Survey of Astronomy and Astrophysics, 2010), the taxonomic community needs an impartial body that does the same, advocates for the community as a whole, and assures steady progress toward a comprehensive species inventory. A mechanism for community coordination is among the most urgent decisions to be made and implemented and can guide the community through the next planning stages. Whether this mechanism is a new professional organization, an NGO, a body or bodies in each country or region somehow elected or appointed, or a committee reporting to the national authorities such as the National Science Board in the U.S., it is critical that it be as representative and as objective as possible. Very difficult decisions will need to be made and until the mission is up and running, these decisions will need to be made on a frequent basis. We recommend that, in the U.S., the NSF fund this crucial planning process immediately to begin organizing efforts within the USA and to provide a model that might be adopted or modified in other nations and potentially provide a step toward an international umbrella organization or consensus. At the same time, we urge every nation to support its biodiversity, taxonomic and natural history museum communities to address this same need.

Taxonomic triage

- Populate global archive of digital images of type specimens.
- Complete digital Biodiversity Heritage Library.
- Mandate registration of all nomenclatural acts**,** including descriptions of new species.
- Establish a ‘Nomenclatural Impact Index’.
- Make specimens accessible remotely.
- Automate digitization of newly accessioned specimens.
- Identify and fill gaps in e-monography and e-publication software.
- Pursue international agreements to open access to scientific collecting and guarantee open access to resultant knowledge.
- Increase NSF funding for collections and population of collections-relevant databases.

Taxonomic triage: immediate steps to cease compounding the problem

Some of the major obstacles to rapid progress in species exploration have to do with bottlenecks in the process. Before the Biodiversity Heritage Library project very little of the past 250 years of taxonomic literature could be accessed in digital form or beyond the walls of a few privileged institutional libraries. Digital images exist for only a fraction of the type specimens in the world’s museums. Complete electronically accessible catalogues of all known species exist for shockingly few higher taxa. Most museums have a large number of unidentified specimens sorted only to some higher taxonomic level, and collections of the most diverse taxa, such as insects, are not yet databased to the specimen level. Each of these cases represents an enormous backlog. Simply databasing the insect collection at the Natural History Museum in London, for example, means transcribing labels from 30 000 000 specimens. While exciting

technologies and projects are being conceived to address these huge backlogs, there is absolutely no excuse for adding to them. All species described from this point forward and every specimen added to a collection from this point forward should be done in a way that is part of the solution and not part of the problem. Below are some of the recommendations for making such forward-looking changes.

Populate global archive of digital images of type specimens

While type specimens are not typical in any genetic or biological sense, they play a critical role in the stabilization of scientific names. The objective use of names requires that taxonomists frequently examine types in order to resolve issues related to the status and use of binominals. Because new sources of data, such as DNA sequences or newly collected specimens, test and improve our ideas about what species are, it is desirable that species concepts change to keep pace with all available evidence. As concepts of species change, whichever revised species a type specimen falls within, there follows the name attached to it. Such changes may require synonymy or new names, but in each case types assure an objective basis for the use of existing names. Today, scientists often must travel to museums in many cities in order to view types and assure that they fit current concepts. While digital images of types (so-called 'e-types') will never replace completely the need to see types first hand, for a great many instances (perhaps more than 90%), an examination of a high-resolution set of images is sufficient. This makes nomenclatural decisions enormously less costly in travel funds and time and accelerates such decisions from weeks to minutes. This benefits everyone who uses scientific names in publications or accesses bioinformatics data. In addition to creating an archive or portal for accessing e-types, we suggest that ways to automate the rapid creation of e-types be explored. Botanists are leading the way (e.g. http://gpi.myspecies.info/content/all-vascular-types-line-global-plants-initiative) and aim to have more than 2 million e-types online by 2013.

Digitization of literature

Taxonomy, more than any other life science, is dependent on access to heritage publications. Every species description published since 1 January 1758 (1753 for plants) must be accessible to taxonomists to meet high standards of scholarship. Access to great libraries has been a major bottleneck for taxonomy, especially for students and scientists in developing countries. Making all descriptive taxonomic literature and related natural history literature digital and openly available represents a major step forward in promoting quality and democratization of taxonomy. The Biodiversity Heritage Library project is making impressive progress and should be supported to complete its mission as rapidly as possible. This effort must also confront the copyright issue for recent literature. Even if interpretive parts of publications remain copyrighted, formal descriptions should be made open access (Agosti, 2006).

