THE FUTURE OF CORAL REEFS

A PRELIMINARY RESEARCH STUDY

APRIL 2018

Contents

HOW TO USE THE REPORT

This paper is organized according to XPRIZE's ImpactMap development process: Insight, Foresight, Action:

- Insight: hi-fidelity research is conducted, aimed at establishing a baseline, that is, a description of the current state of affairs in a given field (or fields). Establishing this baseline is crucial to identifying gaps, which potential XPRIZEs could solve.
- Foresight: forecasting techniques are employed to determine the baseline scenario (extrapolating the current state into the future), and a preferred future, which will require a series of XPRIZEs in order to be achieved.
- Action: ideation techniques are used in order to identify potential breakthroughs, which could later become XPRIZEs.

BACKGROUND

What are coral reefs and why are they important?

Coral reefs are the ocean's most diverse and complex ecosystems, supporting 25% of all marine life, including 800 species of reef-building corals and more than one million animal and plant species. They are close relatives of sea anemones and jellyfish, as each coral is a colony consisting of many individual sea anemone-like polyps that are all interconnected.

Tropical coral reefs, found in warm, clear water at relatively shallow depths, are intricately patterned carpets of life growing on foundations formed primarily by calcium carbonate exoskeletons and coralline algae. These structures fuse over time, enlarging the reef and creating countless nooks and crannies. As the reef grows, species from nearly every major taxonomic group cover every square inch of these tightly integrated systems, providing food and shelter to a spectacular variety of fish and invertebrate species, including many of commercial value.

'Hard' corals use calcium carbonate from seawater to synthesize a hard, mineral protective shell around each polyp. These exoskeletons, along with shells formed by coralline algae, mollusks and tubeworms, spicules made by sponges, and shells of other calcifying species form the structural foundation of coral reefs. Corals catch plankton with their tentacles, but most of their nutrition comes from photosynthetic algae that live in their tissues, using the coral's waste products for their own nutrition and feeding the corals with sugars and other nutritious compounds that leak through their cell membranes.

Deep water reefs, formed by large, long-lived but fragile, soft corals are also architecturally and ecologically complex and teem with life, but lack a calcium carbonate foundation. Though beyond the reach of sunlight, underwater lights reveal them to be nearly as beautiful and colorful as their tropical counterparts.

The condition of coral reefs is important to ocean health because healthy reefs provide many benefits to people, including food, natural products, coastal protection from storms and erosion, jobs and revenue, tourism and recreation, biodiversity and others. Reef tourism alone is worth $36 billion per year globally.

The Problem

60% of reefs are already seriously damaged by local sources such as overfishing, destructive fishing, anchor damage, coral bleaching, coral mining, sedimentation, pollution, and disease. When these types of human threats are combined with the influence of rising ocean temperatures, 75% of reefs are threatened.

The majority of reef loss or damage is not deliberate. Coral reefs are being degraded by an accumulation of stresses arising from human activities. In simple terms, stresses can be grouped by the actions of people extracting material from, and placing materials upon, coral reefs. Overfishing, pollution and coastal development top the list of chronic stressors. In many situations, chronic stresses are overwhelming the resilience, (or the capacity for self-repair), of reef communities. Some coral reefs are covered with sand, rock and concrete to make cheap land and stimulate economic development. Others are dredged or blasted for their limestone or to improve navigational access and safety. In addition to this, long-term changes in the oceans and atmosphere (rising sea temperatures and levels of CO_2), and acute stresses from highly variable seasons, severe storms, earthquakes and volcanic eruptions also affect coral reefs.

Coral Bleaching

Coral bleaching occurs when the symbiosis between corals and their zooxanthellae[1] breaks down, resulting in a rapid whitening of the coral host (thus the term "bleaching"). This is a stress response by the coral host that can be caused by various factors, but more severe and frequent cases are caused by a rise in sea surface temperature (SSTs). If the temperature decreases, the stressed coral can recover; if it persists, the affected colony can die.

The impacts from coral bleaching are becoming global in scale, and are increasing in frequency and intensity. Mass coral bleaching generally happens when temperatures around coral reefs exceed 1 degree Celsius above an area's historical norm for four or more weeks. Sea surface temperature increases have been strongly associated with El Niño weather patterns. However, light intensity, (during doldrums, i.e. flat calm conditions), also plays a critical role in triggering the bleaching response. If temperatures climb to more than 2 degrees Celsius for similar or longer periods, coral mortalities following bleaching increase.

Mass coral bleaching was not documented in the scientific literature before 1979; however, significant mass bleaching events have since been reported in 1982, 1987, 1992 and the strongest sea surface warming event ever recorded occurred in 1998, where an estimated 46% of corals in the western Indian Ocean were heavily impacted or died. In 2005, sea surface temperatures in the Caribbean were the highest reported in more than 100 years, and there was also significant coral

[1] Most reef-building corals contain photosynthetic algae, called zooxanthellae, that live in their tissues. The corals and algae have a mutualistic relationship. The coral provides the algae with a protected environment and compounds they need for photosynthesis. In return, the algae produce oxygen and help the coral to remove wastes.

bleaching following this warming. This year, coral bleaching is being reported in several locations around the world. If sea surface temperatures continue to rise, then the frequency and severity of coral bleaching will also increase, likely affecting the ability of coral reefs, as we have known them, to adapt and to provide many of the services that people and ocean life rely upon.

Why is this happening?

Coral reef ecosystems are complex, dynamic, and sensitive systems. Although they are geologically robust and have persisted through major climactic shifts, they are sensitive to small environmental perturbations over the short-term. Slight changes in one component of the ecosystem affect the health of other components. Changes may be attributed to a number of causes but generally fall into two categories, natural disturbances and anthropogenic, i.e. human, disturbances. Distinguishing between natural and anthropogenic disturbance is not always simple because the impacts of human actions may not be seen until well after the action has occurred or may not be seen until it is coupled with a natural disturbance. Also, some events that appear to be natural may have been influenced by human actions. Impacts may be direct or indirect and may be compounded where several occur. For these reasons, it is often difficult to make cause-and-effect linkages when reef degradation is observed. Anthropogenic influences and natural variability in coral reef ecosystems are discussed below with emphasis on changes or effects seen in the coral reefs of the National Marine Sanctuary System.

