# Coral Health Index CHI 氣

## measuring coral community health

SCIENCETOACTION

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In traditional Chinese culture, Chi represents the flow of energy that sustains living beings. For the purpose of this document, Chi represents holistic, balanced, and healthy coral reefs.

This guidebook contains methodologies that can be found in more detail at: www.science2action.org.

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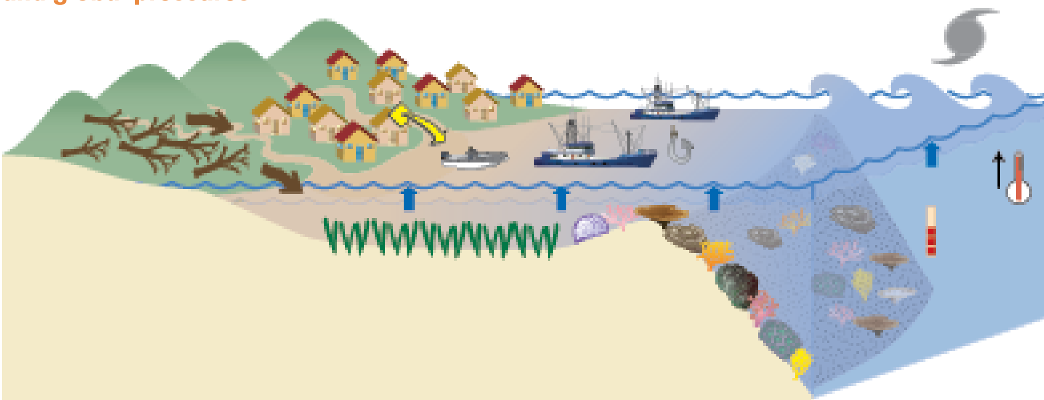
# Coral reefs are in precipitous decline

## The challenge

**A majority (75%) of the world's coral reefs are already threatened due to cumulative local and global pressures[1]**



**Local pressures**

Overfishing reduces populations of grazing fish, so that fast-growing seaweeds can smother corals.

Deforestation results in soil erosion into coastal waters, blocking light and smothering corals.

Coastal development typically results in soil and nutrient inputs to reef habitats and can also lead to physical destruction of coral reefs.

Other types of pollution from land, such as toxic chemicals and pathogens (viruses and bacteria), reduce coral health.

**Global pressures**

Global climate change results in warmer seawater that can stress corals, causing them to eject their symbiotic zooxanthellae (bleaching) and even die.

Ocean acidification associated with climate change impairs corals' ability to build their calcium carbonate "skeletons", resulting in slower-growing corals that break easily.

Rising sea level results in more coastal erosion and stress to deeper-growing corals.

Increased storm variability results in devastation of local reefs.

## The solution

**Local management alleviates direct pressures and increases resilience to global change**

Effective local management of coral reefs has a direct effect on reducing threats and improving overall coral community health. Careful zoning and effective enforcement of resource use within a marine managed area reduces impacts of overfishing, allowing populations of grazing fish to rejuvenate and maintain healthy ecosystem functioning.[2] Coastal land management to reduce deforestation and land-based pollution, and planning for sustainable coastal development can ensure that nutrient and sediment loads to the reef environment are kept low, maintaining a vibrant coral reef community.

Coral reefs that are healthy have greater resilience and ability to recover from chronic and acute stress.[3,4,5,6] Global-scale stresses associated with climate change include elevated sea surface temperatures, ocean acidification, sea level rise, and increasing storm intensity.[7] Adaptive management of coral reef communities will be most effective if a reliable annual indicator of community health is available to resource managers and policy-makers. The Coral Health Index (CHI) is such a tool.

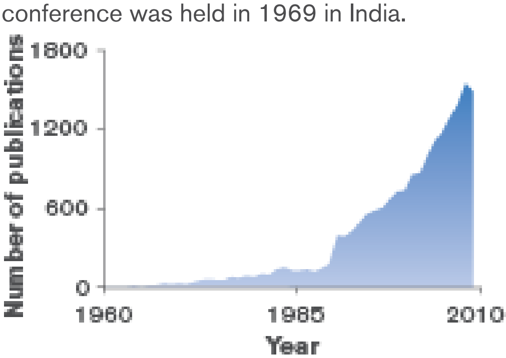
# Four decades of science and management has documented change

## An evolving understanding of coral reef health and impacts

### 1960s and 70s—Reef diversity and value

**Observations**
The advent of undersea diving technology (SCUBA invented in mid-20th century) allowed direct human observations of coral reefs.[8] Popular films, books and television specials (e.g., Jacques-Yves Cousteau) brought coral reefs to the public. Concerns about destructive fishing and direct coral degradation began to be voiced.

