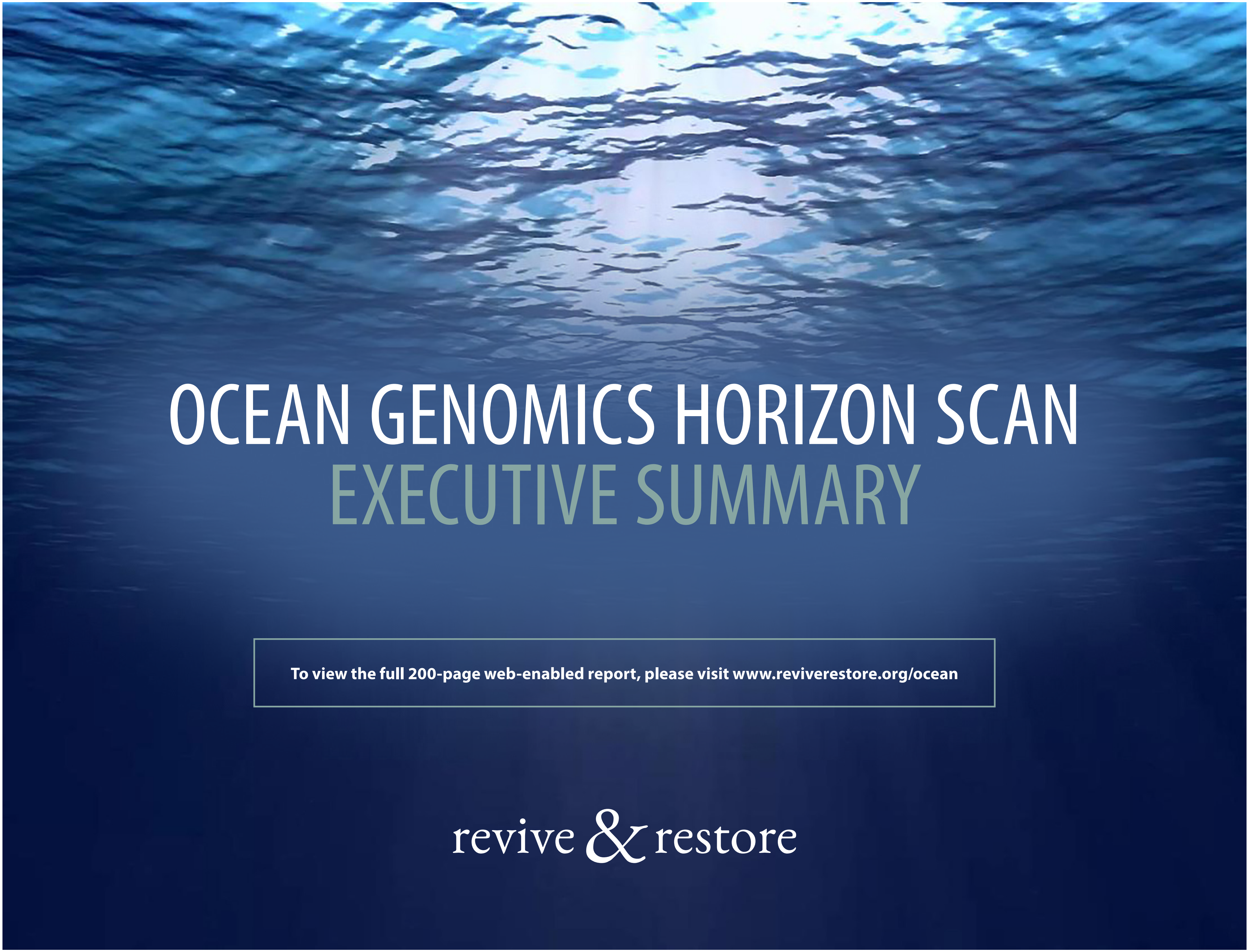

OCEAN GENOMICS HORIZON SCAN

EXECUTIVE SUMMARY

To view the full 200-page web-enabled report, please visit www.reviverestore.org/ocean

revive & restore

OCEAN GENOMICS HORIZON SCAN

Revive & Restore was commissioned in 2018 by a private family foundation to conduct an Ocean Genomics Horizon Scan and to ask this question of leading marine biologists: "How can genomic technologies and synthetic biology help solve some of the intractable problems facing the ocean?" With the help of a dozen researchers and drawing upon interviews conducted with over 100 scientists, the Horizon Scan assesses current threats to marine biodiversity for which new genomic tools could be transformative; highlights pioneering conservation applications of genomic technologies; and identifies innovations that could provide novel solutions for marine conservation.

From this research, we selected a suite of "Big Idea" proposals that would both demonstrate the power of these technologies and address a significant conservation challenge. Each of these ten Big Ideas was developed with a team of scientists passionate about their work; each demonstrates a clear technology development path with early wins and clear milestones; and each is achievable on a two- to three-year timeline.

Revive & Restore stands ready to refine and implement these projects in order to further demonstrate the potential role of these new tools to compliment and transform marine conservation. We have established a Catalyst Fund to accelerate the adoption of these innovative tools and are currently raising awareness and the funding needed to advance these emerging marine conservation innovations.

The full 200-page, web-enabled Ocean Genomics Horizon Scan provides a first-of-its-kind assessment of genomic and biotechnology innovations with the potential to help address marine threats and hopefully restore bioabundance to the ocean. After a full year of research, the report is being made available to the conservation community, foundations, and the public to encourage discussion and further the adoption of a new toolkit for conservation. It can be accessed at www.reviverestore.org/ocean.

This Executive Summary provides a high-level overview of the Horizon Scan and highlights ten of the Big Ideas.

To view the full 200-page web-enabled report, please visit www.reviverestore.org/ocean

PREPARED BY
revive & restore

SUMMER 2019

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INTRODUCTION

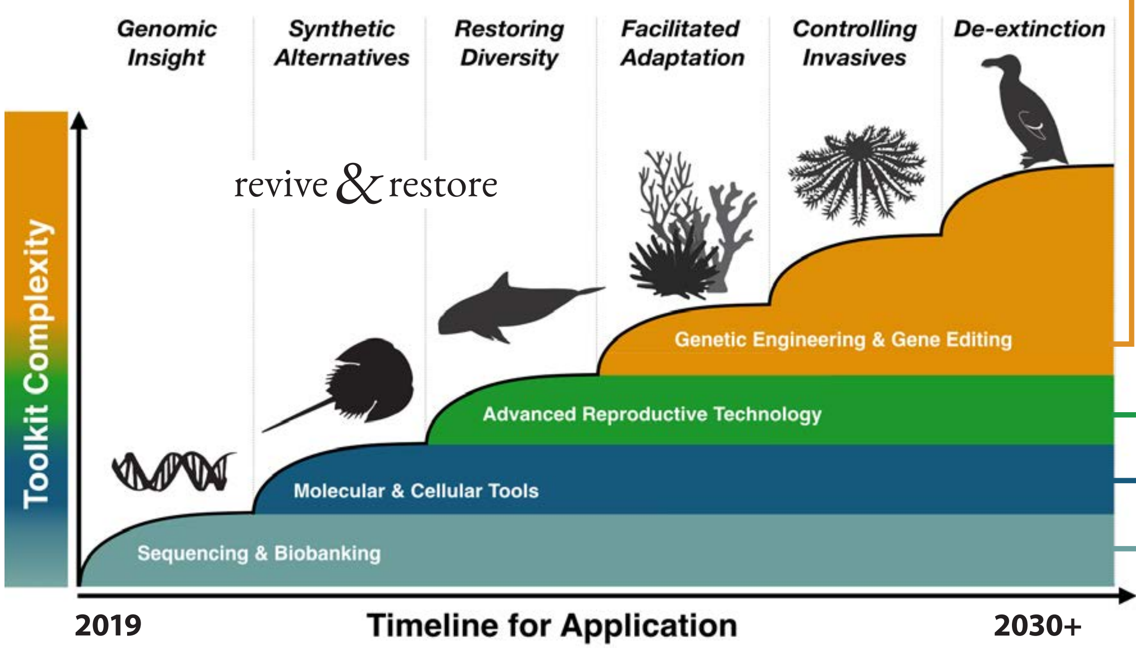
Threats such as pollution and over-exploitation from a rapidly increasing human footprint are severely impairing the integrity of marine ecosystems. Climate change exacerbates nearly all of these threats and reaches parts of the ocean still relatively untouched by anthropogenic effects. Conventional conservation measures like minimizing and eliminating pollution, limiting fishing pressure, and establishing marine protected areas are indispensable strategies to protect marine ecosystems. However, the pace and scale of threats to the ocean demand immediate innovation.

Meanwhile, rapid advances in genomic technologies are opening exciting new innovations in medicine and agriculture. The speed of change and the radical reductions in costs are creating new possibilities for innovation in conservation practice. In some cases, these technologies may have the potential to help save not only single species, but also entire marine ecosystems. Spanning a continuum from insight to intervention, genomic and biotech tools can provide profound new insights to augment conventional conservation strategies (fisheries management or disrupting illegal wildlife trade) and enable more complex genomic interventions, such as controlling invasive species or creating resilient coral. So far, conservation has been slow to adopt these new tools.

Revive & Restore's Ocean Genomics Horizon Scan presents opportunities to bring genomic and biotechnology innovations to marine conservation. To support the development of an emerging "Genetic Rescue Toolkit," Revive & Restore produced a 200-page report that highlights the current use of genomic technologies and synthetic biology, potential future applications, research gaps, the innovative scientists and institutions forging new ground, and the risks and considerations involved in deploying novel, transformative technology to marine conservation. It is important to note that Revive & Restore maintained our focus on conservation applications as opposed to more academic inquiries or research. Genomics can inform very interesting taxonomic and evolutionary research, but the Horizon Scan only features the applications with a direct conservation outcome.

