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Biodiversity Loss and the Taxonomic Bottleneck: Emerging Biodiversity Science

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SPECIAL ISSUE

Global changes in terrestrial ecosystems

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Biodiversity loss and the taxonomic bottleneck: emerging biodiversity science

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Abstract Human domination of the Earth has resulted in dramatic changes to global and local patterns of biodiversity. Biodiversity is critical to human sustainability because it drives the ecosystem services that provide the core of our life-support system. As we, the human species, are the primary factor leading to the decline in biodiversity, we need detailed information about the biodiversity and species composition of specific locations in order to understand how different species contribute to ecosystem services and how humans can sustainably conserve and manage biodiversity. Taxonomy and ecology, two fundamental sciences that generate the knowledge about biodiversity, are associated with a number of limitations that prevent them from providing the information needed to fully understand the relevance of biodiversity in its entirety for human sustainability: (1) biodiversity conservation strategies that tend to be overly focused on research and policy on a global scale with little impact on local biodiversity; (2) the small knowledge base of extant global biodiversity; (3) a lack of much-needed site-specific data on the species composition of communities in human-dominated landscapes, which hinders ecosystem management and biodiversity conservation; (4) biodiversity studies with a lack of taxonomic precision; (5) a lack of taxonomic expertise and trained taxonomists; (6) a taxonomic bottleneck in biodiversity inventory and assessment; and (7) neglect of taxonomic resources and a lack of taxonomic service infrastructure for biodiversity science. These limitations are directly related to contemporary trends in research, conservation strategies, environmental stewardship, environmental education, sustainable development, and local site-specific conservation. Today's biological knowledge is built on the known global biodiversity, which represents barely 20% of what is currently extant (commonly accepted estimate of 10 million species) on planet Earth. Much remains unexplored and unknown, particularly in hotspots regions of Africa, South Eastern Asia, and South and Central America, including many developing or underdeveloped countries, where localized biodiversity is scarcely studied or described. "Backyard biodiversity", defined as local biodiversity near human habitation, refers to the natural resources and capital for ecosystem services at the grassroots level, which urgently needs to be explored, documented, and conserved as it is the backbone of sustainable economic development in these countries. Beginning with early identification and documentation of local flora and fauna, taxonomy has documented global biodiversity and natural history based on the collection of "backyard biodiversity" specimens worldwide. However, this branch of science suffered a continuous decline in the latter half of the twentieth century, and has now reached a point of potential demise. At present there are very few professional taxonomists and trained local parataxonomists worldwide, while the need for, and demands on, taxonomic services by conservation and resource management communities are rapidly increasing. Systematic collections, the material basis of biodiversity information, have been neglected and abandoned, particularly at institutions of higher learning. Considering the rapid increase in the human population and urbanization, human sustainability requires new conceptual and practical approaches to refocusing and energizing the study of the biodiversity that is the core of natural resources for sustainable development and biotic capital for sustaining our life-support system. In this paper we aim to document and extrapolate the essence of biodiversity, discuss the state and nature of taxonomic demise, the trends of recent biodiversity studies, and suggest reasonable approaches to a biodiversity science

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to facilitate the expansion of global biodiversity knowledge and to create useful data on backyard biodiversity worldwide towards human sustainability.

Keywords Biodiversity · Ecosystem services · Backyard biodiversity · Biodiversity science · Applied taxonomy

Introduction

Humans are now a dominant force in restructuring the Earth's biosphere (Vitousek et al. 1997; Botkin et al. 1997; Mac et al. 1998; Heinz Center 2002; Turner et al. 2004; Musser 2005; Dobson 2005; Worldwatch Institute 1984–2005). The human population, which continues to grow by an annual rate of 90 million, could reach 9 billion or more by the middle of the twenty-first century (Cohen 1995, 2005). Humans are rapidly overtaxing natural resources, consuming a disproportionate amount of the Earth's primary production, and transforming native environments into human-dominated landscapes (e.g., Vitousek et al. 1997; Jeroen et al. 1999; Imhoff et al. 2004). The environmental impacts of human activities are apparent throughout the world, and include dramatic changes in patterns of species composition, abundance, and diversity of organisms in various ecosystems (Heywood 1995; Raven 1997; Kim 1998; Stenseth et al. 2002; Heinz Center 2002; Dirzo and Raven 2003; Turner et al. 2004; MEA 2005; Brown 2006; Biesmeijer et al. 2006). These unprecedented changes to biodiversity, referred to by Dirzo and Raven (2003) as the sixth great extinction in the history of life on Earth, include both the extinction of species at the global level (Mittermeier et al. 2000; Myers et al. 2000) and the loss (i.e., extirpation) and introduction of species on a smaller, more local, scale (Daily and Ehrlich 1995; Ehrlich 2004; Sodhi et al. 2004). Such changes contribute to biotic homogenization—the increase in the similarity of biodiversity pattern among locations—which may have considerable secondary economic impacts (Mooney et al. 2004; Ehrlich and Ehrlich 2004; MEA 2005; Olden and Rooney 2006; CBD 2006a, 2006b).

Why should we be concerned about changes in biodiversity patterns? Many who view humans as the most unique and successful species in all of biodiversity's history would arrogantly argue that we have a right to use other organisms as needed for our survival. They might suggest that changes to biodiversity patterns are a necessary by-product of the growth in the human population and its economic activities. Modern technology, particularly satellite technologies and computer models, has enabled contemporary ecology to study global changes in the Earth's systems and the effects of humans on these systems (Dirzo and Loraeu 2005; Schlesinger 2006). Yet, we must also seek to understand how localized, "on-the-ground" human activities (that can lead to global changes) affect smaller-scale biodiversity patterns in order to provide the information needed to guide local management of ecosystems by local human communities at the grassroots level (Rooney et al. 2006; Loraeu et al. 2006; Holt 2006; Nature Editorial 2006). Such enterprises require knowledge derived from site-specific, species-by-species, biodiversity studies focused on particular focal communities. Current trends in taxonomic and ecological science do not reflect this need, suggesting a key gap between science and its application to the sustainable management of local biodiversity resources.

The human species, *Homo sapiens* Linnaeus, like any other species cannot survive alone, independently of its interactions with other organisms. Edward O. Wilson coined the word biophilia to describe humans' "innate tendency to be attracted by other life forms and to affiliate with natural living systems" (Wilson 1984, 1989, 2002). Biophilia implies "a human dependence on nature" (Kellert and Wilson 1993) and the fates of other species cannot be considered completely separate from our own sustainability. The diversity of living plants, animals, and microorganisms is an essential resource for humans because other organisms provide food, medicine, clean water, and air, places for recreation, and other such ecosystem services (e.g., Solbrig et al. 1994; Daily 1997; Grifo and Rosenthal 1997; Kim 2001; Field 2001; Giampetro 2004; Kremen 2005). We cannot afford to continually lose our resources and ecological partners, as their loss compromises the stability of ecosystem services and our ecological life-support system (Raven 1997; Lubchenco 1998; Rosenzweig 2003; CBD 2006a, 2006b). In the face of the rapidly increasing human population and associated global environmental changes, innovative strategies are needed to ensure the protection and conservation of biodiversity on our planet (Dower et al. 1997; Scientific American 2005).

Since the 1992 RIO Convention of Biological Diversity (CBD), visionary leaders of the world community (e.g., scientists, policy makers, civic leaders, and the CBD Secretariat) have actively engaged in attending to the need to protect and conserve biodiversity worldwide, while pursuing sustainable development for the world community (e.g., the 1992 United Nations Declaration of the CBD, the Summits on Sustainable Development, the MEA). Specifically, an ambitious target has been set for the year of 2010 to significantly reduce the rate of biodiversity loss at all levels, which should help the world achieve the 2015 targets of the Millennium Development Goals (CBD 2006a, 2006b). These initiatives were designed to help promote the sustainability (i.e., continued existence in a preferred state) of humanity and the myriad species with which we co-inhabit the Earth (Raven 2002; MEA 2005).