**Science response**
A proliferation of coral reef research stations, including underwater habitats, allowed scientists access to a wide range of coral reefs. The first international coral reef conference was held in 1969 in India.



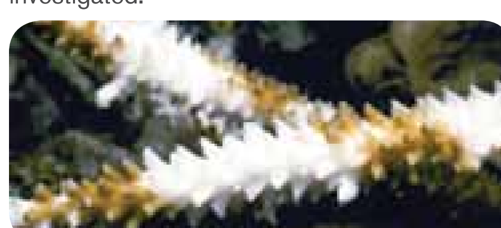

*Number of scientific publications per year on corals.[9]*

**Management response**
Regulated marine parks were established to protect coral reefs: Buck Island Reef National Monument in US Virgin Islands in 1961, John Pennekamp Coral Reef State Park in Florida, USA, in 1963, and the Great Barrier Reef Marine Park in Australia in 1975.

### 1980s—Local and regional impacts

**Observations**
Major local and regional events with significant negative impacts on coral health were recognized. In the 1980s, a die-off of long-spined black sea urchins affected reefs throughout the Caribbean.[10] Outbreaks of crown-of-thorns seastars occurred throughout the Pacific, particularly along the Great Barrier Reef.[11] Coral diseases were reported at various sites in the Caribbean.[12]

**Science response**
The International Coral Reef Society was formed in 1980, and regular international coral reef conferences were held every four years. Coral monitoring documented major declines at various locations, particularly in the Caribbean.[13,14] Research into causes of these declines was initiated, and regional-scale processes affecting coral reefs were investigated.[15]



**Management response**
Regional concerns led to the creation of broad-scale scientific monitoring programs such as the Atlantic and Gulf Rapid Reef Assessment Program, Caribbean Coastal Marine Productivity Program,[16] Global Coral Reef Monitoring Network, and Australian Institute of Marine Science Long-Term Monitoring Program.

## 1990s—Global impacts

### Observations

With increasing awareness of coral bleaching, global impacts to coral reefs were recognized. Significant warm-water events caused widespread coral bleaching in the eastern Pacific, including the Galapagos Islands in 1982–1983,[17] the Indian Ocean and Caribbean in 1998,[18] and the central Pacific in 2000–2002.[19]

### Science response

Coral physiology, specifically related to zooxanthellae, became a major focus in scientific research to aid in understanding the process, causes, and scale of threats posed by coral bleaching.[20]

### Management response

As recognition of coral reef degradation at local, regional, and global scales increased, there was an increased understanding of the need for marine protected areas. Local stewardship was encouraged, and management focused on the establishment of no-take marine reserves, as well as community-based monitoring programs such as Reef Check, Reef Environmental Education Foundation, and Reef Life Survey.

## 2000s—Developing a response

### Observations

There was a continued focus on global-scale challenges to coral reefs and other marine habitats, including reports that 41% of the world's marine area has been heavily impacted by human activity and that 0% remains totally unaffected.[21] Other observations revealed that healthier coral reefs were more resilient to stress, showing much stronger and more rapid recovery from local and global influences.[22]

### Science response

Significant increases in scientific thinking included development of the "shifting baselines" concept, where undocumented gradual changes can go unnoticed.[23] This theory was developed in relation to global fish abundance, and the related scientific focus was on the importance of fish as grazers in coral reef habitats.

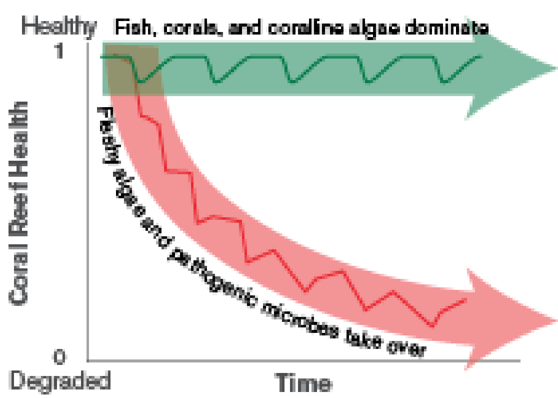
### Management response

The International Union for Conservation of Nature (IUCN) World Parks Congress in 2003 called for 10–12% of each marine and coastal habitat to be placed in protected areas.[24] A large emphasis was placed on identifying if establishment of marine protected areas has been effective in maintaining vibrant coral reef biodiversity and the well-being of human communities reliant on those marine resources for their livelihoods.[25,26,27]