THE GENETIC RESCUE TOOLKIT FOR CONSERVATION

Revive & Restore uses an expansive definition of the concept of genetic rescue that includes genetic-based tools for documenting biodiversity, informing conventional management practices, and in some cases, enabling novel genomic interventions. The practice of marine conservation is notoriously data limited; after all, everything is underwater. The emerging tools of genetic rescue provide powerful new monitoring insights to deepen our understanding of marine species and habitats. These tools and techniques may also bring much needed innovation to address specific threats to marine ecosystems. Each category of tools builds in complexity, and all rely on foundation sequencing work.



The Tools in the Toolkit:

Genetic Engineering

Methods for altering genetic codes by disrupting, deleting, rewriting, or adding genes, including transgenesis and genome-editing techniques like CRISPR, to enable laboratory-assisted evolution or facilitated adaptation.

Advanced Reproductive Technology

Methods that assist population recovery and allow genetic manipulation of natural species, including artificial insemination, in vitro fertilization, somatic cell nuclear transfer (cloning), primordial germ cell transfer, and stem cell embryogenesis.

Molecular & Cellular Tools

Synthetic Biology for designing gene networks and pathways, including metabolic engineering of biosynthetic pathways to enable the manufacturing of natural products traditionally harvested from the wild.

Methods of manipulating DNA sequence in order to create new genetic information, including recombinant DNA technology for moving genes between species, Polymerase Chain Reaction (PCR) for isolating individual genes from full genomes, and DNA synthesis for creating new gene sequences from scratch.

Sequencing

Methods for deriving genetic information from living organisms, including those for reference genome assembly, mapping epigenetic or gene expression patterns associated with phenotypic characteristics, and DNA barcodes for identification or environmental monitoring of a species.

Bio-banking

Methods for the collection and preservation of living and frozen samples of natural biological materials to be used for research or advanced reproductive techniques, including stem cells and gametes.

THREATS AND INNOVATIONS

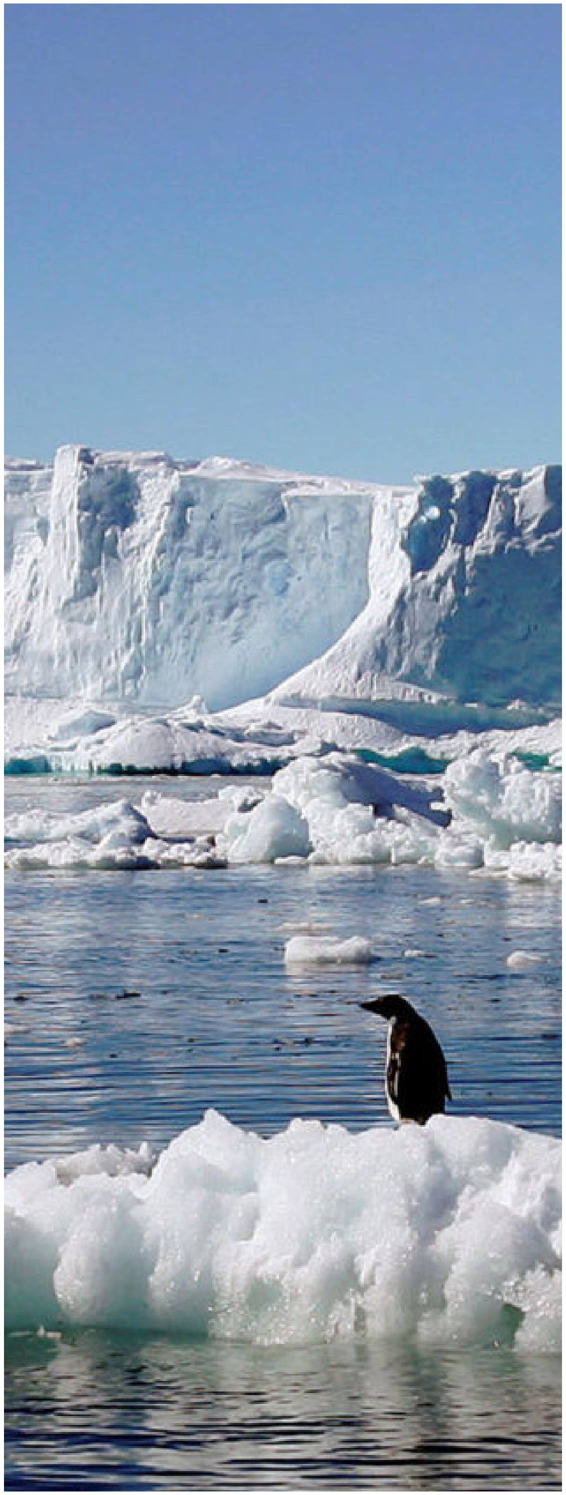
The Horizon Scan identifies promising applications for the use of genomics to address marine conservation, current technologies and leaders in the field, and gaps in our knowledge. Conservation initiatives utilizing genomics to address marine threats are nascent, but show tremendous potential to compliment more conventional conservation strategies. Revive & Restore organized the Horizon Scan according to the threats to marine systems since this fits with how more conventional conservation strategies are deployed.

Modern genomics can be applied to ocean conservation and management in order to better inform management decisions; to identify potential genomic vulnerability and/or resilience to changing ocean conditions; and to drive innovation to directly abate threats to ocean organisms and ecosystems. Despite the potential of these innovations, there is a lag due to a lack of foundation research in biobanking, sequencing, and investigating the genetic origins of traits, as well as the limited molecular tools available to ocean ecologists. Numerous researchers interviewed lamented the disconnect between academia and conservation. Therefore, there is a great need and a great opportunity to make investments in and contributions to building the genetic libraries and molecular tool kits used to understand microevolutionary processes driving ocean life.

CLIMATE CHANGE

Climate-related changes in ocean conditions are having profound impacts on marine ecosystems. The warming ocean and melting polar ice is already causing sea levels to rise and may result in profound shifts in marine currents, bringing widespread impacts. Harmful algal blooms and other marine diseases appear to worsen significantly in warmer water. Meanwhile, the sequestration of global carbon dioxide is making the ocean more acidic. Already, acidification effects have been documented; cracked and dissolving shells have been observed in pteropods, the tiny free-floating mollusks that represent the base of many marine food chains.

Many of the physical and chemical changes in ocean conditions appear to exacerbate other anthropogenic impacts to the integrity of marine ecosystems. Two critically important marine ecosystems, coral reefs and kelp beds, have been especially hard hit. Kelp beds and coral reefs provide essential ecosystem services for coastal communities. Since these habitats rely on living organisms to create the structures that provide diverse niches that drive biodiversity, they were focal ecosystems in the Horizon Scan.



Coral Reefs

THREATS

Coral reefs provide habitat for 25 percent of all marine species and provide ecosystem services to 500 million people who rely on them for food, coastal protection, and livelihoods. Human development and increased ocean temperatures are causing frequent and widespread coral bleaching events and die-offs. Fifty percent of the planet's corals have been lost already, according to recent estimates, and 90 percent will be gone by 2050.

The coral crisis has led to research and restoration initiatives around the world. The dire prognosis for coral conservation deepens the need for innovation and effective responses. Accordingly, academia, conservation organizations and some novel commercial ventures are trying to develop effective response strategies. There is strong consensus that all paths need to be pursued simultaneously and rapidly. Summarized below are some of the most promising approaches. Notably, due to the severity, scope, and immediacy of the crisis, most coral scientists interviewed for this Ocean Genomic Horizon Scan were more open-minded about the use of genomic and biotechnology-oriented solutions for coral bleaching than for any other marine threat.

INNOVATIONS

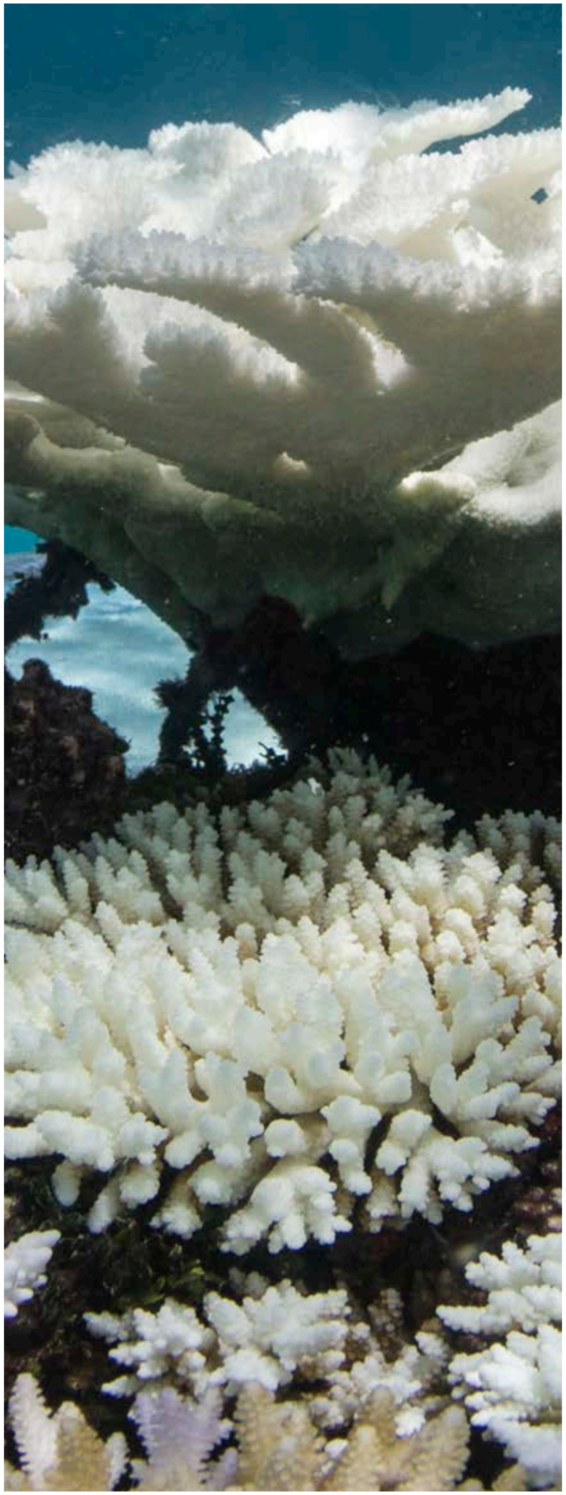
Genomics of Coral Bleaching

Coral bleaching results from the expulsion of photosynthetic symbionts from coral polyps during periods of stress. The loss of algal nourishment can cause the polyps to starve and die. The precise mechanism and genetics of coral bleaching remain unknown and the breakdown of the symbiotic relationship can be triggered by a number of stressors, including high or low temperature, UV radiation, reduced salinity, microbial infection, marine pollutants, and even an absence of light. This suggests the involvement of a complex set of genetic traits, which remain largely unknown to this day. This knowledge gap is a major impediment to the development of effective coral reef intervention and restoration strategies.

