

Research Framework for the Natural History Museum

Background

For the past nine years research in the Natural History Museum has been organised around a series of cross-departmental themes formulated to encourage interdisciplinary research. This has had mixed success. In some case new lines of collaborative research have begun. But in many of the larger themes progress has been restricted to occasional and informal exchanges of information. In retrospect, the main reason why this approach has only been partially successful is that it was built around areas of research activity rather than focussing on what Museum research is trying to achieve.

An alternative approach, centred around a series of 'big questions' was proposed in spring 2002. Between 2002 and 2004 this concept has been developed through various consultations within the Museum to the present point. This 'big questions' approach is designed to increase interdisciplinary research in specific areas, bring added value to the Museum (e.g., through greater success in obtaining grant awards, increased publications output in higher-profile, peer-reviewed journals) and be focused on goals rather than activities. The 'big questions' that have been developed are considered to be important and topical rather than simply broad, and to align with national and international priorities without slavishly following them. It is also expected that these questions—or research targets—will change over time. Therefore some of the Museum's research will fall outside the main questions when it is exploratory in nature.

It is important to note that the question-driven approach is set within the context of the NHM as a collections-based organisation with particular strengths in systematics and taxonomy and with a science mission:

- to explore the diversity of the natural world and the processes that generate this diversity
- to use the knowledge gained to promote responsible interaction with the natural world

A description of the 'big questions' and their context is given on the attached paper. For each question there are a series of subsidiary or focusing questions.

Trustees agreed in principle to this approach in February 2004 as part of a paper entitled *A Vision for Science at the Natural History Museum* with a plan for specific proposals brought to them within six months. They subsequently approved a detailed description in July 2004 as a paper entitled *Research Strategy for the Natural History Museum*. This document represents a revision of the latter into which Trustees' suggestions, comments, and observations have been incorporated. With Trustees' formal approval in July 2004 the 'Big Questions' initiative became the Natural History Museum's Science Research Strategy.

Implications

The research framework will be used by the Science Executive to set priorities and therefore will be more than a re-labeling exercise. These priorities will be used in formulating departmental plans for Museum science departments, managing the performance of existing Science Group staff, recruiting new Science Group staff, allocating resources, and informing the participation of Science Group staff in non-research Museum activities.

The research framework will also provide an architecture for NHM research within which individual researchers or research groups will be free to set their own direction. However these individuals and groups will need to identify how they will contribute to the Museum achieving its research framework within each priority area. Non-hypothesis-driven research such as biodiversity inventory or anatomical studies will be an important part of our research activity, but the role of this activity in contributing to the resolution of the priority questions will be articulated.

The focusing, broadening, and deepening of inter-institutional research collaborations will also be possible using this new research framework. This will result because acceptance of the research priorities will force a concomitant re-evaluation of the Museum's strengths and weaknesses in each prioritized research area. This, in turn, will bring into sharper focus what type of collaborations, and which collaborators, are necessary for Museum research groups to achieve maximum impact in each area, as well as highlighting the advantages partnership with the NHM would bring to external research groups.

Finally, the Research Foci (or 'Big Questions') approach will be applied to our research but will not contain all that NHM science does. These other aspects, such as curation and databasing, will have their own priorities developed alongside and informed by this research framework.

System

The continued development of the research framework will be guided by a newly formed research committee consisting of both leading researchers as well as departmental representatives. There will not be a new administrative structure to deliver the framework. Instead, the allocation of resources will be made by heads of departments either acting collectively or through their individual departments against the commonly agreed framework. Delivering this framework is therefore the responsibility of the science Keepers as it will be for other Science Group strategies.

It is anticipated that this system will be established by April 2005.

Evaluation

This approach to organising our research has particular goals and therefore these will be used in assessing the impact of the approach. Specifically:

- Increase in interdisciplinary working (where beneficial, not compulsory)
- Increased output in higher quality/ higher impact journals
- Greater success in gaining competitive grants (i.e. more evenly distributed across the research staff)
- Aid to making resource decisions
- Better understanding across the Museum and beyond of what science is doing and why

Research Focus 1:

What determines biological diversity in a changing world?

