Top Priority Idea

Environmental and Evolutionary Sciences

How are organisms evolving in response to a rapidly changing Earth and how can that understanding be used to save species and conserve ecosystems?

Human-accelerated environmental change presents one of the greatest challenges of the twenty-first century. The Earth is speeding through a transformation on a planetary scale so profound that a new epoch, the Anthropocene, has been proposed. Major impacts include global climate change; the rapid loss and redistribution of biodiversity; the spread of vector-borne diseases; deforestation and land degradation; over-exploitation of natural resources; alteration of biogeochemical cycles; and the rapid evolution of organisms ranging from microbes to vertebrates. These far-reaching changes harm the functioning of natural ecosystems and, ultimately, will impair the Earth’s ability to support life, including a major impact on human sustainability.

At the same time, unprecedented technological advances in genomics, high-throughput phenotyping, remote sensing, and big data analytics are leading to radical changes in our perspective on the interactions between organisms and the environment. These new technologies have enabled the integration of scientific thinking across environmental and evolutionary sciences, creating a dynamic new scientific discipline. The situation is analogous to advances in precision medicine. Precise and detailed genetic information about individual organisms can likewise be interpreted in the context of tailored ecological analyses, and this is revealing that evolutionary changes and ecological changes are reciprocally related across the entire range of temporal and spatial scales, including (most surprisingly) at the very smallest times and distances.

An extraordinary opportunity now presents itself to accelerate away from the old worlds of descriptive ecology and evolutionary biology toward a new scientific era of mechanistic and predictive understanding. New ways of thinking and new technologies are revolutionizing the research landscape:

- Evolutionary principles are being used in new contexts such as the conservation of species and ecosystems.
- Genomic methods are now increasingly available for many species – not just model organisms.
- Routine genotyping of tens of thousands of single nucleotide polymorphisms can be used to reconstruct phylogenetic relationships between species that date back many millions of years, or to reconstruct the evolution of a single species over the past several decades in response to environmental change, or even to elucidate the parentage of individual organisms.
- Interventions that manipulate organisms in natural environments are now enabled by CRISPR and Gene-drive technologies, which will be used, for example, to stop the spread of invasive organisms, or for conservation efforts to save species at the brink of extinction.
- Remote sensors – orbiting in space and placed in terrestrial and aquatic habitats – provide a vast and diverse stream of precise data on environmental variables and even individual organisms (e.g., migration paths of individual birds), making it possible to achieve mechanistic insights based on differences between individuals.
- High-throughput phenotyping encompasses many methods to characterize differences in the structure and function of organisms, from metabolomics to 3D imaging. Conveyor-belt automation to monitor large numbers of samples and infrastructure for mega-data storage and computational analysis have become a reality.
• A “big data explosion” is now occurring in organismal biology due to the growing volumes of genomic data and automatic sensor data. New computational methods, such as machine learning, are being developed to analyze and synthesize this flood of new data.

Yale’s exceptional potential to spearhead this new science

Yale has a deep and influential history stemming from the pioneering work of G. Evelyn Hutchinson, who is widely regarded as “the father of ecology,” and Yale is well-positioned to harness cutting-edge technological advances to unify the evolutionary and environmental sciences. Yale has major thought-leaders and experimentalists in this area already, as well as a basic foundation of the necessary infrastructure on campus:

Many excellent faculty members in FAS, including those in the departments of Ecology & Evolutionary Biology, Geology & Geophysics, and Environmental Engineering, as well as in Forestry & Environmental Studies are uniquely positioned to bridge the ecology-evolution gap, and have already developed innovative research programs at this intersection utilizing a wide range of cutting-edge technologies. This is illustrated by four short examples.

1. **Carbon recycling from fallen trees by fungi:** The decay of dead trees represents a major contribution to the carbon cycle. Predicting the rate of wood breakdown by combinations of >100,000 fungal species found in the Northeast may seem intractable. However, the opposite is true. Interactions between fungi yield predictable outcomes due to the ways that these organisms cope with environmental stressors and community interactions. Molecular genomics for fungal identification and rapid fungal phenotyping are essential to this research. Predictability emerges in wood breakdown rates, microbial biodiversity, and, most importantly, in carbon recycling rates. These findings have been incorporated into the Earth System Models of carbon cycle-climate feedbacks.

2. **Rapid evolution of keystone species:** A fish called the “alewife” demonstrates how the rapid evolution of a single “keystone” species can have large-scale impact on the environment. Alewife populations have evolved rapidly in response to environmental change: changes in their foraging morphology and behavior alter their predation of zooplankton, changing entire food webs and primary production. This research now informs the conservation and management of aquatic resources across the Northeast.

