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Taking Biodiversity to School: Systematics, Evolutionary Biology, and the Nature of Science

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Abstract—A concept map for taking biodiversity to school is proposed here using a novel approach that combines systematics, evolutionary biology, and the nature of science. The concept map is tied to the recently published next generation science standards (NGSS). The problem of biodiversity is presented as a way to justify the need to take it to school. Biological classification is presented as a hypothesis about order in nature that is based on the evolutionary history of the organisms. Classification is the reference system of the entirety of biology with predictive and explanatory power. Homology is the concept that connects systematics to evolutionary biology. Evolutionary biology explains and systematics reflects the unity and diversity of life.

Keywords—Biology's reference system, broader impact, education, homology, NGSS K-12.

> When our schools truly become laboratories of knowledge-making, not mills fitted out with information-hoppers, there will no longer be need to discuss the place of science in education.
>
> John Dewey (1910)

The April 2013 publication of the next generation science standards (NGSS) (NGSS Lead States 2013), a science education milestone promoted by the American Association for the Advancement of Science (AAAS), the National Science Teacher Association (NSTA), the National Academy of Sciences (NAS), and Achieve Inc., has created a new opportunity to think about the central concepts for K-12 science education in the twenty-first century. One of those concepts is biodiversity.

We propose here a framework for taking biodiversity to school that:

• uses evolutionary biology, systematics, and the nature of science as basic concepts, all tied to NGSS,

• views biological classification as a basis for hypotheses about order in nature and as the reference system for the whole of biology,

• connects systematics to the nature of science, using the NGSS statement: "Scientific knowledge assumes an order and consistency in natural systems,"

• adds the concept of homology (not included in the NGSS) as "evidence of common ancestry" and as the bridge between evolutionary biology and systematics.

The current school biology curriculum and the proposed NGSS tangentially address systematics. The focus, however, is primary classification and instruction misses the importance of systematics in the preservation of biodiversity. Many of the underlying concepts of systematics, both traditional (e.g. homology) and those that have emerged during the last 20 yr (e.g. modern phylogenetic reconstruction) are also omitted. In addition, the current approach fails to demonstrate the dynamic nature of systematics and the ways in which research in this area reflects the nature and methods of science as a way of knowing (Moore 1984).

Figure 1 is a concept map that shows our framework for taking biodiversity to school. A concept map is a diagram that shows relationships between concepts; it is a graphical tool used to organize and structure knowledge (Novak 2010). Our concept map shows the relationship among the nature of science (scientific method), evolutionary biology, and systematics presented in a way that is compatible with the three-dimensional approach (disciplinary core ideas, crosscutting concepts, and practices) established by the NGSS.

We have proposed a novel approach in our concept map that would allow scientists conducting research in comparative biology to present their research projects and findings in a format useful to teachers, students, and the general public. This is particularly germane because many funding agencies will no longer consider a research proposal unless it can demonstrate the projects' "broader impacts" on science or society at large (Lok 2010).

Education and the Problem of Biodiversity—Biodiversity, the product of biological evolution, refers to the variety and variability among living organisms and the ecological complexes in which they occur. Biodiversity provides humans with renewable resources such as food, fuels, fertile soils, clean water and air, medicines, as well as surroundings of inspirational value. According to the estimates provided by systematists (scientists who generate biological classification), the number of scientifically known species on Earth is around 1,700,000. A conservative number of scientifically unknown species remaining to be discovered is 6,987,000 (Mora et al. 2011) or more. This biological treasure, with the vast majority scientifically unknown, is now facing ruin and devastation because biodiversity is being lost around the world in an escalating epidemic of extinctions. This is clearly the result of human appropriation of natural resources, modification of climate, loss of habitats and the spread of pathogenic, exotic, and domestic plants and animals (Naeem et al. 2012). Without systematics, ecologists and conservationists do not know which species exist within ecosystems, and cannot discover which are thriving and which are under threat of extinction. The science of systematic biology, therefore, is a vital discipline that underpins the conservation of the earth's biodiversity.

The target adopted by the world's governments in 2002 to achieve by 2010 a significant reduction in the rate of loss of biodiversity has not been met (Secretariat of the Convention on Biological Diversity 2010). This is a collective failure that will be severe for all, affecting the poor first and most severely, and compromising the principal objectives, food security, eradication of poverty, and a healthier population,