Natural Disturbances

Coral reef ecosystems are naturally dynamic and experience natural disturbances that vary on both temporal and spatial scales. Natural disturbance events that affect coral reefs include: tropical storms, outbreaks of coral predators, disease, extended periods of elevated or low water temperatures, and extremely low tides. Although these events disturb the reefs and may kill a significant amount of coral, they are part of a natural cycle that may benefit the reef ecosystem in other ways. The destruction caused by a hurricane, for example, opens space for reef organisms that have been excluded by larger and longer-lived corals. Hurricanes also flush out accumulated sediment within the reef and create more substrate for organisms to settle and grow on. A healthy reef ecosystem will eventually recover from natural disturbance events. However, when these natural disturbances occur on a reef system that has also been impacted by human activities, the reef system may have a reduced capacity or complete inability to rebound.

Anthropogenic Influences

The expanding human population and its activities are already impacting coral reef health in a number of ways. Development, urbanization, and agriculture lead to increases in polluted runoff, sedimentation, and nutrient inputs. Growing industry and automobile usage cause an increase in emissions contributing to the greenhouse effect and ocean acidification. Commercial and private vessel traffic mean the possibility of fuel leaks or spills, vessel groundings, and anchor damage.

The harvest of reef resources is also taking a toll on the health of coral reef ecosystems. Overfishing on reefs leads to an unbalanced ecosystem, allowing more competitive or less desirable organisms to become dominant. Fishing methods such as the use of explosives and poisons severely harm reefs and reef organisms. The harvesting of coral skeletons for souvenirs depletes healthy corals or substrate where coral larvae might have settled. Increased tourism in areas of coral reef habitat contributes to increased pressure from scuba diving, recreational fishing, and vessel traffic.

INSIGHT

TREND ANALYSIS

METHODOLOGICAL NOTE

Trend analysis is a method of analysis that allows us to identify the key drivers that will shape the future, how this future will look, and the key areas one needs to change or impact in order to shape a different, more desired future (from a subjective point of view). Another way to describe trend analysis in the context of XPRIZE's studies is environmental scanning–the possession and utilization of information about occasions, patterns, trends, and relationships within an organization's external environment.

SOCIAL/DEMOGRAPHIC TRENDS

World economic growth: Is projected at 3.1% per annum, close to its average for the past twenty-five years, with higher growth rates in developing countries and the transition economies, and lower rates in the OECD area. World population is expected to increase substantially, albeit at a gradually slower pace, reaching 8 billion in 2020 and 9 billion in 2050. Consequently, related development, urbanization, and agriculture will continue leading to increased freshwater runoff, polluted runoff, and sedimentation.

Coastal development: The growth of coastal cities and towns generates a range of threats to nearby coral reefs. Where space is limited, airports and other construction projects may be built on land reclaimed from the sea. Sensitive habitats can be destroyed or disturbed by dredging activities to make deep-water channels or marinas, and through the dumping of waste materials. Where land development alters the natural flow of water, greater amounts of fresh water, nutrients and sediment can reach the reefs causing further degradation.

Unsustainable tourism: Tourism generates vast amounts of income for host countries. When unregulated however, tourism pressures can cause damage to the very environment upon which the industry depends. Physical damage to the coral reefs can occur through contact from careless swimmers, divers, and poorly placed boat anchors. Hotels and resorts may also discharge untreated sewage and wastewater into the ocean, polluting the water and encouraging the growth of algae, which competes with corals for space on the reef.

TECHNOLOGY

Scaling restoration: The pace of coral destruction is overwhelming compared to the pace and scale of restoration technologies and techniques that do not come close to meeting the scale of the problem. To understand how to solve the problem we need to understand the scale of the coral crisis from a first principles approach, and this was summarized by astrophysicist and technology expert Tom Chi, co-founder of Google X:

We have lost over half of coral reefs already, and a 100 x 120m patch of coral is lost every minute. Restoring at the same rate just breaks even over time, and current approaches do not come close to matching this rate of loss. Hand planting, which is the primary method of restoration, can plant 6-8 corals per hour covering 1-2m per hour. Paying divers just $10/hour would require $173 million per day and take 720,000 divers continuously planting to reach a pace of 100 x 120m restoration rate. Full restoration using current techniques could cost upwards of $1 trillion dollars using current technologies and more than double that to maintain. Radical reduction in cost and deployment is needed for global coral restoration - 100x lower is necessary, and right now 10x examples are needed to drive large-scale investment. The current methodologies of protecting healthy reefs in hopes of repopulation through seed banking will only save about 1% of coral reefs. Current leading restoration technologies like BioRock would cost $99 million/day including significant rebar costs and would require 120 installations per minute. Current technologies for coral restoration do not scale to the scope of the coral crisis and are conducted by small groups of scientists with little rapid experimentation, virtually no competition or innovation, and only a few small private sector companies with little resources.

ECONOMIC/FINANCIAL

Overfishing: Increasing demand for fish has resulted in over fishing of not only deep-water commercial fish, but key reef species as well. Overfishing of certain species near coral reefs can easily affect the reef's ecological balance and bio-diversity. For example, overfishing of herbivorous fish can also lead to high levels of algal growth. From subsistence level fishing to the live fish trade, inadequate management of fisheries is leading to the decline of fish stocks, which in turn puts more pressure on coral reef systems.

Destructive fishing methods: Fishing with dynamite, cyanide and other methods that break up the fragile coral reef are highly unsustainable. Dynamite and cyanide stun the fish, making them easier to catch. Fishermen say they have no other option if they are to compete with trawlers and overcome a smaller supply of fish because of previous overfishing. These practices generally do not select or target particular fish species and often result in juveniles being killed in the process. Damaging the coral reef habitat on which the fish rely will also reduce productivity, with further impacts on the livelihoods of fishermen.

Global aquarium trade: It is estimated that nearly 2 million people worldwide keep marine aquariums. The great majority of marine aquaria are stocked with species caught from the wild. This rapidly developing trade is seeing the movement of various fish species across borders. Threats from the trade include the use of cyanide in collection, over-harvesting of target organisms, and high levels of mortality associated with poor husbandry practices and insensitive shipping. Some regulation is in place to encourage the use of sustainable collection methods and to raise industry standards.

