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FRONTIERS IN POLAR BIOLOGY IN THE GENOMIC ERA

Polar biological sciences stand poised on the threshold of a revolution, one involving the application of genomic sciences and other enabling technologies to address numerous issues, many of which were unrecognized as little as a decade ago. Whether studying the effects of global warming or systematically prospecting for gene products useful to human health, the era of "genome-enabled" biology allows us many opportunities to attain a level of understanding about fascinating biochemical processes never before possible.

Ten years ago, we could not begin to understand hibernating mammals whose body temperatures plunge below freezing in winter, or fish whose blood remains in the liquid state at sub-zero temperatures because of antifreeze proteins. But now we have the tools. The "novel" or "exotic" nature of many polar species cannot fail to spark the curiosity of anyone interested in how species evolve, survive, and make their homes in icy Arctic and Antarctic communities.

The Antarctic toothfish thrives in icy waters and is considered a "swimming library" of cold-adapted genes and proteins just waiting to be read.
Photo by Kevin Hoefling

Polar ecosystems merit intensified study not only because they are fascinating but because they increase our knowledge of basic biological principles that are important everywhere. In understanding the mechanisms by which different species adapt to environmental extremes, we gain fresh insights into the fundamental characteristics of these systems. We study polar ecosystems as well because they are likely to be among the ecosystems most strongly affected by global change. The more fully we grasp the overall effects of global change, the more prepared we will be to predict and address these changes and their societal impacts in the years to come.

Polar biology, then, is an adventure into perhaps one of the last frontiers on earth. It is a study of intricate ecosystems largely unknown, but nonetheless dynamic and elegant, organized and full of information. *Frontiers in Polar Biology in the Genomic Era* is the first report from the National Academies on this subject. It is a story about surprising phenomena and the interconnectedness of all things.

WHY STUDY THE BIOLOGY OF POLAR REGIONS?

The most important questions of polar biology as identified by the report are focused in four major areas: the genomes of polar organisms, polar physiology and biochemistry, polar ecosystems biology, and human impact on polar ecosystems.

The Genomes of Polar Organisms. Polar species and, in particular, ectotherms, provide exceptional models for analyzing adaptive evolutionary change in extreme environments. In light of global climate change, it has become of more than purely academic interest to identify the genetic mechanisms that allow species to adapt to environmental change.

Each species has a different story to tell. The family of Antarctic notothenioid fish (photo above), for example, thrives in the icy waters of the Antarctic as a result of an evolutionary history in a highly stable environment. At the same time, these fish will perish at temperatures above 4º C (39º F) because they have lost from their genomes the raw materials to fabricate proteins to survive warming. Accordingly, these fish are genetically compromised in their abilities to face rising water temperatures. The loss of the physiological ability to cope with increases in temperature characterizes some invertebrate species, as well as fish, suggesting that this problem may be widespread.

What types of genetic information have been lost during evolution under the extremely cold but stable thermal conditions present in most polar seas? How widespread among polar species is the depletion of the "genetic tool box"? Will species that have lost their abilities to acclimate to higher temperatures and to extract oxygen from warmer waters face extinction as oceans increase in temperature? How will the extinction of one species affect species in neighboring niches and in the overall ecosystem?

Polar Physiology and Biochemistry. The abilities of polar species to carry out the physiological and biochemical processes required for metabolism, growth, and reproduction under extreme climatic conditions are based on widespread adaptive change. Proteins, membranes, and other key biochemical components of polar species exhibit a broad suite of adaptations that may at once "fit" their biochemistry to polar conditions while at the same time limit their functional range to only the extreme conditions of the poles.

Can insights from the study of cold-adapted proteins guide the development of commercially useful molecules such as enzymes that work rapidly at low temperatures? What types of molecules serve as "antifreeze" agents? How do these molecules work? What biotech and medical potential is represented by these molecules? Box 1 lists several potential applications of gene products from polar species.

Box 1. Potential Gene Products from Polar Biota May Benefit Humankind

Human Health
New and improved pharmaceuticals such as those used to treat heart, stroke, and trauma patients. New and improved cryopreservation biological materials important in transplantation.
Agriculture
Genetically modified plants that resist freezing and drought, extending the range of farmland on earth. Gentically modified fish and other animals, increasing the world's supply of food.
Environment
Genetically modified microorganisms to eat and degrade pollutants, then recycle nutrients to the environment.
Biotechnical/Industrial
"Cold-adapted" enzymes for use in food processing, chemical production, and medical applications.