# Today's choices will determine the future state of the world's coral reefs

## Reef assessments are essential to catalyze global action

A consistent and reliable means to assess the health of a coral reef ecosystem is needed. By measuring and comparing reef health among places and through time, managers and scientists can compare coral reefs and assess whether management measures are successfully achieving their goals of protection and rational use. Management actions established today will determine whether coral reefs are healthy or degraded in the future.




## Crustose coralline algae pave the way for coral recovery

Crustose coralline algae (CCA) or fleshy algae can grow over the bare space left when corals die from bleaching or other disturbance. If CCA colonize the bare space, they cement the reef, encouraging coral larvae to settle and accelerating coral recovery.[28] Instead, if fleshy algae colonize, coral larvae will not settle and the coral reef will not recover. The presence of fishes and invertebrates that eat fleshy algae help to favor the growth of CCA on reefs.

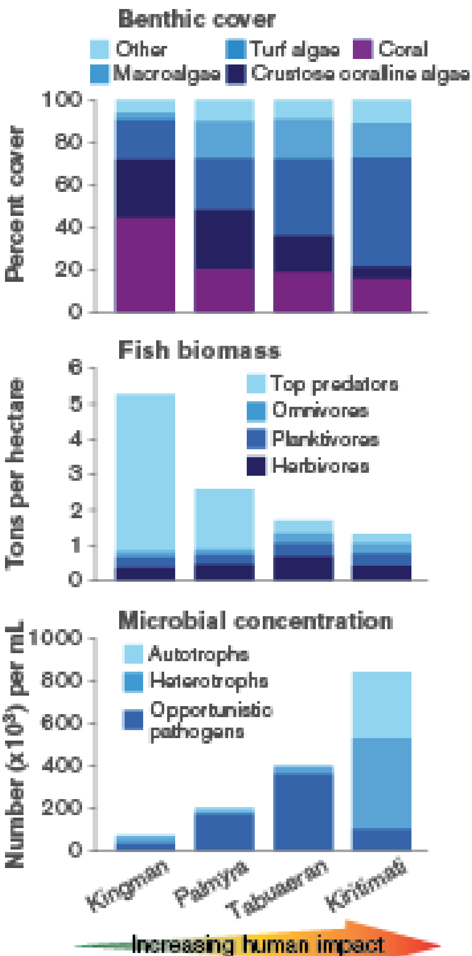
*Juvenile coral (center top) growing on a thick patch of crustose coralline algae.*

Some fleshy algae also negatively affect existing corals. Fleshy algae can secrete nutrients into the water near the corals that change the microbial assemblage from healthy to unhealthy. A healthy microbial assemblage is symbiotic with the corals and helps preserve reef health. An unhealthy assemblage includes opportunistic pathogens that can cause coral disease.[29]

CCA trigger a feedback loop that leads to healthier reefs, while fleshy algae trigger a feedback loop that leads to reef decline. The presence of CCA after a bleaching event means that not only is the system moving in the right direction, but that there is a positive feedback loop that will help keep the reef in a healthy state. The system is both healthy and resilient.

# Human impacts assessed on central Pacific Ocean coral reefs

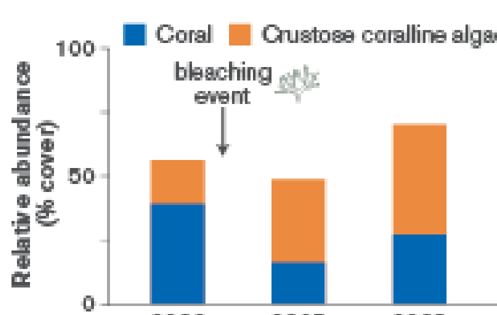
The Northern Line Islands are small, remote islands with coral reefs representing a gradient from healthy at pristine, non-impacted reefs (Kingman) to degraded at places subjected to successively greater human impacts (Kiritimati).[6]




Recent expeditions to the Line and nearby Phoenix Islands utilized standard and reliable metrics to understand and quantify this gradient from healthy to degraded condition. The data collected on benthos (organisms on the seabed), fishes, and microbes answer questions about the impacts of human activities and whether all key functional groups are equally threatened. If impacts affect only one group, there might be a capacity for rapid recovery. In the Northern Line Islands, however, scientists found that dramatic changes occur in the benthos, fishes, and microbes, as shown in the graphs above.[6]


The Southern Line Islands and Phoenix Islands had similar pristine coral reef communities and endemic species until 2002, when a mass bleaching event affected only the Phoenix Islands. This provided a natural “experiment” for comparison and to help understand how reefs might recover from bleaching in the absence of local human impacts.