The availability of lower-cost genome and transcriptome sequencing and analysis techniques has opened the door to conducting population-based field assessments of corals that have survived or died in bleaching events. This work enables the identification of adaptive (or maladaptive) traits in wild stocks and informs hypotheses about how genotype-phenotype interactions affect bleaching. Population-based assessments are underway on several reefs around the world, and a number of labs have begun using comparative methods to explore coral functional genomics to develop actionable insights into heat resilience in corals.

Reef Restoration and Translocation

Despite the promise of genetic engineering applications, none are ready for use in corals. Currently, the only practical approach to improving reef resilience is identifying and breeding more heat resilient coral strains for translocation to wild reefs. Improved understanding of adaptive genetic and epigenetic traits will help ensure successful translocation of resilient corals. This knowledge would provide the data necessary to enhance restoration practices, including routine genotyping of propagated stock, assessments of performance based on traits,



and assisted migration and assisted gene flow. These new perspectives would improve translocation practices from "simply moving" corals towards targeted long-term reef restoration and revitalization.

Cryopreservation

Due to recent losses, there are already fewer healthy corals to sample and preserve, and there will be even fewer in the years to come. Only a fraction of corals around the world have been cryopreserved, and very few laboratories have developed coral cryopreservation techniques. Although breakthroughs have been slow, Mary Hagedorn's coral conservation program at the Smithsonian Institute is developing innovative coral fragment cryopreservation techniques. Coral fragment cryopreservation will enable reefs to be rapidly banked in a simpler manner, without the need to capture sperm and eggs during annual spawning events.

Stem Cell Technology

Stem cells derived from adult tissues can be kept in culture and used for experimentation, or for cloning and propagating an individual organism without sexual reproduction, which would be a useful and versatile new tool for restoration programs. Since stem cell biology is unknown in corals, some coral experts believe that developing techniques to isolate and grow coral stem cells should be the top priority for engineering genetic resilience in corals. Presently, no such stem cell capability exists in coral biology, and no stem cell lineages are available. In the short term, the challenge is to demonstrate the basics of coral stem cell isolation. In the medium term, the challenge is to assemble operating stem cell hardware-software-wetware systems to meet real experimental objectives. These systems are the automated tools needed to precisely manipulate coral stem cells.

Inducible Coral Spawning

Corals broadcast spawn once a year under very specific conditions. The annual spawning event represents a severe limitation to scaling coral restoration and even having sufficient coral samples for research. However, Jamie Craggs's Project Coral iniative at the Horniman Museum in London has figured out how to induce coral spawning in captivity by simulating natural spawning conditions. Perfecting and expanding the deployment of inducible spawning techniques could enable multiple promising pathways to contend with the coral crisis. These pathways include enabling assisted gene flow between resistant corals, supplying restoration programs and research with spawned corals, and creating a steady source of coral germplasm for functional genomics experiments.

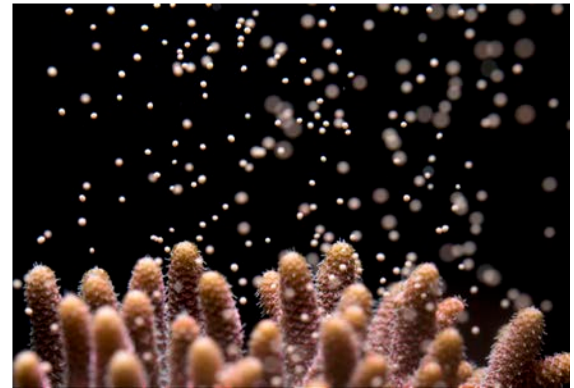
Despite the potential, inducible coral spawning remains a niche technique, and its nascent state and limited momentum is stalling progress. There is an opportunity to expand the practice and technology and to develop regional collaborations to perfect spawning techniques.

Taken together, the three projects above represent a potentially transformative program to advance coral science.

See Big Idea: Advanced Coral Toolkit

Adaptation and Conditioning

The ability to generate "pre-adapted" coral colonies and larvae via conditioning could enable the seeding of resilient corals that repopulate reefs naturally, without the potential reduction of genetic diversity caused by selecting corals or the large effort required to restore reefs through continuous transplantation of individual colonies. Also, the revolution in next-generation sequencing approaches



BIG IDEA:
ADVANCED CORAL TOOLKIT

This project will develop the research and restoration tools necessary for responding to the coral crisis. Research and development of techniques for the cryopreservation of coral eggs and micro-fragments and increasing the use of inducible spawning techniques will provide more restoration options. Longer term research in stem cell capabilities may open genetic engineering pathways.

Project Team:
Edward Perello; Mary Hagedorn; Jamie Craggs: Nikki Traylor-Knowles; Benyamin Rosental

Technology(ies):
Cryopreservation; Coral micro-fragments; Inducible Spawning; Stem Cells

Timeframe:
3 Years

provides innovative opportunities for exploring conditioning factors in coral resilience. However, adaptation and gene expression are extremely complex and adaptive capacity could be highly variable across different coral species.

Characterizing and Manipulating the Holobiont

Corals are "holobionts," or meta-organism communities, in which a single "individual" is composed of the host coral animal, one or more species of symbiotic algae, and a collection of bacteria, viruses, fungi, and other microorganisms that cycle essential nutrients and generate protective compounds. These types of interactions between at least four members of the coral holobiont have been documented. Some scientists see the holobiont as providing a pathway for an ecosystem approach to reef resilience. An important first step is to better characterize the holobiont community and what affects it. While the algal symbionts have received the most attention, documenting the role of bacteria and other members could transform our approach to coral conservation.

Recent research has shown that coral reefs adjacent to atolls or islands with intact seabird populations have healthier reefs than those where invasive rodents have virtually eliminated seabirds. The loss of seabirds appears to disrupt the transfer and concentration of marine-derived nutrients between terrestrial and marine habitats, and this disruption appears to dramatically alter the health and resilience of coral reefs. However, the causal factors are unknown. It is suspected that the holobiont is responding to the differential nutrient inputs. Environmental DNA (eDNA) and metagenomics can be used to understand these interactions at multiple trophic levels. Uncovering these connections could provide new strategies to respond to protecting corals by enhancing the condition of the coral reef ecosystem. It would also further illustrate the ecosystem-level benefits of restoring colonial nesting waterbirds on islands and adjacent marine ecosystems.

See Big Idea: Restoring Island to Restore Reefs

BIG IDEA:
RESTORING ISLANDS TO RESTORE REEFS

Research has uncovered strong correlations between vibrant seabird colonies and more resilient nearshore ecosystems. This study would explore and confirm the causal benefits of restoring seabird colonies by eradicating invasive rats. The findings could transform our understanding of contributing factors of resilience in a changing climate.

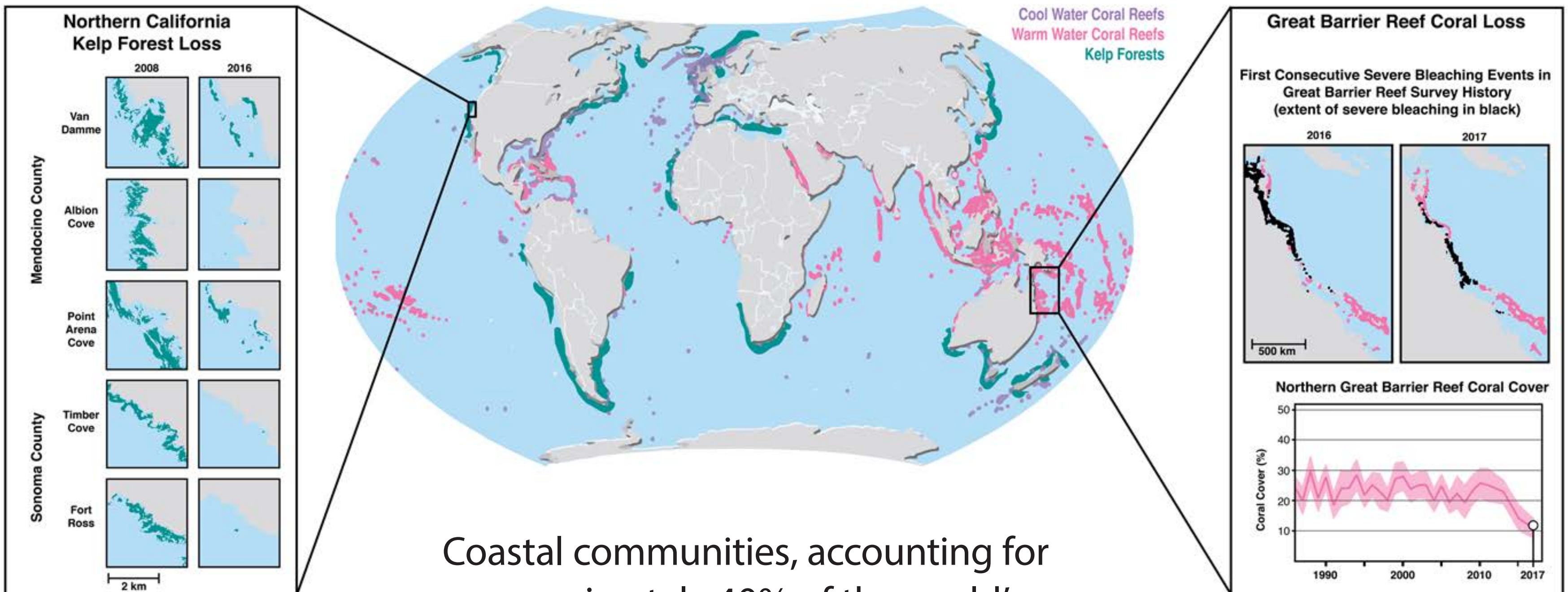
Project Team:
Heath Packard; Rebecca Vega Thurber; Deron Burkepile; Richard Griffiths

Technology(ies):
Environmental DNA (eDNA)

Timeframe:
5 Years

Budget:
$3,078,000

Distribution of Kelp Forests and Coral Reefs



Coastal communities, accounting for approximately 40% of the world's population, often live alongside kelp forests or coral reefs. The livelihood and security of these communities is threatened by the increasing degradation of these habitats as climate change, disease, pests, and pollution worsen.