The pursuit of a sustainable human society is challenging because the protection of biodiversity is often in direct conflict with human activities (Palmer et al. 2004; Musser 2005). As human populations increase and economic development ensues within a given geographical area, human-mediated transformation of ecosystems generally destroys natural habitats and their biodiversity and also alters ecosystem services without regard for the consequences of their loss in the immediate and distant future (Balmford et al. 2002; CBD 2006a, 2006b). Humanity, at global and localized scales, is challenged to redirect demographic and land-use patterns toward avoiding continued negative changes in local and global biodiversity and ecosystems, i.e., to avoid irreversible destruction of our life-support systems (MEA 2005; CBD 2006a, 2006b). This challenge requires the involvement of no less than each and every one of us concerned about the future of humanity and the biosphere (e.g., Ehrlich and Wilson 1991; Kim and Weaver 1994; Wilson 2002; MEA 2005; Brown 2006).

The issues

Considering the rapid increases in human population and urbanization, the pursuit of human sustainability requires adoption of new conceptual and practical approaches to refocus and energize the study of biodiversity. The scientific study of biodiversity, including its conservation, management, and relationships with ecosystem services, is encompassed by many areas of biology, but especially taxonomy and ecology (Eldredge 1992; Savage 1995; Gotelli 2004). Ecologists and taxonomists have made substantial progress in recent decades in increasing knowledge about biodiversity patterns and ecosystem processes (e.g., Eldredge 1992; Savage 1995; Palmer et al. 2004; Kremen 2005; Hooper et al. 2005). Yet, the capacity of taxonomists and ecologists to advance our knowledge and gather the necessary information about biodiversity, as well as the training of biodiversity-related scientists in institutions of higher learning has been hindered for the following key reasons:

(1) Current biodiversity strategies are often overly focused on research and policy at the global scale, which may have little relevance to, or impact on, studies and conservation of localized (i.e., kilometer-scale) biodiversity patterns.
(2) Our knowledge base of extant global biodiversity is embarrassingly small, perhaps less than 20% of the species on Earth.
(3) There is a lack of site-specific data on local biodiversity and species composition of habitat communities, which would be needed for ecosystem management and conservation practices.
(4) Many studies of biodiversity patterns and of the impacts of humans on ecosystems lack taxonomic precision and rigor and rely on misguided use of taxonomic surrogacy (i.e., there is a lack of reliable species identification) (Bertrand et al. 2006).
(5) The number of trained and practising taxonomists is declining worldwide (a taxonomic bottleneck) at a time when demands for taxonomic science are increasing.
(6) The resources (e.g., museum collections) and educational infrastructure for training new generations of taxonomists is in decline, which hinders the advancement of biodiversity science.

These six limitations are directly related to contemporary trends in research, conservation strategies, environmental stewardship, and environmental science education. Current research emphasis is directed at global trends and patterns of biodiversity without specific reference to local-scale patterns, especially in human-dominated landscapes. Today's biological knowledge is based on less than 20% of the commonly accepted estimate of 10 million species on planet Earth. Thus, ‘‘backyard biodiversity’’, defined as biodiversity that exists in areas of human habitation, needs to be explored, documented, and conserved as it is the backbone of sustainable economic development for all countries around the world, especially those that encompass ‘‘biodiversity hotspots.’’ Much biodiversity conservation policies and planning is likewise based on general knowledge derived from global trends and patterns without realistic programs for grassroots movements. However, taxonomy, a key science needed to help document and describe unknown species, has declined precipitously over the past several decades and has now reached a point of nearing complete demise. There are very few professional taxonomists and trained local parataxonomists worldwide, despite the fact that the demand for taxonomists and the need for taxonomic data for use by ecologists, conservation biologists, and natural resource managers is rapidly increasing. In addition, systematics collections, the core of material information on biodiversity, are being increasingly neglected and orphaned, particularly at institutions of higher learning, perhaps in part because large parts of these collections lack species identification (due to lack of taxonomic expertise) and are of no use to science.

In light of the limitations recognized here, we discuss the essence and complexity of biodiversity and the issues surrounding these limitations. We then offer possible conceptual and methodological solutions that will help advance the study of biodiversity and ecosystem services so that biodiversity scientists can maximize their contribution toward the development of sustainable human societies. We also introduce a perspective of biodiversity science that integrates taxonomy, ecology, and conservation to explore, document, study, and conserve biodiversity. As biodiversity is a critical natural resource that provides biotic capital for human societies, we must consider a business-like approach to providing necessary taxonomic services, namely an Integrated Biodiversity Assessment Center (IBAC), with a specific focus on backyard biodiversity, which is urgently required in underdeveloped and developing countries where most biodiversity hotspots are located (Reid 1998; Kim 2005b). Such centers networked throughout the world should facilitate biodiversity research and education and thus help advance biodiversity science, expand our knowledge of backyard biodiversity, and enrich the core of our understanding of global biodiversity.

The essence of biodiversity

Global biodiversity issues in developed countries, particularly western industrialized nations like the United States, are far removed from the daily lives of most people in developing and underdeveloped countries and the concerns of their political leaders. Therefore, they may not think of biodiversity as something to be deeply concerned about (Biodiversity Project 1998, 2002; Turner et al. 2004; Miller 2005). To viewers of the Discovery Channel, biodiversity loss may be equated with endangered charismatic mega-fauna such as pandas or Siberian tigers. To schoolchildren, biodiversity signifies the rapidly declining tropical rain forests. To many landowners, biodiversity is anathema because it represents issues associated with conservation legislation (e.g., the United States Endangered Species Act) and threats to private land-ownership. Even in the scientific and conservation community, biodiversity is often discussed in abstract, nebulous terms as something that is to be conserved but with only superficial understanding of what species are present at a location, how they interact and affect ecosystem services, and how backyard biodiversity relates to the environment and local economy. Because of these factors, the public may be left with a general impression that biodiversity is a feel-good, aesthetically driven, academic buzzword that has little relevance to everyday human lives. Nothing could be further from the truth (CBD 2006a, 2006b). It is therefore important that current knowledge about the critical importance of biodiversity is communicated to people around the world in more effective and creative ways (Kim 2001).

Biodiversity is defined as the total variety of life (i.e., all species of plants, animals, fungi, and microbes) including genetic, population, species and ecosystem diversity, and the ecological roles and interrelationships (e.g., predator–prey) among organisms in biological communities. Biodiversity is a concept that encapsulates both organisms that can be observed as well as the intricate web of species interactions and ecosystem processes that we cannot see (Pimm 1991; Hooper et al. 2005). Despite the fact that humans use natural products and services derived from biodiversity, the general public may not understand the importance of biodiversity to humanity because of its somewhat fuzzy, unobservable enigmatic aspects. It may be more pragmatic for education programs to emphasize what we view as the essence of biodiversity: its inherent, multidimensional complexity across space and time (i.e., biodiversity as part of complex ecosystems; Levin 2005). This might help shift the focus of biodiversity discussions away from individual species toward appreciating the importance and ecosystem consequences of diverse webs of interacting species for humanity and sustainable development.

Today's biodiversity is the end-product, and also the continuum, of the long evolutionary processes that have provided humans with natural resources (i.e., capital) for ecosystem services and economic enterprises. The pattern–process complexity that provides the essence of biodiversity is awe-inspiring as a scientific concept and physical reality, and has given rise to a diversity of interpretations and perspectives regarding its definition, measurement, importance, and conservation (e.g., Gaston and Spicer 2004; Hooper et al. 2005; Wilson et al. 2006). Setting semantic and conceptual debates aside, it is now well understood that biodiversity determines the structure and function of ecosystems and, conversely, that ecosystem structure and function determine patterns of biodiversity (e.g., Prugh 1995; Naheem and Li 1997; Redford and Richter 1999; Ricklefs 2004; Hooper et al. 2005; Lovelock 2005; Levin 2005). In other words, patterns of biodiversity are related to ecosystem processes and services, which in turn are intricately linked to the condition of the entire Earth system by which human-mediated global changes to biodiversity patterns can translate into loss of ecosystem services (Pimentel et al. 1997; Raven 2002; Imhoff et al. 2004; MEA 2005).

