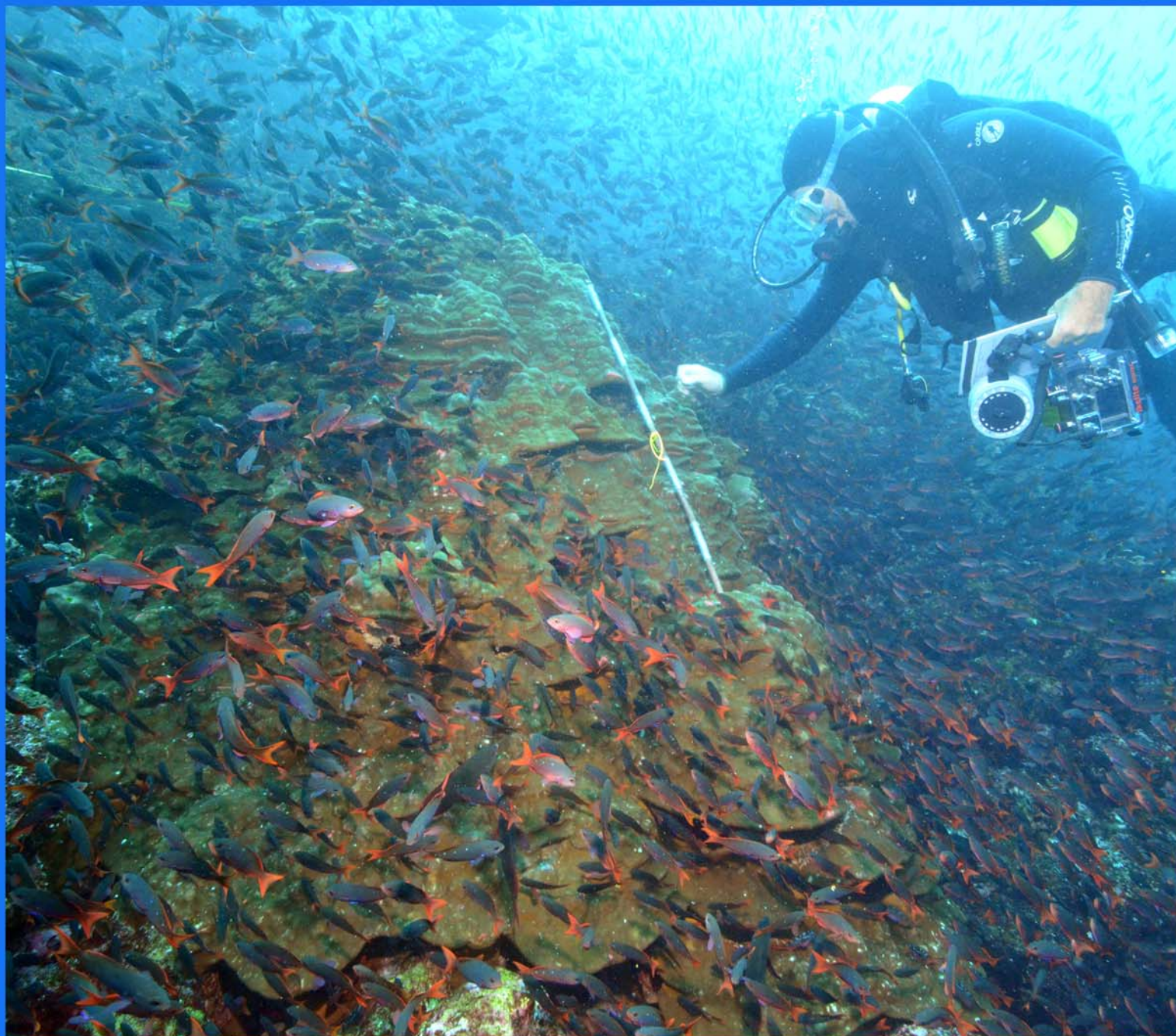


Galápagos

Coral Reef and Coral Community

Monitoring Manual



Khaled bin Sultan
Living Oceans
Foundation

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Front cover: Dr. Bernhard Riegl assessing a large colony of *Porites lobata* at Wolf Island, Galápagos. Photo by Joshua Feingold.

Back Cover: Divers conducting coral research in the Galápagos. Photos by Joshua Feingold, Andrew Bruckner and Philip Renaud.

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Galápagos Coral Reef and Coral Community Monitoring Manual

Andrew Bruckner

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FORWARD

This monitoring plan was developed at the request of the Galápagos National Park in response to coral surveys undertaken by the Khaled bin Sultan Living Oceans Foundation (KSLOF) during our Global Reef Expedition (GRE). It is intended to serve as a practical guide for scientists, managers and dive operators to document changes to the condition of coral reefs and coral communities within the Galápagos.

The manual does not include all monitoring techniques that have been developed and applied to coral reefs around the world. Rather, it explains some of the most widespread and useful techniques used in various coral reef ecological monitoring programs. An emphasis is placed on the methodology implemented by KSLOF to document the status and trends of coral reefs examined during the GRE, which were applied in the Galápagos in June 2012. KSLOF survey approaches were designed to 1) collect baseline information on the composition, abundance, population structure and condition of corals in shallow marine habitats; 2) determine the current status of these habitats; 3) evaluate the extent of recovery from past disturbances; and 4) predict their ability to withstand future perturbations associated with acute stressors and climate change. Other organisms and attributes (e.g. fish, benthic structure) were included in the assessments because of their important linkages with the corals and roles in regulating community structure and health.