Investigations relating biological diversity to our changing world are directly applicable to conservation, our understanding of climate and environmental change, environmental stressors (such as pollution, novel technologies and acidification) and the role of humans in effecting and ameliorating these changes. Work within this Research Focus draws heavily on our skills at alpha taxonomic work, phylogeny reconstruction in addition to collections-based and facilities-based research in general. It interacts most closely with Research Foci 2, 3 and 6.

1-1: Measuring extinction and recovery: does scale matter?

Man's effect on biological diversity change may only be judged against patterns of change deemed natural. As descriptors of the past, or predictions for the future, extinction and recovery may be perceived differently at different scales. These perceptions affect conservation activities with most currently taking place at the gene, species, and ecosystem levels. The scales of measurement are space, time, and form, that together provide a powerful framework within which biological diversity can be assessed. Patterns of global diversity change over many millions of years may be different in kind from those over thousands of years in single areas, regions, or continents; and these, in turn, may be different from short-term ecological change. This question seeks to identify the relationships between these scales through empirical study of evolutionary histories and by the integration of those observations with data from contemporary ecological settings.

1-2: What happens when biological diversity changes?

The world has been subject to many perturbations (e.g., cooling events, periods of increased volcanism, Ice ages), all of which have been followed by changes in biological diversity. This question addresses issues relating to patterns of speciation, adaptive radiations, and patterns of morphological evolution following such events. It will identify any patterns of evolution that may be useful for predicting future trends in biological diversity and involves research programs from a wide a variety of earth and life sciences.

1-3: How important are the effects of short-term environmental change?

Modern ecological studies have indicated that biological processes are disturbed and modified as a result of short-term environmental change, including those induced by Man. This problem has been largely addressed using predictive models that, of course, rely on some empirical base. In the Museum we have the historical data of biotic distributions in time and space—along with critical taxonomic data, at the gene, species and family levels—upon which models of change can be evaluated both qualitatively and quantitatively. By introducing greater taxonomic rigour into the data used by environmental modellers, we seek to improve our understanding of the roles of short-term environmental changes in mediating biological diversity. Ultimately this will improve the ability of these models to predict future trends. We can use our collections to help design evidence-based conservation strategies and allow for a sustainable use of biodiversity while keeping ecosystem services viable.

1-4: How does the biosphere respond to climate and environmental change?

Our existing and new collections can be used as proxy records of past environments using faunal and floral assemblage data, the chemical composition of fossils, morphology, and skeletal records. Multiple time scales and many potential responses need to be considered (diversification, extinction, morphological or ecological changes, geographic range change and human cultural change) to establish critical information about conditions and responses before and after anthropogenic impact.

Research Focus 2:**How do large-scale physical and biological processes and their interactions influence the evolution of the Earth and other planets?**

The Earth, including life at its surface, is a complex system that has evolved over thousands of millions of years. Questions in this category address our understanding of earth-system processes.

Sub-question 2-1: How did the solar system form and what processes have shaped its development?

In order to understand the formation of the solar system we must investigate the original materials from which the Earth formed, and how and when these materials were altered by subsequent events. Understanding the processes deep within the interiors of planets, and of how material is transferred between planetary interiors and surfaces, is critical to achieving this knowledge. Such studies will tell us how mineral formation in the distant past differed from that operating today, and the reasons why. Such investigations will also shed light on how mineral formation may have stimulated the initiation of life. In particular, Mars and Earth have both had long histories. Comparative studies of these two planets can tell much about what is common and what is unique about those histories. Study of the Moon will tell us how it evolved and how its presence has affected Earth.

2-2: What are the interactions between global processes and life and how are they recorded in the earth's history?