Backyard biodiversity from a global perspective

Our definition of biodiversity is explicitly silent about the scale of its scope because biodiversity patterns can be examined at any spatial and/or temporal context. When discussing it in any specific context, biodiversity must be defined explicitly by the space and time over which biodiversity patterns can be examined since different patterns can be observed and different interpretations made about them at different scales (Wilson and Peter 1988; Dirzo and Raven 2003; Ricklefs 2004). Here, we are concerned with two spatial scales: global and local. Global biodiversity refers to the totality of biodiversity on planet Earth, its patterns of distribution, and changes within and among continents and oceans. This scale has been the focus of extensive research, discussion, and conservation planning, which provide an indication of the state of global changes in global biodiversity and the biosphere, and identify and predict potential causes and dangers (e.g., Constanza et al. 1997; Dirzo and Raven 2003; Ricklefs 2004). In contrast, local biodiversity, which usually has unique features relevant to the grassroots, represents the localized biodiversity and species composition of spatially defined communities at or near sites of human habitation. In reality, therefore, the management of natural resources and the environment from the perspective of biodiversity and ecosystems has to be site-specific and relevant to local economic well-being and environmental stewardship.

Backyard biodiversity highlights the importance of appreciating local biodiversity patterns on a scale where human activities ultimately determine local ecosystem services and, in turn, the economic well-being of human populations (Lundmark 2003). In addition, backyard biodiversity emphasizes the importance of local-scale grassroots conservation efforts and their leadership in ultimately determining the priorities and effectiveness of biodiversity conservation efforts (Schwartz et al. 2002; Mascia et al. 2003; Berkes 2004). This concept also recognizes the diversity of organisms inhabiting the spatial scales encompassed by people's private properties, neighborhoods, and local municipalities (i.e., villages, cities). All these perspectives are relevant to the local needs, culture, and land-use regulations pertaining to the human populations that share the same location with species comprising backyard biodiversity (Center for Wildlife Law 1996; Farber et al. 2006).

Although conservation plans and policies are usually developed at global or national levels (WRI, IUCN, UNEP 1992; Alcorn 1993; Center for Wildlife Law 1996; Schwartz et al. 2002; Broberg 2003; Berkes 2004; Ricklefs 2004; CBD 2006a, 2006b), biodiversity conservation and ecosystem management must occur at a local scale where factors related to the local human population (e.g., local politics and attitudes) are more effectively understood and addressed. Because of the predominant focus on biodiversity issues at a global or, perhaps more often, country level, local-scale conservation and ecosystem management efforts can be shortchanged, and often lack the required resources and technical guidance. (However, this point is not meant to discount the ingenuity and creativity of many successful smaller-scale conservation efforts that have progressed without professional technical assistance, especially in developing or underdeveloped countries.) In most locations around the world, there is practically no information about backyard biodiversity patterns, particularly in human-dominated (i.e., agricultural and urbanized: Schwartz et al. 2002; McKinney 2002) ecosystems, as well as in areas that have been the focus of global conservation efforts (i.e., biodiversity hotspots: Myers 1988, 1990; Myers et al. 2000; Mittermeiyer et al. 2000). In general, however, current trends in biodiversity science and conservation efforts suggest that the future prospects for activities aimed at studying and documenting biodiversity at the backyard and grassroots levels, which are needed for the development of sustainable ecosystem management practices, are not very good.

Applied taxonomy and shrinking biodiversity

Discovery of new plant and animal species continues to be hyped widely by the news media throughout the world. These discoveries have generally been made in different parts of the world during special expeditions, led usually by western scientists (e.g., MONGABAY.COM 2006). Reading about these discoveries helps remind us that most of the Earth's extant biodiversity is unexplored and undescribed (i.e., an estimated 5–30 million species; Groombridge 1992; Hammond 1995; Heywood 1995). Our current knowledge about global biodiversity (i.e., 1.75 million named and described species) represents the cumulative efforts of taxonomists, ecologists, and natural historians working over approximately three centuries. Using 10 million as a reasonable intermediate estimate, an average of ~7,000 species have been described per year since the time of Linnaeus (1707–1778), the father of taxonomy, who established the binomial classification system (Linnaeus 1751, 1758). At this rate of species description, it will take another 1,429 years to complete the documentation of 10 million species.

Because so many species remain undescribed and unstudied, our current biological knowledge base is derived from perhaps less than 20% of the extant global biodiversity on the planet. To our chagrin, this fact too often goes unacknowledged or completely ignored among biologists. Is this knowledge base sufficient to advance scientific understanding and sustainable management of the living world and meet the needs of rapidly expanding humanity? Our answer is an emphatic No! The current knowledge base of global and backyard biodiversity is too meagre and is badly in need of rapid expansion. Yet, the very science fundamental to the study of biodiversity—taxonomy—has been in decline for the last three decades, and remains in a state of deterioration.

Taxonomy (or systematics) is the fundamental discipline of biology dedicated to the description, naming, and cataloging of organisms and their relationships (Mayr and Ashlock 1991; Knapp 2000; Wheeler 2004; Wheeler et al. 2004). Taxonomy provides identities and names for newly discovered organisms, which provides a central framework for the discipline of biology (i.e., organization of biological knowledge) and offers key tools for the identification of all known organisms, which other biologists, primarily taxonomists in practice, can use to facilitate dissemination of their study subject and better communicate about the organisms with which they work (Savage 1995). In addition, taxonomists have also contributed to fundamental natural history knowledge of species, which facilitates studies by other biologists and environmental scientists. The Linnean revolution had an enormous positive impact on the description of local flora and fauna (Knapp 2000). Throughout the eighteenth, nineteenth, and most of the twentieth centuries, most biologists studied taxonomy and natural history [e.g., Brunfels 1530; Bauhin 1623; Linnaeus 1751, 1758; Fabricius (1745–1808), cited in Tuxen 1973; Leconte JL (1825–1883), cited in Lindroth 1973]. Throughout the immediate post-Linnean period, species discovery, description, and naming comprised the main focus of biological science, with the completion of comprehensive and detailed monographic works that described major groups of organisms (Tuxen 1973; Lindroth 1973).

With acceptance of Darwinian evolution as a cornerstone of modern biology, taxonomists gradually integrated phylogenetics (i.e., the study of evolutionary patterns) into their objectives such that the naming and classification of species should be based on hypothesized evolutionary relationships. Due in large part to Julian

Huxley's *New Systematics* (Huxley 1940), issues related to the taxonomy of infraspecific groups (i.e., populations), speciation, and phylogenetics became the predominant subjects in systematics (i.e., functional taxonomy), followed by two decades (1960s–1980s) of largely taxonomic methodology (e.g., numerical taxonomy or phenetics and phylogenetic systematics or cladistics), at the expense of fundamental alpha-taxonomy, i.e., the finding and describing of new species (Wortley et al. 2002; Wheeler 2004; Wheeler et al. 2004).

Throughout the last quarter of the twentieth century, alpha-taxonomy declined precipitously in numerous ways compared to its historical prosperity. The financial support and training for, as well as the prestige associated with, alpha-taxonomy has been drastically eroded, a situation dubbed a taxonomic "crisis" or "impediment" (for further discussion see: Wortley et al. 2002; Hopkins and Frekleton 2002; Wheeler 2004; Wheeler et al. 2004; Sodhi et al. 2004). This erosion involves broad aspects of systematics and taxonomy related to basic research, biodiversity inventory, education at all levels, and availability of professional employment and other research support. Particularly troubling is the rapid decline in the number of practising taxonomists, particularly for insects and related arthropods (Gaston and May 1992). A recent estimate suggests that the number of professional taxonomists worldwide is only 4,000–6,000 (Haas and Häuser 2006), a number certainly too low to deal with the some 8 million-plus undescribed species on Earth. As we have seen at many institutions of higher learning, the reduction in educational requirements for taxonomy and natural history training in college undergraduate and graduate curricula is producing many bright biologists who are knowledgeable about molecular biology, genetics, and perhaps phylogenetics but who have little understanding of species concepts or basic methods for classifying and identifying organisms. Thus, a whole generation of biologists is now ill-prepared to grapple with the tasks of naming, describing, and identifying species at the level of the whole organism. The contemporary decline in fundamental alpha-taxonomy severely compromises our ability as a community of biologists to continue discovering, describing, and documenting Earth's unknown biota and their ecology (Gaston and May 1992; Savage 1995; Wheeler 2004).