Mandate registration of nomenclatural acts

Without impinging on intellectual freedom in taxonomy, registration of all nomenclatural acts, including descriptions of new species, should be considered seriously by the entire community. Today, nomenclatural acts (e.g. new species, new combinations, etc.) are published in thousands of publications. The fragmentation is so severe that it takes about two years to simply locate and compile a listing of all new species described in any calendar year. Registration merely makes nomenclatural acts known to the community and presents no danger of intellectual censorship (e.g. Polaszek *et al*., 2005; Pyle & Michel, 2010). This would immediately improve the quality of all work by making up-to-the-minute information and ideas easily and openly accessible. As of 1 January, 2013, all new names and combinations in fungi must be entered in an online registry (Norvell, 2011); other taxonomic groups are encouraged to follow suit.

Establish an automated nomenclatural impact index

As the community completes a comprehensive catalogue of species and registration of nomenclatural acts, and as biological journals migrate to electronic platforms, it becomes feasible for the assembled, validated data to become a service to editors of journals by which all binominals are checked for accuracy, availability, spelling and current usage, and hyperlinked to primary descriptions and images. At the same time, an automated system could track the use of binominals in the biological literature, both to credit individual taxon experts for their intellectual property and to maintain an up-to-date biological bibliography for all species. Secondary literature used to identify species is often uncited, much less the primary descriptive literature. Such an automated impact index would redress this gap in intellectual attribution.

Make specimens remotely accessible

Museums should be connected in a network of remotely operable digital microscopes so that type and rare specimens can be studied and photographed by experts without need for travel or shipment of specimens. This would drastically accelerate the recognition of new species, verification of identifications of rare species, and facilitate collaboration among experts located in different institutions. It would also have applications in both formal and public

education. As experts study specific characters, images would accumulate in digital archives, reducing the need to handle individual specimens. Over time, and in response to immediate needs and interests, such archives would grow in their comprehensiveness. While an initial set of digital images will meet many needs, such connection of taxon experts with specimens will flesh out image collections to include the most informative morphological data. Such direct access would avoid mistaken identifications and accelerate taxonomic and nomenclatural decision-making.

Automate digitization of accessioned specimens

Automating imaging of specimens would enable collections to digitize all newly acquired specimens as they are incorporated into museums as well as digitizing specimens when they are returned from loan with up-to-date identifications. Imaging and annotating unidentified specimens would make their existence known to experts who could request their loan for study, and misidentifications could be caught be experts perusing images. When synonymized binominals are included, it has been estimated that perhaps 5–6 million type specimens exist of which only a small fraction have been imaged. To digitize all existing specimens in biological collections would involve a backlog of 3 billion specimens. Rather than adding to these backlogs, automated systems instituted could avoid adding to this already enormous impediment.

Improve software for descriptive work

Creative projects are underway to modernize online publication and to create ontologies that allow the effective tracking of concepts of homology through time and across taxa (e.g. Blagoderov *et al*., 2010; Yoder *et al*., 2010). Further investments in software are urgently needed to streamline revisions and encourage collaborative work. This should include further development of existing software as well as competition to conceive alternative ones. Speeding production of revisions, however, is likely an intermediate step. At some, perhaps not too distant future, hypotheses about individual characters and existing species should be tested as rapidly as specimens and data are collected with new species described and made instantly accessible. Computer-generated 'designer' publications could be generated on demand by users from an up-to-date taxon knowledge base as has been done through scratch pads (see Blagaderov *et al*., 2010). Such publications, whether electronic or printed on demand, would amount to monographs that never go out of date and include keys, checklists, maps and descriptions that include all the latest advances in information and understanding (Wheeler, 2008).