It is important to note that there are many different monitoring approaches applied in coral reef ecosystems. All of these methods can provide relevant data on corals, benthos, fish or other attributes. The methods described in this manual can be modified as necessary to be more similar to other approaches, or to address a specific question being asked. Slight modifications should result in similar levels of data acquisition and confidence. The critical aspect of a monitoring program is to select a method pertinent to the scale of the effort, the level of expertise of the observers, and the specific questions asked. Once a method is implemented it is important to keep with that method so data collected over time are comparable.

Of note, one of the key aspects of the methods presented here is that they include the most common attributes measured on coral reefs, benthic coverage. Most monitoring programs focus their evaluation on documenting changes in cover of corals over time. We feel, however, that this alone provides an incomplete indication of the health of reefs and can lead to incorrect conclusions about status and trends. Because corals are modular organisms, they are affected by partial mortality, and can survive loss of some of their tissue. In addition to estimates of the amount of partial mortality, measures of their size are a critical attribute of their life history as this dictates their reproductive potential as well as their likelihood of survival. Furthermore, size structure provides information on the state of a coral population. A coral population with high cover could consist of all small corals, all large corals, or a mix of small and large – each of these provides a different picture of their past history and future direction. By combining cover with measures of size and mortality, managers can understand the population dynamics of the corals, factors responsible for the changes observed, and future trajectories of coral communities.

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JUSTIFICATION FOR A CORAL MONITORING PROGRAM

The Galápagos is an isolated archipelago of volcanic islands that straddle the equator, about 1000 km (620 miles) off the coast of Ecuador, in the Eastern Pacific Ocean. There are 14 main islands and over 100 small islets that sit on a deep platform and are surrounded by deep (2000-4000 m) water. Shallow waters adjacent to the islands support large populations of marine mammals, turtles, cartilaginous fishes and bony fishes, as well as hundreds of species of invertebrates and diverse algal communities. Stony (scleractinian) corals are one of the key habitat forming species present throughout much of the archipelago.

Scleractinian corals in the Galápagos are represented by characteristic eastern Pacific species, with no known endemics. They consist of many fewer species than found in the Caribbean and IndoPacific (22 in total) and form true coral reefs in only a single location, off Darwin Island. In other locations, the coral communities typically occur as scattered colonies, and infrequently as carbonate build-ups. Coral communities in the Galápagos Islands are dominated by aggregations of massive corals, *Pavona clavus*, *Pavona gigantea* and *Porites lobata*. Scattered colonies of branching *Pocillopora* species occur in many locations, but *Pocillopora* build-ups that were common prior to 1982 appear to be much more restricted today. Unique assemblage of free-living fungiid corals and *Psammocora* sp. are also found at Devil's Crown and a few other locations.

Coral communities in the Galápagos appear to be both fragile and resilient. They have adapted to extreme environmental conditions, but they have also been severely impacted by catastrophic widespread disturbances (e.g. El Niño Southern Oscillation). Scientists have documented rapid changes to these ecosystems, and also recovery in several well studied northern locations (Darwin, Marchena, Wolf), but data from southern islands remains patchy. Establishment of a monitoring program in the Galápagos that targets corals and associated species is necessary to document future changes to these communities. Monitoring and research on corals can also help us better understand the effects of climate change in the Galápagos and other tropical regions world-wide. Four key reasons to monitor coral communities in the Galápagos are:

1) The Galápagos Archipelago is one of the best regions to understand the potential implications of ocean acidification on corals under natural conditions.

In areas affected by upwelling, the seawater has abnormally high concentrations of dissolved carbon dioxide (CO₂) (Manzello et al. 2008, Manzello 2010a, 2010b). High levels of CO₂ are known to suppress aragonite saturation states, which can affect the ability for corals to build skeletons and grow. The archipelago is located downstream from the Peruvian upwelling current, which brings deeper waters to the surface that have been enriched in CO₂ from the microbial breakdown of organic matter in the deep sea. Seawater in the Galápagos mimics what is expected for the entire tropics (a doubling of the pre-industrial levels of atmospheric CO₂, the greenhouse gas responsible for global warming). Monitoring of water chemistry and

coral growth rates can provide a window by which to view coral reef structure and function of the future.

2) Shallow environments are exposed to rapid and extensive temperature changes; monitoring will determine their ability to adapt to temperature perturbations.

Reefs and coral communities are frequently affected by water temperatures that drop to the lower end of their tolerance limit, and by infrequent, periodic warming events that exceed their upper tolerance range. High variability in the marine climate, from tropical to temperate conditions within kilometers, and the equatorial location in the Eastern Tropical Pacific make the Galápagos one of the most susceptible regions to the direct effects of the El Niño-Southern Oscillation (ENSO). Two recent El Niño events (1982-1983 and 1997-1998) caused mass mortality of corals. During the 1982-1983 event, the reef framework was subsequently bioeroded after sea urchins underwent a population explosion. Remarkably, the reef systems have shown unusually high resilience, progressively rebounding from this catastrophe (Feingold 1995; Feingold and Glynn 2005; Glynn et al. 2009). What was most unusual about the 1997-1998 event is that bleaching mortality was much more patchy (even though water temperatures in some areas were higher), and some taxon (e.g. *Pocillopora*) that bleached and died during the 1982-1983 event showed only minimal bleaching during 1997-1998 and much less mortality. Nevertheless, *Pocillopora* communities have not rebounded to their former (pre-1982) abundance and these species are now rare or absent in several areas that once contained flourishing communities (e.g. Urvina, Isabela, Devil's Crown). Monitoring of colonies of these species will be useful in predicting stability of populations to future temperature fluctuations and their potential to rebound, while monitoring of changes in their symbiont communities can help determine their ability to adapt to temperature stress.