In the last century taxonomy represented the heart of biology and nearly all biologists were fluent in taxonomy, which invariably advanced biological and taxonomic sciences. At the turn of the twenty-first century, however, science has become an enterprise with responsibilities and greater accountability to the public domain (due, in part, to competition for limited government funding; see Lubchenco 1998; Raven 2002; Palmer et al. 2004). In this era of socially contracted science (sensu Lubchenco 1998), taxonomy has not met the new challenges of biodiversity science and has become marginalized from the rest of biology. As Ehrlich (2005; p 132) aptly pointed out, the major reason that systematics has made little impact on the promotion and conservation of biodiversity is the narrow intellectual perspective of most contemporary systematists on species and biodiversity. Most taxonomists have become accustomed to working on their specialty taxon without concern for relating their work to other disciplines or broader environmental and societal issues. Taxonomy should be reinvigorated and reinvented through collaborative, interdisciplinary research that brings taxonomic insights to bear on topics important to twenty-first century society (e.g., food security, invasive species, and ecosystem services). Furthermore, taxonomic information is crucial to the advancement of community ecology (Gotelli 2004) and research about relationships between biodiversity and ecosystem functions and services (Hooper et al. 2005; Kremen 2005; see below), and can be used to broaden the scope of molecular biology and biotechnology. That fact that taxonomy has not yet been reinvigorated as a central science for the twenty-first century is certainly a limitation to our current progress in understanding the current and future state of life on Earth. There is certainly no question that taxonomy is fundamental to fulfilling science's social contract for contributing to our understanding of biodiversity and its relationships to sustainable development. The key question then is: "how can taxonomy, as a science and practice, be re-born with the vitality it once had" (Godfray 2002; Ehrlich 2005).

Answering this question addresses the way contemporary taxonomists approach taxonomic research and how their research is related to biodiversity and other related sciences. Taxonomists usually study specimen-based taxa at the species level of a higher taxon (i.e., genus or family) from which phylogenetic analyses are conducted and a classification is developed and about which taxonomic monographs or revisions are produced. As such, it is common taxonomic practice to focus on collecting specimens, especially rare ones, for a specific taxon and generally only from limited or known habitats and exotic locations (Ehrlich 2005). Taxonomists, therefore, have historically been interested in collecting or adding new specimens and gathering additional data for completing taxonomic revisions or classification of select taxa. While this work should remain an important objective for taxonomy, such practices have contributed little to the study of backyard biodiversity patterns. Yet, it has been shown that many unnamed or new species can be found in unfamiliar habitats of human-dominated environments, as demonstrated by examples from the state of Maryland and in New York in the United States (see below). Such publicity-garnering discoveries can help foster excitement among taxonomists and the public about looking more closely at biodiversity in our everyday surroundings. Considering the scarcity of knowledge about backyard biodiversity worldwide, taxonomists need to involve themselves in backyard biodiversity studies while pursuing taxonomic descriptions and revisions. Such studies would lend themselves ideally to educational events such as bioblitzes (Lundmark 2003) that engage the public to think about what biodiversity is, why it is important to humanity, the effects of human activities on the environment and, perhaps, but no less important, the inherent beauty, wonder, and complexity of the biosphere. Taxonomists can and should play a major role in reinvigorating biodiversity science by producing taxonomic keys and identification tools for those users who are not taxonomically savvy in conservation and resource management practices, which should benefit all scientists concerned about expanding information on backyard biodiversity (Gotelli 2004; Mace 2004).

Many different proposals have been made over the past two decades about ways in which taxonomy can be rebuilt and reinvigorated (e.g., Gaston and May 1992; Wheeler 2004; Wheeler et al. 2004). However, little impact has been made on limiting the continued decline of initiatives in training and hiring the next generation of taxonomists. At this juncture, taxonomy, as the core of biodiversity science, must be reshaped to meet the challenges of twenty-first century science (e.g., Godfray 2002; Gotelli 2004; Ehrlich 2005). To do so we must focus on the issues concerning the contemporary shortage of taxonomic expertise and trained taxonomists around the world, as the trend of taxonomic decline has now reached a critical point where the lack of contribution from taxonomic science to the study and conservation of biodiversity is now crippling future progress (e.g., Gaston and May 1992; Godfray 2002). This situation may be described as a ''bottleneck'' in which the continued loss of taxonomic experts will severely hinder the training of taxonomists by those most familiar with the history of the discipline. Thus, the key challenge facing biodiversity science today is reinvestment in taxonomy education programs that seek to produce new generations of scientists who are competent in describing and identifying unknown species and who are willing, able, and enthusiastic about collaborating with others in biodiversity research. Furthermore, this challenge should be directed at countries and regions where hotspots of global biodiversity are located, as the backyard biodiversity of these locations has only rarely been studied and described (e.g., Kim 1994; Sodhi et al. 2004; Kim 2005b).

The issues at hand for emerging biodiversity science are serious matters of science, ecosystem management and, ultimately, human sustainability. We must come up with new underlying philosophies and practical strategies to help bring alpha-taxonomy back in line with contemporary scientific perspectives (e.g., Lubchenco 1998; Raven 2002; Palmer et al. 2004). We introduce the concept of ''applied taxonomy'' to describe alpha-taxonomy when it is applied to the study of biodiversity science, specifically when species identification and species-related taxonomic information is utilized for basic and applied ecological and environmental research that seeks to describe biodiversity patterns, human-impacts on those patterns, methods of conserving biodiversity, and the relationships of species to ecosystem functions and services. Applied taxonomy seeks to bring alpha-taxonomy to the forefront of discussion within biodiversity science to acknowledge the contribution of taxonomic databases and knowledge to the study of broad, interdisciplinary issues related to biodiversity. This perspective of applied taxonomy should not only expand our knowledge of global and backyard biodiversity for biodiversity science as a whole but also provides systematics and taxonomists with vigorous opportunity to enrich taxonomic data for better classification and phylogeny. Applied taxonomy also offers a means to develop and support taxonomic technological resources (e.g., internet-based museums and keys) and to maintain specimen-based collections (i.e., museums), which benefit advancement of community ecology (Gotelli 2004) and research into relationships between biodiversity and ecosystem functions and services (Hooper et al. 2005; Kremen 2005).

Ecology and biodiversity

Current trends in ecology and conservation biology indicate that the study of backyard biodiversity has begun and that biologists do need and utilize taxonomic information in their research. Urban ecology is now a rapidly developing field (UNEP 2002; Redman et al. 2004; Heemsbergen et al. 2004; Shochat et al. 2006) and conservation biologists are increasingly recognizing the importance of urbanized landscapes in biodiversity protection (e.g., Schwartz et al. 2002; McKinney 2002; Pellet et al. 2004). All these scientific endeavors require information on the structure and composition of backyard biodiversity, for which taxonomy and taxonomists are needed to systematically explore and document taxa in human-dominated ecosystems. However, contemporary taxonomists are not readily available for such research or local conservation projects. Advancing ecosystem management in urbanized environments demands site-specific biodiversity information for conservation and management guidelines in human-managed habitats and those that face immediate destruction due to human landscape transformation (e.g., national parks and suburban forest remnants) (Kim 2001; Schwartz et al. 2002; Mahan et al. 2004; Turner et al. 2004; Kim 2005a). Inventory of backyard biodiversity offers extraordinary opportunities for taxonomic discoveries, as exemplified by two recent species discoveries in urban environments in the United States: a new earthworm species from Maryland (Czuzdi and Szlavecz 2002) and a new centipede species found in Central Park, New York (Foddai et al. 2003). Additionally, increasing our knowledge of the biodiversity in our backyards would provide enormous insights into the effects of human activities on biodiversity patterns as well as the relationships between biodiversity and ecosystem services.