Increase funding for collections and collection databases

Funds for collection improvement grants from the US National Science Foundation have not increased in more than a decade in spite of growing awareness of the biodiversity crisis. Given the importance of collections to the documentation and understanding of biological diversity (NSTC, 2009), it is unconscionable that so little funding is made available for the maintenance, growth and improvement of natural history collections. Further, and related, funds should be made available to populate collections-related databases and to network collections such that accessing them to explore taxonomic, phylogenetic or environmental questions is scalable from local to global spatial scales. Significant EU and US investments have been made in developing several generations of software, yet few funds are available to make records related to museum specimens available to the community by simply populating appropriate databases. And only now are funds being allocated in significant amounts to begin the process of digitization of specimens.

Accelerate species discovery by order of magnitude

- Complete catalogue of world species.
- Maximize time for descriptive work by existing taxon experts.
- Provide a support team to active taxonomists.
- Provide path for serious amateurs to attain professional-level status in contributions.
- Engineer domain-specific cyberinfrastructure and digital instrumentation.
- Accelerate the peer review and e-publication processes.
- Open access to type specimens through a digital archive and telemicroscopy.
- Remove regulatory impediments for non-commercial, scientific species exploration.
- Fund international, inter-institutional collaboratories focused on revisionary work.
- Mine existing collections for undescribed species.
- Work with social scientists, industrial engineers and project managers to maximize efficiency and cooperation.

Accelerate rate of species discovery

In order to meet our target of describing ten million species in 50 years or less, it is critical to increase the annual rate of species discovery. In recent years, the annual output has been about 18 000 species per year. A number of

technological, workforce and methodological options exist, several combinations of which could boost species description rates to 200 000 species per year, the minimum to make the goal achievable.

A low-tech option would be to support 2000 taxonomists worldwide to each describe 100 species per year. Investing in modernization of taxonomy through a domain-specific cyberinfrastructure, e.g. instruments, communication tools, databases and software, the rate could be further or alternatively increased. As another option, NSF Planetary Biodiversity Inventory projects demonstrated that teams of taxonomists can describe or re-describe several thousand species in a short period of focused work (Knapp, 2008; Page, 2008). Serious investment in almost any combination of personnel, technology, and collaborative research could quickly achieve or exceed the order of magnitude increase required.

Complete catalogue of world species

A significant bottleneck for species exploration is the absence of a complete, reliable and up-to-date catalogue of the names of all species described since 1758. Taxa lacking comprehensive catalogues, not surprisingly, include many of the largest and most problematic groups. A really useful catalogue would include not just names but also a current view of the number of accepted names or, put another way, which names are synonyms. Excellent catalogues exist for many taxa, some quite large, including flowering plants, fishes and spiders. Others lag far behind or are fragmentary and decades out of date. Several large-scale projects have been working diligently to contribute to a complete catalogue, such as Species2000, ITIS, The Plant List, and OBIS. Investments in appropriate individuals, professional societies, and projects to complete a catalogue should be a top priority for immediate action.

Maximize use of existing expert knowledge

Taxonomists are comparatively rare and most carry research, administrative or teaching loads that dilute the impact of their unique knowledge. Often, they must include other-than-taxonomic activities in grant proposals in order to secure funding for revisionary, monographic, floristic or faunistic work. All of this takes time from species exploration and phylogenetic classification (see Joppa *et al*., 2010). Recognizing that each institution has its own priorities, it is nonetheless the case that knowledge acquired over decades is not being pressed into service to meet the urgent need for reliable information about species. Increasing the number of grants available for revisionary work such as the RevSys programme of the NSF, can have an immediate impact on the hiring and productivity of taxon experts.

Provide support staff

Taxonomy is labour-intensive science. One of the simplest ways in which to accelerate species exploration is to connect adequate support staff to active taxonomists. We suggest that, on average, provision of three support staff could assure an output of at least 100 new species per year by each taxonomist so funded. The precise nature of the staff should be specified to meet the needs of each expert and would be as diverse as DNA sequencing technicians, field collectors, preparators, biodiversity informaticists or scientific illustrators.