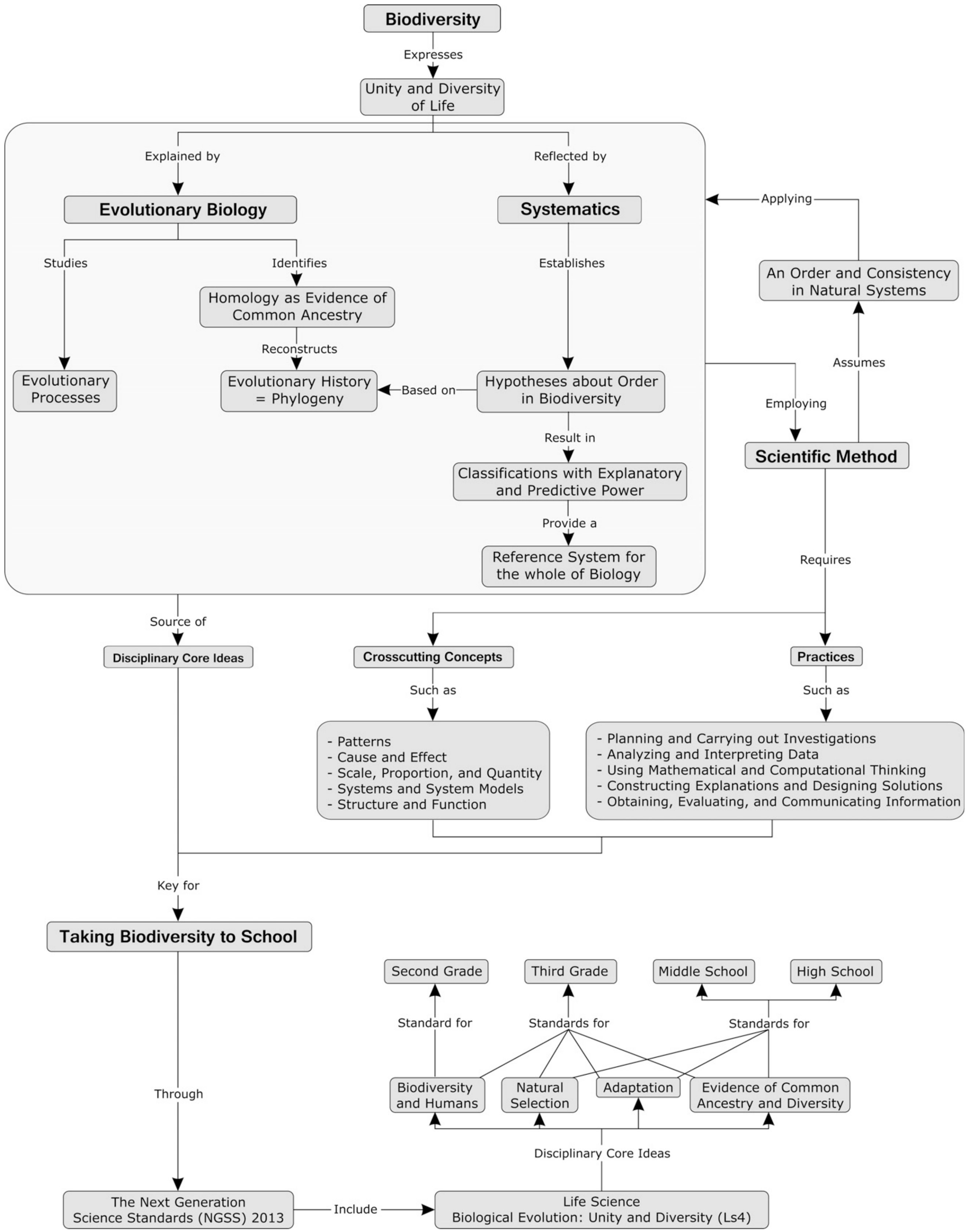

FIG. 1. Concept map showing the relationship among biodiversity, nature of science, evolutionary biology, systematics, and the next generation science standards (NGSS).

outlined in the Millennium Development Goals, a blueprint agreed by all the world's countries and all the world's leading development institutions through the United Nations (2000). This failure is rooted more in education than in politics. Politics in democratic societies is the result of education, as John Dewey (1916) put it clearly when he connected democracy and education: "Democracy and education are inextricably bound together. The one without the other is a perilous delusion." Therefore, the world's schools require a far greater effort in education in biodiversity to create worldwide public awareness of the issues at stake. Only an educated, global constituency for biodiversity can generate the pressure to ensure that we take the path to a sustainable future.

The escalating loss of biodiversity poses new challenges to education systems: how can schools and universities prepare students, tomorrow's citizens, to become more sensitive to the loss of species and to understand the role of species, especially through evolution and systematics, in maintaining biodiversity? It has been suggested by Beck et al. (2012) that education about biodiversity should become a component of the preparation of future physicians, proposing an additional core competency for the pre-medical curriculum. Beck et al. (2012) state that future physicians should "demonstrate an understanding of taxonomic diversity and fundamental ecological processes and how they relate to human health." These authors also mentioned that approximately 50% of the 100 most-prescribed medicines and 63% of 1,073 new small molecule drug approvals from the Food and Drug Administration between 1980 and 2010 are derived from natural products. Also, approximately 75% of newly emerging infectious diseases in humans are zoonotic, predominantly from wildlife. The question arises, of course, how to know which species are valuable or potentially harmful if we don't even know what they are? The questions and methods of systematics and evolutionary biology provide numerous opportunities for students to encounter the nature of science; to see science as a unique and powerful form of inquiry that provides rational explanations for our observations about the natural world.