In 2009, it was evident that the Phoenix Islands reefs were regenerating with extraordinary vigor. Given the high abundance of parrotfishes and surgeonfishes, the bare space left by coral bleaching and coral death was colonized by CCA (see page 6) rather than fleshy algae.[30] Many juvenile corals established on the preferred CCA, and coral coverage greatly expanded. The reef is repairing itself and demonstrates how coral reefs can be resilient against global climate change, if local human impacts are minimized.




*Coral and crustose coralline algae cover in the Phoenix Islands following a 2002 bleaching event.*

# Key metrics provide vital insights about reef processes and health

## Benthic, fish, and microbial metrics keep measurements simple


### Benthos

Benthic monitoring traditionally involves the painstaking collection of vast amounts of data. While developing CHI, it became evident that the most important measurement was the area covered by live coral and crustose coralline algae (CCA). Live coral indicates the current state of the reef, while CCA indicates the anticipated trend of the reef. Combining them gives information on the health of the reef now and expected health into the future. *Scored 0 (degraded) to 1 (healthy) based on proportional cover of coral and CCA.*

### Fishes

Fishes can be measured in many ways. However, estimating the biomass of all non-cryptic fishes is sufficient to diagnose the health of a coral reef. There are many roles played by reef fishes, but the total biomass of the assemblage relates well to the capacity of the community to effectively fill many niches. *Scored 0 (degraded) to 1 (healthy) as a fraction of total fish biomass from the Kingman reference site (approximately 5 tons per hectare.*

### Microbes

As demonstrated in the Northern Line Islands, pristine reefs have a microbial community that reflects and promotes a healthy coral reef (see page 7). As human activities around reefs become more intense, pathogenic bacteria become much more abundant. These are mainly *Vibrio* bacteria—those responsible for cholera and gastroenteritis. The microbe score for CHI is inversely related to the number of *Vibrio* present, where more *Vibrio* is related to reduced health. *Scored 0 (degraded) to 1 (healthy) based on an inverse relation of* Vibrio *concentration.*

# Combined metrics yield a Coral Health Index—CHI

## A cumulative index reveals reef status and trends

The Coral Health Index (CHI) is composed of three metrics (benthos, fishes, and microbes) to describe reef health. These are three different diagnostic parameters that work together to provide information about the health of a single coral reef ecosystem. That combination is important because even if one of the components (e.g., fishes) is low-scoring, the overall score will be relatively high, indicating that the system can recover in the future. The reason three metrics are used is because the system is not always in perfect synchrony, and each metric can give information on the current state and future trends of a reef community. All three metrics are scaled to give a score from zero (degraded) to one (healthy). These scores are then equally weighted and averaged to give the final CHI score.


*Coral Health Index calculated for reefs across the Line Islands archipelago.*

| Reef | Benthos | Fishes | Microbes | CHI |
|---|---|---|---|---|
| Malden | 0.81 | 1.00 | 0.99 | 0.93 |
| Kingman | 0.71 | 1.00 | 1.00 | 0.90 |
| Millennium | 0.70 | 1.00 | 1.00 | 0.90 |
| Vostok | 0.85 | 0.81 | 1.00 | 0.89 |
| Starbuck | 0.45 | 1.00 | 0.98 | 0.81 |
| Flint | 0.92 | 0.42 | 1.00 | 0.78 |
| Palmyra | 0.48 | 0.51 | 1.00 | 0.66 |
| Tabuaeran | 0.38 | 0.34 | 0.90 | 0.54 |
| Kiritimati | 0.21 | 0.26 | 0.68 | 0.38 |

*Benthos, fishes, and microbes metrics used to calculate the Coral Health Index (CHI) in the Line Islands.*

CHI has been used to assess the relative condition of reefs across the Line Islands archipelago. These central Pacific atolls differ in their size, oceanography, and level of human impact (both historic and present). A team of researchers visited each of the islands to quantify the benthos, fish assemblage, and characteristics of the microbiota (see methods on page 12). Because of the natural variability of marine populations, these measurements are replicated across each island to provide an island-wide estimate of each metric (approximately 10 sites for each benthos and microbes, and approximately 20 sites for fishes). These data allow the status and trend of each reef to be determined.