Path to excellence for amateurs

It is an historic fact that some of the best (and worst) taxonomic work has been done by amateurs. Most taxonomic work until the late nineteenth century was done by non-professionals and thousands of new species are described each year by amateurs. In the past, access to early literature, type specimens and museum specimens in general was difficult for all but the professional. As publications, types and rare specimens are digitized, however, amateurs will find fewer obstructions to how far a taxonomic interest can go. Steps should be taken to enable and encourage serious amateurs to achieve professional-level excellence in their taxonomic work. This might include online courses and testing to certify competencies, perhaps utilizing course materials associated with degree programmes. It should go beyond techniques and practices to include a foundation in relevant theoretical matters.

Engineer domain-specific cyberinfrastructure

Many aspects of taxonomy, especially comparative morphology, lend themselves to digital ways of working. Digital instrumentation, such as remotely operable microscopes, SEMs and CAT scanners, combined with tools to capture, analyse and visualize complex anatomical characters are already revolutionizing descriptive taxonomy. These and related online research resources, such as textual and image databases, in concert with software that adds efficiency to preparation of descriptions, publication and video conferencing can greatly speed the process of species description. Cyber-enabled taxonomy, or cybertaxonomy, should be understood to include the application of information and digital technologies to as many aspects of taxonomic and museum-based research as imaginable.

Accelerate peer review and e-publication processes

The community needs to assess the peer review process and modernize it to cope with the fast pace of electronic

publication. This will become especially true if or when proposals that species be 'published' directly into online knowledge bases rather than in traditional journals are considered seriously. In such cases, we should be prepared to pass judgement on individual species as they appear. The community also needs to critically assess what it expects from peer reviewers. With telemicroscopy, it soon will be possible for reviewers to examine even single specimens in real time and compare them with the submitted description. On the other hand, a case can be made that peer review is inherently ill-suited to descriptions of new species and that some system of post hoc review is more appropriate, with the collection of additional specimens or characters automatically triggering a reassessment of the status of proposed species. These are all issues known well to the taxonomic community. It is the speed of online publishing and the urgency of providing up-to-date taxonomic information to environmental scientists that suggests improvements. As an intermediate step, efficiencies can be added to how taxonomic information is published in online journals and how those texts are linked to further information such as image archives. Ultimately, descriptive taxonomy is likely to migrate from traditional publication format to dynamic online knowledge bases in which data are accessed by users to perform real-time analyses or summaries such as distribution maps, checklists, cladistic analyses, etc.

Reduce regulatory impediments for scientific (non-commercial) collecting

Understanding species diversity can no more be accomplished within the artificial borders of a country than the understanding of plate tectonics. Well-intentioned safeguards against bio-piracy have backfired in respect to biodiversity exploration and conservation (Wheeler, 2009). In order to corroborate species and make them identifiable, taxonomists must compare material collected throughout the range of an entire clade, sometimes worldwide. New understandings articulated in the Nagoya Protocol (see http://www.cbd.int/abs/text/) have the potential to help in this regard as do long-term institutional relationships between collection institutions worldwide. Legal safeguards should protect the property rights of sovereign nations while at the same time opening borders for fundamental species exploration. Improved taxonomic knowledge will allow for more effective management of resources within countries while allowing taxonomy in general to advance. There needs, however, to be a quid pro quo between developed and developing nations. In exchange for opening ecosystems to exploration, all that is learned, all observations, specimens and properties of species discovered, must be returned to the country of origin and its citizens and scientists through comprehensive, open-access knowledge bases. Success in overcoming regulatory obstacles ultimately relates to values and how we see the relationship between the biosphere and humanity as a whole (Wilson, 1984; Vane-Wright, 2009).

Create international, inter-institutional collaborators' network

The revision and monograph have for centuries been the gold standards of excellence in taxonomy by virtue of their comprehensively comparative contents and cyclic critical testing of known species. They have also served as the traditional high-throughput methodology due to the efficiency of comparing a large number of species simultaneously. A challenge to the taxonomic community is to preserve the best aspects of such scholarly studies while compressing the time frame for testing species hypotheses and describing new species. Revisions in hyper-diverse taxa may only happen once or twice per century, a rate of hypothesis testing untenable in a biodiversity crisis. By building a new research platform based on cyberinfrastructure, it is conceivable that experts distributed in many countries and institutions can work efficiently together in a 'classificatory commons' where taxonomic decisions and advances happen over hours or days instead of decades. Most of the infrastructure required to enable this kind of electronic real-time monography exists.