ENVIRONMENTAL

The challenge of climate change: Climate change increases land and sea temperatures and alters precipitation quantity and patterns. The ocean absorbs 90% of all anthropogenic warming, and this is already causing massive disturbances to individual marine species and entire marine ecosystems like coral reefs. This results in the rise of global sea levels and intensifies the risk of coastal erosion along with an expected increase in the severity of weather-related natural disasters. Changing water levels, temperatures and flow will in turn affect food supply, health, industry, transport and ecosystem integrity. Climate change will lead to a loss of biodiversity and significant economic and social impacts with some regions and sectors likely to bear greater adverse effects.

Pollution: Coral reefs need clean water to thrive. From plastics, sedimentation, untreated sewage, agricultural nutrient runoff, pesticides, and heavy metals, to waste oil, water pollution is damaging reefs worldwide. Pollution from human activities inland can damage coral reefs when transported by rivers into coastal waters. 96% of locations that mix coral reefs and humans have a sewage pollution problem. Additionally, approximately 25% of coral reefs are threatened by exposure to sediments, nutrients, and chemical pollutants. And the variety and severity of threats are growing, a new study based on four years of diving on 159 reefs in the Pacific shows that reefs in four countries–Australia, Thailand, Indonesia and Myanmar–are heavily contaminated with plastic. The plastic clings to the coral, especially branching coral. And where it clings, it sickens or kills the coral. The likelihood of disease increases from 4% to 89% when corals are in contact with plastic.

Rising sea levels: Observations since 1961 show that the average temperature of the world's oceans has increased even at depths of 3000m (Intergovernmental Panel on Climate Change, report), and that the ocean has been absorbing more than 80% of the heat added to the climate system. Such warming causes sea levels to rise and creates problems for low lying nations, islands, and coastal cities.

Ocean acidification: This is the name given to the ongoing decrease in the pH of the Earth's oceans, caused by their uptake of anthropogenic carbon dioxide from the atmosphere. Ocean acidification is already impacting the growth rate of some species of corals and if this continues some corals will dissolve faster than they can grow.

Coral disease: During the last 10 years, the frequency of coral disease appears to have increased dramatically, contributing to the deterioration of coral reef communities around the globe. Most diseases occur in response to the onset of bacteria, fungi, and viruses. However, natural events and human-caused activities (e.g. water pollution) may exacerbate reef-forming corals' susceptibility to waterborne pathogens.

Crown of thorns starfish (COTs): The Crown of Thorns Starfish is a voracious coral reef predator. Populations of COTs have increased since the 1970s and large outbreaks of this fish can manifest and wipe out large swathes of coral reefs. Few animals in the sea are willing to attack the spiny and toxic COT, but some shrimp, worms and species of reef fish do feed on larvae or small adults. The decline of these predators, through over-harvesting and pollution, is one factor contributing to the rise in the population of the starfish.

Alien invasive species: Species that have been moved as a result of human activity, intentionally or unintentionally, into areas where they do not occur naturally are called "introduced species" or "alien species." In some cases where natural controls of an introduced species are lacking (such as predators or parasites), the species may multiply rapidly, taking over its new environment, often drastically altering the ecosystem and out-competing local organisms. The damage caused by invasive species can be devastating and can include the alteration of ecosystem dynamics, biodiversity loss, reduction of the resilience of ecosystems, and the loss of resources, which has environmental, economic as well as socio-cultural impacts.

POLITICAL

Coral reef protection is gaining ground on the political front as well, particularly among Pacific Island nations. In June 2017, the presidents of the Republic of Palau, the Federated States of Micronesia and the Republic of the Marshall Islands participated in a summit with scientific and policy experts at the 13th International Coral Reef Symposium in Hawaii, where they signed a call to action for strong and immediate engagement and partnerships in support of joint coral reef stewardship.

In the months following the summit, Pacific Island nations have been working with scientists and legal experts to create an effective plan for bridging science to policy, and increasing regional cooperation and coordination for marine resource protection. Several meetings have already been held between presidential staff and resource personnel, such as the recent U.S. Coral Reef Task Force meeting in Guam and Saipan, and the Pew Fellows meeting in the Netherlands. These meetings brought to light much of the new science that could readily be applied to coral reef policy development and enforcement, and made clear the need for a strong legal framework in which to apply this science.

WHAT'S IN, WHAT'S OUT

METHODOLOGICAL NOTE

Determining what the Future of Coral reefs study entails also means determining what it does not. Therefore, it is important to set boundaries and determine the scope, as it helps focus activities and allows for significant creativity within the defined zone of focus.

AREAS OF FOCUS

Core: Coral Restoration, Coral Bleaching Recovery, Coral Fertilization/Reproduction, Egg Broadcasting Techniques, Assisted Evolution, Breeding and Genetics for Climate Resilience, Endangered Coral Species Recovery, Settlement Structures, Coral Disease, Coral Nursery Design, Coral Planting Techniques, Scalability, Temperature Control through Upwelling and Shading, Mechanized Planting, Assisted Evolution Field Trials, Jumpstarting with 3-D Printed Coral Structures.

Periphery: Outreach, Awareness, Education, Marine Protected Areas, Overfishing, Illegal Fishing, Habitat Destruction, Water Quality, Political Will, Dynamite Fishing, Tourism Impacts, Seed Banking from Healthy Reefs, Choosing and Protecting Specific Healthy Reefs, Indoor Seed Banking, Artificial Reefs.

WHO'S DOING WHAT? (BENCHMARK ANALYSIS)

METHODOLOGICAL NOTE

Benchmarking is a way of discovering the highest level of performance being achieved–whether in a particular company, by a competitor, or by an entirely different industry. This information can then be used to identify gaps in an organization's processes in order to achieve a competitive advantage. However, unlike business-driven benchmark analysis, in the context of XPRIZE prize development, benchmark analysis is aimed at answering the following questions: Who (innovators, academics, corporates) is developing solutions to a similar problem? What solutions are they developing? And who is providing funding in this area?