3) Corals play a critical role in the health of the oceans by building habitats used by other species, and by regulating ocean chemistry through skeletal deposition of calcium carbonate (CaCO₃).

Ocean warming and ocean acidification associated with climate change are predicted to worsen in the future. As a direct consequence of warming, coral bleaching and mortality may become more frequent and severe, with cascading impacts on other species. Through implementation of a comprehensive monitoring program for shallow marine communities, managers can better understand linkages between associated species and their biology and symbiotic associates, as well as a host of ecological processes (e.g. bioerosion, herbivory), natural stressors (disease, predation and bioerosion), and chemical, physical and environmental parameters. Together, this information will contribute to an understanding of

the resilience of coral reefs and coral communities in the Galápagos, and actions that must be taken to preserve and protect these precious resources.

4) Stony corals play a critical role in the ecology of tropical marine environments, the physical dynamics of coastal areas, and the economies of tropical regions.

Corals form a strong barrier to wave and tidal energy that would otherwise erode shorelines and damage valuable coastal property. Corals also provide a three-dimensional (3D) structure that serves as habitat for the diverse biological community that inhabits coral reef ecosystems. Fish and crustaceans harvested for food depend on the stony coral as habitat and nursery grounds. Pharmaceuticals developed from natural products are most often discovered in reef areas with high biological diversity. Furthermore, corals also play a critical role in economies of tropical nations. Stony corals, and the reef community that they harbor, can generate a strong tourism economy by attracting visitors, boaters, recreational anglers and recreational divers.



Fig. 1. A diverse, high relief coral reef off Darwin Island constructed by boulders of *Porites lobata*.

INTRODUCTION

Monitoring is the repeated surveying of organisms, the human dimension and environmental (physical and chemical) parameters, over long time periods. Data from these surveys help us understand the condition of particular habitats, the diversity and population structure of the organisms, natural and anthropogenic processes and changes in the environment. The data are used to characterize the health and long term trends of a site, responses to a natural or human-induced disturbance, and the effects of human activities. Monitoring data can also help determine the types of action or decisions managers must take to protect the environment, and can provide information on the effectiveness of particular management actions.

Ecological monitoring includes physical, chemical and biological monitoring, and aims to assess the status and trends of the coral reef ecosystem.

Physical and chemical monitoring includes repeated measurement of parameters that describe the environment surrounding reefs and how the environment changes. Examples include measurements of depth, currents, temperature, water quality, visibility, and salinity.

Biological monitoring measures the status and trends of the organisms on coral reefs and factors responsible for the observed trends in health. These include measures of 1) the amount of the bottom covered by corals, sponges, algae and non-living material; 2) species composition, size structure and condition of reef building corals; 3) community structure of fish populations; and 4) populations of motile invertebrates such as crabs, lobsters and sea urchins.

Socioeconomic monitoring includes an assessment the human dimension and aims to characterize how people use, understand and interact with coral reefs.

Ecological monitoring can be achieved through a combination of rapid assessments conducted randomly throughout a site and more detailed evaluation of permanent plots within the site, both undertaken repeatedly at discrete (e.g. quarterly, annually) time intervals. It includes observations and measurements recorded on a slate and paper underwater, video and photographic documentation, sample collection followed by laboratory analysis of samples, and measurements using instantaneous and deployed sensors. The required frequency of monitoring varies depending on the questions and objectives, the sampling unit (e.g. biological, physical and/or chemical parameters), the history of the site (e.g. the stability of the system and/or frequency of disturbance), type of management interventions, and the resources and budget.

Most biological monitoring programs for coral reefs involve periodic assessment of the substrate, benthic organisms, mobile invertebrates and fish, to determine trends in the amount of the bottom covered by those organisms, the size (numbers, biomass) of organisms, and the condition of populations of animals and plants, to characterize the amount and type of changes that occurred since the previous survey. This approach typically provides a detailed picture of the

condition of the site at the time of the survey, and how the site has changed between surveys, but it may fail to identify factors responsible for the changes.

Detailed monitoring of a single factor or threat, such as coral disease or bleaching may provide critical information on the prevalence or incidence of that threat. It may also help elucidate the cause(s) and impact. Monitoring focused only on a particular threat may miss information on related environmental or biological processes critical to understanding why the threat arose.

Conversely, targeted monitoring may be undertaken to characterize specific ecological processes such as coral recruitment, herbivory and predation.

An ideal monitoring approach would consider biological monitoring, monitoring of specific threats, and monitoring of key ecological processes along with repeat measures of physical factors (temperature, wave exposure, tides, salinity etc.), chemical factors (water quality monitoring), and human uses, implemented through a well designed, integrated, multifactorial approach. This type of a monitoring program would provide population, community, and ecosystem level data for the dominant animals and plants, water quality and environmental data, and information on the human dimension at various spatial and temporal scales.