The average of the benthos, fishes, and microbial metrics gives an estimate of CHI for each island. Three isolated islands have a CHI value of at least 0.90, an indication that the reefs are very healthy. Three islands have values between 0.75–0.90, consistent with the geographic characteristics limiting reef growth and water clarity. Palmyra, with a score of 0.66, reflects historic human impacts associated with military installations on the island. Tabuaeran and Kiritimati are the only two currently inhabited islands in the survey, and the local fishing and pollution have reduced the observed health of these reefs, as reflected by their reduced CHI scores.

# Coral Health Index can be broadened for global application

## Examples from East Africa, the Caribbean, and Hawai'i

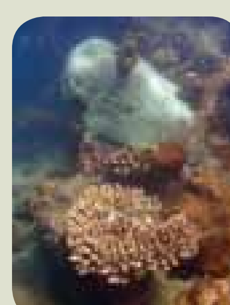
Healthy coral reefs are celebrated for the exuberance of life that they support and display. However, they are not static and change over evolutionary time and differ from one locale to another. These natural differences make it very difficult to compare one coral reef to another. Scientists have studied whether individual reef communities have enough in common that they can be compared via a globally relevant coral reef health measure. Utilizing a dynamic indicator of reef health makes it possible for practitioners and decision-makers engaged in supporting different conservation programs to see where progress is being made.

The Coral Health Index (CHI) measures the common elements associated with coral reef health everywhere. A healthy reef has lots of live coral. From what is known about the dynamics of coral recruitment, if a reef has a large proportion of crustose coralline algae (CCA), then the reef is on a trajectory towards having lots of live coral. If the reef has too many pathogenic microbes, it will not have abundant and healthy corals. The amount of live coral is a status descriptor, and the CCA and types of microbes are process/trend indicators. For example, CHI assessments may show a reef to have a lot of healthy coral, but if it has a poor microbe score without much CCA in open areas, then the reef may be healthy now but will not be resilient when encountering future natural or human-induced disturbances.

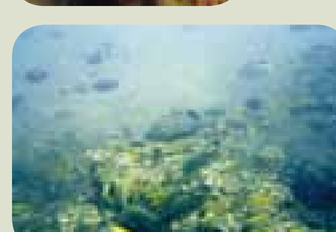
The microbial metric of CHI is extremely important,[31] but due to its novelty, this dimension of CHI has yet to be broadly applied. The benthos and fishes metrics have already been calculated at many sites in the Caribbean Sea and the Pacific and Indian Oceans. To date, these two metrics appear to scale very well with all other attributes that scientists consider to be "good" and "bad" in coral reef communities. A CHI score based on only benthos and fishes metrics reveals differences between more- and less-protected zones. These two-dimensional CHI scores match intuitive expectations about coral reefs that are remote versus those close to human habitation; there is a very strong negative correlation between a reef's CHI score and cumulative human impacts in close proximity to them. Thus, CHI gives a quantitative indicator to assess differences across locations or change through time at a particular reef.

### East Africa

Kenya's population, like most developing countries, is growing so fast that pressures even on well-protected marine protected areas (MPAs) are significant. Corals within and outside of MPAs died back in the Indian Ocean-wide bleaching event of 1998, and they are recovering slowly, particularly in the southern-most MPA, Kisite. Fishing pressure outside of MPAs is high, and biomass within MPAs is far below the standard identified for the Coral Health Index (CHI) in the Pacific. Northern reefs in Kiunga and Lamu are more algae-dominated due to high nutrients from the Somali Current, but fish populations are better, as human population density is low. In total, the overall CHI of reefs is relatively low, indicating a high risk of further degradation in the future.