EXAMPLES

Electrical biorock stimulates coral growth

The plight of coral reefs is most problematic in the Caribbean. The Global Coral Reef Monitoring Network (GCRMN) found coral cover in the Caribbean has declined over 80% since the 1970's. These ecosystems have been severely degraded by the confluence of overfishing, pollution, and climate change. For the tiny Caribbean island of Grenada, damage to its marine ecosystem could be detrimental to its emerging tourism industry[2]. Its vibrant and diverse aquatic wildlife makes it a hugely popular spot for scuba diving. Marine tourism has consequently become a major source of income to Grenada's economy.

To help preserve and restore the island's coral, scientists in Grenada are using an innovative technology called biorock. To build a biorock reef, an electrically

[2] For this reason, in 2015, Grenada launched a coral reef restoration project

conductive frame is anchored to the seabed. A small electric current is passed through the water, initiating an electrolytic reaction and causing the formation of natural mineral crystals. Then, coral fragments from other reefs are transplanted to the biorock structure where they will grow, flourishing from the natural mineral crystals.

According to the Global Coral Reef Alliance, the biorock process is a revolutionary regenerative technology that provides the most cost-effective solution to a wide range of marine resource management problems.

3D mapping and bathymetry[3] to monitor reefs

In the Indian Ocean, almost 15,000 km from Grenada, the Maldives face a battle to save their coral reefs. The country is made up of 26 natural coral atolls and more than 1,000 isolated reefs. Much like Grenada, the Maldives rely on tourism as a major source of income. Many tourists are seduced by the promise of crystal clear waters and vibrant sea life, but the Maldives have seen their coral cover severely depleted in recent years.

Until recently, measuring the growth or decline of coral was a task undertaken by scuba divers with primitive tools. However, the advent of 3D mapping has allowed scientists to monitor reefs more closely.

Sly Lee, a marine scientist and co-founder of the The Hydrous (a non-profit), has invented a system that uses 3D mapping to track changes to the coral’s size, color and surface area. Coral reefs can also be monitored using bathymetry, a type of high resolution satellite imagery that creates mapping images of marine landscapes. This is

[3] Bathymetry is the study of the “beds” or “floors” of water bodies, including the ocean, rivers, streams and lakes

a technique that has been widely used to monitor Australia's Great Barrier Reef and Hawaii's Kailua Bay.

3D printed coral encourages reef restoration

Bonaire, a Dutch Caribbean island in the Leeward Antilles, has a long history of marine conservation. Its entire coastline has been a marine sanctuary since the foundation of Bonaire National Marine Park in 1979. Now, Bonaire is taking revolutionary steps to preserve the region's threatened ecosystem by 3D printing coral reefs. The technology has been introduced to the island as a result of a partnership between ocean preservationist Fabien Cousteau and the island's Harbour Village Beach Club.

The artificial corals will be identical in size, shape, texture and will have the same chemical makeup as the real thing. The hope is that the printed reefs will attract free floating coral polyps along with other species such as algae, anemones, octopi and crabs.

Interventions to increase climate resilience at the biological level

These include tools such as assisted gene flow[4] (AGF), assisted evolution and synthetic biology. AGF, in the form of assisted larval dispersal or assisted adult migration, might facilitate the spread of genotypes with heritable traits. Complementing the idea of translocating existing coral genotypes is the concept of generating new capacities for climate resilience through assisted evolution and synthetic biology. Assisted evolution builds on the principle of selection using existing genetic material, whereas

[4] The idea here is to move warm-adapted corals to cooler parts of the reef. Corals in the far north are naturally adapted to 1C to 2C higher summer temperatures than corals further south. This means there is an opportunity to build resistance to future warming in corals in the south under strong climate change mitigation, or to decades of warming under weaker mitigation.

synthetic biology could involve genome editing using natural or synthetic genes, for example using CRISPR-associated 9 (Cas9) technology. These techniques, paired with natural or synthetic gene drives, could enable the rapid spread of climate-adapted genotypes of species that serve key ecosystem functions, and preserve species which would otherwise succumb to climate change without such interventions.

Assisted evolution and synthetic biology

Assisted evolution and synthetic biology could offer more opportunities than risks for climate-hardening coral reefs, as long as such technologies are developed and deployed under a stringent and adaptive framework that includes extensive societal consultation. For example, the risk of a new engineered coral genotype dominating a reef ecosystem becomes a benefit if native coral genotypes are predicted to decline under climate change. However, a downside of these or any other laboratory-based or resource-intensive technique is that only a subset of the million species on coral reefs could feasibly be made climate tolerant.

Under severe climate change, tropical sea surface warming may eventually exceed the physiological tolerance limits of even these emerging genetic-based technologies. Since habitat-forming corals are among the most vulnerable to ocean warming, acidification and storms, the development of engineered reef habitats could become necessary to protect key reef-dependent species, including fish and invertebrates. The challenges for such engineering solutions include society's acceptance of artificial structures as replacements for natural habitats that underpin the richest biodiversity of the oceans, and careful spatial triage for what would be a costly intervention. Although engineered habitats would not protect the underlying integrity and diversity of coral reef systems, they could become essential to maintain some reef-related ecosystem of goods and services.

Swarming robots

A group of scientists based at Heriot-Watt University in Scotland, are working on setting loose swarms of small robots on dying reefs to have them transplant healthy coral into places where it's needed. Each robot has a video camera, along with the ability to process images, and basic tools, such as scoops and "hands" that can grab the coral.

The robots, called coralbots, would need to learn to identify healthy coral and distinguish it from everything else in that environment. And they would need to be able to navigate their way around the ocean bottom and keep from running into other obstacles including healthy coral.

A key to this approach is how successful the scientists are at programming the robots with "swarm intelligence." They would work together like ants or bees to perform complex tasks, with different robots having different roles. One might know how to spot places where coral can be planted and another might focus solely on planting.

Shading structures

Some early shading experiments in the 1970s actually increased turbidity and killed corals. Recently though, scientists at the Great Barrier Reef Foundation have announced development of an eco-friendly film that could help protect corals against bleaching. The biodegradable film is just one molecule thick and made out of calcium carbonate–the same thing that coral skeletons are composed of. It's intended to float on the ocean's surface, where it will reduce the intensity of sunlight reaching the coral. In lab studies the film was found to reduce the amount of light hitting corals by 30 percent and may help reduce bleaching events.