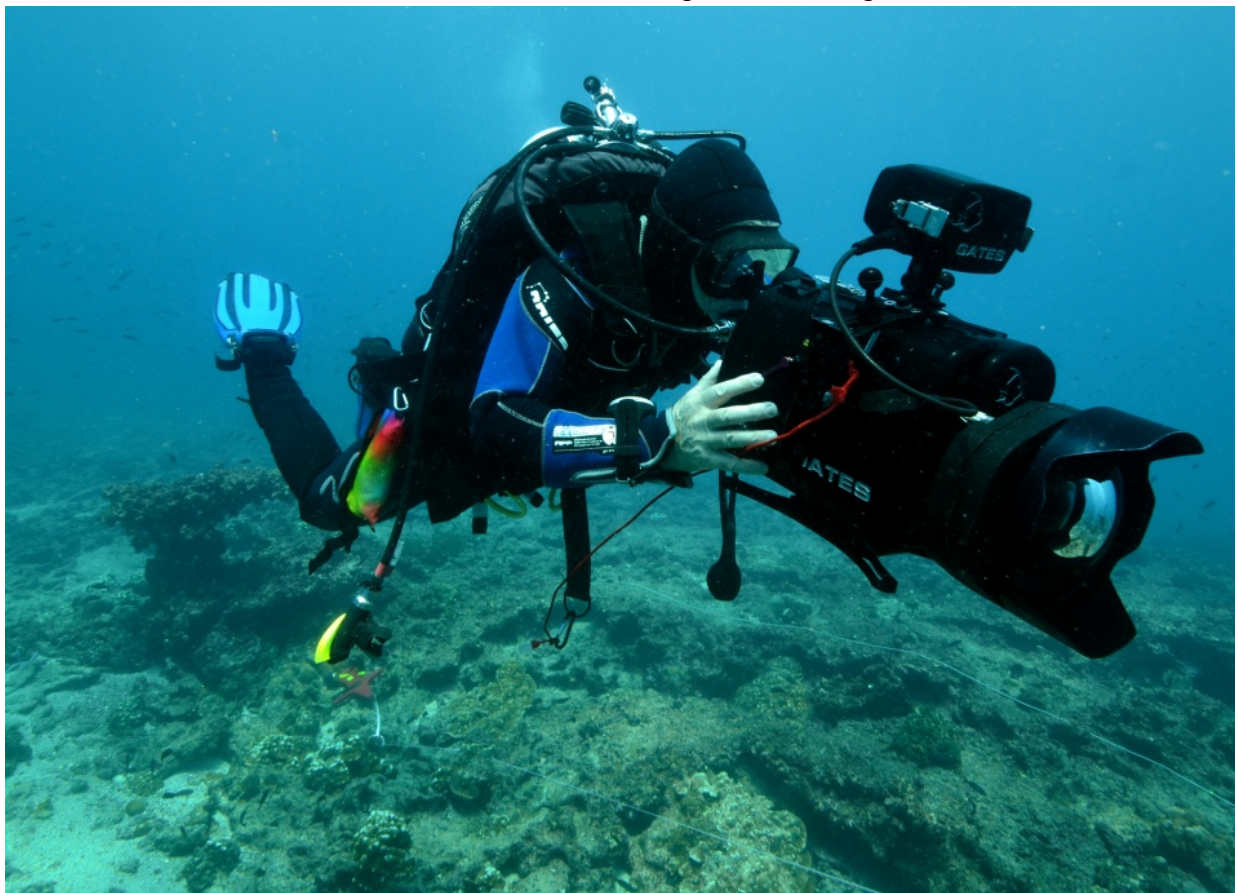


Fig. 2. Video documentation of a coral community at Marchena.

BENEFITS OF ECOLOGICAL MONITORING

Monitoring can contribute to an effective ecosystem management plans for coral communities and coral reefs in the following manner:

- 1. Habitat Distribution and Extent** - monitoring can provide information on what and where the coral reef resources are. This includes the size and location of different habitats types and the resources contained within these habitats.
- 2. Status and Long-Term Trends of Corals and Reef-associated Resources** – monitoring can help determine the status of these resources and how are they changing over time.
- 3. Impacts of Large-Scale Disturbances** – monitoring will provide information on the impacts of global stressors such as coral bleaching, cyclones, predator outbreaks and disease events.
- 4. Impacts of Human Activities** – monitoring will help managers understand how the activities of people affect the coral community and its resources.
- 5. Performance Evaluation and Adaptive Management** - monitoring can measure the effectiveness of specific management actions and can help determine additional interventions necessary for conservation.
- 6. Education and Awareness Raising** – monitoring results will raise awareness and education of user groups, communities, government, and other stakeholders and can help gain support for the conservation of the coral reef resources.
- 7. Building Resilience into MPAs** – monitoring can provide information on the resilience of a site and other data useful in the design of MPAs to enhance their resilience to large-scale disturbances associated with climate change.



Fig. 3. Photo-documenting an unusual field of free-living fungiid corals (*Diaseris distorta*) near Devil's Crown.

DESIGNING A MONITORING PLAN

When designing a monitoring plan it is critical to clearly identify your objectives and how to answer specific questions relating to those objectives. Specific questions you should ask include:

- What are your objectives?
- What information do you need?
- What are you going to monitor?
- Where are you going to monitor?
- How often will you collect data?
- What methods will you use?
- Who will conduct the monitoring?
- What resources are available?
- What training and quality control will be undertaken?
- What will you do with the data?