The assembly and rearrangement of continental plates has been happening for at least 3 billion years and has intimately influenced the history of life. This question addresses how biogeography and climate have been altered as a result of plate movements, how continental configurations can be investigated using fossil evidence, and how biogeochemical cycles drive diversity in the marine realm. Minerals are modified in many ways, through chemical changes and many of these changes lie behind processes of global change. Many mineral transformations relate to the generation of soils, crucial to the success of life and agriculture.

2-3: What is the geodiversity of the Earth and how do we exploit its resources in a continued way whilst maintaining environmental quality and well-being?

A better knowledge of the Earth's geodiversity will contribute to the sustainable use of geological resources and management of their waste products. Such knowledge will enable us to predict where these deposits may be found, and to identify the types of deposits that can be exploited in minimally damaging ways. Investigations of how pollutants move through the environment will facilitate the construction of better predictive models for containing future contamination. Knowledge of mineral formation can be used to predict and control the distribution of chemical species in the environment, as well as helping determine aspects of past global change.

Research Focus 3:

The relationships between biodiversity and ecosystem functioning

Ecosystems provide goods and services essential to the continued well-being of the planet and to the survival of human society. Without properly functioning ecosystems the quality of human life is degraded. Depletion of soils, loss or pollution of water, and loss of species are all effects of ecosystem degradation. We need to know how biological diversity contributes to ecosystem processes and how they are affected by such degradation, especially in the intensively managed agricultural systems that have come to dominate so many regions of the world. The complex relationship between taxonomic and functional diversity and key ecosystem processes has become a major research theme for the global science community. These studies in this area provide the most powerful scientific rationale for species conservation, as well as the theoretical basis underpinning the principle of sustainable use—that exploitation of biodiversity should not degrade the health of any ecosystem beyond the point where it ceases to provide the goods and services upon which society depends.

3-1: What are the components of ecosystems and how are they assembled?

Local species richness is heavily influenced by the size and structure of the regional species pool from which the local biota is drawn, as well as by interactions with global scale processes through time. These processes, in turn, contribute significantly to how species are assembled into functional units. Understanding the biogeographical and historical factors that determine species richness and functional diversity requires extensive knowledge of species the basic biological components of ecosystems as well as their relationships and their natural histories. Such studies depend on the Museum's strengths in descriptive taxonomy for the identification and naming of species, both fossil and living. Areas of exceptional species richness (hotspots) are often prioritised as targets for conservation effort. Comparative studies will enable us to assess whether hotspots are different in the degree of phylogenetic relatedness of their biota. In contrast, extreme ecosystems are typically characterised by low diversity, but tend to be inhabited by endemic organisms. Studies of extreme ecosystems generate insight into how such faunas and floras originate, how they survive long term despite their patchiness in space, and whether their inhabitants possess unique properties that enable them to survive.

3-2: How can we measure biodiversity?

The Museum collections are a unique resource for the recognition of patterns in the distribution of biodiversity through time and in space. Simple measures of biological diversity (e.g., species richness) provide practical methods for comparing ecosystems. Other measures integrate more quantitative information on function, relative abundance or on phylogenetic relatedness of the species present. Currently there is a pressing need to determine which measures are best for detecting changes in biodiversity in different ecosystems (both past and present) and how we can apply these indices practically to achieve a better understanding of biodiversity patterns.

3-3: How do invasive species impact ecosystems?

Non-native species, whether introduced accidentally or deliberately, can cause profound changes in natural ecosystems, displacing indigenous species and unbalancing systems by appropriating resources such as space or primary production. The breadth of expertise of Museum systematists put them in the frame for the identification of newly arrived alien species. Nevertheless, new research initiatives are required to understand why some introduced species fail to establish themselves while others undergo explosive population increase and become invasive, and how these species affect local ecosystems in a changing environment.

3-4: How are ecosystems responding to ongoing climate and environmental change?