Bubbling pre-industrial CO2 levels on corals

In lab experiments, Stanford scientists demonstrated that bubbling air through seawater for a few hours in the early morning can enhance the transfer rate of CO_2 between the ocean and the air up to 30 times faster than natural processes, resulting in a significant reduction in local marine concentrations of CO_2. This could help combat local impacts of acidification on corals and may improve coral growth rates. It is proposed that if a group can operate a bubbler in an area that is upstream of a large section of coral, you may reduce CO_2 levels for an entire reef which could improve some coral growth rates to pre-industrial levels.

Lab fertilization of coral eggs

In Curaçao, a small coral-rich island in the Caribbean, a team of scientists are finalizing a technology that could distribute fertilized coral eggs across the ocean, repopulating reefs worldwide. In the wild, the coral reproductive success rate is only 0.2% but in lab experiments, 90-100% of the corals' eggs are fertilized. By inducing successful reproduction in the lab and releasing them strategically onto settlement platforms, these techniques could grow millions of baby corals in the wild.

Improved nursery design

NOAA has awarded competitive grants for improved nursery designs and out-planting to improve the efficacy of the 27 coral nurseries that they operate. These underwater safe havens serve a dual function. Not only do they provide a stable environment for injured corals to recuperate, but they also produce thousands of healthy young corals, ready to be transplanted into previously devastated areas. Nurseries can be engineered to improve the growth rates and scalability of restoration efforts and grow millions of corals.

Selective breeding for climate tolerance

Researchers at the Australian Institute for Marine Science crossed individuals of branching coral *Acropora millepora*, from the warmer far north of the Great Barrier Reef, with members of the same species at Orpheus Island, 540 km south. The corals of the north passed on their heat tolerance to their offspring, they found. The scientists now wish to confirm the role of mitochondria in heat tolerance, suggested for the first time by the study.

Table 1: Stakeholder Analysis

Type of Organization	Name	Program/Work
NGO/Non-Profit	Conservation International	CI has worked with the government of Kiribati to create the world's largest World Heritage Site, the Phoenix Islands Protected Area
NGO/Non-Profit	Palumbi's Lab	Research on coral tolerance to heat stress
NGO/Non-Profit	Blue Voice	Documents transgressions against marine life on film
NGO/Non-Profit	Coral Reef Alliance	Works with global communities around the world, helping to solve coral reef conservation challenges
NGO/Non-Profit	Coral Restoration Foundation	Engages communities in coral nursery and restoration efforts by encouraging long-term involvement
NGO/Non-Profit	Earth Island Institute	Serves as an incubator and support network for more than 30 conservation and restoration projects
NGO/Non-Profit	Florida Oceanographic Society	Inspires environmental stewardship of Florida's coastal ecosystems through education, research, and advocacy
NGO/Non-Profit	Gilli Eco Trust	Is a local non-governmental organization, first created in 2000 to protect coral reefs from destructive fishing

Type of Organization	Name	Program/Work
		practices around the three Gili islands of Lombok Indonesia
NGO/Non-Profit	Marine Conservation Biology Institute	Works to protect and restore marine life
NGO/Non-Profit	Marine Megafauna Foundation	Has a mission to save threatened marine life using pioneering research, education, and sustainable conservation solutions, working toward a world where marine life and humans thrive together
NGO/Non-Profit	Monterey Bay Aquarium	Coordinates marine conservation and research programs
NGO/Non-Profit	National Environment Trust's Global Legacy Campaign	Is a broad national effort to build support for ocean and fish protection
NGO/Non-Profit	Natural Resource Defense Council	Uses law, science and activism to protect the planet's wildlife and wild places
NGO/Non-Profit	New England Aquarium	Provides leadership for the preservation and sustainable use of aquatic resources
NGO/Non-Profit	Oceana	Works to restore and protect the world's oceans through policy advocacy, science, law and public education
NGO/Non-Profit	National Academy of Sciences	Carrying out study to review the science and assess potential risks and benefits of ecological and genetic interventions to protect and save coral reefs
NGO/Non-Profit	Smithsonian's National Zoo & Conservation Biology Institute	Examines and implements coral reproduction and cryopreservation
NGO/Non-Profit	The Safina Center	Focuses on deepening connections between humanity and living seas. Formerly the Blue Ocean Institute
NGO/Non-Profit	Sea Save Foundation	Strives to protect our oceans by raising awareness about the beauty of marine ecosystems and their fundamental importance to human survival
NGO/Non-Profit	The Cousteau Society	Is dedicated to the preservation of nature for future generations

Type of Organization	Name	Program/Work
NGO/Non-Profit	United Nations Environment Program (UNEP) Coral Reef Unit	Seeks to catalyze and promote international cooperation within the UN system and other key partners to foster assessment, environmental management, and promote sustainable development
NGO/Non-Profit	The Ocean Conservancy	Seeks to inform, inspire, and empower through science-based advocacy, research, and public education
NGO/Non-Profit	The Marhaver Lab	Led by Dr. Kristen Marhaver, the lab's 3-year mission is to develop, optimize, and share improved settlement surfaces and effective bacterial probiotics for 10 coral species
NGO/Non-Profit	The Ocean Project	Works to promote ocean conservation through zoos, aquariums, and museums
NGO/Non-Profit	50 Reefs Initiative—Bloomberg Philanthropies, Tiffany & Co. Foundation, The Paul G. Allen Family Foundation	Brings together leading ocean, climate and marine scientists as well as conservation practitioners from around the world to develop a list of the 50 most critical coral reefs to protect
NGO/Non-Profit	The Tiffany & Co Foundation	Promotes the preservation of precious corals and healthy marine ecosystems through awarding grants
NGO/Non-Profit	Reef Check	Works to restore and maintain coral reef health
NGO/Non-Profit	Reef Environmental Education Foundation	Seeks to educate and enlist divers in the conservation of marine habitats
NGO/Non-Profit	Reef Guardian International	Works to protect coral reefs
NGO/Non-Profit	Reef Relief	Works to preserve and protect living coral reef ecosystems
NGO/Non-Profit	Seacology	Works to preserve the environments and cultures of islands
NGO/Non-Profit	SeaWeb	Works to link the media to marine conservation groups
Government/Academia	United States Geological Survey	Deep ATRIS acquiring high-resolution imagery of the sea floor