The first steps to develop overarching monitoring objective involve defining the target population (where you are going to monitor), the sampling approach (the methods you will use and how often you will monitor) and the sampling unit (what you will monitor).

To measure changes of coral reef condition through a long-term monitoring program, the target population should include the major stony coral populations in the region. A sampling approach needs to be designed to accurately characterize the members of the target population that will be sampled. Because it is usually not possible to monitor every coral in a population, sampling should be targeted towards a subset of each population that is representative of the entire population. If the population is widespread it should include a sampling regime that examines corals at different depths, habitat types, and islands, as well as other biological parameters relevant to the coral population such as associated invertebrates and fishes, algae, and substrate types and physical parameters such as temperature.

The sampling unit is defined as the specific fraction the target population is divided into. This will depend on the desired detail and scale of your monitoring program. It is important to include multiple, replicate sampling units within each target population. The unit could include a single quadrat or transect, or it could include multiple quadrats or transects within a station, such that each unit is considered individual and indivisible. If multiple quadrats within a station are considered a sampling unit, all quadrats must be aggregated for a single station value.

SITE SELECTION

It is important to understand the types of habitats and/or zones contained within the region of interest and how these differ between islands or locations. It is unlikely that every single location with corals can be included in a coral monitoring program due to the level of effort and cost that would be incurred. This level of effort is probably unnecessary as selected sites can serve as representative locations for other similar sites. The number of sites necessary for inclusion also will vary depending on 1) the objectives; 2) how detailed and labor intensive the methods are that you plan to use; 3) the diversity of habitats that will be monitored; and 4) the degree of similarity among sites. Further consideration must be given to the accessibility of the site. The more easily the site can be accessed, the larger the scale of effort can be and the more frequent the sites can be monitored.

Representative sites: When stratifying sampling or surveys over an entire island it is important to include as many different areas as possible, targeting different depths, exposures, habitats, zones and species assemblages. Initial characterization and mapping of all shallow areas can aid in selection of sites for monitoring.

Control Sites: To assess changes due to human impacts and natural stressors, or to measure the effectiveness of management measures, both affected (or managed) sites as well as sites that exhibit similar environmental characteristics, but have not been affected by a particular stress or are not under the same management scenario should be included.

Impacted Sites: To evaluate patterns of recovery following an acute disturbance, such as an El Niño event, or to document changes to sites affected by chronic stressors, monitoring should be conducted across a gradient of disturbance with inclusion of similar control sites that are not impacted. Furthermore, characterization of the response of the sites to a particular acute impact or chronic disturbance, a series of biological indicators should be identified and measured across this gradient. In absence of other stressors, a particular stressor (e.g. sewage) should impart a consistent change with distance from the center of the input.



Fig. 4. A monitoring plan should include coral sites located off undeveloped coastlines near Floreana (left) as well as sites near populated areas such as Villamil Bay, Isabela (right).

SAMPLING DESIGN

Monitoring programs are usually designed for status and trend reporting.

Status monitoring assesses the current condition of the resource and can answer questions about the organisms present and their population dynamics. For example: *What is the size distribution of stony corals in the region?*

Trend monitoring detects change over time and will answer questions on fluctuations in the abundance, population dynamics or health of the resource. For example: *Has the diversity, richness or size distribution of the corals declined during the last five years?*

Random Sampling: *Random sampling is the selection of representative stations such that every location has an equal chance of being selected. Each station is considered a representative unit of the entire region sampled.* Locations of surveys or sampling conducted within a certain depth, habitat or zone should be randomly selected to avoid biasing your data.

Surveys to address status and trend questions must use randomly selected sampling locations which represent all locations across the region. As many locations as possible should be examined. It is not feasible to examine every location, therefore it is important to ensure these represent the variation of sites within the region. As necessary, new stations can also be selected using a modified random sampling design.

Targeted sampling: *Targeted sampling is the selection of stations at specific locations to obtain information on a particular question or stressor. Information from targeted sampling cannot be extended to represent other locations or the region sampled.*

A targeted site selection can be used to measure the responses of specific indicators of human disturbance or certain key environmental parameters such as sites affected by upwelling events. Sampling stations are targeted inside, across and outside an area of high human activity (or within and outside areas of upwelling or other environmental variable) to ensure responses will be measured from both impacted and unimpacted locations.

Stratified sampling: For sites that contain different depths, habitats and/or zones it is important to divide the sampling into homogeneous zones with replicate surveys conducted in each zone.

Timing of monitoring: To understand trends over time, the same stations should be revisited at least annually, or more frequently if the sites are subject to frequent disturbances. In response to a broad scale acute impact such as an El Niño event associated with widespread bleaching, it is beneficial to survey a site **at the onset of the event, at its peak, and at decreasing intervals following the event** to determine the impacts and changes associated with that event.

TYPES OF SAMPLES

Qualitative Information: A general or subjective description of a site without actual measurements. This includes a description of the site, with observations on the types of organisms present and their approximate abundance and/or cover, habitat characteristics, habitat quality or condition, and other details, along with photographic or video documentation of the site. This type of descriptive information can be used to support quantitative information. This information cannot be used to measure change, except in general terms, as it is subjective and likely to vary depending on the observer. Certain broad scale survey approaches, such as manta tow, and long distance swims will often provide qualitative data.