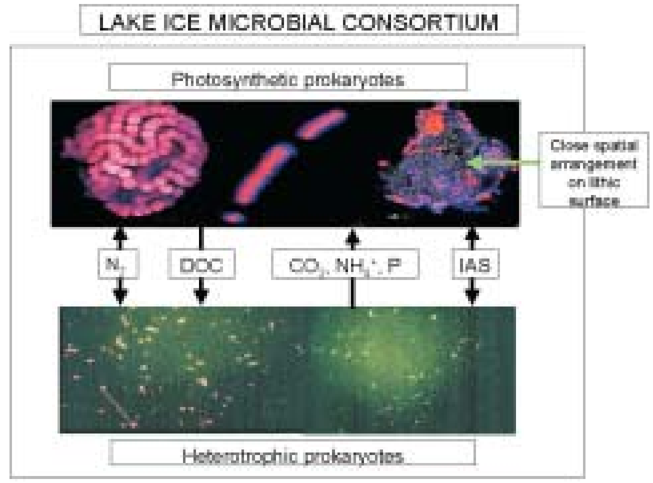

Figure 1*. Photosynthetic microorganisms thrive in the permanent ice covers of Antarctic lakes by forming "microbial consortiums" - close groupings of organisms that mutually exchange nutrients and other substances they need to survive.*
Source: Priscu et al., in press

Polar Ecosystem Biology. Most of the earth's biosphere is cold, with 14 percent being polar. Ninety percent (by volume) of the ocean is filled with water colder than 5º C (41º F). More than 70 percent of the earth's freshwater occurs as ice and a large portion of the soil ecosystem exists as permafrost.

Microbial and biogeochemical activity in polar marine waters and ice-covered lakes occurs when microorganisms build communities on sedimentary particles. The individuals within these communities are thought to interact closely with one another, where the presence of one species enhances the activity of the other. (See Figures 1 and 2). Potential rewards of these new lines of study are vast and include contributions to both aquatic and terrestrial biology on earth. Understanding Earth's cold biosphere will not only help us on this planet, but also offer clues to possible conditions beyond Earth.

Extraterrestrial bodies that have been conjectured to harbor life are icy, thus polar icebound microorganisms may serve as models of life (if any) on Mars as it cooled. Attention is especially focused on species such as those dwelling in the perennially ice-covered lakes of the McMurdo Dry Valley of the Antarctic. Similarly, the communities of Lake Vostok may model possible life on Europa, one of the moons of Juniper.

What is the lower temperature limit for evolving life on earth and beyond? How will global warming and the thinning and shrinking of the ice cover influence the distribution of polar species?

Assessment and Remediation of Human Impact on Polar Ecosystems. Human impacts are widespread in polar ecosystems, ranging from the direct impacts of activities such as fishing and the harvesting of marine ecosystems to the indirect consequences of atmospheric modifications by greenhouse gases and ozone-destroying chemicals.

Human-manufactured chemicals have been destroying the ozone layer, which serves as a filter for UV-B light. The impact of elevated UV-B light as a result of ozone depletion in some areas led to a 15 percent decrease in the production of phytoplankton (microscopic algae) in the Southern Ocean. How does the cascade of events that result from UV-B disturbances of these phytoplankton communities affect zooplankton (microscopic cons-umers), fish, and mammalian populations farther up in the polar food web?

The warming of the oceans as a result of increased greenhouse emissions is threatening salmon populations in the northern latitudes. According to some predictions, if present warming trends continue throughout the century, sockeye salmon could be excluded from the Pacific Ocean. The economic and cultural consequences of this change would be severe. Genetic tools could test whether all salmon populations are similarly threatened by warming.

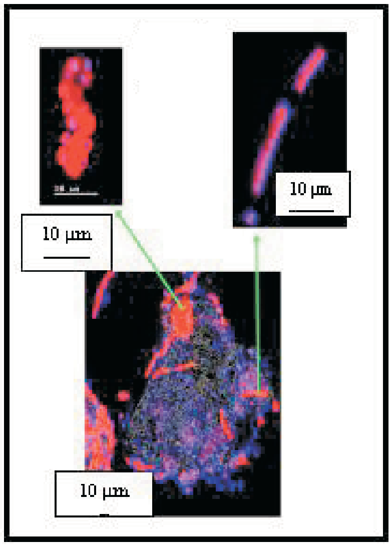

Figure 2. Bacteria living on a sediment particle, seen with a confocal laser microscope, reveal information about how microbes aggregate. In this image, blue is cyanobacteria, red is light emitted by chlorophyll, and gray is sediment particles.
Source:Priscu et al., 1998

Incredibly precise genetic technologies also play a role in assessing the impacts of humans on the world's fisheries. Through the use of "molecular forensics," or molecular markers, introduced species can be precisely monitored and managed. Forensics also can help to discourage the illegal harvesting of protected species in waters around the world.