Kelp Beds

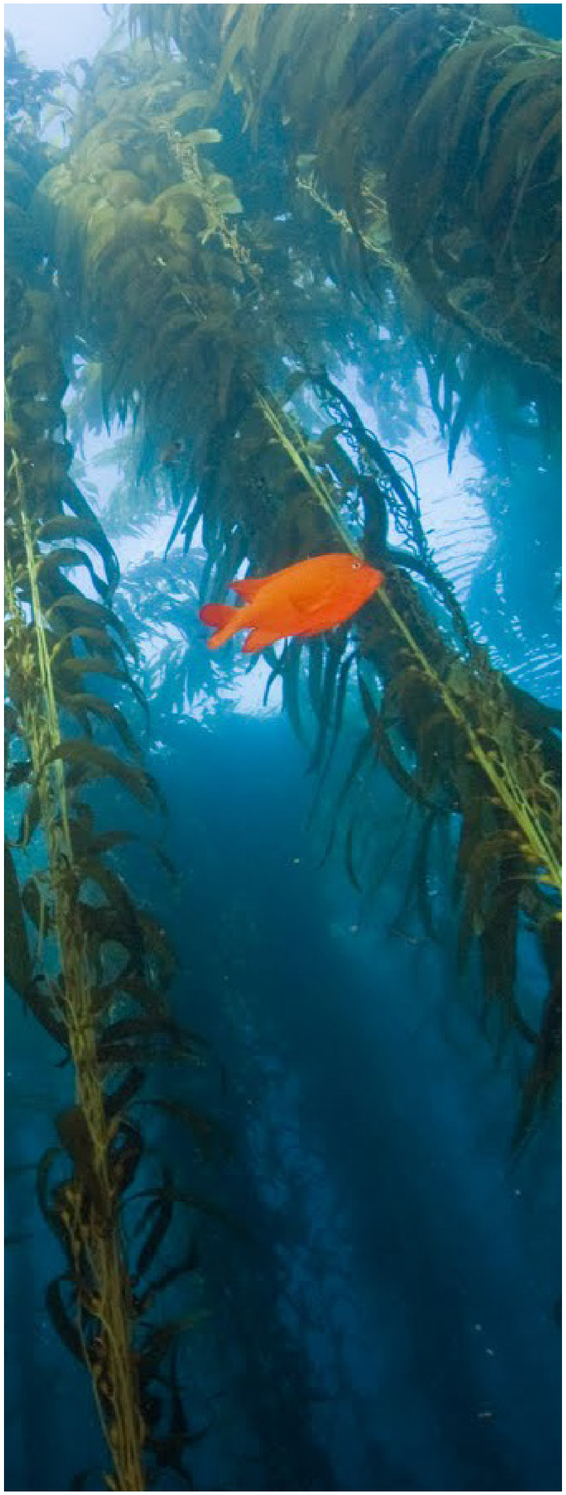
THREATS

The various species of kelp occupy 43% of the world's marine ecoregions along coastlines of islands and all continents except Antarctica. But in the last few years, dramatic losses of kelp have been documented globally. In addition to driving significant marine biodiversity, kelp beds provide essential ecosystem services such as shoreline protection, localized amelioration of ocean acidification, and support for fisheries. Some research suggests kelp also provides ecosystem services in the form of "blue carbon" sequestration. However, more research is needed to confirm the actual long-term sequestration effects from natural kelp beds.

INNOVATIONS

Unfortunately, any biotech-based response to the global loss of kelps is hampered by the size and complexity of kelp genomes as well as the biology of the various species. Because only a single kelp species has been sequenced to date, sequencing of additional species may provide an opportunity to fill this gap. For kelp forest ecosystems, there are very few examples of research collaborations between marine ecologists and the '-omics' fields of study. This lack of transdisciplinary research is likely limiting progress. Convening of thought-leaders in the respective fields of study could facilitate the development of genomic tools for kelp conservation, similar to the collaborative response to the coral crisis that is underway.

Commercial utilization of kelp (either cultivated or harvested from the wild) is one strategy to increase the reuse and sequestration of carbon. Kelp and seaweeds can be used for a wide range of products in fertilizer, cosmetics, animal feeds, and biofuels. Innovations are also occurring in aquaculture to farm kelp at greater scales and as part of more integrated aquaculture systems. One notable company, Primary Ocean Producers, has a multi-pronged approach to environmental services by creating seaweed farms in the Pacific in order to draw down CO_2 and reduce ocean acidification in an effort to fight climate change. The farmed seaweed would then be harvested to create biofuels, fertilizers, cattle feed, and other agricultural products.



OVERFISHING

THREATS

Global fisheries are among the most valuable exported food commodities, particularly in developing nations. In 2016, fishery exports were worth an estimated $148 billion. While global aquaculture production outpaced wild-caught fisheries for the first time in 2018, roughly 90 percent of the world's fish stocks are fully or over-exploited, with more than a third fished at unsustainable levels. Overfishing not only threatens marine ecological integrity, but also puts coastal economies at risk.

The expansive undersea environment limits the available data, while conflicting ecological and economic incentives makes assessing fish stocks extremely challenging. In addition to difficulties with managed fisheries, illegal, unreported, and unregulated fishing threatens to undermine the sustainability of fisheries in even the most conservation-oriented countries. The increased reliance on aquaculture has exposed important forage fish species to overfishing pressures, and because forage fish are the base of marine food chains, this is an urgent threat. Climate change is further exacerbating these issues causing significant disruptions in the availability of wild-caught fish from range shifts, altered timing of migrations and more frequent and severe harmful algal blooms.

INNOVATIONS

Broadening the base of genomic knowledge of fisheries would enable profound new ecological and management insights. New low-cost sequencing technologies enable important new understanding

of the population dynamics of fisheries. It is now possible to use "genetic tagging" to determine abundances and responses to fishing pressure rather than unreliable or biased fishery catch or effort data. Genetic tagging also known as "close-kin mark and recapture" has been most notably used to determine the annual production of the critically endangered southern bluefin tuna to help inform catch limits. These genetic methods could also revolutionize our ability to estimate demographic connectivity over large spatial scales. These techniques now inform fisheries management of salmon in the North Pacific. In a more novel approach, this tool is being used to evaluate marine protected areas (MPAs). Additionally, eDNA monitoring could inform models of fishery stock distributions, enabling more accurate mapping of the spatial extent and timed movements of a fishery.

Improving Fisheries Management

Recent advances in genetic scanning technology includes portable and cheap DNA barcoding that enables the identification of species data from fish at checkpoints throughout the supply chain, potentially reducing of illegal, unregulated, and under-reported fishing. Efforts are also underway to identify the genetic markers of specific fish populations, which could radically improve supply chain transparency by allowing consumers and suppliers to identify the specific geographic origins of fish. One of the leading programs, FishPopTrace in the European Union, seeks to use genomic and molecular tools to build a framework of end-user tools for fish population analysis and fish (product) traceability as well as policy related to monitoring, control, surveillance, and enforcement in the fisheries sector.

While genomic tools are providing insights into the pressures of fishing on heavily exploited species, the availability of meaningful data for any of the strategies described above is contingent upon sufficient sequencing, at a coverage level high enough to identify unique species and from a sample size large enough to identify genetic variation within a species. To date, genetic data for many species of concern is inadequate.

As noted above, the aquaculture industry relies heavily on forage fish as the main ingredient in fish meal feeds. Fish meal and fish oil provide favorable ratios of essential amino acids, minerals, phospholipids, and fatty acids that support development, growth, and reproduction. Aquaculturists have learned to depend on fish meal for high nutrient and protein value as well as palatability. The significant threats posed by industrial-scale fishing for forage fish have inspired several initiatives that are attempting to develop efficacious replacements to fish meal and fish oil. Companies and research teams are exploring the production of replacement protein and other essential nutrients at scale from bacteria, plant, insect, and animal by-products. Other teams are trying to streamline the use of fish processing waste for aquaculture feed. In Japan, 90% of fish processing waste is repurposed for fish feed. One particularly novel approach developed by the U.S. start-up NovoNutrients uses carbon dioxide from industrial processes to fuel bacteria growth that is then converted to fish meal.

Genomics Guiding MPAs

See Big Idea: Genomics Guiding Marine Protected Areas

Proving the ecosystem benefits from MPAs to nearby marine habitats has been a huge challenge, primarily due to the difficulties of observing and documenting the movement of fish offspring from an MPA to

BIG IDEA:

GENOMICS GUIDING MARINE PROTECTED AREAS

An innovative genomic-based tool known as "close-kin mark and recapture" will leverage a $1M study to monitor the effectiveness and ecosystem benefits of marine protection, a potential game-changer for planning and evaluating marine protection strategies.

Project Team:
J. Carlos Garza; Mark Carr

Technology(ies):
Genotyping; Close-Kin Mark and Recapture

Timeframe:
3 Years

Budget:
$600,000

adjacent areas. The "genetic tagging" methods represents a huge leap in the ability to understand population connectivity, their dynamics, and the influence of oceanographic features. These insights can help managers evaluate an existing MPA network and potentially to guide the design and siting of new MPAs.

A notable study (funded by the National Science Foundation) genetically sequenced more than 6,000 kelp rockfish in the Monterey Bay National Marine Sanctuary to develop inter-generational tags of their offspring. This study confirmed the out-migration of juvenile kelp rockfish to adjacent MPAs and open ocean, demonstrating the ecosystem benefits of California's MPA network. This work must now be leveraged and expanded in order to further demonstrate the benefits of MPAs.