Semi-quantitative Information: Estimates of specific parameters such as abundance, cover, size, frequency (e.g. prevalence) of a particular condition, generally collected on a reef-wide or over a large scale, without the use of more detailed quantitative measurements (e.g. quadrat or transect). These data may be ranked for comparison among and between sites. This approach is often used to get a sense of the general health or resilience of a site, and can be used to detect large scale changes to a site. However, because these are not actual measurements, their precision (e.g. actual magnitude of change or error between samples) is likely to be fairly low and may not be comparable among different observers.

Quantitative Information: Measurements of a particular organism, feature, or physical parameter collected over a specific area. This is expressed as a number. It includes measures of cover, abundance, and size. It is collected using a standardized approach (e.g. quadrat, line transect or belt transect) and is comparable between sites and time periods.

Replicates: To understand the amount of variability within a site, it is important to collect multiple measurements or samples at a site using the same technique. More than one sample in a site is called a replicate. The number of samples necessary to adequately represent a site increases with the size of the site, the variability of the site and (for biological samples) the rarity of the organism measured. The more samples taken, the more precise your estimate will be for the specific parameter. It is important that each replicate is spaced out over the study site as widely as possible, ensuring that the samples are representative and do not overlap. Typically, you would select the particular habitat, depth, or zone you wish to monitor, and then select the number of samples that are necessary to adequately cover the selected area. Pilot studies may be necessary to determine the adequate number of samples.

Repeat Sampling: To measure change in a site over time, it must be reexamined at a specific time interval. Surveys can be conducted in random, haphazardly selected locations or within permanent plots. Permanent plots allow a finer detection of change within a finite area and they offer the greatest amount of consistency, repeatability and reliability. However, too few permanent sites or too small of an area may fail to detect change over an entire site, if the site is

highly variable or the controlling factors are patchy. They may also fail to identify the occurrence of certain localized or patchy stresses or changes, such as a disease outbreak that is concentrated in a discrete area. A random design requires more surveys to achieve the same statistical significance, but it is more likely to detect certain phenomena or changes that are not site-wide. Optimally, a monitoring program should strive for a balance between permanent plots and random surveys.

Permanent, fixed survey sites must be marked to allow relocation of the exact spot and also so that the transect or quadrat can be placed as close to the exact position as previous surveys.

- Insert rebar, preferably stainless steel, into the substrate to mark the boundaries of the site, the beginning and end of the transect line, or the center of a radial site.
- Quadrats can be permanently fixed to the substrate, attached with nails or epoxy, or the four corners of each quadrat can be marked with stainless steel nails or stakes to allow repositioning the quadrat in the same location.
- Draw a detailed map of the site.
- Mark the site with surface or subsurface buoys.
- Take GPS coordinates of the site (and/or of each rebar) to aid in the relocation of the permanent sites.



Fig. 5. Inserting a rebar on a reef off Darwin Island to permanently mark the center of a site.

SAMPLE SIZE

One of the largest challenges in monitoring is to determine the appropriate number of samples necessary to characterize the community of interest and document changes to that community. The data characterizing the community should maximize both precision and accuracy.

Accuracy refers to how close to the true mean (μ) the measurement is while **precision** refers to the repeatability of our measurements of the true sample mean. A researcher attempts to avoid any **bias** in measurements. A measurement is biased if it consistently over-estimates or under-estimates the true mean. Bias may arise if the selection of sample plots or transects are nonrandom with respect to the abundance of the target organism or condition being assessed. Precision is affected by a number of factors:

1) **Measurement error.** This is avoided through careful counts or measurements of organisms and a consistent manner in which transects or quadrats are placed.

2) **Total area sampled.** The larger the area that is sampled, the more precise the measurements will be. However, there are limitations (cost, time, team size etc.) on the amount of sampling effort that is possible.

3) **Dispersion of the population.** Precision is affected by the distribution of the populations. Populations may be aggregated, evenly spaced, or randomly dispersed and these dispersion patterns often vary depending on the spatial scale of the reef community or the size of the quadrat or transect used for sampling. The optimal size of the transect and/or quadrat typically depends on the dispersion pattern of the population, the size of the organism being sampled, and its abundance within the sample area.

Conduct a pilot study within your chosen study site to determine the size and/or number of samples needed to maximize precision and accuracy:

- First, select a number of sites within the reef or community you want to monitor;
- Then select multiple random locations within each site to deploy your quadrat or transect.
- Record the data of interest within several different size transects/quadrats or along multiple transects/quadrats within a location. For example, deploy a 30 or 50 m transects and collect data along individual sections (e.g. from the first 10 m, first 20 m and 30 m) and compare the precision of the different lengths.
- Calculate the mean precision (P) and standard error (SE) for each transect length and plot these against transect length. The point where the slope of the graph begins to level out reflects the minimum effort necessary to achieve high precision. Additional sampling beyond this point requires much more effort but may offer little further increase in precision.
- Use the following equations to determine precision and standard error:

$$P = s \div \sqrt{n} \qquad SE = s \div \mu$$

SE = standard error; s = standard deviation; μ = mean; n = sample size; P = precision
A small P is equivalent to a higher precision.

For more information see: Sale and Sharp 1983; Andrew and Mapstone 1987; English et al. 1997; Stevens and Olsen 2004.

