Systematics: The Science of Biodiversity

Use of a systematic perspective is burgeoning, and the need for the field is becoming ever greater

Beryl B. Simpson and Joel Cracraft

Systematic knowledge unifies all of biology by establishing a conceptual framework for interpreting the properties, activities, and distributions of species and groups of species. In so doing, systematic discoveries, data, and interpretations are an essential component of efforts to conserve and manage the world's biotic resources.

Human societies face unprecedented challenges in meeting the goal of conserving and sustainably using their biological resources. Human activity is changing habitats and ecosystems at accelerating rates. Increasing also is the global rate of dispersal of exotic species that threaten human societies via deleterious effects on agriculture, human health, and natural ecosystems. As biological diversity shrinks, so too does the opportunity to discover new species and gain understanding that is of great potential benefit to us all.

These challenges to our future place a premium on the knowledge provided by the biodiversity sciences. Of those, systematics is fundamental, because biologists must know the identities of the organisms with which they work. Systematics is also synthetic, because it links disparate fields (e.g., biogeography, ecology, physiology, biochemistry, and molecular biology) through the historical nature of organisms. Systematics is the analysis of the historical thread that binds life together.

Systematics analyzes the historical thread that binds life together

Over the last half century, systematics has undergone a revolution not only as a consequence of the rapid incorporation of new technologies but also because of the adoption of a phylogenetic approach (see box page 671). Phylogenetic systematics has made the discipline predictive and explanatory.

Paradoxically, at a time when the use of a systematic perspective has burgeoned and the need for the field has become ever greater, the number of practicing systematists has decreased. This reduction results from decades of neglect—both fiscal and intellectual—on the part of governmental agencies and academic institutions.

The growing awareness of a biodiversity crisis has highlighted the obstacles facing systematics, leading many governmental and nongovernmental institutions to call for a major initiative to address what is termed the *taxonomic impediment*. We cannot assess, let alone intelligently conserve and use, biodiversity without the work of systematists who are familiar with all forms of life. Most of our planet's biota consists of arthropods and microorganisms. Unfortunately, few systematists study these smallest and least known organisms. In the articles that follow, the successes of systematic work, as well as the future consequences arising from its disregard, are described across a spectrum of disciplines.

The imperative for additional systematic knowledge in biodiversity research and in assessing potential effects of global change is highlighted by Jay M. Savage (this issue), who points out the need for the study of biodiversity in all aspects of our lives. He puts forth the concept of biodiversity stations that would allow inventories of selected taxa in sites across the globe and provide a mechanism for determining the extent and rate of change in biodiversity as a result of global change.

Douglass R. Miller and Amy Y. Rossman (this issue) point out the critical importance of systematics for agriculture. All modern human societies are agrarian and increasingly dependent on high crop yields to sustain Earth's exponentially growing human population.

Fifty years ago, society complacently believed that synthetic pesticides would control the insects, pathogens, and weeds that reduced yields. However, as these pests have evolved resistance to synthetic pesticides and the health hazards of pesticides have become appreciated, there has been increased emphasis on biological control and sustainable agriculture. A basic prerequisite of these approaches

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Methods of phylogenetic systematics

Over the last two centuries, systematics has changed from a science that catalogued static diversity to one that interprets species and their characteristics in terms of rigorously formulated evolutionary hypotheses. More recently, systematics has adopted the principles of phylogenetic systematics, which bases relationships among taxa on the shared possession of derived characters. Before the rise of this approach, commonly known as cladistics, species sharing the greatest overall similarity in their characters were generally grouped together. But it is now widely appreciated that this approach often leads to misrepresentations of relationships, because taxa are clustered together as a result of sharing primitive characters.

Table 1, for example, shows a hypothetical matrix for five taxa (A–E) and for eight characters. In this example, taxon A has the primitive condition for all characters and is designated as the root of the tree.