Classification as Hypothesis—Systematics is a scientific discipline that classifies, describes, names, and determines relationships among the Earth's biodiversity. A central misconception about systematics is that it is purely descriptive and consists only of observations. *Homo sapiens* is by nature a classifying animal. Our continued existence depends on our ability to recognize similarities and differences between objects and events in our physical universe and to communicate these similarities and differences linguistically.

Scientifically, one classification scheme is better than another if it is more fruitful in suggesting scientific laws and generates better explanatory hypotheses. A condition to produce a classification with explanatory power is the existence of a generative system responsible for the observed attributes: the generative system of biodiversity is biological evolution. Therefore, classification systems are hypotheses about order in nature. Scientific hypotheses go beyond evidence (observations) for which they purport to account. They have greater scientific content (e.g. predictability) than the empirical propositions they cover. An example is the fruit fly (*Drosophila melanogaster*), named and described by J. W. Meigen in 1830. Meigen's hypothesis about order in nature has predictive and explanatory power that geneticists used for more than a century when they studied a few individuals and assumed that the results were valid for all the members (past, present, and future) of the species.

Thus, systematics provides a reference system for all of biology and therefore can be seen as the most basic area of biology because organisms cannot be discussed or treated in a scientific way until some classification has been achieved to recognize them and give them names (Crisci 2006; Vink et al. 2012). For example, without systematics, ecologists and conservationists do not know which species exist within ecosystems, and cannot discover which are thriving and which are under threat of extinction. In an insightful work, Bortolus (2008) examined and discussed that although overlooked and underestimated, cascade methodological errors in ecological works originate from trivial taxonomical problems that shift into a profound practical problem affecting our knowledge about nature, as well as the ecosystem structure and functioning, and the efficiency of human health care programs.

Bridging Evolutionary Biology and Systematics—Systematics is intimately linked with evolutionary biology, because evolutionary biology explains, and through systematics reflects, the unity and diversity of life on Earth. The goals of evolutionary biology are to discover the history of life (phylogeny), and to investigate the processes that account for that history. Systematic studies of living organisms have provided a vast amount of evidence for the reality of evolution. Comparative information amassed by early systematists suddenly made sense in light of Darwin's theory that living organisms have descended from common ancestors. From the comparative data gathered by systematists, we can identify several patterns that confirm the historical reality of evolution, and that make sense only if evolution has occurred (Futuyma 2013). One of the most important principles of evolution is that features of organisms almost always evolve from pre-existing features of their ancestors. The wings of birds, bats, and pterodactyls are modified forelimbs. In other words, related organisms have homologous characters, which have been inherited (and sometimes modified) from an equivalent organ in the common ancestor. Homology is the basic concept of both systematics and evolutionary biology; therefore its inclusion in an educational attempt to take biodiversity to school becomes fundamental.

The Need of a New Approach to Taking Biodiversity to School—Teaching systematics and evolutionary biology in a way consistent with the nature of science means to replace rote memorization as a traditional goal of learning, and put the emphasis on thoughtful inquiry and decision making. This approach encourages students to view science as an ongoing, relevant process of learning, as well as a body of currently available information and theories. Students come to understand and appreciate the tentative nature of science and its continuing importance to, and impact on, their lives.

Activities compatible with our concept map should develop a student's:

- understanding of classification as hypothesis about order in nature and the reference system of the whole of biology,
- observational and writing skills, familiarity with the nature and methods of science, and knowledge of the organisms that inhabit their local area,
- conceptual understanding of homology as a way for inferring the evolutionary relationships among organisms and reconstructing their evolutionary history, and how the classification of organisms reflects their evolutionary relatedness,

• conceptual understanding of biodiversity origin, loss, and conservation.

In the past years there has been an expansion of interest in inquiry-based science education as a reaction to students' rote memorization as a traditional goal of learning. Inquiry-based science education encompasses classroom and laboratory practices and materials which encourage students to take an active part in making sense of events and phenomena in the world (Harlen 2013). Previous attempts embracing inquiry-based science education to take biodiversity to school using systematics and evolutionary biology were successfully developed (Crisci et al. 1993; Andrews et al. 2002).

Education is an essential management tool that recognizes the central role of people in biodiversity conservation efforts. Indeed, although a conservation goal may be focused on a biological problem, effective conservation strategies must incorporate educational programs including biological systematics, evolution, and the nature of science designed to affect people's awareness, attitudes, and behaviors toward biodiversity (Crisci and Katinas 2011a, 2011b).

In 1984, Edward O. Wilson published *Biophilia* which sought to provide some understanding of how the human tendency to relate with life and natural processes might be the expression of a biological need. The biophilia hypothesis proclaims a human dependence on nature that extends far beyond the simple issues of material and physical sustenance to also encompass the human craving for aesthetic, intellectual, cognitive, and even spiritual meaning and satisfaction. This hypothesis involves some challenging assertions. Among these is the suggestion that all living beings that exist (or have existed) are bound in brotherhood because they share that precious moment of the origin of life 3.5 billion years ago. Education on biodiversity should remind us of that extraordinary moment 3.5 billion years ago and nurture in the students, and us all, a sense of stewardship for our planet's biodiversity, of which we are but a small part.

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