SURVEY METHODS

A variety of methods are available to quantify coral community dynamics and assess change to these communities (Rogers et al. 1994; Hill and Wilkinson 2004). The appropriate method will vary depending on the questions asked, the level of detail required, the type and size of the particular habitat monitored, and the scale of the effort. Broad scale sampling involves very large areas and multiple habitats; these require rapid methods to cover these areas efficiently, such as manta tows and timed swims. Medium scale methods may be used for smaller areas such as patch reefs or a specific depth within a reef system; these usually involve transect methods. Fine scale methods look in detail at a very small area and can include quadrat methods, monitoring of individual corals, or settlement plates (Fig. 6).

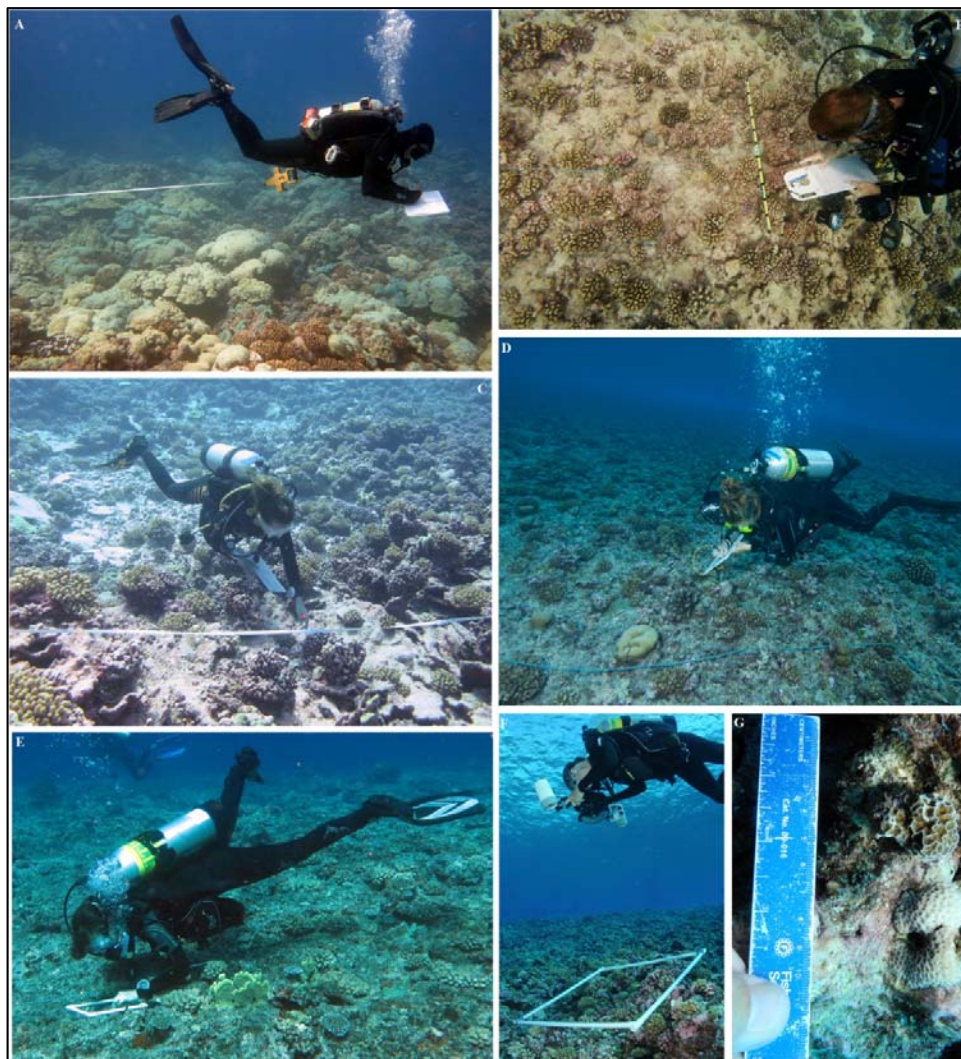


Fig. 6. Monitoring methods used in the Galápagos in 2012. A. Diver conducting a belt transect to assess fish community structure. B. Belt transect to characterize the coral community. C. Line intercept transect to characterize coral cover. D. Point intercept transect for benthic community cover. E. Quadrats (0.25 cm X 0.25 cm) to identify coral recruits. F. Photo-quadrats (1 m X 1m). G. Measurement of coral recruits.

Table 1. Summary of widely used monitoring methods.