Ecology, by definition, encompasses the study of biodiversity, particularly at the community and ecosystem level. The range of basic and applied ecological questions that can be asked about biodiversity is bewildering and provides for an exciting area of science (Ehrlich and Wilson 1991; Gaston and Spicer 2004). The ecology of biodiversity can be studied using a variety of perspectives and temporal and spatial scales by evolutionary, genetic, population, community, ecosystem, or landscape approaches. Historically, ecologists studied biodiversity through the rigorous sampling of organisms from natural environments to describe patterns and address specific questions and hypotheses. In recent years, biodiversity studies have become more manipulative through the use of field and laboratory experiments and have also begun to focus on biodiversity in human-dominated ecosystems. Some current research foci includes: (1) describing patterns and mechanisms of global and local species distribution (Ricklefs 2004); (2) estimating species richness in communities through extrapolation of sampled species (Gotelli 2004); (3) examining determinants of community and food web structures (e.g., Straub and Snyder 2006); (4) relationships between biodiversity patterns (e.g., species richness, evenness, and identity) and ecosystem functions (Hooper et al. 2005); and (5) the evolutionary ecology of biodiversity, e.g., speciation, niche construction (Schluter 2001). In addition, but not least in importance, ecologists are increasingly involved in developing research about relationships among biodiversity patterns, human–social systems, and sustainable development (Liu et al. 2003; Palmer et al. 2004; Redman et al. 2004). As such, human-induced changes to biodiversity patterns (e.g., the extirpation and invasion of species) have received a great deal of attention especially as related to the study of ecosystem services (Kellertt 1993; Coleman and Hendrix 2001; Kremen 2005). Rigorous ecological research continues toward understanding the ecology of biodiversity and ecosystem services, as this is considered essential for the development of sustainable human societies (Ehrlich and Wilson 1991; Palmer et al. 2004; MEA 2005). It is critical to recognize that ecological research on biodiversity inherently requires basic taxonomic knowledge generated by taxonomists (Gotelli 2004).

After reviewing current research trends on the ecology of biodiversity, we identified three major areas of limitation that might prevent further developments in biodiversity science, especially concerning the identification of species and understanding the relationship of species to the structure of ecosystems and the services they provide.

First, we know next to nothing about patterns of backyard biodiversity in total and their relationships to ecosystem functions and services. This is largely a historical artifact attributable to a tendency of ecologists to focus on natural systems. Even recent, high-profile ecological studies have been conducted in simplified experimental systems (mostly temperate grasslands) that may have little relevance to more complex human–social systems (see references in Hooper et al. 2005). Such manipulative studies, which are crucial to understanding the ecology of biodiversity, must eventually be translated into field-based in situ studies so that our management of organisms and ecosystems is better informed. Incidentally, this trend is growing in agroecology (Giampetro 2004) and urban ecology (Schwartz et al. 2002; Turner et al. 2004; Shochat et al. 2006). Certainly, ecological research on backyard biodiversity must expand in order to help advance technology for the conservation, restoration, and management of biodiversity in human-dominated ecosystems where local organisms make vital contributions to the maintenance of critical ecosystem services (Palmer et al. 2004; Kremen 2005; MEA 2005).

A second major limitation in most community-scale and biodiversity studies is the taxonomic breadth and depth of the organisms included in them. Ecological research lacks the baseline data on biodiversity and species composition of study sites at community and ecosystem level because biodiversity inventory is not usually included in the research plan. In general most ecological studies include a small number of taxa, often with data reported at the order, family, or, at best, generic level, and address broader "biodiversity" patterns. To validate and illustrate this point, we conducted a literature review of community ecology field studies (focused on invertebrate animals) published in five key ecology journals over 10 years (1994–2004) (L.B. Byrne and K.C. Kim, unpublished manuscript). The majority of studies included less than five orders, with only a handful including less than ten taxa (Fig. 1). Our review showed the apparent negative relationship between number of orders and species included in each study—with few exceptions, studies that included more orders identified a smaller number of species and vice versa. The majority of papers included 1 or 2 orders with less than 200 species and only five papers reported 14 or more orders with more than 200 species (Fig. 1). In these studies, taxonomic scale and depth are limited to the minimal level acceptable to the objectives of each study for which simplified ("standard") techniques are used to

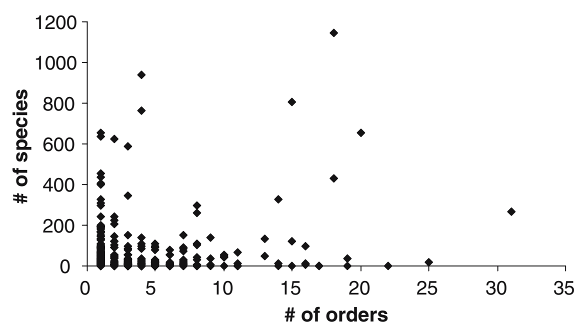

Fig. 1 Scatterplot of number of orders versus number of species within a given field-based study of invertebrate biodiversity. Data were gathered from a literature review of 353 papers published in five journals (*Ecology*, *Conservation Biology*, *Environmental Entomology*, *Agriculture Ecosystems and Environment*, and *Forest Ecology and Management*) over a 10-year period (1994–2004)

collect specimens and samples. It should be pointed out that the narrow taxonomic focus in most biodiversity and community ecology studies prevents development of deeper insights into details about patterns of biodiversity dynamics and ecosystem functions. In taxonomy and biodiversity assessment, species is the basic unit. However, recent studies in biodiversity assessment and measurements have used taxonomic surrogates rather than species (or taxonomic morphospecies, e.g., *Musca* species 1) for methodological and taxonomic expediency. The use of taxonomic surrogacy without care could often result in confusing or ambiguous conclusions (e.g., Warwick and Clarke 1995; Balmford et al. 2000) involving taxonomic and ecological complexity (Bertrand et al. 2006). The lack of taxonomic breadth and depth in many ecology studies represents one of the biggest challenges to advancing integrated biodiversity science. As key proponents of this science, ecologists should strive to be armed with better taxonomic knowledge and skills as gained through coursework and the practice of identifying organisms.

This raises the third issue in ecology that limits its ability to contribute to the development of biodiversity science programs. Contemporary ecologists are not routinely trained in taxonomic methods and in the taxonomy of plants and animals, and thus may not be familiar with the names and natural histories of the organisms of their study site that are not the focus of their research interest. This may also be due, in part, to the general lack of collaboration between ecologists and taxonomists and the absence of the application of taxonomic information to ecological research (see above; Gotelli 2004). As evidence of this disciplinary divide, in the same literature survey described above, we found that only 37% of papers (130 out of 353) reported collaboration between ecologists and taxonomists to identify the studied organisms (L.B. Byrne and K.C. Kim, unpublished manuscript). (We were, however, unable to determine how many of the papers' authors had taxonomic training, although we suspect that it was very few.) Nonetheless, detailed taxonomic and natural history information is certainly essential to the mechanistic understanding of ecological patterns and processes. In short, taxonomy and ecology have a common need for descriptive data about organisms (Gotelli 2004); it is somewhat surprising therefore that practitioners of the two disciplines do not collaborate more often.

Nonetheless, it can be argued that ecologists need taxonomists more than ever. Increasing numbers of community ecology studies suggest that species identities (i.e., community composition) and their natural histories (e.g., feeding rates, dispersal abilities) are more important for determining community structure and ecosystem processes than species richness per se for a wide range of taxa (e.g., bacteria: Cavigelli and Robertson 2000; plants: Symstad et al. 1998; invertebrates: Heemsbergen et al. 2004; Scherber et al. 2006; Straub and Snyder 2006; see also Olden and Rooney 2006; Rooney et al. 2006; Loraeu et al. 2006; Holt 2006). For example, Symstad et al. (1998) showed that the effects of plant biodiversity on ecosystem functioning were variable, and that changes to ecosystem functioning were altered more by removing specific species rather than a particular number of species from the community. Similarly, a study by Scherber et al. (2006) revealed that herbivory rates on plants were independent of species richness in a community but were affected by the presence of certain species. Such studies provide strong support for our contention that taxonomic information is critical to ensuring the rigor of ecological studies and that ecologists should be more aware of the taxonomic nuances of their studies. In light of the dire situation of contemporary descriptive taxonomy and the increasing need for species-level taxonomic information among ecologists, greater integration of taxonomy and ecology should be a priority for both fields with the expectation that both could benefit enormously (Gotelli 2004).