Type of Organization	Name	Program/Work
Government/Academia	NOAA Coral Reef Conservation Program	Partnership between NOAA Line Offices that work on coral issues using expertise from across NOAA for a multidisciplinary approach to understanding and conserving coral reef ecosystems.
Government/Academia	Government of Australia Department of Foreign Affairs and Trade	Established a coral reef innovation facility to drive innovative solutions to coral reef management challenges in developing countries
Government/Academia	Australian Institute of Marine Science	Engaged in a 10-year program to undertake large-scale recovery, restoration and adaptation of the Great Barrier Reef
Government/Academia	Commonwealth Scientific and Industrial Research Organization (CSIRO)	Conducts research in the sustainable use of Australia's marine resources, the ocean's role in climate, and effective conservation of the marine ecosystem
Government/Academia	University of South Pacific–Fiji	Coral reef ecology and management programs
Government/Academia	Department of Fisheries and Oceans (Canada)	Promotes conservation and sustainable resource use, scientific research, marine safety and environmental protection
Government/Academia	Initiative Francaise pour les Recifs Coralliens (IFRECOR)	French coral reef initiative to ensure awareness of policy makers and public of the cultural, social, ecological, economic and political importance of coral reefs; also promotes French participation in the Global Coral Reef Monitoring Network
Government/Academia	Institut Francais de Recharche pour l'Exploitation de la Mer (IFREMER)	Conducts programs on the marine environment, marine science, and marine resources
Government/Academia	National Center for Marine Research (Greece)	Government research institution in all fields of the aquatic environment and technical support to public on marine environment

Type of Organization	Name	Program/Work
Government/Academia	Kenya Marine and Fisheries Institute (KMFRI)	Does research on fisheries, aquatic biology, chemical and physical oceanography, coastal zone management, training facilities, pollution monitoring
Government/Academia	Netherlands Institute for Sea Research	Multi-disciplinary specialization in transfer and transport of matter and energy in the sea, sediments, ecology of marine species, community dynamics and biodiversity, temporal variability in marine systems and climate change
Government/Academia	National Oceanic and Atmospheric Administration (NOAA)	US government agency dealing with all aspects of oceans including programs to manage the nation's coastal and ocean resources
Government/Academia	Bureau of Oceans and International Environmental and Scientific Affairs, US Department of State	Ocean policy and law of the sea, marine environment and science, fisheries, marine conservation and invasive species
Government/Academia	US Office of Naval Research	Coordinates science and technology programs of US agencies
Private Sector	Reef & Beach Resilience Insurance Fund—Sponsored by beachfront hotels and other businesses along coast of Puerto Morelos, Mexico	The fund pays premiums to the insurance company Swiss Re AG in the event of a major storm that could damage the coral, Swiss RE will quickly offer payouts that can be used to restore the reef so it can continue to attract tourists and protect coastal in property in the future
Private Sector	Exposure Labs	Broadcasting & media production company behind the documentary Chasing Coral
Private Sector	Coral Vita	Restores threatened reefs by growing resilient corals and transplanting them into degraded sites
Private Sector	Google X—Tom Chi	Tom is bringing together the world's top scientists to help save the ocean's coral reef

Type of Organization	Name	Program/Work
Private Sector	Biorock	Led by Professor Wolf Hilbertz and Dr. Tom Goreau of the Global Coral Reef Alliance, Biorock technology has been researched and developed by a pioneering team of dedicated individuals for the last 30 years. The method is used to solve a wide variety of marine and coastal problems including coral reef and fishery habitat restoration

GAP ANALYSIS

METHODOLOGICAL NOTE

Gap analysis involves the comparison of actual performance with potential or desired performance. Simply put, gap analysis addresses three questions:

- Where are we? (the present state); and
- Where do we want to go? (the target state)
- What must be addressed to get from today to the target?

The first question is answered through the previous research components, that is, the trend and benchmark analysis. These two components are basically a description of the present state and the elements that will shape the future. The second question is answered through the description of the desired end-state. So, if we know where we are (current state), what the desired state is, and who is working on solving related-challenges, we can also identify what areas are being neglected (and for what reason). These areas (and reasons) are the gaps.

The gaps described below give rise to the problem of finding an optimal time path, new technologies, modes of international co-operation, and innovative policy incentives to meet the grand challenge in a cost-effective way.

GAP DESCRIPTION

Lack of public awareness – In order save coral reefs, it's imperative to increase awareness and understanding of the ecological, cultural, and socioeconomic importance of coral reef ecosystems among the widest possible audience. Increased awareness is critical to helping people understand the value of coral reef ecosystems and ways to avoid damaging them. Reducing human impacts on coral reef ecosystems requires changing behavior, beliefs, and decision-making about conserving these vital ecosystems. An informed, engaged public, policymakers, industry representatives, nongovernmental organizations along with other stakeholders is fundamental to achieving widespread change. People will be more likely to alter their actions and support conservation if they understand why coral reefs are important, realize how their actions affect the conditions of coral reefs, and are aware of reef protection activities and how they can benefit their communities.

Slow scientific progress - More information is needed to identify the mechanisms by which most diseases kill their hosts, and how they are transmitted. The onset of coral disease has been shown to spread following coral bleaching events, so the evidence of a connection between warmer-than-normal water and coral disease is growing stronger. There is also evidence to indicate that low water quality increases incidences of this. It is critical that governments and managers continue their efforts to reduce (or stop) the effects of other major reef threats (sediments, pesticides, nutrients, overfishing, etc.) while this scientific information is gathered, if we are to give coral reefs a fighting chance of survival.

Conflicting values - The decision to adopt or dismiss new interventions pits two fundamental values against each other: the wish to conserve the natural biodiversity of coral reefs and the desire to maintain ecosystem functions, goods and services in the face of external threats. Some interventions carry a risk of unintended ecosystem disruptions and might transform coral reefs into new or hybrid systems. However, reefs are already in transition, driven by differential species responses to environmental change. The challenge is to steer that transition towards ecosystem states that can maintain key functions and values. This will involve difficult trade-offs– which species and ecosystem functions are most important to conserve given limited resources? Although an interventionist pathway may be at odds with the tenets of traditional conservation and its emphasis on minimalist human intervention, it has already become the necessary trajectory for both natural and cultured ecosystems. For example, artificial selection and gene modification for drought and disease resistance in crops has been driven by necessity.