Mine collections for new species

Thousands of species new to science sit undescribed in our herbaria and natural history museums (Bebber *et al*., 2010). Several steps should be taken to translate these specimens into biodiversity knowledge by including them in revisionary studies, creating digital images of 'unknowns' that can be examined by experts online, increasing the frequency with which such backlogs are either loaned to experts or experts invited as visitors to collections.

Maximize efficiency of taxonomic practices

Social scientists, industrial engineers and project managers should be engaged in a critical assessment of every facet of species exploration to assess workflow, workforce deficiencies and optimal strategies to advance knowledge toward the ultimate goal of the mission: a comprehensive inventory of the planet's species.

What are the Probable Impacts on Science and Society?

The impacts of charting the species of the biosphere would be immediate, enduring and far-reaching (for examples, see Fig. 1 and Appendices A and B [see supplementary material which is available on the Supplementary

tab of the article's Taylor & Francis Online page at http://dx.doi.org/10.1080/14772000.2012.665095]). For science, the benefits include three broad categories. First is environmental biology by creating baseline data on species occurrences. Ecologists would be able to identify any species at any study site, retrieve knowledge of its role in the ecosystem, and compare local observations and experimental results with those from other parts of its geographic range. Ecosystem scientists would be able to fine-tune predictions about species interactions and ecosystem models could be scaled to much finer-grained levels. Conservation biologists would be able to more efficiently recognize threatened species, assess and prioritize places and ecosystems for conservation, and track the local increase or decrease in biodiversity (Stuart *et al*., 2010). We have mentioned the emerging capacity of systematics collections to address a vast array of biodiversity questions as a result of their digitization. While such data have limitations due to their non-systematic collection (Graham *et al*., 2004), they have the advantage of extending point occurrence records of species into past historic times.

Second is evolutionary biology. Our understanding of the history of the origin and diversification of life on our planet is in its infancy, with most of the story of evolution untold. The best evidence of the history of life on earth is told in the genomes and phenotypes of its species, soon to be diminished by the biodiversity crisis. The best assurance of continued growth of evolutionary knowledge is gained by development of collections as reflections of the species and phylogenetic diversity of life. Cladistic analyses and theories about evolutionary patterns and processes will advance time and again as additional data and alternative interpretations of facts are advanced. That is why natural history collections, as permanent physical evidence of the results of evolutionary history, are invaluable to our continued exploration of the biosphere. Such collections preserve records of times, places, circumstances and species that may no longer exist. The ideal ultimate aim of natural history collections should be nothing less than a comprehensive record of species diversity, mirroring in breadth and detail the full phylogenetic diversity of life on earth.

Given that we know fewer than one quarter of all eukaryote species (Chapman, 2009; Costello *et al*., 2011; Mora *et al*., 2011), what are the chances that the best model organism has been found for any particular biological question? A historical-evolutionary frame of reference is essential for deep understanding of biological processes and the origins of most phenomena studied by experimental biology. Similarly, it is a combination of macroecology and historical biogeography, based on phylogenetic patterns, that helps account for the distribution and co-occurrences of species we see today. Charting species and placing them in a predictive phylogenetic classification will mean that every biologist can efficiently explore the best model organisms to pursue a line of inquiry.

Third is biomimetics. At scales from nano (Mao *et al*., 2003) to macro (Benyus, 1998), among species are found evidence of varied evolutionary solutions to the practical problems associated with life. Through detailed descriptions of species, predictive classifications, reliable binominal identifiers and up-to-date databases, scientists, engineers and designers can find answers, clues and inspiration in biodiversity from architecture to chemistry (Dujardin & Mann, 2002; Turner, 2007; Valdes & Valdes, 2010). Such applications of knowledge of species blur the distinction between benefits to science and society. Examples are as numerous and diverse as species themselves.