Climate change will alter the physical and biological setting in which individual taxa live, and ecological interactions among taxa will alter resulting in changes in the functioning of ecosystems. To better predict system-wide responses requires information about a broad range of ecological attributes (e.g. community structure, nutrient cycling, abundance distributions, trophic structure, and ecological complexity) which can be extracted from existing collections supplemented by well-designed collecting programmes. Relevant data can contribute to quantitative ecological models used to assess how the effects of climate change can cascade across complex ecological systems.

Research Focus 4:

How do interactions between hosts and their parasites impact on disease epidemiology and control?

Parasites are everywhere and man has more than most. The parasite burden on the health and well being of the human population is colossal, particularly in the developing world. The statistics are shocking: for example, around one million children under the age of 5 die of malaria each year in sub-Saharan Africa and worms infect more than one third of the world's population with the most intense infections in children and the poor. Parasites are of considerable agricultural concern infecting domestic and wild animals, fish stocks and food crops. Their diversity, behaviour, ecology and evolution continue to provide fascinating insights into the interactions and intricacies of life on this planet. The emergence of parasitic diseases usually results from a mixture of evolutionary and environmental changes. Evolutionary factors concern the interaction of the parasite with its hosts and include infection, virulence, immunity and transmissibility; and interactions of parasites and their hosts with environments, includes climate, land cover, habitats and ecosystems. Under changing conditions, both sets of factors may combine to make a parasitic infection more or less prevalent than before, or spread into new areas. Understanding the nature, origin and maintenance of these interactions is crucial for controlling some of the most dangerous parasitic diseases, especially in third-world settings. Understanding how environmental changes can impact on both parasites and their vectors has important consequences for planning land use strategies for agriculture, forestry, leisure and the conservation of biodiversity.

4-1: What are the consequences of environmental change on the distribution and spread of parasitic diseases?

Of all parasitic diseases, those involving intermediate hosts and vectors are most likely to respond to environmental changes. These diseases are not only dependent upon carriers that are themselves very sensitive to their environment, but also have some of the greatest capacities for rapid increase over short periods of time and for rapid evolutionary responses to new situations. They represent a significant component of human diseases likely to be affected by environmental and climatic changes in Europe as well as the tropics.

4-2: What factors and processes shape the evolution of hosts and parasites?

Parasites and their hosts are locked in a close evolutionary embrace. The more success a parasite has, for example, in either infecting more hosts or obtaining more resources from each host, then greater will be the forces on the host to develop its defence system to enhance its chances of survival. This constant battle between parasite and host produces a strong and complex evolutionary drive. In addition to this conflict between parasite and host, human populations place pressures on both with the use of control measures (e.g., chemotherapy, vaccines, insecticides, molluscicides and environmental change) that impinge on their evolution.

Sub-question 4-3: How is disease epidemiology affected by variation in the biological and molecular characteristics of parasites and their vectors?

Precise identifications at individual, population, and species levels are required to determine the vectors (or intermediate hosts) and parasites involved in transmission and disease. There is a need to combine molecular and morphological data for many host parasite systems, but little consensus on how to do so. The recent massive generation and expansion of genome data provides many new opportunities to examine genetic traits in parasites and vectors that influence transmission.

4-4: Why is parasitism such a successful lifestyle?

The interface between phylogenetics and parasitology allows us to ask questions about how parasitism began, its history, and, in the face of accelerated environmental changes, its likely future?

Research Focus 5:**The diversity of phenotypes, genes and genomes and their relation to environment and evolution?**

Research in this area links whole organism biology, genomics (the study of living things in terms of their full DNA sequences), and the environment. The NHM's contribution comes from our strong comparative-taxonomic ethos and our strength in understanding the morphology of many different groups of organisms, both fossil and living. Meaningful interpretation of both morphological and genomic information requires an understanding of the evolutionary development and history of lineages and species, linking this Research Focus closely to the study of the Tree of Life (RF6).

5-1. How do morphological and genetic diversity relate to function, behaviour and environment?