The "Genomics Guiding MPAs" Big Idea will sample an additional 240 miles and 10,000 rockfish. Estimates of dispersal will be used to validate modeled predictions of larval movements in local ocean currents. This offers profound new insights into the role of MPAs as sources of fish in adjacent unprotected waters and to nearby protected areas. Such a data-driven documentation of widespread ecosystem benefits would advance the science of marine protection and provide a model for evaluating protection strategies globally.

Coupling Tech for Biosurveillance

Recent multilateral agreements call for the development of tools for accurate and cost-effective monitoring, control, and surveillance of fisheries.

Many developing countries report monitoring capacity to be one of their major hurdles in improving fisheries management, including deficiencies in training and technical capacity. Conventional tools are limited because they are time-consuming and require expertise in fish identification.

Emerging genetic and satellite-based technologies provide a new opportunity to solve this long-standing monitoring challenge. The "Coupling Tech for Biosurveillance" Big Idea would develop and implement eDNA and genetic barcoding methods to determine the composition of targeted catch and by-catch in fishing vessel wastewater. Since screening the composition of every landing from every vessel is impractical and cost-prohibitive, this project aims to narrow the monitoring focus to vessels with suspicious fishing behavior detected by satellite-based Automatic Identification System (AIS) data.

This field pilot study will use publicly-available AIS data to track and profile the behavior of Thai fishing vessels and then use eDNA methods to identify fish landings (including bycatch) to species-level accuracy across time and location. By comparing genetic data to vessel-reported fish manifests, we will demonstrate the feasibility and application of a versatile, powerful, and accurate monitoring method at the start of the seafood supply chain. These tools will be freely transferable to fisheries stakeholders worldwide in order to spur a global transformation of fisheries monitoring.

See Big Idea: Coupling Tech for Biosurveillance

BIG IDEA: COUPLING TECH FOR BIOSURVEILLANCE

This project will transform traceability in global marine fisheries by coupling emerging molecular genetic tools, such as environmental DNA, with satellite-based fishing vessel tracking systems.

Project Team:
Demian Willette

Technology(ies):
Environmental DNA (eDNA)

Timeframe:
2 Years

Budget:
$381,150

POLLUTION

THREATS

Pollution is a major threat to ocean health, and one of the greatest challenges for mitigation efforts is the scale and diversity of pollution sources, which are tightly coupled to human activity and the global economy. It is essential that methods are developed to eliminate ocean pollution at the source and existing waste already in the marine environment, using new technologies that replace polluting industrial practices and products.

INNOVATIONS

Surfing, swimming, and fishing are all important ways that people connect to the ocean and represent a significant economic driver for coastal economies. However, pollution can carry microbial pathogens that create unsafe conditions for these activities. Recent technological advances allowing for field detection of the DNA of specific bacteria from human digestive systems (indicating the presence of human waste) presents the opportunity to transform water quality monitoring and the protection of public health. Microbial DNA from these organisms can be identified through digital PCR (digital quantitative polymerase chain reaction) in a matter of minutes rather than days.

There are three potential areas for innovation: a DNA sequencing diagnostic platform, sampling approach, and data processing and visualization. The diagnostic platform relies on deploying digital PCR machines to detect selected indicator bacteria. This can be accomplished with portable machinery on local desktops. Also, the current methods for sampling environmental DNA for the indicator organisms rely on costly human-based collection. There is a clear opportunity to significantly reduce monitoring program costs by developing and deploying remote aerial and aquatic drone platforms. Lastly, data visualization tools will engage the public in ways that foster increased involvement in the condition of local waters.

The project team has developed a comprehensive framework to more effectively characterize coastal water quality and human health risk by integrating rapid and low-cost DNA sequencing diagnostic tools, remote aerial and aquatic water sampling, dynamic environmental informatics, machine learning, and data visualization. With this platform, data can be presented to end users within hours.

See Big Idea: Transforming Pollution Detection

Bioremediation

New biologically-based remediation (bioremediation) of oil and plastic pollutants holds promise to ameliorate marine pollution. Bioremediation is the process by which naturally occurring or deliberately introduced organisms metabolically break down waste chemicals in the environment. While the natural process of bioremediation is effective, it is slow and toxins can persist in the food web. Recent biotechnological advances, particularly in the area of synthetic biology, could potentially improve the efficiency of bioremediation and pollution sensing, both in the ocean and at pollution sources.

In particular, advances in genetic engineering have enabled the creation of new strains of bacteria capable of breaking down complex mixtures of

BIG IDEA:
TRANSFORMING POLLUTION DETECTION

This big idea includes three areas for innovation: diagnostics, sampling, and data visualization. The diagnostics relies on deploying digital PCR machines to detect selected indicator bacteria. The project will reduce monitoring program costs by developing and deploying rapidly evolving remote aerial and aquatic drone platforms. Lastly, data visualization tools will engage the public to foster increased involvement in pollution abatement.

Project Team:
Sequence Environmental

Technology(ies):
eDNA; Digital Quantitative Polymerase Chain Reaction

Timeframe:
2.5 Years

Budget:
$400,000

hydrocarbons. With bioinformatic tools, scientists can systematically explore new metabolic pathways that will transform pollutants into safe products. While research in plastic-degrading organisms and other solid waste is less developed, newly discovered plastic-degrading microbes could similarly be engineered for efficient remediation of plastics.

The identification of oil-degrading pathways through bioinformatic analysis is dependent on the availability of sequenced genomes and the ability of bioinformatic algorithms to recognize relevant patterns in the gene sequences or genomic structures. However, the major challenges to these synthetic biology approaches are in scaling the manufacturing of engineered microbes and in gaining regulatory approval for environmental release. To date, most engineered microbes have been designed for use in closed environments, such as large fermenters. In order to adapt engineered microbes to *in situ* bioremediation applications, several innovations and controls will be required.

Synthetic Alternatives to Pollutants

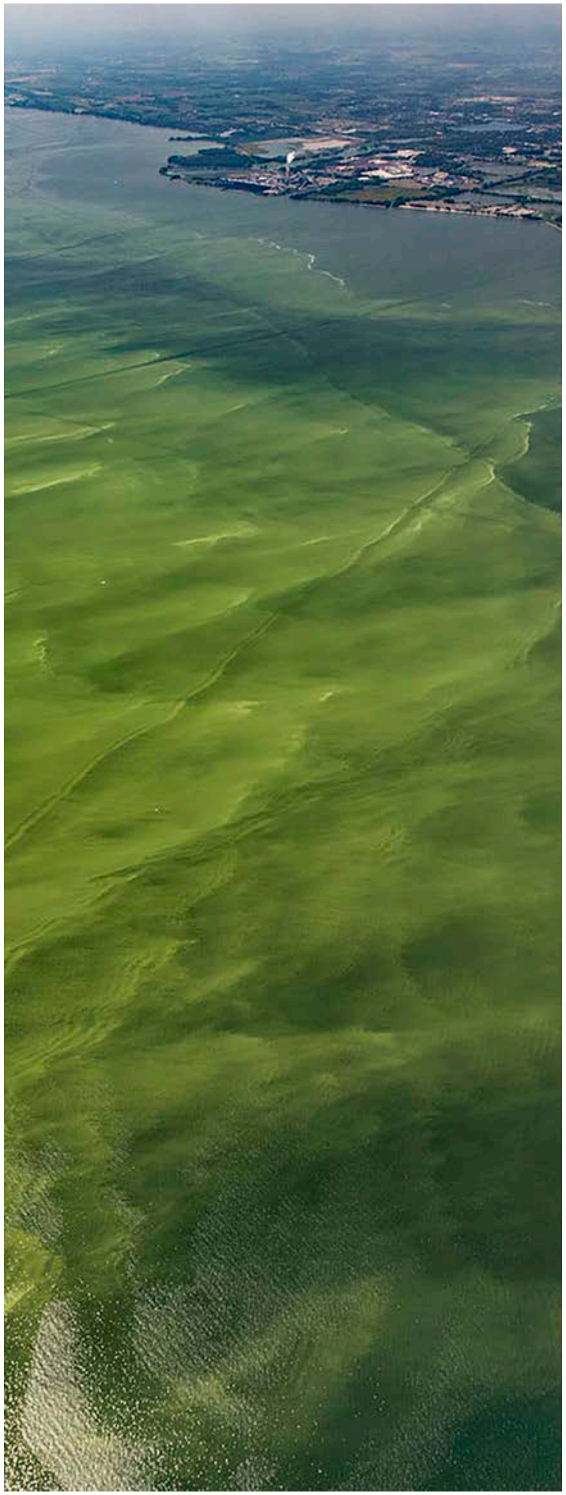
Biofuels

Cultivated microalgae can be engineered to produce substances (such as starch or various types of oils) for manufacturing diverse biofuels. For instance, starch recovered from algae is easily converted and fermented into biofuels. It is also possible to genetically modify algae to produce ethanol through photosynthesis. Triglyceride oils produced by algae are readily converted to biodiesel. Algal biomass may be fermented to produce biogas, a mixture of methane and carbon dioxide. The biomass may also be fermented to produce hydrogen.

Each of these approaches are technically possible; however, applications of these innovative technologies have not scaled as anticipated. Due to multiple bottlenecks, sustained fuel production from algae (engineered or otherwise) has not been feasible with the current technologies due to unfavorable economics. Despite this, big corporations, including Exxon Mobil, Shell, and Reliance (India), have recently revived their previous algal biofuels efforts.

BioPlastics

With a range of potential applications, algae products can provide plastic alternatives to single-use plastics, such as packaging and straws, that biodegrade much more readily. Examples of these algae products include fermentable sugars and starch used for polymers (bioplastic), di-acids for nylon production, algae protein used in thermoplastics, mannitol used in biomaterial (polyether polyols) as well as amino acids/peptides and omega-3-fatty acids used for polyurethane production. The product market sizes for these biomaterials/plastics appears to be expanding rapidly and several startups are responding to the opportunity. One notable company, U.S.-based Lolliware Inc., uses kelp to directly produce glassware and straws that have experienced remarkable uptake in the market.