Biodiversity assessment and ecosystem management

Biodiversity provides, as summarized above, natural capital for human economic systems, resources for sustaining our life-support system, and the basis on which the persistence of core ecosystem services rest. These factors provide the rationale for humanity's collective concern about the fate of biodiversity (especially that of our backyards) and its conservation (Rooney et al. 2006). Many contemporary development activities of human societies are clearly not sustainable because of the negative changes they bring to bear on the Earth's systems, biodiversity patterns, and ecosystem services (e.g., Ehrlich 2004; Lovelock 2005; MEA 2005). Thus, global efforts that address humanity's need to conserve and manage biodiversity (exemplified by prolific efforts in recent years by the United Nations, and visionary political leadership throughout the world) are much needed. However, many more efforts focused at the grassroots, local level are also needed to bring forward new paradigms and innovative strategies to minimize destruction of biodiversity on the backyard scale (e.g., Ehrlich 2004; Lovelock 2005; MEA 2005).

Biodiversity conservation is challenging in many locations because it may be in conflict with human goals for land use and economic development. As an example, consider the biodiversity within a forest ecosystem that is located near a village whose residents wish to cut down trees in the forest for lumber to build new houses on the land. In economic terms, the forest yields a service to the villagers in the form of providing lumber—a commodity. However, from an ecological standpoint, the forest is more than just a source of wood. It is an ecosystem containing diverse habitats occupied by perhaps as many as several thousand species. Interactions of all these species among themselves and with physical factors give rise to other ecosystem services provided by the forest ecosystem to the villagers, such as producing oxygen and regulating water flows. By protecting and conserving the trees rather than chopping them down, the biodiversity and ecosystem services yielded by the forest ecosystem are sustained and, as a result, provide future opportunities for selective harvesting of the lumber commodity. In this manner, management of the commodity (i.e., resource) becomes ''ecosystem management,'' the paradigm which now guides natural resource and biodiversity management in many public lands around the world (Grumbine 1994, 1997; Christensen et al. 1996; Salwasser et al. 1996).

Ecosystem management offers holistic perspectives on managing ecosystems and landscapes for sustaining their dynamic ecological functions, productivity, and biodiversity, all of which will ultimately contribute to the well-being of local human populations (e.g., Farber et al. 2006; Fischer et al. 2006). Successful ecosystem management requires detailed data on the species composition at each location as well as species relationships to overall ecosystem structure and services. However, as described above, such information about relationships among all species within an ecosystem and ecosystem services is almost entirely lacking for most ecosystems that need to be managed, particularly in human-dominated ecosystems.

To adopt sustainable ecosystem management practices for a location requires that a great deal is known about the structure and function of the targeted ecosystem unit: (1) what organisms are in these systems (species composition of habitat sites), (2) what roles the organisms play (i.e., their natural histories), and (3) how various human-mediated changes to the systems influence the structure and function of these communities (impact assessment). Few contemporary research topics and educational programs provide the needed framework to generate this required knowledge, which integrates taxonomy, natural history, ecology, and conservation all within a framework of ecosystem management. Therefore, developing successful ecosystem management practices begins with the assemblage, analysis, and synthesis of existing data on geological features (including hydrological and soil patterns), biodiversity, as well as historical human land-use patterns and present and future needs. Integrated layers of ecosystem data can then be generated by such information (e.g., using geographic information systems), in turn providing the scientific basis for ecological classification of study sites, the sampling designs for biodiversity studies, and guidelines for sustainable landscape use. Subsequent ecosystem management thus encompasses three major processes: (1) the inventory process, during which the occurrence and distribution patterns of biodiversity are assessed along with documentation of endangered and threatened species; (2) the monitoring process, during which changes in biodiversity due to human-induced stressors and/or management inputs are evaluated; and (3) the mitigation process, during which changes are made to land-use patterns and management practices to reduce their negative effects on biodiversity and ecosystem services (Mahan et al. 1998).

There is no standardized survey technique currently available for inventory and assessment of backyard biodiversity although there are large volumes of literature on taxon-based inventory and survey techniques used by taxonomists (e.g., Beattie et al. 1993; Stork and Davies 1996; Debinski and Humphrey 1997; Mahan et al. 1998; USGS/DOI 2001). These have been developed by taxonomic specialists, primarily for taxonomic or biogeographic research, using specific collecting or survey techniques suitable for specific taxon (e.g., rapid assessment techniques) that have been successfully utilized throughout the world to discover many new species (MONGABAY.COM 2006). Such methods have provided important taxonomic and distributional baseline data for a specific taxon within specific areas of interest. Such data have enriched the knowledge of taxonomy and systematics for specific taxa but have not contributed much to the broader knowledge base needed for biodiversity conservation and ecosystem management. Most biodiversity inventories conducted to date lack information on all-taxa biodiversity at specific habitats and associated substrata or plant/animal hosts of the species (Baldi 1999). Quite simply, they do not provide a total picture of species composition for a defined community including seemingly obscure in taxa that may be important for maintaining ecosystem structure and function (Kim 1993). Taxon-specific biodiversity inventories that ignore organisms of other taxa such as invertebrates, fungi, and microorganisms are incomplete and can lead to biased application in scientific analysis and incorrect interpretation, leading to erroneous conclusions or conservation actions (Boone et al. 2005).

A thorough assessment of backyard biodiversity as required for rigorous ecosystem management should include: (1) lists and digitized catalogs of resident species with data on ecological associations (which will grow with subsequent surveys); (2) analyses of species presence or absence (with focus on species of special concern, e.g., endangered or threatened species); (3) analyses of both species richness and the interrelationships of species within a defined spatial context; and (4) assessments of which species are involved in critical ecosystem services for which conservation efforts should be focused to benefit local human populations. Such work requires a basic understanding and application of taxonomy in order to accurately describe and analyze community structure (Humphries et al. 1995; Hunter 2005).

Taxonomic bottleneck and biodiversity infrastructure

Considering contemporary global trends of rapid conversion of natural habits into human-dominated landscapes (e.g., urbanization), it is urgent that we better understand how human activities that modify and manage ecosystems affect local biodiversity patterns and how to sustainably conserve and manage biodiversity in human-dominated ecosystems. These endeavors require information on backyard biodiversity. Unfortunately, most backyard biodiversity is little known, especially in terms of invertebrates, fungi, and microorganisms (e.g., Groombridge 1992; Heywood 1995). Even in relatively taxonomically well-known regions like North America less than one-half of the arthropod biodiversity estimated to exist has been described (Kosztarab and Schaefer 1990). Similarly, South Korea's *Biodiversity Korea 2000* (Lee et al. 1994) reported that Korea's biodiversity is barely known, despite the fact that it is being lost rapidly due to economic development and urbanization as reflected by expanding lists of endangered and threatened species for all taxa. This assessment is representative of most Asia Pacific countries (e.g., Sodhi et al. 2004; Kim 2005b).

Methods needed to guide the study of backyard biodiversity are currently lacking. The detailed protocols that must be developed for rigorous and repeatable biodiversity assessment should include recommended sampling designs, sampling methods for diverse types of organisms, ways of sorting, classifying, and identifying the collected specimens, as well as procedures for organizing, managing, and analyzing the resultant data (Kim 1993; Danks 1996; Mahan et al. 1998; Boone et al. 2005). The process between field sampling and species identification, involving alpha-taxonomy, referred to here as taxonomic service, is lengthy and laborious but important in maintaining quality control and data integrity (Grove 2003). Rigorous species identification, particularly for invertebrates, microbes, and less-well-known plants, is a taxonomic domain requiring the expertise of competent taxonomic specialists. Demand for taxonomic services is rapidly increasing concomitantly with increased adoption of practices associated with ecosystem management (Kim 1993; Botkin et al. 1997), community-based conservation (Berkes 2004), integrated pest management (US Congress Office of Technology Assessment 1995; NRC 1996; Benbrooks et al. 1996) and for the prevention and control of invasive, non-indigenous species (Shigesata and Kawasaki 1997; Mooney et al. 2004). Also, biodiversity-related research usually requires taxonomic services for measuring anthropogenic impacts on ecosystem health and to assess the state of community and ecosystem dynamics.