Lack of sufficient funding - Governments around the world fund various initiatives to fight the disappearance of coral reefs. Existing funds are usually split across several priority areas: many local stressors, from pollution to overfishing, affect the reefs in different ways in different places, so tackling them locally seems like a logical way to intervene. The problem is that these stressors interact and amplify each other's effects. This shows that spreading the money so thinly is a risky move, because successfully tackling any one problem rests on successfully tackling all the others. Focusing purely on local issues risks diverting attention from wider problems.

For example, the unprecedented back-to-back mass bleaching that catastrophically damaged the Great Barrier Reef in 2016 and 2017 was a direct result of global climate change. For this reason, funding packages offered by governments have unsurprisingly been criticized for not attempting to "cure" the ultimate problem that ails coral reefs. Local interventions such as the ones being funded are often called out for being Band-Aid solutions.

Lack of private sector involvement – About 80% of funding for biodiversity is generated from non-market mechanisms. Except for philanthropy, non-market mechanisms are public sector mechanisms relying on government regulations for their implementation. They cover domestic budget allocation, official development assistance, debt-for-nature swaps and subsidies reform. The allocation of public finance is primarily a question of political will (and public opinion) and these mechanisms therefore tend to vary with political cycles. Although these mechanisms could scale-up in the future, market-based mechanisms have a greater potential to increase in scale. Long-term, reliable sources of market financing for reef conservation must be established and strengthened.

GRAND CHALLENGES

METHODOLOGICAL NOTE

Grand Challenges (GCs) are lists of difficult but important problems articulated by the research team to encourage the discovery of (mainly) technological innovation (i.e., breakthroughs) that could potentially solve the main issues. In other words, a GC is one or more specific critical barrier(s) that, if removed, would help solve an important problem with a high likelihood of global impact through widespread implementation.

Articulating important challenges that have the potential to deliver real impact and allocating significant resources to address these GCs later in the process, allows XPRIZE to bring the best minds to the table by engaging crowds who might not otherwise be engaged in global research.

KEY CHALLENGES

- Current solutions are difficult to scale;
- Funding to protect and sustainably manage coral reefs around the world are not only inadequate, but disproportionate to how much reefs offer humans in food, livelihoods, medicine, and environmental protection;
- Lack of understanding and awareness among the general public of the importance of coral reef ecosystems and of how precarious the situation is;
- Lack of political will to appropriately address the situation and provide solutions.

FRAMING A GRAND CHALLENGE

- **Widely applicable problem…**Coral reef ecosystems provide society with resources and services worth $375 billion per year. They support 25% of all marine life, feed hundreds of millions of people, enable the discovery of new pharmaceuticals, and provide work and income through the tourism and fisheries industries. Despite this, we have lost one fifth of the world's coral reefs, with some estimates placing the loss of live coral as high as 50%. These fragile and vital ecosystems are being rapidly degraded as a result of warming sea temperatures due to climate change, overfishing, destructive fishing, ocean acidification, as well as a range of land-based activities.
- **For which scientifically sound solutions are imaginable…**Like research into coral genetics so that they can tolerate a warmer ocean, new innovations to grow corals bigger and faster, and new technologies including 3-D coral reef printing hold tremendous promise for saving coral reefs and for enhancing their sustainability.
- **but not quite at hand…**Some of these innovations are still years away and gaps in information still persist.
- **with deep societal importance…**Reefs are among the most fragile ecosystems on the planet and are essential to both marine and human life. But they are highly sensitive to climate change and are dying at a dramatic rate. Timely intervention and new innovations are needed now to save the planet's reefs and sustain an invaluable resource.

FORESIGHT

METHODOLOGICAL NOTE

Scenarios inform present-day decision-making by exploring different possible futures. In contrast to forecasting, scenarios examine what is most uncertain and surprising as a mechanism to generate insight and provoke action regarding future-focused risks and opportunities. Scenarios can stretch our thinking about divergent plausible futures. Importantly, the value of scenarios analysis is to examine all of the possible futures identified—rather than focusing on the more desirable ones—with the understanding that any scenario may occur. Thus, scenarios are a tool to uncover blind spots and broaden perspectives about alternative future environments in which today's decisions might play out. The implications drawn from the scenarios are designed to trigger discussion, rather than serving as prescriptive outcomes.

The link between elevated temperatures and coral bleaching in recent decades leads to speculation that anthropogenic climate change is increasing the frequency and severity of coral bleaching events. A number of recent studies use the output of global climate models to estimate the effects of ocean warming on future occurrences of coral bleaching. These studies generally conclude that mass coral bleaching could become a biannual event by the 2020s or 2030s at many of the world's coral reefs, without any adaptation by corals and their symbionts.

Global climate models predict that the planet's climate could warm by 2–4° Celsius by the year 2100, without substantial effort to reduce greenhouse gas emissions far below current levels (IPCC 2007). Continued climate warming may, therefore, pose a serious threat to the long-term health of coral reef ecosystems. At the same time, higher concentrations of atmospheric carbon dioxide are expected to reduce the rates of coral calcification and reef accretion.

PREFERRED FUTURE

The preferred future is typically captured as a vision. A vision is an image of the future. It creates an attractive mental picture of an outcome that people can strive for. Most people think of the future in ideas rather than images. Attractive ideas include progress, security, enjoyment; unattractive ones include overpopulation, pollution, sickness, and death. None of these are visions, however, because they are not images. What does it look like? How does it feel? What does it taste like, sound like? The vision is something tangible and concrete–something that excites people and enables them to take action in support of reaching the preferred future state.

A future of plenty or a future of scarcity is certainly not a given. It's possible to address system failures to leverage, shift, or even reverse trends—even global mega trends—by enabling and incentivizing bold actions. But to truly think boldly, we cannot start with today. It's imperative to start with a preferred future state. The following scenario is an example of a preferred future.