*Typical Kisite/Mombasa reef with acroporid and favid corals on shallow platforms.*



*Kiunga reefs showing moderate fish populations and low live coral and CCA cover.*


## The Caribbean: Netherlands Antilles

The coral reefs of Curaçao and Bonaire have been studied for decades and researchers have noted a consistent decline in live coral cover[32] and fisheries catch (see photo, right). Efforts to manage the reef resources into the future depend on having quantitative benchmarks to assess changes in health. The figure above summarizes CHI data from the reef at 20-meter depth in 2000. CHI scores suggest that the protections afforded by the Bonaire Marine Park have slowed the degradation of the reefs' health relative to those of Curaçao.

In order to fully assess the current state and resilience of the world's coral reefs, work is needed now to collect comprehensive, three-dimensional CHI data at a global scale. However, the examples shared here demonstrate that very good two-dimensional data exists for describing benthos and fishes in many locations. These data can be used to calculate a preliminary CHI value, offering initial insights into the relative health of reefs from many regions. This two-dimensional CHI will also be invaluable for following time trends of reef health that capitalize on archival data to provide novel insights for effective coral reef management today.

## Hawai'i: Lanai and Maui

Hawaii is a popular tourist destination with its beautiful beaches and rich ocean culture. The coral reefs near the resort towns on the island of Maui attract hundreds of thousands of visitors. These reefs, however, have been dramatically degraded by relatively uncontrolled fishing and pollution. Diving and snorkeling charters now travel to the shores of nearby Lanai to show their guests more healthy coral reefs. With improved management of the reefs and the protection of algae-eating parrotfishes and surgeonfishes, residents of Maui hope to restore their reefs and regain some of the island's natural capital.

# Coral Health Index methods are reliable and reproducible

## Accepted methods for benthic, fish, and microbial data

The methods for collecting data to calculate CHI are standard and reliable. Data are collected by scientifically trained people and can be performed quickly and consistently. There are many different ways to lay a transect or analyze photos and videos, but the methods chosen for CHI are based on being easy to perform and replicate. In order to compare the world's reefs, the methods must apply equally to the variety of reefs encountered. (Complete methodologies can be found at www.science2action.org.)

### Benthos

Photographic surveys are the most reliable and replicable means of describing the reef benthos. While photos provide data necessary for estimating CHI, they also can be archived for future reference and more detailed analyses. In a survey site, a transect line is placed and quadrats are selected randomly along the line. A photo is taken of each quadrat using a digital camera. The benthic type under randomly selected points is assessed. At least five benthic categories should be identified: hard coral, crustose coralline algae (CCA), turf algae, macroalgae, and undescribed. Results are averaged across photos to provide a site-specific estimate of benthic composition. The summed proportional cover of hard coral and CCA provides the CHI estimate of the benthos (maximum = 1.0)

### Fishes

Underwater visual censuses are an invaluable means of determining the composition of the fish assemblage on coral reefs. Belt transect methodologies provide one of the most robust and replicable approaches for these censuses. A pair of divers swims along adjacent belt transects, recording the species and size of all fishes within the area. Divers will census three such belt transects at each site. Using relationships between length and weight, the mass of each fish can be estimated. Summing these masses across all fishes surveyed provides an estimate of total biomass of the fish assemblage, reported in grams per square meter. Total fish biomass is reported as a fraction of 500 grams per square meter (maximum = 1.0) to provide the CHI estimate of fishes.

### Microbes

Thousands of microbe types can be found in the reef environment, but *Vibrio* are ubiquitous, and a numerically and functionally important group. CHI uses simple approaches to estimate the concentration of culturable *Vibrio*. Samples of seawater are collected above the reef benthos. Small subsamples of the seawater are spread onto plates and allowed to culture. After 24 hours, the number of colony-forming units is counted on each plate. The average number of colonies per plate is the site-specific estimate of *Vibrio* concentration (reported in number per microliter). Two final mathematical steps are needed: (1) divide the average number of colonies per microliter by 100 and add 1, and (2) take the inverse of this number. This number is the CHI estimate of the microbes. Note that a lower concentration of *Vibrio* gives a higher CHI score (maximum = 1.0).