MARINE INVASIVES

THREATS

Invasive species and irruptive species can cause significant ecological harm: displacing native species, reducing biodiversity, decreasing ecosystem function, impeding ecosystem services, impacting human health, and causing substantial economic harm. It's estimated that invasive species in the United States cause economic losses totaling $120 billion per year.

Rapid globalization and increasing global trade, travel, and transport have accelerated marine biological invasions by increasing the number of introductions through shipping, navigational canals, aquaculture, and the aquarium trade. Furthermore, climate change is expected to increase the frequency and extent of invasions. At the same time, the detection and control of invasive and irruptive species can be particularly challenging in marine environments. Conservation managers often rely on time and labor-intensive manual removal. Genomic tools have the potential both to improve detection of invasive species and to provide a mechanism for biocontrol of invasive and irruptive species.

INNOVATIONS

The early detection and rapid response to invasive species is essential for controlling invasions. To that end, environmental DNA (eDNA) is now being used to detect invasions in freshwater environments. Scientists and managers predict that rapid growth, widespread deployment, and automation of eDNA techniques will transform the sensitivity, speed, and scale with which invasive organisms are detected in all ecosystems.

In marine settings, eDNA detection of invasive species in the ballast water of incoming vessels at ports and in marine protected areas is a strategic focal point for monitoring efforts.

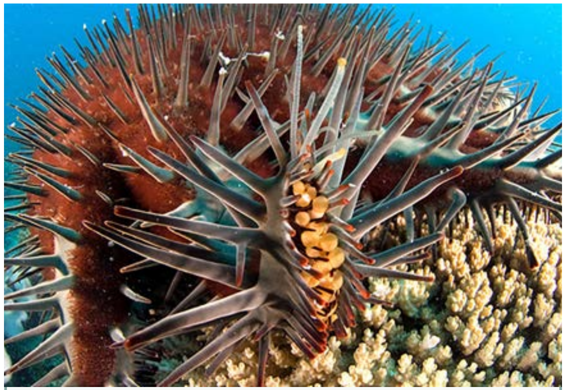
Current biocontrol measures for marine invasive and irruptive species primarily involve manual techniques, such as killing or capture by divers. While these efforts have had some success, they are expensive, labor-intensive, and difficult to scale. Furthermore, these methods rarely eliminate every individual, allowing for the region to be repopulated.

Genetic biocontrol methods have the potential to be effective control strategies. Potential mechanisms for genetic biocontrol include repressible lethal, sex-specific repressible lethal, pheromone disruption, synthetic species, and gene drives. Each of these genetic interventions may be suitable for different species and use cases; each is at a different level of development; and each presents significantly different technical considerations and risk factors.

With life histories conducive to genetic manipulation, crown-of-thorns starfish (COTS) and Northern Pacific sea stars are two potential targets for genetic biocontrol using the repressible lethal disruption system. In this approach, the genetic circuits of the invasive species are engineered to require the presence of a "repressor" molecule (often tetracycline) to prevent the expression of a toxic gene during immature life stages. Any offspring that inherit the conditional lethal gene will die due to the absence of this repressor in the wild.

There are significant challenges to using genomic tools for biocontrol. A sizeable amount of foundational and proof-of-concept research will be required prior to field implementation. Specifically, ecological and population genetic research must be conducted on the target species to determine the feasibility and effectiveness of the specific biocontrol method. The timeline to develop a comprehensive field trial proposal is estimated to be at least five years. Also, interventions using genetic biocontrol methods are controversial. It is essential that the field moves forward cautiously and obtains social license from the public and policy makers. The timeline and financial investment required for genetic control methods to be ready for field implementation could be five to 10 years.

See Big Idea: Targeting Invasives



BIG IDEA:
TARGETING INVASIVES

This proof-of-concept project brings much needed innovation to the intractable problem of marine invasives. Genetic biocontrol could reduce pest species populations while minimizing the off-target effects of other control options. A partnership with CSIRO is central to the early foundation steps in developing these biocontrols.

Project Team:
Maciej Maselko; Russ Babcock; Bernard Degnan; Scott Cummins; John Keesing; Owain Edwards: David Westcott

Technology(ies):
Genetic Engineering (for repressible lethal & pheromone disruption traits)

Timeframe:
3 Years

Budget:
$450,000

WILDLIFE DISEASE

THREATS

Emerging infectious diseases in wildlife are increasing in frequency and severity, largely due to human impacts on natural environments. Recent marine disease outbreaks have occurred in sea turtles, mammals, corals, sea stars, mollusks, and several groups of aquatic plants. Marine disease outbreaks are often associated with compounding factors including climate change, pollutants (nutrients, toxics, or noise), poorly planned aquaculture, invasive species, and habitat loss. Diseases in marine ecosystems pose a particular challenge due to several factors: lack of adequate monitoring for early detection and management, a gap in baseline data for current biodiversity and microbial assemblages in healthy states, and the sheer vastness of the ocean.

INNOVATIONS

Given the potential increase in the prevalence and severity of marine disease, it is not too soon to innovate using technology and genomic tools. These include the establishment of a centralized database for marine disease reporting across taxa. The establishment of mobile laboratories equipped with real-time sequencing machines may uncover important correlations between abiotic factors and disease outbreaks. Collection and analysis of eDNA could help to rapidly characterize and monitor microbial community diversity and associations with disease. Lastly, a precision medicine model for wildlife species could use a comparative "omics" approach to inform treatment options.

Genomic technologies hold great potential to improve conservation measures for marine wildlife threatened by infectious disease. Large-scale whole genome resequencing of host populations can help to identify resistant populations and genetic variation associated with resistance. Understanding how genetic variation is linked to resistance can inform modeling. It can also accelerate the development of disease-resistant stocks through marker-assisted selection, which may be a crucial strategy for coral conservation. Finally, whole transcriptome sequencing studies in both controlled experimental settings and wild populations can help identify genomic pathways involved in the host response to stress and disease.

WILDLIFE TRADE

THREATS

Wildlife trade is one of the biggest drivers of biodiversity loss, and the scale of the trade in marine species is massive. Between 63 and 270 million sharks and untold numbers of rays are killed each year for their fins, meat, and gill plates. Despite a moratorium on commercial whaling, more than 2,000 whales and 90,000 dolphins are killed annually. All 27 species of sturgeon are threatened due to the trade of caviar, including 16 species that are critically endangered. Every year, approximately 37 million seahorses are caught and sold into the traditional medicine trade. Enforcement and monitoring are the greatest challenge for both the legal and illegal trade of marine species.

INNOVATIONS

There are a number of potential opportunities to employ genomic tools for monitoring and reducing the illegal and/or unsustainable trade of marine wildlife. New genetic tools can enable the rapid identification of species by enforcement staff at ports and borders. For successful implementation, these methods need to be easily deployed in the field without a full lab and technical training, be affordable enough for regular use, and be able to test multiple samples rapidly and accurately. Currently on the market are three low-to-moderate-cost, portable devices (ChaiBio Open qPCR, Biomeme, and ConservationXLabs Scanner) that use polymerase chain reaction (PCR) methods for rapid analyses of species-identifying DNA barcodes. The base technology and assays have been developed for certain species, including shark fins for CITES-listed species, but specific primers for other species of interest must be developed for this technology to effectively disrupt illegal trade.

With successful uptake, PCR technology provides a model that has the potential to transform the monitoring and interdiction of the wildlife trade, and could also be adapted to tackle illegal, unreported, and unregulated fishing. Longer-term genomic solutions to reduce or eliminate the demand for wild populations will require the development of either recombinant-based or genetically-engineered synthetic replacements products.

See Big Idea: Disrupting Illegal Trade

BIG IDEA:

DISRUPTING ILLEGAL TRADE

Enhanced monitoring using modern genomic tools could transform the interdiction of illegal wildlife trade. This project would couple advanced market commitments for hand-held sequencers with focused training programs to help officials monitor and stop the trade in illegal wildlife and fisheries.

Project Team:
James Askew; Lee Crockett

Technology(ies):
Reverse-Transcriptome Polymerase Chain Reaction (RT-qPCR)

Timeframe:
3 Years

Budget:
$415,800

ISLANDS INVASIVES

THREATS

Invasive rodents on islands are one of the greatest threats facing global seabird populations. Recent research shows that rodent invasions also disrupt the natural cycle of nutrient subsidies found in seabird guano to near-shore marine environments, a process that promotes the growth of both corals and fishes. Genetic tools are some of the most promising tools to increase the scale, scope, and pace of eradications on islands.

INNOVATIONS

The Genetic Biocontrol of Invasive Rodents (GBIRd) program is a partnership of geneticists, biologists, social scientists, ethicists, and conservationists from research universities, government agencies, and other not-for-profit organizations. The program is investigating the feasibility and suitability of using genetic tools, specifically RNA interference (RNAi) or gene drives, to save native island species by efficiently eliminating invasive species.

While technical challenges remain, successful eradications of agricultural insect pests and rodents using RNAi suggests the technique could be applied in wildlife settings. For success in the wild, genetic engineering could be used to distribute fitness-reducing genes throughout a population to drive it to local extinction. Gene drive research has started with the house mouse, a model organism with a natural gene drive. Any progress that controls population levels in mice will lead directly to applications for invasive rats and other problematic invasive mammals on islands. Obstacles related to social and regulatory acceptability are potentially more significant than technical factors, and these components must be developed as thoughtfully as the technical and scientific elements for any potential field trial or future release.

See Big Idea: Restoring Islands to Restore Reefs (on Page 7)

HIGH SEAS EXPLOITATION

THREATS

The high seas — defined by the United Nations (1982) as open ocean waters that lie beyond the economic zones and jurisdiction of any one country — account for two-thirds of total ocean area. Fishing and mineral exploitation have expanded into the high seas over the past few decades. Meanwhile, the International Seabed Authority (ISA) has recently granted licenses to 29 mining contractors for exploitation activities on the seabed of the high seas. Over a 15-year period, a single mining operation could damage marine systems over an area of 50,000 square kilometers. There is no universal law protecting high seas biodiversity, and just one percent is closed to commercial use.