Humans face the same survival challenges repeatedly met by other species and can learn from their innovations. Turning to evolutionary answers often has the added benefit of directing us toward sustainable alternatives. As we learn more species, the rate, number and diversity of such discoveries will increase. Which and how many discoveries ultimately make it to market is less important than that humanity has options for problem-solving. A few recent reports illustrate potential benefits to society from unlikely places: a protein in the mucus of the vineyard snail that is a potential adhesive (Li & Graham, 2007); colour-changing sweat of the hippopotamus that has both sunscreen and antibiotic properties (Saikawa *et al*., 2004; Hashimoto *et al*., 2007); the use of bacteria to remove hydrocarbons from contaminated soil (Teng *et al*., 2010); and renewable plant-based fibres being developed into new classes of bio-composites as alternatives to current petroleum-based materials (Mohanty *et al*., 2002).

Increase public awareness of biodiversity and species exploration

- Fifty grand challenges.
- Biome blitzes.
- Collection cannonades.
- Biodiversity national treasure.
- Top 10 new species.
- State of Observed Species (SOS) Report.
- Museum exhibits.

How can we galvanize public opinion?

Few people are aware of just how little we know about life on earth. Even among those who care deeply about the environment, ecological services and Nature in general, most would be shocked to learn how many species are unknown to science, including most of the species that we hope to conserve and the majority of species necessary for the sustainability of natural ecosystems. In order to build and sustain public support for the investments necessary in workforce, cyberinfrastructure, collections and collaborations, it is vital that

plans for the mission include frequent sharing of discoveries and possibilities with the public. Some possibilities for increasing public awareness follow.

Fifty grand challenges. The community should identify 50 major questions or challenges for which solutions require taxonomic information or knowledge. This would graphically illustrate the relevance of taxonomy to other communities, build important partnerships and attract funding from diverse sources. As one example, the National Institutes of Health could lead an exploration of every species living or feeding in or on the human body, from viruses to symbionts, parasites and vectors. This could be a fascinating compendium, particularly with an adequate sample of variation across human populations and geographic regions (e.g. Arumugam *et al*., 2011; Zimmer, 2011).

Biome blitzes. Focusing bio-blitzes, that is, intensive 24-hour events that seek to collect and highlight as many species as possible in a single location is a powerful mechanism to attract local media attention, heighten awareness of the natural environment nearby, and illustrate how many species can be seen in one day. Comparing qualitative and quantitative results would emphasize the ecological diversity of the biosphere. Bio-blitzes have already proved successful in engaging people in many countries, but long term results in terms of sustained interest in and commitment to biodiversity will need time to tell.

Collection cannonades. Analogous to a bioblitz in a living system, we recommend that taxon specialists converge upon collections in herbaria and natural history museums (this might involve a lot of taxon experts over a short period of time, or an unbroken chain of teams of experts in rapid fire focusing on one taxon after the next) to sort through the backlog of unidentified specimens in search of new and rare species. Bebber *et al*. (2010) have demonstrated the fruitful promise of such work. This would be of great local media interest, too, and make the public more aware of the rich contribution of botanical gardens and museums to species exploration.

Biodiversity national treasure. Another option could involve focusing the world's attention on one relatively well-known, small nation in an attempt to rapidly bring its flora and fauna close to encyclopaedic knowledge. The most obvious choice would be the UK which has world-class infrastructure and in-country expertise, many taxa that are already well known and excellent existing literature and collections. Experts on well-known taxa could focus on expanding knowledge through more thorough inventories, DNA barcoding or other activities, while experts on less-well-known taxa would focus on recognizing species new or new to the UK. It may be observed that the majority of the top 100 ecological questions proposed for the UK (Sutherland *et al*., 2006) depend on some level of taxonomic information in order to be answered. Such a comprehensive national inventory would then serve as a model for others.

Top 10 new species and SOS reports. A collaboration among the International Institute for Species Exploration (IISE), International Plant Names Index (IPNI), *Zoological Record*, the International Commission on Zoological Nomenclature (ICZN) and the *International Journal of Systematics and Evolutionary Microbiology* has resulted in two awareness-raising activities that can play an important PR role in the mission. First is an annual list of the Top 10 new species selected by an international committee of taxonomists (currently chaired by Dr Mary-Liz Jameson, Wichita State University) and aimed at highlighting the most surprising and fantastic among thousands of new species. Second is an annual *State of Observed Species* (or SOS) *Report* (e.g. IISE, 2012) that summarizes the new species reported for the most recent calendar year for which data have been compiled. Both have attracted national and international print and broadcast media attention.