# Coral Health Index can provide insights into reef health and resilience

## Trajectories can be predicted and tracked

Any ecosystem can exist in a variety of states. When a coral reef is in a healthy state, it provides maximum benefits for biodiversity and human well-being, including sustaining local livelihoods. Action is needed to ensure that reefs exist in a healthy state, despite natural and human-induced disturbances. As healthy coral reef ecosystems have the greatest chance for resilience to these perturbations, it is essential that humans provide good stewardship and management of these fragile natural resources.[20]

## Degradation: Discovery Bay, Jamaica in 1980s

### Not resilient and needs help to return to desirable state

Before the Caribbean Sea's mass coral and herbivore die-offs of the 1980s (see pages 4-5), the reefs had high coral cover but few fishes or other herbivores. If CHI had existed at this time it would have registered the reefs as unstable with low resilience, unlikely to recover after a major disturbance. After coral bleaching plus coral and sea urchin plagues swept Discovery Bay, reef health worsened considerably and has still not recovered a quarter century later. Elevated nutrients in coastal waters may aggravate the problem.[33]

**Before: 1978**

*Reefs composed of lush coral but scarce in herbivorous and predatory fishes. Abundant sea urchins hold fleshy algae at bay.*


**After: 2000**

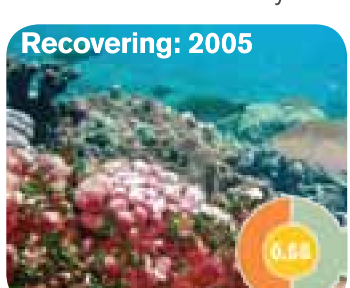
*Corals and urchins devastated by disease and coral bleaching. Few herbivores remain and large seaweeds dominate, indicating poor health and no quick return to abundant live coral cover.*

## Recovery: Phoenix Islands

### Resilient around desirable state

When the Phoenix Islands reefs bleached in 2002 (see pages 6-7), the coral died but the fishes remained and pathogenic microbes were controlled and/or absent. The large biomass of herbivorous fishes ensured that the exposed substratum remained in a heavily grazed state, which is conducive for the recolonization of crustose coralline algae (CCA), but not for the undesirable fleshy algae. This ensured the reefs' trajectory from a fair state in 2005 back towards a familiar and "healthy" state in 2009.[30]


**Before bleaching: 2002**



**Recovering: 2005**

**Strong recovery: 2009**

*CHI values calculated from in situ field assessment data.*

# Coral Health Index is critical to local and global long-term monitoring efforts

## CHI is a needed tool for effective adaptive management

The world's coral reefs are declining at a rapid rate from a well-recognized suite of threats from local and global sources. Although numerous local efforts have been launched over the past 30 years to protect and restore coral reef communities, comprehensive ecological information is still lacking to determine if these efforts are working or not. An important step towards resolving this challenge is to maintain and expand local monitoring efforts to a global level and measure conservation effectiveness against established baseline conditions.

The benefits of moving annual local monitoring results into an annual global coral reef health assessment are that site managers and decision-makers would be more regularly informed and better able to support adaptive management. Adapting management actions at local, national, and regional scales to maximize the health of coral reef ecosystems is the only way to ensure the long-term survival of these magnificent and economically important natural systems.

For any location being managed for reef health, it is critical to understand the current state of the coral reef and the change over time. Monitoring data provide the raw material for investigating how a reef is responding to management actions. Only by knowing how a reef is changing can management activities be tailored to maximize positive benefits. The CHI provides reliable and accepted metrics to track management progress, both for maintaining and for rebuilding reef health.

It is recognized that the incorporation of a microbial metric makes CHI more labor intensive and expensive. However, this is at the benefit of greatly improving the holistic understanding of reef health. Likewise, the use of fish biomass instead of species richness and abundance ensures a more holistic metric to inform resource managers if the reef is truly restoring itself to full health and resilience to perturbations. As a holistic measure, CHI helps ensure that society will have a more complete picture of reef health and will take action on important sources of stress before it is too late for coral reefs to recover.

The time has arrived for using the best tools available in assessing coral reef health and taking local action based on what is learned. The promotion and adoption of CHI can be more easily realized if the following recommendations are considered and acted on:

**Govenment Agencies:**
***Utilize*** CHI scores when establishing strategies to protect coral reefs and when assessing reef recovery.

**Local Communities:**
***Participate*** in CHI data collection activities and become aware of the importance of CHI scores.

**Marine Scientists:**
***Conduct*** CHI monitoring worldwide and validate analyses and interpretation of CHI findings.

**Marine Managers:**
***Coordinate*** data collection and participate in understanding, reporting, utilizing, and disseminating CHI results.

**Private Businesses:**
***Invest*** in local capacity-building for CHI assessments and conduct business in ways that maximize CHI.

**Non-Government Organizations:**
***Support*** CHI approach with wide adoption, promotion, and dissemination of results to stakeholders.

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