INNOVATIONS

To fill the gap in governance, the United Nations is developing a legally-binding agreement to protect marine biodiversity on the high seas: Biodiversity Beyond National Jurisdictions (BBNJ). The protection and sustainable use of the high seas will ultimately depend on understanding the high seas ecosystem, and conserving and managing ocean resources will require incorporating scientific advice into policy-making decisions. Therefore, genomic tools have the potential to make the implementation of the UN treaty more affordable and effective, easing regulation for states, and streamlining regulatory compliance for commercial interests.

The goal of the BBNJ treaty is to implement global governance of marine genetic resources, establish effective and equitable marine protected areas, utilize environmental impact assessments to understand the impacts of different economic activities on high seas ecosystems, and build capacity in and transfer marine technology to developing countries. Genomic tools could be transformative in each of these four priority areas. With this in mind, it is not too soon to develop global protocols and practices to share genetic resources and revenue. Further development of genetic tools and libraries can establish ecological baselines for assessing potential impacts and identifying biodiversity hotspots, vulnerable marine ecosystems, and ecologically significant areas that need protection. Genomic tools, such as eDNA, can be used to document biodiversity and streamline the assessment of environmental impacts in a cost-effective manner.

See Big Idea: Environmental DNA to Protect the Seabed and High Seas

BIG IDEA:

ENVIRONMENTAL DNA TO PROTECT THE SEABED AND HIGH SEAS

Exploitation of the high seas is increasing and exacerbating threats to biodiversity, which is both poorly known and difficult to study. In response, negotiations at the United Nations have been initiated to create a governance structure to assess, share, and protect these global resources. Environmental DNA technologies represent a potentially game-changing tool to assess and protect these resources. This competitive project would accelerate the development of critically needed eDNA tools.

Project Team:
To be determined. Leaders include: Woods Hole Oceanographic Institute, Monterey Bay Aquarium Research Institute, Scripps Institute

Technology(ies):
eDNA, Machine Learning, Bioinformatics

Timeframe:
3 years

Budget:
$3,000,000 for competitive grants

BIODIVERSITY LOSS

THREATS

The cumulative and synergistic effects of the threats described throughout this report are expected to significantly increase both the rate and the extent of the extinction of marine species. For each marine threat assessed in this report, our research and the experts we interviewed emphasized that the rate at which marine taxa are banked and sequenced must accelerate exponentially in order to preserve biodiversity and provide resources for future genetic rescue efforts. Therefore, a banking and sequencing initiative that prioritizes species of conservation concern could be transformative for marine conservation.

INNOVATIONS

Marine Banking and Sequencing Fund

Any genetic rescue effort requires two resources: (1) a high-coverage reference genome, ideally based upon a composite of genome sequences of individuals from different populations of the species, and (2) a source of viable cells or tissue (a voucher) from that species. These essential resources for genetic rescue are desperately lacking for a wide range of marine fish, wildlife, and ecosystems.

Revive & Restore proposes to establish a Marine Banking & Sequencing Fund that would accelerate the banking and sequencing of marine species of high conservation significance. The Fund would identify potential marine conservation solutions that are currently hampered by a lack of genomic insight and fund the creation of a high-quality reference genome from cryopreserved samples, which will be made available as open source data. This targeted but comprehensive approach will accelerate the pace of genetic rescue for marine environments and allow research data to be fully leveraged for the benefit of conservation.

See Big Idea: Marine Banking & Sequencing Fund

De-Extinction

Although only a few extinctions in marine environments have been documented, each extinction event likely has had widespread impacts. Extinctions can degrade complex ecological interactions such as food chains, ecosystem interactions, and mutualistic relationships. Though marine biodiversity is more difficult to catalog and monitor than that of terrestrial life, more than 15 known extinctions of marine species have occurred in recent times, including the great auk.

Restoring the roles of extinct species through reintroduction or translocation can have valuable ecological benefits and can reverse the ecological damage caused by an extinction. With advances in paleogenomics and gene-editing, the practice of "de-extinction" may recreate ecotypes of lost species. In the marine environment, two extinct species have been identified as potential candidates for de-extinction: the Steller's sea cow, which went extinct in 1768, and the great auk, which went extinct in the 1850s. The severe hunting pressure that led to each species' extinction is no longer a threat, and extensive habitats are available for their recolonization.

BIG IDEA:

MARINE BANKING & SEQUENCING FUND

This initiative brings an innovative conservation focus to generating sequences and banking life for critical conservation needs and threatened wildlife by identifying novel applications that would benefit from the use of genomic data.

Project Team:
Edward Perello; Devaughn Fraser; Dan Distel; Oliver Ryder; Beth Shapiro; Gavin Naylor

Technology(ies):
Cryopreservation; NextGen Sequencing

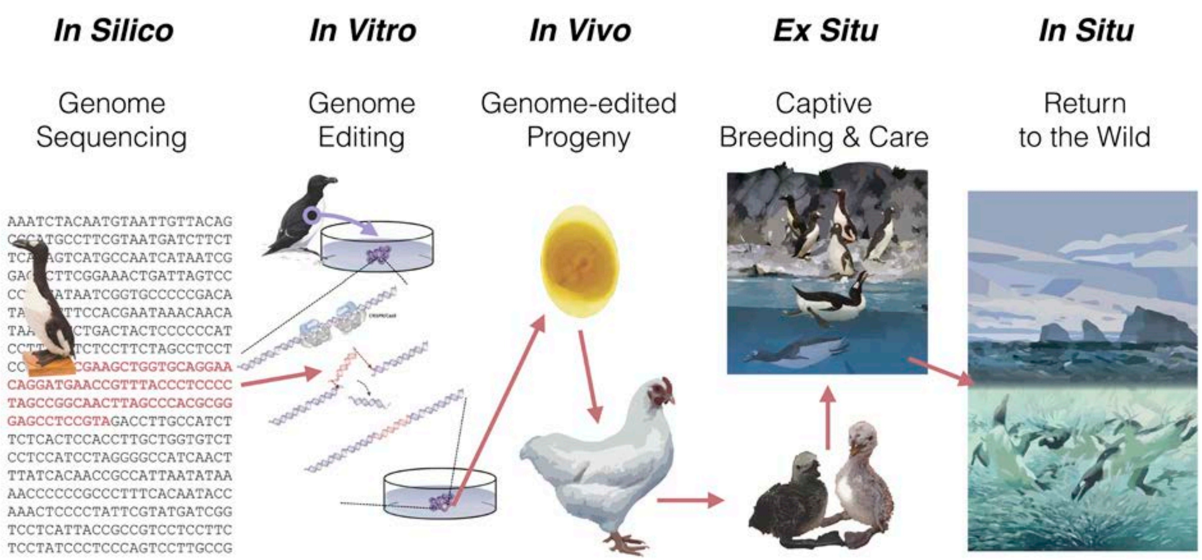
Timeframe:
2–3 Years

Budget:
$2,025,000

De-extinction of the great auk would be a decades-long process. Scientists must first sequence the genomes of both the great auk and the razorbill (its closest living relative) and conduct comparable genomics to identify genes and alleles that influence phenotype; then make gene edits to reproductively-competent cells of the razorbill in order to incorporate the traits of the extinct species; develop advanced reproductive technologies to hatch great auks from razorbill surrogates; propagate a great auk flock in captivity for wild release; and release the birds to the wild for monitored and managed recovery. At each step, avian de-extinction research will generate foundational science that could transform bird conservation.

See Big Idea: De-Extinction of the Great Auk

The 5 Phases of Great Auk De-Extinction



BIG IDEA:

DE-EXTINCTION OF THE GREAT AUK

This project begins the scientific research necessary for bringing back the great auk. In addition to potentially replacing a key component of North Atlantic ecosystems, the pursuit of de-extinction of the great auk would likely create new techniques to facilitate adaptation and enhance resilience in threatened marine birds.

Project Team:
Ben Novak; Rosemary Walzem

Technology(ies):
Avian germ-line transmission

Timeframe:
3 Years (First Phase)

Budget:
$675,000

MARKET ALTERNATIVES FOR OCEAN PRODUCTS

SYNTHETIC ALTERNATIVE TO HORSESHOE CRAB BLOOD

THREATS

Since horseshoe crab blood is extraordinarily sensitive to bacterial contaminants, the four species of horseshoe crab have been integral to the safe manufacturing of injectable medications for the past 40 years. Today, a derivative of horseshoe crab blood is used in an estimated 70 million safety tests each year. The production of these tests requires the bleeding of 500,000 horseshoe crabs annually in the US alone, and at least 15 percent of the crabs die from the bleeding. The current overexploitation of horseshoe crabs is dangerously similar to that of other mismanaged species that have been driven to extinction and causes ecosystem-level impacts in the estuaries where crabs spawn.

INNOVATIONS

A synthetic alternative, known as recombinant factor C (rFC), was developed in 1997 using recombinant DNA. More than a decade of research has proven that rFC is just as efficacious as the test that has been used for the past 40 years, yet uptake of the synthetic alternative by the pharmaceutical industry has been limited. To dispel lingering concerns over efficacy, Revive & Restore collected data from 10 independent studies and published a review in PLOS Biology in 2018 that demonstrated the reliability of using rFC as a replacement for the assay conducted with blood-derived factors of the horseshoe crab.

The existence of an effective synthetic alternative to the wild-sourced horseshoe crab blood provides the biomedical and pharmaceutical industries with an opportunity to modernize procedures and to significantly contribute to the conservation of horseshoe crabs and their ecosystems. Eli Lilly and Company was the first pharmaceutical manufacturer to adopt rFC, and three of its largest U.S. manufacturing facilities have converted to rFC for quality testing of process water. Switching to the synthetic alternative just for the testing of process water will reduce the number of horseshoe crab-derived safety tests performed at each facility by 90 percent.