The hypothesis of relationships shown in Figure 1a was generated by clustering the taxa on the basis of overall similarity (phenetic analysis). Thus, taxa B and C are united because they share the primitive conditions of characters 3–8, whereas D and E are linked as a result of sharing the derived states of the same characters. Figure 1b, in contrast, shows a phylogenetic hypothesis in which the taxa have been clustered using cladistic analysis. In this case, only derived characters are taken as evidence for descent from a common ancestor (monophyly). Given the available data, the most parsimonious hypothesis unites taxon C with D and E because they all share the derived condition of character 2.

Table 1. A hypothetical matrix for five taxa and eight characters. Following comparisons with close relatives of these species, some character-states are postulated to be primitive (0) and others derived (1).

	Characters							
Taxa	1	2	3	4	5	6	7	8
A	0	0	0	0	0	0	0	0
B	1	0	0	0	0	0	0	0
C	1	1	0	0	0	0	0	0
D	1	1	1	1	1	1	1	1
E	1	1	1	1	1	1	1	1

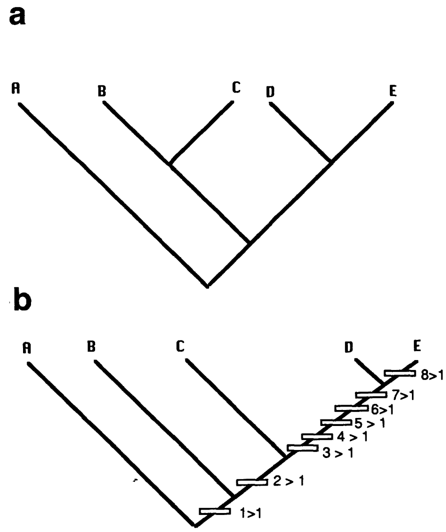


Figure 1. Hypothetical relationships among five taxa. (**a**) The relationships generated by clustering the taxa on the basis of overall similarity. (**b**) The relationships generated by a phylogenetic hypothesis in which the taxa have been clustered using cladistic analysis. Only derived characters are taken as evidence for descent from a common ancestor.The horizontal bars indicate character-state changes. The numbers indicate the character and the state to which it changes (e.g., 3>1 shows that at the point on the tree indicated, character 3 changes to state 1).

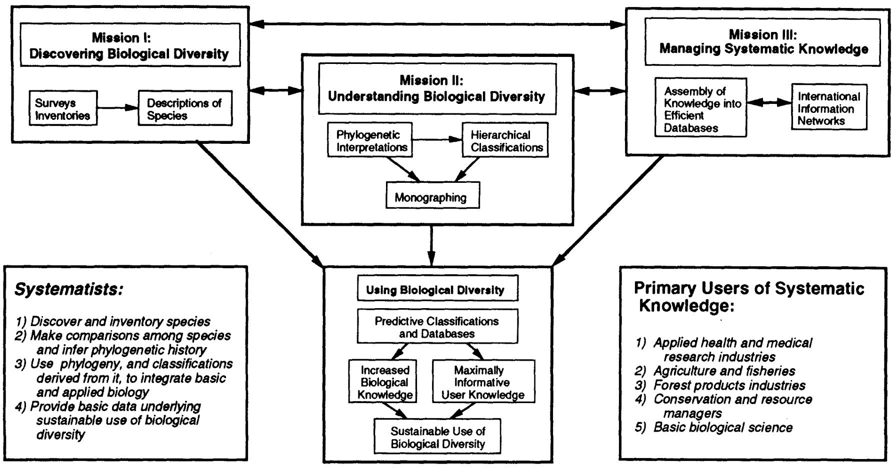
is a knowledge of the identities of the pests involved and their natural control agents. Similarly, we need to understand the interactions of crops with soil organisms and the relationships of crop species to their wild ancestors.

Miller and Rossman provide a sobering summary of the complexities of dealing with this array of diversity. They describe several instances in which the lack of adequate systematic knowledge led to mistakes in identification and subsequently in planning control measures of potentially devastating pests. They liken the current approach toward averting agricultural disasters to fighting brush fires—rushing from place to place to put out each new blaze. They propose the obvious: that with a more complete knowledge of the world's biota, more rational strategies could be devised.