Although demand for taxonomic services is rapidly increasing for biodiversity and ecosystem research and management, it is increasingly difficult to obtain competent taxonomic services at the species level (or even at lower taxonomic—genus and family level) for biodiversity assessment and impact studies, for a reasonable fee. At the same time it is commonly presumed that there is a lack of funding for inventory and assessment and a shortage of qualified taxonomists who can identify known species and describe new ones. As a result, biodiversity inventory and assessment are scarcely undertaken for ecosystem management, although site-specific biodiversity information is fundamental to community/ecosystem ecology, conservation, and management of backyard biodiversity, which provide information on biodiversity structure, and the status of endangered and invasive species. Ensuring taxonomic precision in ecological research and ecosystem management is a major challenge, and the lack of taxonomic expertise available for such work is a problem that must be rectified quickly (Büchs 2003).

In most biodiversity studies, the unavailability of a taxonomic service usually slows down the data collecting process because trained staff are not readily available to provide taxonomic information. Thus, the widespread decline in taxonomic science and numbers of taxonomic experts worldwide has become a major stumbling block in advancing the study and management of biodiversity. Historically, species identification and taxonomic information were the domain of taxonomic specialists employed at federal and state agencies, such as natural history museums and universities, who usually provided taxonomic services at no cost. With declining demands in agriculture and changes in funding mechanisms along with curricular changes by societal demands due to changing technology and job markets, the number of taxonomists working at these institutions has declined in North America. Many land-grant universities, where many taxonomists and systematists have historically been trained, no longer offer courses in natural history and taxonomy or maintain the systematics collections needed to help train students. As a result, invaluable and irreplaceable biodiversity collections are deteriorating and, in some instances, are being discarded.

In the light of the increasing need for taxonomic work and biodiversity information, however, it is clear that new initiatives and innovative strategies are needed to help maintain biodiversity collections and train new generations of taxonomic scientists. It is urgent that taxonomic infrastructure is rebuilt on an entirely different strategic premise, which should be self-supporting and sustainable to serve the needs of biodiversity science and as well as society.

Emerging biodiversity science and creation of an Integrated Biodiversity Assessment Center

As DIVERSITAS proclaimed in ''Integrating Biodiversity Science for Human Well-Being''—the first open science conference in Oaxaca, Mexico in 2005 (Dirzo and Loraeu 2005)—the time has come to promote Biodiversity Science as the core of sustainability science for the future of humanity. The scientific study of biodiversity requires the integration of diverse scientific and scholarly perspectives and knowledge of contemporary disciplines from the natural and social sciences and the humanities that also demands various methodology and new technologies from other disciplines. Taxonomy, ecology, and conservation biology represent core disciplines around which integrated biodiversity science should be developed. However, as we view it in this article, integrated biodiversity science is born of the need to conserve biodiversity for the sustainability of humanity. Thus, social sciences and even understanding of topics from the humanities disciplines must inform all discussions related to the study of biodiversity and its relationship to humanity. Biodiversity science must organize itself in such a way that it should not be dormant, with huge global organizations and promotional slogans with little focus on inventory, assessment, research, and conservation of backyard biodiversity throughout the world, particularly in those countries and regions that occupy the majority of biodiversity hotspots but have no means to advance conservation and sustainable use of their own biodiversity, natural resources, and economic assets for sustainable development (e.g., MEA 2005; Dirzo and Loraeu 2005; Zedan 2005; CBD 2006a, 2006b).

The study of integrated biodiversity science as well as the practice of biodiversity conservation from the local to the global scale involves consideration of patterns relating to (at least) six major factors: (1) biodiversity, (2) geophysical templates, (3) land use and cover, (4) human demography, (5) values and ethics, and (6) policy and legislation (Fig. 2). Considering these factors, applied taxonomy and backyard biodiversity are explicitly related to global biodiversity patterns as are ecosystem services, which are also affected by the geophysical template as well as land use and cover. Ecosystem services must also be considered in the context of human values and ethics because these are the underlying factors that drive the way in which humans view the environment and the services that it should provide. In combination with policy and legislation, our ethics and values guide biodiversity and ecosystem management practices. Similarly, human values also influence applied taxonomy as they influence thoughts about the organisms we choose as the focus of our studies. These are only some of the relationships that can be teased apart by careful thought about the interdisciplinary perspective that is needed to fully develop a rigorous integrated biodiversity science. In addition, the above-proposed "Integrated Biodiversity Assessment Center" (IBAC) could provide the infrastructure supporting the training of integrated biodiversity scientists who are well versed in the six fundamental themes encompassed by the practice of biodiversity conservation (Fig. 2).

By virtue of the complexity inherent in its focal subject, biodiversity science requires its practitioners to be broad-thinking, creative individuals whose vocabularies integrate terminology, methods, and perspectives from many traditional disciplines (especially, but not limited to, ecology, taxonomy, sociology, demography, political science, and philosophy). Because few, if any, traditional disciplines (and even many newer, interdisciplinary, programs) currently provide the interdisciplinary breadth and depth needed to train truly transdisciplinary biodiversity scientists, we suggest that new programs should be created from the ground up. Although this would involve an enormous financial and intellectual investment, debate and possibly even failed attempts, such educational undertakings have been undertaken in the past (e.g., witness the rise of computer science as a discipline over the past 20 years) and could be achieved again given the right vision and collective will-power. Integrated biodiversity science research and education initiatives are needed to maximize the abilities of the scientific community to contribute knowledge to the sustainable conservation, management, and restoration of biodiversity and ecosystem services around the globe. Fortunately, many factors that would be required for this development are already well established.

The proposed infrastructure to promote the study of applied taxonomy, backyard biodiversity, ecosystem services and their relationships with humanity is the IBAC (Kim 2006a, b). A network of independent national, regional, or institutional IBACs will provide the infrastructure needed to promote and train biodiversity scientists and taxonomic expertise throughout the world (Kim 2006a). Additionally, IBACs will provide the necessary taxonomic services for identifying specimens collected in backyard biodiversity studies and developing and managing biodiversity databases for specific clients.

The IBAC network is proposed as a partial solution to meet the urgent demands for taxonomic resources and services needed for biodiversity research, assessment, monitoring, and conservation around the globe (Kim 2006b). The establishment of IBACs would provide a permanent solution to reverse the worldwide decline in taxonomy and taxonomic human resources. A network of IBACs should better serve the scientific community by providing taxonomic services including species identification and biodiversity database information and thus begin to remedy problems generated by the taxonomic bottleneck and advance applied taxonomy and biodiversity science. Ultimately this would benefit not only the scientific and conservation communities but also resource managers, policy makers, and the public at large.

IBACs will provide taxonomic services that include: (1) planning and execution of field sampling and collection; (2) sorting and preparation of field samples for identification and management; (3) providing species identification; (4) developing individualized biodiversity databases; and (5) providing long-term storage and management of voucher collections and field samples. Each IBAC must be built on or associated with systematics collection for specific taxa or backyard biodiversity as defined in its goals and objectives (in the United States, for example, there are numerous biodiversity collections that are inactive or orphaned at the land-grant universities). To maintain reliable taxonomic services, IBAC will require a steady staffing for its service operations, and thus reliable financial support. After establishment, IBACs are expected to be self-sustaining, supported by service contracts, grants, and cost-based outreach programs. State or regional IBACs could be networked to form an international IBAC Consortium that would coordinate to standardize sampling protocols and collection management practices, to share