3. **Macroscale eco-evolutionary feedbacks:** The past may provide insights into the precipitous changes of the Anthropocene. Major transitions in the Earth’s geological history include mass extinctions, atmospheric oxygenation, ice ages, and dramatic episodes of rapid evolution. Plankton with calcium carbonate shells suddenly appeared about 200 million years ago, creating a deep-sea reservoir of carbonate that can buffer periodic large emissions of carbon dioxide. Outsize volcanic events triggered two of the largest mass extinctions in the history of life before the evolution of calcareous plankton – but not afterward – thanks to their buffering effect on the carbon cycle. Understanding such eco-evolutionary feedbacks on a macro-scale has the potential to predict key tipping points that may be imminent in the current epoch.

4. **Evolutionary clues for organism engineering:** The quest to engineer C4 photosynthesis, which is a more efficient form of photosynthesis than C3 photosynthesis, in rice and other crops seeks to enhance the productivity of these important food plants even under the stress of drought and heat, and thus to adapt our agricultural systems to climate change. Studies of leaf structures across many grass species revealed the unanticipated finding that key anatomical components of C4 metabolism evolved prior to C4 photosynthesis. This has provided the conceptual framework
necessary to engineer C4 photosynthesis in rice: first engineer the required anatomy, then
introduce the C4 genes.

Yale has made significant investments in facilities and specialist expertise that are essential to this new
enterprise in Environmental and Evolutionary science. The Yale Institute for Biospheric Studies has
created centers for spatial analysis to support environmental and organismal monitoring using remote
sensors. The Peabody Museum has made enormous investments to mobilize museum specimen records
that allow us to track spatial and temporal changes over the past century. The Peabody is also actively
assembling a new informatics team to address the challenges in rapid data capture, machine learning, and
other advances. The Yale School of Forestry & Environmental Studies (FES) is internationally known for its
efficiency and serves as a locus for research on local, regional and global environmental issues. The
Environmental Engineering program encompasses the scientific assessment and development of
engineering solutions to environmental problems affecting land, water, and air. The three health science
schools are engaged in research outlining impact on human health from Anthropocene era effects,
including shifts in disease vectors, air particulate morbidity and mortality, and population displacement.
Collectively this provides Yale with a unique community of scholars who can drive innovative ideas and
new approaches in the field - uniquely fusing evolutionary biology and ecology to make far better
predictions about the world spanning from the microscale to the planetary scale.

To capitalize on University-wide efforts at the interface of Environmental and Evolutionary Sciences,
we offer the following recommendations:

• **Organizational Structure**: Establish an Institute of Environmental and Evolutionary Sciences – possibly
  the G. Evelyn Hutchinson Institute – to newly integrate the environmental and evolutionary
  sciences. This Institute will:
  
  o Unite environmental and evolutionary sciences across lower Science Hill, including Forestry
    and Environmental Sciences, Geology and Geophysics, Ecology and Evolutionary Biology, and
    also relevant segments of Environmental Engineering, Anthropology, Psychology, and the
    Yale Schools of Public Health, Nursing and Medicine.
  
  o Support collaboration among faculty and students across these departments and schools

  o Facilitate access to big data and new analytical techniques

• **Faculty and Students**: Expand the size of the faculty in Environment and Evolution through strategic
  hiring.
  
  o We recommend the identification of a pool of 4-5 half-slots that are allotted to the Institute
    and made available to departments or schools willing to commit an equivalent resource to
    hire in this area.
  
  o As faculty are added, there should be a commensurate increase in the number of students in
    the relevant graduate programs.

• **Space**: The University should identify dedicated space sufficient to house at least six research
  groups across multiple departments and schools. There should also be sufficient space to convene
  students and faculty from the larger Environment and Evolution community to participate in
  Institute functions.
  
  o The space should be located at or near the base of Science Hill, in close proximity to the
    relevant departments and schools. One potential location is a renovated Osborn Memorial...
Lab following the move of the MCDB department from OML into the new Yale Science Building.

- The faculty who are physically housed within the Institute should have primary appointments in FAS, SEAS and/or FES departments. Physical co-location with the Institute should not be specific to a single school or department.
- Given the large scale of environmental and evolutionary research underway at Yale, not everyone doing this research needs to be, or even can be, physically co-located.
- The Institute space should include seminar rooms, meeting spaces, core facilities and hoteling offices needed to convene the larger community.

- **Core Facilities**: We recommend further investments in Core facilities to support research at this interface (see Core Facilities recommendation above). This would include access to high-throughput phenotyping, equipment and analytical expertise that would allow us to fully exploit the “big data explosion” in organismal biology, rapid phenotyping capabilities and diagnostic tools that are specifically relevant to addressing environmental problems.

- **Education**: The Institute will serve as an intellectual home and ‘collision space’ for students bridging disciplinary divides and integrating new technologies. We envision the development of a laddered series of courses for sophomores, juniors and seniors that would culminate in the completion of a senior thesis within the Institute. Earlier courses would focus on intellectual themes relevant to Institute research programs as well as the mastery of techniques that will prepare them for their own research projects.