Museum exhibits. Every local museum and botanical garden supporting scientists engaged in species exploration should create public exhibits that highlight the latest discoveries made by their staff. Among the millions of visitors to collections-holding institutions each year, few realize that research collections exist behind closed doors or that species exploration science is happening on site. Such exhibits are low cost and high impact for a local audience.

Costs

We did not estimate the cost for the proposed 50-year project at the workshop because costs will be determined by strategic decisions made at the outset of the mission. The greater the initial investment in cybertaxonomic tools and infrastructure, the greater the efficiencies and the lower the per-species cost of discovery and description. Carbayo and Marques (2011) estimated that the cost of describing about 5 428 000 animal species will be about US $263.1 billion. This assumes no investment in modernizing infrastructure and seems excessively high.

By comparison, consider the following scenario based on the 2000 taxonomists mentioned above as the minimum workforce to achieve the 50-year goal. If each were paid $100 000 per year and provided with three support staff (each paid $50 000), we arrive at a personnel cost total of $500 million per year and a productivity of 200 000 species per year. Doubling this number to allow for investments in cyberinfrastructure (that would further lower the per-species cost) and growth of collections to $1 billion per year still falls far below the Carbayo and Marques (2011) estimate. These expenses would not all fall de novo to the

collective project, of course, since many experts are already salaried and many institutions and government agencies could be expected to fund aspects of the mission relevant to their goals. And these investments would be spread across many nations and funding sources.

We emphasize that not knowing species comes with a high price tag, too (TEEB, 2010). The US Geological Survey estimates the annual environmental, economic and health-related costs associated with 6500 invasive species to be about US$130 billion, exceeding those of all other natural disasters combined (http://ecosystems.usgs.gov/invasive/). One uncorrected 80-year-old mistaken species identification is leading to the possible extinction of a commercially important fish species (Iglésias *et al*., 2009). And unreliable taxonomic information carries enormous risks for agriculture, environmental biology and conservation in general (Miller & Rossman, 1995; Mace, 2004).

There is perhaps an even greater cost associated with lost opportunities. From biomedicine to architectural design, time and time again Nature yields processes, structures and materials inspiring new and sustainable solutions to environmental problems. How might we better avoid negative impacts of environmental change or biodiversity loss if we have access to full and reliable information about what species exist to begin with? How many solutions to scientific, engineering, manufacturing and design problems (Benyus, 1998) will disappear before we have discovered them?

Conclusions

Participants in the 'Sustain What?' workshop concluded that the time for exploring Earth's species and mapping their distribution in the biosphere has arrived. Building on the strength of existing data, collections and expertise, and leveraging recent advances in technology, we concluded that an all-out effort to explore, discover, describe, classify and map the species of our planet is within reach with comparatively modest investments. To maximize the rate of progress and breadth of benefits of such a mission, we strongly recommend that this massive-scale mission be planned in partnership with experts from diverse fields of engineering, science, social science and humanities. Strategic investments in workforce, collections, cyberinfrastructure, methodology and planning can make it possible to describe 10 million species in less than 50 years, to vastly enrich and expand the environmental and evolutionary sciences, and to return unlimited dividends to society in innovative solutions to countless challenges. We recommend the formation or identification of a guiding organization or organizations, to drive the planning process. An essential subset of this biosphere mapping mission must involve inter-institutional and international coordination across the collections and taxonomic research communities to focus specifically on the workforce and infrastructure needs to deal with descriptive taxonomic components of the mapping project. Considering the magnitude of the biodiversity crisis, threats of climate change and richness of innovations that are the result of nearly four billion years of evolutionary adaptation, undertaking such a massively comprehensive exploration of the biosphere could not come at a better time for science or society. Scale of and return on investment compares favorably or exceeds that of other "big science" such as NASA's request for $5 billion to address enduring questions about space or the $4.2 billion price tag of the Large Hadron Collider. Were the entire cost of our project borne by the U.S. it would cost less than the equivalent of one pint of beer per day per person. We cannot imagine a more timely nor important investment, or any competing science project with the capacity to deliver so many immediate and lasting dividends.

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