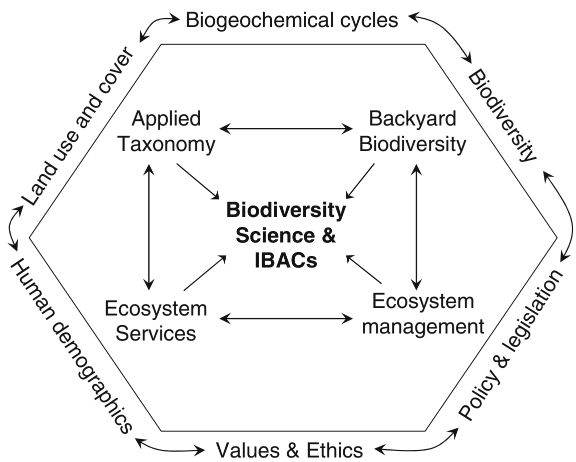

Fig. 2 The fundamental shape of integrated biodiversity science. This conceptual framework includes the key patterns that comprise coupled social–ecological systems (*outer hexagon*) and the four interdisciplinary concepts (*inner square*) that form the foundational perspectives comprising integrated biodiversity science. Integrated Biodiversity Assessment Centers (IBACs) would facilitate backyard biodiversity studies. Pair-wise relationships exist among all the patterns of the social–ecological system although they are not shown for visual clarity. The phrases are, however, arranged such that key relationships among the patterns (i.e., between land use and cover and biogeochemical cycles and human demographics) are shown with *arrows*. At the *top* of the *hexagon* is the pattern of global biodiversity, formed from the emergent patterns of backyard biodiversity around the globe. Moving to the *left* around the *hexagon*, the underlying geophysical template (i.e., continents, oceans, mountains, etc.) determines, in part, global biodiversity. In addition, this template affects patterns of human land use (e.g., farming, inhabitation) and their associated land-cover types, both of which are greatly affected by human demographic patterns (e.g., population distribution). Human values and ethics can determine human demographic patterns (e.g., through birth rates) and can also influence governmental policies and legislation. Policies and legislation (e.g., the Convention on International Trade in Endangered Species—CITES), in turn, directly and indirectly affect biodiversity patterns. In addition to these direct relationships, more complex indirect relationships and feedback loops exist among the six patterns (not shown) and should be considered in future efforts that develop integrated biodiversity science perspectives. Relationships among the six characteristic patterns of social–ecological systems and each of the four core concepts (*square*) can also be discussed (links not shown)

taxonomic expertise and biodiversity informatics, and to offer seminars, workshops, and training programs to enhance applied taxonomic capacity among biologists. In particular, IBACs would offer taxonomic short courses or workshops on specific taxon or methodology for alpha-taxonomy and taxonomic identification guides for parataxonomists and advanced students. Likewise, they would help establish graduate degree programs in biodiversity science and applied taxonomy at affiliated educational institutions (Kim 2006a, b).

The IBAC is thus an important infrastructure to advance all biodiversity-related sciences and to enhance scientific research and conservation measures. In short, effective IBACs will encourage biodiversity assessment and monitoring programs for conservation by resource management agencies and private land owners by providing the facilities needed for identifying organisms collected from specific locations. Every project IBAC undertakes will add new biodiversity information to the true picture of local backyard-level biodiversity. These data then can be used to enhance understanding of regional and global biodiversity patterns, which will provide powerful tools and vehicles for sustainable development in underdeveloped and developing countries. Being associated with educational institutions, IBACs can promote biodiversity science as an important field of study for the twenty-first century and help attract ambitious young students to the disciplines of taxonomy and ecology.

Conclusions

Broad consensus exists across the scientific community that humans are the dominant species on Earth and that their activities have had, and continue to have, negative impacts on biodiversity around the world (Vitousek et al. 1997; Dirzo and Raven 2003; Palmer et al. 2004). As a result, the ecosystem services that comprise humanity's life-support system have been eroded, with potentially irreversible effects on the continued sustainability of the world as we know it (Daily 1997; Kremen 2005; Hooper et al. 2005; MEA 2005). Global efforts, unprecedented in human history, are needed to minimize and remediate these negative changes on biodiversity and ecosystem services (Wilson 2002; MEA 2005; Brown 2006). In this context, scientists have a moral and professional responsibility for rigorous research and outreach to rectify these issues, which threaten maintenance processes of the biosphere for human sustainability (e.g., Lubchenco 1998; Raven 2002; MEA 2005).

Scientists who study biodiversity, particularly ecologists and taxonomists, must play leading roles in exploring, describing, and managing biodiversity with the explicit goal of ensuring the sustainability of humanity (e.g., Ehrlich and Wilson 1991; Gaston and May 1992; Eldredge 1992; Savage 1995). In the last several decades, powerful pronouncements have been made by prominent scientists concerning issues of threatened biodiversity, including species loss and decreases in the number of taxonomists, all in the context of sustainability of the biosphere (e.g., Vitousek et al. 1997; Botkin et al. 1997; Heinz Center 2002; Dirzo and Raven 2003; Turner et al. 2004; Imhoff et al. 2004; Musser 2005). The discussion continues today with a much larger number of participants who are contributing greater insight into the function of species in ecosystem services (Hooper et al. 2005; Kremen 2005) and the coupled dynamics of social–ecological systems (Berkes 2004; Redman et al. 2004). In addition, conservation scientists have contributed immensely to our understanding of biodiversity patterns and the perspectives and methods needed to conserve species, populations, and ecosystems (e.g., Alcorn 1993; Berkes 2004; Wilson et al. 2006).

In this paper, we have critically reflected on the contemporary state of taxonomy and ecology related to biodiversity and biodiversity science at large and discussed how biodiversity scientists, particularly ecologists, taxonomists, and conservation scientists, might be challenged to think in new ways about biodiversity studies and conservation. We suggested that ecology and taxonomy are associated with several key limitations that prevent them from making maximal contributions to biodiversity science, particularly related to relationships between biodiversity and ecosystem services. For taxonomy, these limitations include: (1) a worldwide reduction in the number of professional taxonomists and associated taxonomic specialists, and a decline in taxonomic educational programs; (2) the little interest shown by professional taxonomists in all-taxa assessment on the backyard scale; (3) the slow discovery and documentation of unknown species in backyard biodiversity; (4) the little effort made by taxonomists to produce taxonomic tools (i.e., species descriptions and identification keys) for use by non-taxonomic scientists; and (5) the lack of collaboration with ecologists and other biodiversity scientists. For ecology, key limitations to progress in biodiversity research are: (1) deficient taxonomic knowledge and lack of taxonomic training of ecologists; (2) lack of information about backyard biodiversity (Shochat et al. 2006); (3) inadequate or deficient data on species composition of study sites in published papers; and (4) lack of collaboration with taxonomists (Gotelli 2004).

We introduced two concepts that can help ecologists and taxonomists work together by refocusing and energizing their study of biodiversity research: backyard biodiversity and applied taxonomy. Although not wholly new, these two concepts represent two new perspectives on taxonomic and ecological research giving a unitary focus on biodiversity; integration of research between the two disciplines would advance greater understanding of biodiversity patterns and dynamics (Gotelli 2004), which, with the related concept of ecosystem services, focuses our attention on the interdisciplinary nature of issues pertaining to the patterns and importance of biodiversity and its conservation. Backyard biodiversity offers a focal point for integrating applied taxonomy and ecology, with a particular focus on species composition of communities in human-dominated ecosystems. Information about the effects of human activities on biodiversity and ecosystem services is needed to guide their conservation and management in locations where humans reside and most need sustainable environments.

Integrated biodiversity science, therefore, should have three primary objectives: (1) to study backyard biodiversity and its contribution to critical ecosystem services in human-dominated environments; (2) to establish a network of IBACs for advancement of biodiversity science in each country or region to provide the necessary taxonomic services for assessing localized backyard biodiversity; and (3) to develop biodiversity science education programs to train a new generation of broad-thinking, transdisciplinary scientists who are well versed in the complex issues surrounding the study and conservation of biodiversity on a human-dominated planet.

Paul Ehrlich aptly stated: "The 'human predicament' is the expansion of humanity's impacts on (ecosystems) to the point where both the long-term biophysical and the socio-political stability of society are seriously threatened" (Ehrlich 2005). Here, the human predicament is intricately and inextricably linked to the biodiversity predicament—the reality that all species inhabit a human-dominated planet where their futures may be in jeopardy. Humans should be concerned about the future of other species because they collectively contribute to the provision of innumerable ecosystem services on which the existence of humanity ultimately depends. Thus, solutions to the human predicament and the biodiversity predicament are one and the same. Integrated biodiversity science should be one of the central topics about which all members of humanity should be educated. If this educational objective is quickly adopted by human societies around the globe, planet Earth, even if it remains human dominated, will be managed by a species that has a greater understanding and appreciation for the biodiversity which we share with all other organisms in our backyard.

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