Environmental adaptations are controlled by the genome and expressed through the phenotype. At the genetic level, the diversity of adaptive or functional traits can be related to the activity of particular genes or alleles. In addition, morphology determines the interactions between organisms and environment, and can be assessed through phenotypic analyses and studies of functional morphology. Integrating phenotypic and genomic studies can establish the causal relationships of the fitness of organisms in their environment, and serve as the basis for investigating the responses to climatic and environmental change on ecological and evolutionary timescales. Moreover, genic and morphological differences both play a part in speciation; species formation and persistence are influenced by the interaction of genes, phenotypes, and the environment.

5-2: How do genes relate to whole organisms, and why do organisms look the way they do?

Morphological characters used in systematics are the result of often complex developmental processes, controlled through genetic diversity and timing of gene action. Developmental biology studies of the key genes involved, coupled with comparative analyses of gene sequences and gene expression patterns ('evo-devo'), provides insights into the evolution and differentiation of body plans, and into the generation of diversity. How do smaller and larger differences between genomes result in such a wide array of physical forms in organisms? A systems biology approach, integrating traditional evo-devo studies with wider genomic and morphological perspectives using non-model organisms, will yield results in a comparative framework provided by studies of the Tree of Life.

5-3: What are the patterns and processes of genome evolution?

Genome evolution is dynamic, involving duplications, loss, and rearrangements at various scales. Comparing genetic sequences can reveal major transitions in the evolution of organisms, the diversification of genes and changes in gene evolution throughout the history of Life. The aim is an evolutionary synthesis of sequence data through comparative (phylogenetic) analysis. Frequent duplications and gene transfer can complicate studies of individual gene sequences; for example, horizontal gene transfer, whether it occurs naturally or through genetic modification in agricultural or microbiological systems, can have profound effects at a variety of time scales. Knowledge about homology of gene sequences across species is critical for studies of gene function and evolution, and for a molecular understanding of the differences between lineages of living organisms. The study of genes with important adaptive functions in non-model organisms has great potential to impact ecology, biotechnology, and our understanding of origins of evolutionary novelty.

Assembling the Tree of Life

The idea that all organisms are related through lines of common ancestry in one great Tree of Life is one of the fundamental and awe inspiring insights of biology. Discovering how different kinds of organisms are related is a central aim of biology. Knowledge of relationships provides the basis for classification and is essential to the interpretation of comparative data from across the entire spectrum of biology. The fundamental importance of taxonomy – knowledge of the identity and relationships of organisms – links this focus closely to the ecological and biodiversity issues of RF3 and RF4, and the developmental and genomic issues of RF5.

6-1. How many species are there?

Species are hypotheses about what biodiversity exists on Earth. Circumscription and taxonomic description of species provides basic units used in most quantitative studies of biodiversity and the tips of most phylogenetic trees. Conservative estimates suggest that many species await discovery and description at a time of unprecedented biodiversity loss. Groups with well-founded taxonomies are important for biodiversity measurement and setting conservation priorities and often provide particularly good opportunities to investigate diversification and to contribute to understanding why it is that some groups are more diverse than others.

6-2. How is Life interrelated?

The immense size of the Tree of Life makes deducing all its structure a long-term and necessarily collaborative, international effort. The NHM undertakes phylogenetic work addressing important controversies in biodiversity and biogeography and which underpin phylogenetic classification. Knowing how closely related different species are helps us to distinguish whether any similarities they share are the result of common ancestry or convergent evolution. Adding a temporal scale to phylogeny through calibration using palaeontological and/or molecular data can establish when branching events occurred, and provide additional opportunities to test hypotheses about the causes of biodiversity change.

6-3. How best can we infer the Tree of Life?

Phylogenetic inference is not always straightforward because different lines of evidence can conflict. In order to have confidence in our inferences we must have suitable data and appropriate methods. NHM researchers contribute to the development of improved methods for inferring trees and for assessing their reliability. Most phylogenetic work is compartmentalised and focussed just on one part of the Tree of Life. How we can best combine these small-scale studies into an increasingly complete understanding of the Tree of Life remains an open question, to which NHM researchers are contributing answers by evaluating existing and newly devised methods and measures.