Two articles in this issue of *BioScience* show how phylogenetic systematics has allowed ecological and behavioral research to expand in new directions. They stress the importance of an integrative approach to biology in which systematics is combined with studies of ecology, behavior, anatomy, and physiology. Known as comparative biology, this perspective has led to many new interpretations of the structures of organisms and the ways in which they interact with each other and their environment. The authors of these articles show how phylogenetic studies allow biologists to distinguish the origin of a character found in a group of organisms from factors contributing to its maintenance.

Daniel R. Brooks and his colleagues (this issue) demonstrate that knowledge of phylogenetic history can lead to powerful explanations of the origins of sociality in wasps, or the separation of sexes (dioecy) in plants. Comparing patterns of speciation across groups of organisms and geography can also help to distinguish between biogeographic hypotheses that suggest evolution of diversity in situ versus the accumulation of diversity as a result of immigration or dispersal.

Likewise, George V. Lauder and his colleagues (this issue) demonstrate that comparative morphology and physiology have gone beyond descriptive phases to assess features of organisms from a phylogenetic perspective. These authors explore how phylogenetic systematics has allowed biologists to determine historical constraints on form and, as a result, the spectrum of potential mechanical ways in which organisms can function. They show



Systematics Agenda 2000: Charting the biosphere.

that one can construct what is termed a *potential space (array) of functional design* and then examine how much of this space is actually occupied by living or fossil organisms. The failure to fill portions of the space can be explained by the inability of organisms to switch to a radically new design once evolution has fixed the trajectory of a developmental pathway. Like Brooks and his colleagues, Lauder and his coauthors stress that individual species should not be considered as independent datapoints and that the degree of independence across species can be ascertained only by examining phylogeny.

Finally, George M. Davis (this issue) provides a sobering assessment of the uses of systematics in the arena of public health, as well as of the dire consequences for ignoring such information. He points out the essential role that systematic biologists play in finding and characterizing organisms that cause disease and in determining how pathogenic organisms differ from their more benign relatives. Health scientists draw upon this knowledge to help predict the course of disease and hence what policies should be followed in containing the spread of pathogenic organisms. In some instances, intermediate nonhuman hosts harbor a parasite or pathogen for a part of their life cycles. Effective control programs, therefore, depend on systematists for correct identification of these host species.

In contrast to the widespread belief, in the recent past, that we knew of and were on the verge of conquering all microbial diseases, Davis points out that there has been an influx of previously unknown pathogens, including those that have been linked to Legionnaires' disease, Lyme disease, and toxic shock syndrome. In several instances, the time it took to characterize the organisms or strains involved in these diseases was unnecessarily protracted, in part because of a lack of systematic knowledge of bacteria and viruses.

The increased number of immunocompromised individuals as a result primarily of the AIDS epidemic and organ transplants has also led to many normally benign microorganisms becoming pathogens. Taxonomists familiar with these groups have played essential roles in identifying the species or strains involved or describing them if they are new.

One of the complicating factors in dealing with pathogenic organisms is the occurrence of sibling species—clusters of species so similar in easily observed characteristics that they are often mistakenly considered as a single species. Davis details several instances in which pathogens or intermediate hosts have been discovered to belong to sibling species of the species originally implicated. Consequently, the earlier control measures (of the wrong species) proved to be useless.

The articles in this special issue of *BioScience* demonstrate that the survival of humans on Earth depends on our comprehension of global biodiversity and our prudent interactions with it. As part of an international effort to understand and conserve biodiversity, the systematics community has proposed a global research initiative—called Systematics Agenda 2000—that seeks to answer four fundamental questions:

- What are Earth's species?
- What are their properties?
- Where do they occur?
- How are they related?

This agenda outlines a program to discover, describe, and inventory the species diversity of Earth, to analyze the information gained from this global effort into classifications that reflect the history of life, and to organize this information in a form that best serves the needs of science and society (figure at left).

The articles included in this issue of *BioScience* underscore the limitations of our current knowledge about biodiversity. They also demonstrate how the discovery of Earth's species and the development of predictive classifications have enhanced our ability to understand biological patterns and processes and therefore our quality of life. They point not only to the need for an expanded systematics-science research initiative but also to the urgency with which it must be instituted.

Acknowledgments

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