MARKET ALTERNATIVES FOR SEAFOOD

THREATS

Annual global seafood production has grown from approximately 20 million tons in 1950 to roughly 170 million tons today. The United Nations projects the demand for seafood will increase by more than 47 million tons in the next decade. Seafood consumption is fundamentally unsustainable due to the preferential consumption of large predatory fish, overfishing, and issues with aquaculture, including damage to natural ecosystems caused by site selection, disease, and over-harvesting of forage fish. There is an urgent and substantial need for innovations in both wild-caught and cultivated seafood to sustainably meet the ever-increasing global demand.

INNOVATIONS

There are three primary areas where innovation in genetic technology can reduce the environmental hazards of producing seafood and lead to a more bio-abundant ocean. First, biotechnology is currently being used to improve the efficiency of aquaculture, which could help farmers keep pace with growing consumer demand. Second, there are several promising new approaches to reduce or eliminate the use of forage fish in aquaculture. Finally, biotechnology is being used to create new alternative seafood products that do not rely on animals for producing seafood and fish meal. This is known as cellular agriculture.

Private philanthropy can play an important role in advancing the development of cellular agriculture to replace wild-caught seafood. Specifically, by investing in research to create stem cell lines of commercially viable fisheries, private philanthropy can remove a significant barrier for private companies to enter the market and develop products. The success of the Impossible Burger™ suggests that there may be a viable market for cultured seafood products.

However, to meaningfully penetrate markets, farmed-fish and seafood alternatives will need to compete on price. To compete with the economics of wild-caught fisheries, producers of cultured seafood must reach price parity. Similar considerations apply to replacement products targeting forage fish.

Public acceptance of genetically modified foods is a significant concern for the development and consumer adoption of genetically modified seafood.

ABOUT THIS HORIZON SCAN

Revive & Restore was given the extraordinary opportunity to systematically assess where genomics and biotech could compliment and even transform marine conservation. Our researchers interviewed over 100 experts in marine conservation, evolutionary biology, genomics, biotech, ecology, and fisheries. These interviews were supported by an extensive literature review of over 250 cited articles.

Necessity is the mother of invention, and it is clear that marine conservation needs to expand its toolkit and options for contending with ever-increasing threats. The featured Big Idea projects were selected due to their conservation benefits as well as their significance as innovations in marine conservation. As noted above, advances in genomics offer profound new insights into the ecology of marine species, and in a couple cases, potential interventions to contend with threats.

We recognize that biotechnologies that have potential for conservation applications present a diverse spectrum of ethical, social, and legal challenges. For example, genomic insight for the management of fisheries is a precise and relatively uncontroversial tool to understand population dynamics. In contrast, genome engineering that limits the reproductive potential of an invasive species is controversial because its an intervention in the natural evolutionary process and may have far-reaching and unintended consequences. No matter the level of intervention, responsible innovation will require that potential benefits and risks be objectively weighed alongside thoughtful consideration of ethical concerns. Philanthropy, non-governmental organizations, and public agencies have the ability to help catalyze this field and to evaluate the benefits, risks, and controversies.

About Revive & Restore:

With the mission to enhance biodiversity through the genetic rescue of endangered and extinct species, Revive & Restore has a unique role in conservation. We embrace the full spectrum of activities that entails: scanning the horizon for innovations, guiding demonstration projects, engaging on the ethical and policy considerations and visioning the potential to enhance conservation practice with innovative new tools.

revive & restore

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OCEAN GENOMICS HORIZON SCAN

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For this report, Revive & Restore interviewed almost 100 marine biologists, conservationists, and technologists representing over 60 institutions. Each was challenged to identify ways that rapid advances in genomics could be applied to address marine conservation needs.

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Mary Hagedorn, *Smithsonian Conservation Biology Institute*

Gator Halpern, *Coral Vita*

Ove Hoegh-Guldberg, *University of Queensland*

Ling Ding Jeak, *National University of Singapore*

Robert Jones, *The Nature Conservancy*

Ryan Kelly, *University of Washington*

Natalie Kofler, *Yale University*

David Lang, *OpenROV*

George Leonard, *Ocean Conservancy*

Petra Lundgren, *Great Barrier Reef Foundation*

Molly Lutcavagge, *Large Pelagics Research Center*

Skyli MacAfee

Kristen Marhaver, *CARMABI Research Station*

Matthew Markus, *Pembient*

Mark McAnallen, *Biomeme*

John McCosker, *California Academy of Science*

Chris Meckley, *ACI Aquaulture*

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Michael Moore, *Woods Hole Oceanographic Institution*

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Larry Niles, *Consulting Biologist*

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Heath Packard, *Island Conservation*

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Caroline Palmer, *Plymouth University*

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Cynthia Smith, *National Marine Mammal Foundation*

Liz Specht, *Good Food Institute*

Dirke Steinke, *International Barcode of Life & University of Guelph*

Eric Stiles, *New Jersey Audubon*

John Teem, *International Life Sciences Institute*

Sam Teicher, *Coral Vita*

Karsten Temme, *Pivot Bio*

Nina Therkildsen, *Cornell University*

Tierney Thys, *National Geographic*

Sasha Tozzi, *Microbiotech Solutions*

Miller Tran, *Triton Algae Innovations*

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Kyle Van Houtan, *Monterey Bay Aquarium*

Madeleine van Oppen, *Australian Institute of Marine Science*

Rebecca Vega-Thurber, *Oregon State University*

Amanda Vincent, *Project Seahorse & University of British Columbia*

Nate Walworth, *University of Southern California*

Tariq Warsi, *Syntheseas*

Luke Warwick, *Wildlife Conservation Society*

James West, *Catalina Sea Ranch*

Demian Willette, *Loyola Marymount University / UCLA*

John Wise, *University of Louisville*

Alex Worden, *Monterey Bay Aquarium Research Institute*

WHAT SUCCESS LOOKS LIKE

Threats to our oceans are forcing innovation to turn the tide on species loss, and hopefully create a more bioabundant future. Brilliant scientists and conservationists are seeking ways to transfer innovations in 21st century biotechnology to marine conservation. The Big Ideas identified in this Horizon Scan will transform our understanding of conservation of marine biodiversity and build a new toolkit for marine conservation practice. These promising efforts give hope that with focused effort and funding, we will have a wholly new set of tools to enhance and restore marine ecosystems. Furthermore, acting today will likely spur additional innovation and help to set a course for a new more bioabundant ocean.

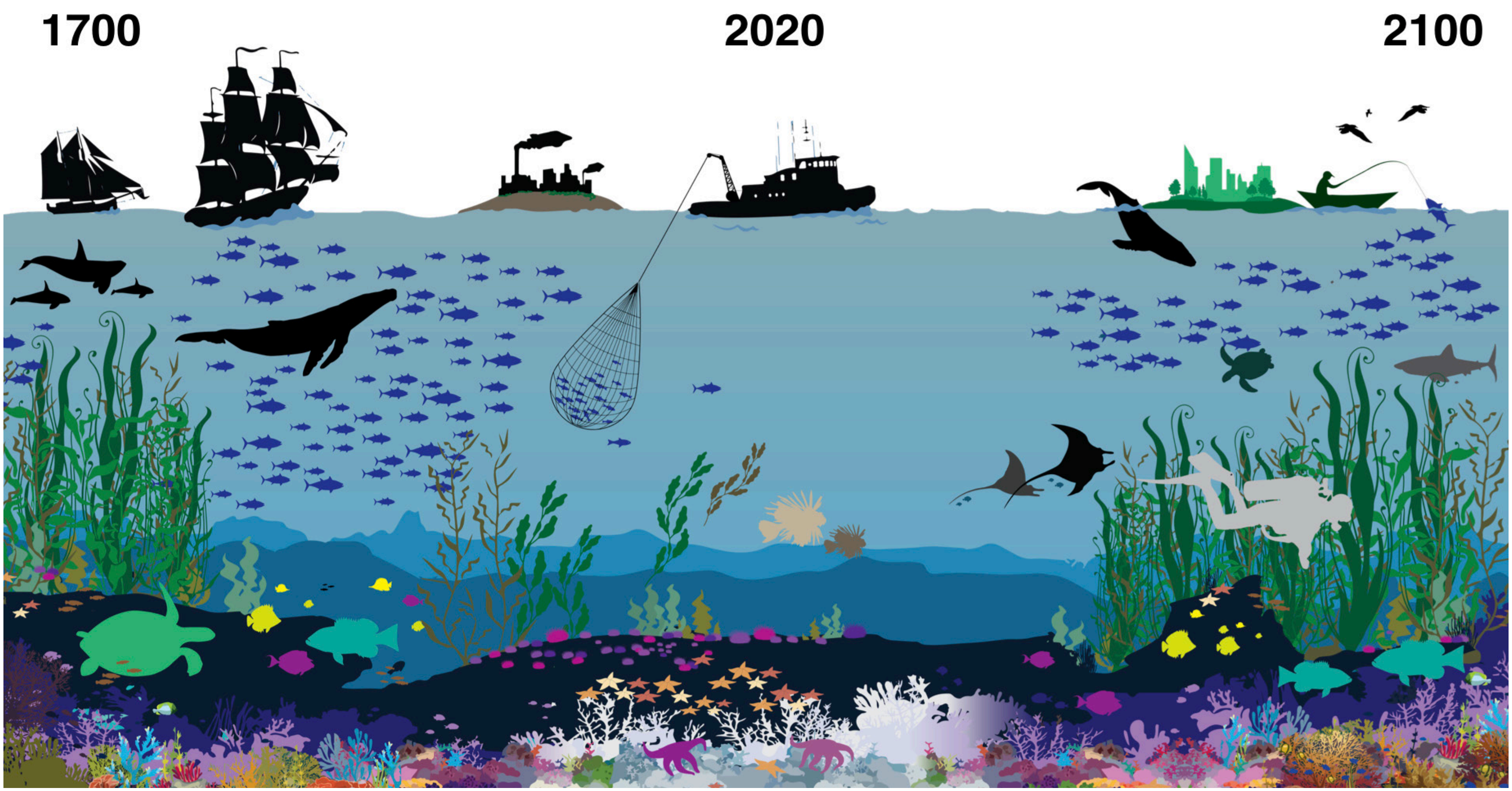

Illustration credit: Revive & Restore