The Polar Genome Science Initiative

Effective strategies for exploring polar ecosystems using approaches based on genetic science and other technologies can rapidly advance our understanding of all aspects of polar biology. The establishment of a Polar Genomic Science Initiative would help to coordinate efforts to better understand why polar species are different, what genetic mechanisms allow them to survive extremes in temperature, and how Arctic and Antarctic species compare with each other and with relatives in temperate environments.

The report proposes that the selection of microorganisms, plants, and animals to be studied should be based on whether such study would address broad and significant scientific questions or reveal cellular processes that may be of clinical or biotechnological interest. The overall aims of the Initiative include genetic and physical mapping of genomes, sequencing of DNA and expressed genes, gene identification and annotation, and assorted molecular analyses of the selected individuals.

Monitoring physiological and biochemical processes in ecosystems is the key to linking data generated by the Initiative to understanding and predicting species' response to abrupt environmental change. The advancement and success of future polar genetics research depends not only on the new technologies available and the expertise of individual researchers, but also the quality and availability of equipment, infrastructure, and facilities that will enable researchers to do their work. Improved procedures for collecting and shipping specimens are required as are improved facilities in key locations. Also important is the establishment of a "freezer farm" to serve as a repository for frozen samples.

The report makes the following recommendations to the National Science Foundation for exploring polar ecosystems:

- Develop a major new initiative in polar genomic sciences that emphasizes collaborative multidisciplinary research.
- Capitalize on data from existing programs. The Long-Term Ecological Research sites and Microbial Observatory sites offer a wealth of data from geographically distributed sites. Ideally, ensure that research can be conducted at sites with comparable conditions at both poles.
- Form a scientific standing committee to establish priorities and coordinate large-scale efforts for genome-enabled polar science. The need for research coordination involves increased communication both among polar scientists and nonpolar scientists who might lend support, particularly in high-tech areas.

- Support some mechanism such as a virtual genome science center to facilitate gene sequencing and related activities beyond the budget of any individual principal investigator. New infrastructure is not needed, rather some type of coordinating body.
- Develop ancillary technologies such as observatories, ice drilling, remote sensing, mooring and autonomous sensors, and isotope approaches to support the application of genetic technologies to polar studies.
- Improve biological laboratories and research vessels in the polar regions and improve year-round access to field sites.

Integration of Research Activities

The integration of research activities and the synthesis of knowledge on the genomes, physiologies, and biochemistries of polar species and the biogeochemical and physical characteristics of polar ecosystems are important challenges that must be addressed if polar biology is to realize its full potential. Every effort, therefore, must be made to encourage collaborative research as well as conferences and workshops to unite the scientific community both within the United States and internationally. The report recommends the following actions:

- Remove impediments to cross-directorate funding. Because integrated polar science requires interagency cooperation, NSF should lead by example and form partnerships with NASA and others as relevant.
- Establish international research partnerships and facilitate collaborative efforts.
- Survey researchers and research groups who would potentially work in both poles to identify impediments to bipolar studies, and take steps to address them.

Education and Outreach

Finally, an effort should be made to increase the flow of knowledge about polar biology to a broader audience because polar ecosystems play an important role in global-scale phenomena. The key mechanism for reaching nonscientists is the mass media. Education and outreach should especially target the indigenous communities that are part of the arctic ecosystem. This local effort should be two-way with scientists communicating what science is being conducted and why, while also inviting the contributions and learning experiences of local residents. Respecting local culture and customs can open the door to sharing scientists' excitement about local biological issues among secondary school children, which may result in their entry into research careers.

The report recommends that the NSF continue short- and long-term efforts to increase public awareness of polar biology. Plans should include the incorporation of polar biology in K-12 curricula, undergraduate, and graduate studies. At the postdoctoral level, fellowships could encourage young scientists to engage in this field of research.

For More Information: Contact Evonne Tang of the National Academies' Committee on Frontiers in Polar Biology at 202-334-3648; ETang@nas.edu. Frontiers in Polar Biology in the Genomic Era is available from the National Academies Press; 2102 Constitution Avenue, N.W. Washington, DC 20055; 800-624-6242 or 202-334-3313 (in the Washington metropolitan area); Internet: http:///www.nap.edu. This report was sponsored by the Office of Polar Programs and the Directorate for Biological Sciences at the National Science Foundation.

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