"By 2040 we have restored coral reefs to their pre-industrial levels, and coral reefs around the world are healthy, thriving, and sustainably managed and protected by local communities. These healthy coral reefs are resilient to a changing climate and have regained high levels of marine biodiversity. They create various services to society such as biomedical research, ocean science, coastal protection, nurseries for fisheries, tourism jobs, and inspiration for future generations that show great appreciation for corals and the benefits they provide."

ACTION

METHODOLOGICAL NOTE

Solving grand challenges is complex. XPRIZE only launches the most impactful prizes, those that when launched in conjunction with others will achieve a moonshot and radically transform a given domain. XPRIZE begins this process by developing a Futures ImpactMap that maps the full landscape of what is currently happening, what needs to change, and which breakthroughs would not happen unless the crowd was incentivized to develop radical innovations. Once we know which breakthroughs will not be achieved by traditional actors alone, XPRIZE sources brilliant Visioneers in the crowd to vet and evaluate which breakthroughs should become the next XPRIZE.

BREAKTHROUGH EXAMPLES

- The world community tackles global climate change urgently through major reductions in greenhouse gas emissions and the development of effective mechanisms to permanently sequester existing CO2.
- Global climate change treaties include coral restoration as part of blue funds and debt swap initiatives - creating a sustainable funding model.
- Coral restoration technologies improve 10x in scalability and cost. Coral restoration has a thriving private sector with over 10 competing companies that are employing and partnering with local coral reef communities in restoration efforts. Significant investments are made, in the hundreds of millions of dollars, into global coral restoration efforts from public/private partnerships. Restoration efforts have scaled to match the rate of depletion.
- Damaging human activities (unsustainable fishing, nutrient pollution and poor land use) are controlled to improve the resilience of coral reefs and help them resist and recover from climate change threats.

- Assistance is provided to developing countries and communities to:
    - Reduce population pressures on coral reef resources;
    - Develop alternative livelihoods that take pressures off reefs;
    - Improve local catchment and coastal management practices;
    - Develop strategies to cope with climate change damage; and
    - Improve national capacity for better management, monitoring and enforcement of regulations.
    - Create and enforce no-take marine protected areas (MPAs) for more coral reefs sites that include reducing land-based sources of pollution. These thriving reef systems act as biodiversity reservoirs, research centers, coral seed banks for improving nearby reefs, and are creating sustainable tourism industries.
- Economic valuation, which attempts to capture the economic value supported by coral reefs, to set priorities for the use of coral reefs, and to suggest policy options for reef management based on economic drivers;
- Application of policy instruments that promote integrated coastal zone management, creating awareness of the economic benefits of options to better manage the coral reefs; and
- Participation of stakeholders, including poor coastal communities, with a focus on increasing awareness of the economic goods, services and functions provided by reefs; encouragement of livelihood security; the building of new institutions; the establishment of values for coral reefs; and the potential for poverty alleviation through the equitable use of coral reef resources.

CONCLUSION

Transformational change is the process of creating a new era. It begins with one or more bold leaders who see that the old era is no longer suitable for the present, much less the future. These bold visionaries articulate a preferred future for the new era and enroll others in the campaign to bring that future about. These leaders and those that follow face enormous obstacles from the doubts and resistance of the majority to the challenge of leaving behind old ways of doing things even before the new ones are ready. Nevertheless, they are compelled to engage in this work because it must be done sooner or later, and it's best to start today before the terms of change can be dictated.

APPENDIX A: DEFINITIONS

1. **Breakthrough:** To overcome "Grand Challenges" and achieve a "Preferred Future," it's essential to identify potential breakthroughs that can create massive, global impact. Breakthroughs are evaluated based on 4 criteria: impact potential, level of audacity, market readiness level, and desired timeline for impact.
2. **Domain:** XPRIZE operates within 7 domains: shelter and infrastructure; energy and resources; planet and environment; health and wellness; learning and human potential; space and new frontiers; and civil society. Emerging exponential technologies and other innovations in policy and financing have the potential to address grand challenges in these areas, but require new action by key stakeholders and innovators from around the globe.
3. **Futures ImpactMap:** Is an analytical tool for understanding persistent problems and barriers that make up grand challenges in various domains as well as the actions that key stakeholders can take to overcome them and achieve a preferred future state. XPRIZE uses Futures ImpactMaps to help identify potential XPRIZE competitions and other actions that can accelerate a bridge to abundance for all across domains.
4. **Grand Challenge Area:** Is a topic area like "Corals," which comprises a combination of complex and overlapping social, technological, economic, environmental, and policy issues. Only the most effective actions will address these issues and accelerate progress toward a more positive future.
5. **Grand Challenge Statement:** A problem statement, which defines the issue to be solved.
6. **Preferred Future:** Is typically captured as a vision—an image of the future. It creates an attractive mental picture of an outcome that people can strive for.

7. **Scenario:** Scenarios inform present-day decision making by exploring different possible futures. In contrast to forecasting, scenarios examine what is most uncertain and surprising as a mechanism to generate insight and provoke action regarding future-focused risks and opportunities.
8. **XPRIZE:** The XPRIZE Foundation is the global leader in designing and implementing innovative competition models to solve the world's grandest challenges. XPRIZE utilizes a unique combination of gamification, crowdsourcing, incentive prize theory, prize philanthropy, and exponential technologies as a formula to make 10x (vs.10%) impact in the grand challenge domains facing our world. The XPRIZE philosophy is that—under the right circumstances—igniting rapid experimentation from a variety of diverse lenses is the most efficient and effective method to driving exponential impact and solutions to grand challenges.
9. **XPRIZE (competition):** An XPRIZE is an incentivized prize competition designed to create 10x impact on the world. The exponential trend of computing power has led us to this period in time, where technology that was just 30 years ago only available to industries like NASA is now on the smartphones in our pockets. XPRIZE competitions leverage this exponential technology with the power of the crowd to spur innovation in areas where there is market failure, empowering individuals across the globe to become the world's next change makers. The competitions are engineered for success: they are required to meet a series of 10 criteria through a rigorous evaluation at our Visioneers Summit in order to be deemed ready for launch. Each XPRIZE competition results in audacious breakthroughs that have scalable impact, leading us closer to the XPRIZE Foundation's vision of a future in which humanity as a whole benefit by having access to what was once scarce, and is now made abundant.