Tool	Approach	Purpose
Manta tows	A diver/snorkeler is towed behind a small boat at a slow and constant speed for a fixed time interval.	Allows rapid coverage of large areas. Provides estimates of coral cover, dominant coral types, species occurrence, broad-scale mortality and impacts over an entire reef.
Timed swims	A diver/snorkeler swims a predetermined route recording parameter of interest. Area may be estimated from swimming speed (e.g. number of fin kicks to cover a certain distance).	Allows survey of large area to assess the prevalence of certain conditions such as bleaching or disease or relative abundance of certain organism.
Line intercept transects	Measurements of biotic and abiotic components are made along the entire length of the line.	Assess cover of benthic organisms and/or approximate size of organisms on the horizontal plane of the habitat.
Point intercept transects	Biotic and abiotic components recorded at certain pre-defined intervals along transects (i.e., every 0.5m provides 50 data points on a 25m transect).	Provides information on cover of various benthic organisms including coral as well as substrate types.
Benthic belt transects	All corals and other sessile organisms within a predefined area (i.e., 1x10 m) are counted, measured and condition is recorded. Mobile invertebrates and fish can also be quantified and frequency of occurrence of particular conditions (e.g. disease) can be determined.	Provide detailed data on coral community structure. Allows whole colony assessment. Determine density, abundance, size structure, and health status of population. Provides abundance data for macro-invertebrates and fish and measures of impacts within a defined area.
Circular plots	The abundance, population dynamics, and condition of benthic invertebrates or the prevalence of a syndrome are quantified within a circular area with a 5 or 10 m radius.	Provides data on community structure and frequency of occurrence of a particular condition over a larger area of reef than a belt transect. Used for coral disease studies.
Benthic quadrats	Quadrats (1 m ² 0.5 m ² , or 0.25 m ²) are placed at predetermined intervals along a transect or haphazardly/randomly on the bottom.	Provides data on algal structure and relative abundance of turf, macro and crustose coralline algae, algae biomass, abundance of small invertebrates, coral recruits.
Photo transects	Replicate photographs are taken at specific intervals and from defined height above bottom. A line, quadrat and/or scale bar is inserted into photos for size determination.	Provides a permanent record of a site. Allows collection of large amounts of information quickly, but requires post analysis using computer program to determine diversity, abundance and cover of benthic categories, including substrate, coral and other sessile organisms.
Belt transects for fish	Diver assesses all fish within a “window” of pre-established size along belt transects (e.g. 4 X 30 m).	Provides assessment of fishes within defined window; tend to miss large pelagic species in water column and may underestimate roving schools.
Point counts for fish	Diver assesses all fish within an imaginary cylinder of a certain diameter by slowly rotating in a circle over a predetermined time interval and recording fish from the bottom to the surface of the water.	Provides assessment of fishes within large areas, from water’s surface to benthos.
Roving surveys	Diver/snorkeler swims for a fixed time along a single depth gradient or within a predefined area and records fish species and size. Can also be used to assess macro-invertebrates.	Identify large pelagic species, predatory fishes and small cryptic or rare species; diversity assessments; semi-quantitative abundance estimates.

Broad Scale Methods

These methods are best used for assessing the spatial extent of certain habitats, the relative abundance of a rare organism, the occurrence and spatial extent of a stressor or disturbance, or broad changes to benthic communities. They allow a visual assessment of a large area in a short amount of time and can be used to identify specific areas of interest for more detailed monitoring. Broad scale methods are useful for determining the representative nature of certain habitat types or zones, or the variability of the environment.

Manta Tow

A rapid survey method for large areas where a diver is towed by a small boat along a reef contour (Fig. 7). This method is best to:

- 1) Obtain a general description of large reef areas;
- 2) Characterize different habitats and transitions between habitats;
- 3) Obtain semi-quantitative data on benthic coverage and reef condition;
- 4) Assess the range of a species and measure broad change in abundance and distribution of that species;
- 5) Assess the occurrence and impacts of large scale disturbances such as storm damage, crown of thorns outbreaks, and bleaching events; and
- 6) Characterize population structure of large motile invertebrates, pelagic fishes, or turtles and marine mammals that are difficult to quantify using more conventional stationary census techniques.

Methods: Typically, a snorkeler is towed over a reef by a small boat in a predefined pattern to cover all ecological zones within the location of interest. The snorkeler holds onto a manta board which contains datasheets, cameras and other equipment. The manta board is attached to the boat using a harness and tow rope. On the fore reef, the boat operator navigates slowly (1-2 knots or up to 2.5 km/hr), parallel to the reef crest, in 1-10 m depth. The diver surveys the reef below, covering a width of up to about 10 m (less in low visibility conditions). In lagoonal environments, the boat operator may need to modify the direction to maximize coverage and to surveys back reef habitats, reef contours, areas adjacent to the reef, sand and algal flats and grassbeds. The boat operator usually has a GPS, maps or aerial photographs of the location of interest, a depth sounder and a watch. Each manta tow should cover a known distance, measured by the boat operator with use of the GPS, charts and maps. A typical transect of about 300 m should take about 6-7 minutes. The boat operator may stop periodically at predetermined intervals (e.g. every 1-5 minutes, depending on the type of survey) to allow the observer to record specific data.

Manta tow surveys can also be done using SCUBA. Data are recorded in broad categories. For instance, benthic cover of coral, algae or substrate type may be estimated in 10-20% categories.

It is possible to attach small video cameras (e.g. Go-Pro camera) or high resolution digital SLR camera to the towboard. The cameras can be either forward facing (to record fish) or downward facing (to document benthic communities). For quantitative assessments of images, the camera should have some type of scale bar (e.g. laser pointers). Photo and video documentation are best done using SCUBA. The diver steers the towboard, maintaining a distance of 1-2 m above the substrate for benthic videos. The boat operator maintains a constant speed of 1-1.5 knots and record the time and a GPS track. The diver and boat operator synchronize their watches to allow georeferencing of the footage. A minimum of three people is required (a boat operator, the snorkeler, and the manta tow director and GPS logger).

Equipment needed:

- Small boat
- Manta board, tow rope (20 m) and harness
- Maps and charts
- Watches, GPS, depth sounder
- Slate, paper and/or underwater datasheets, pencil
- Camera and/or video camera

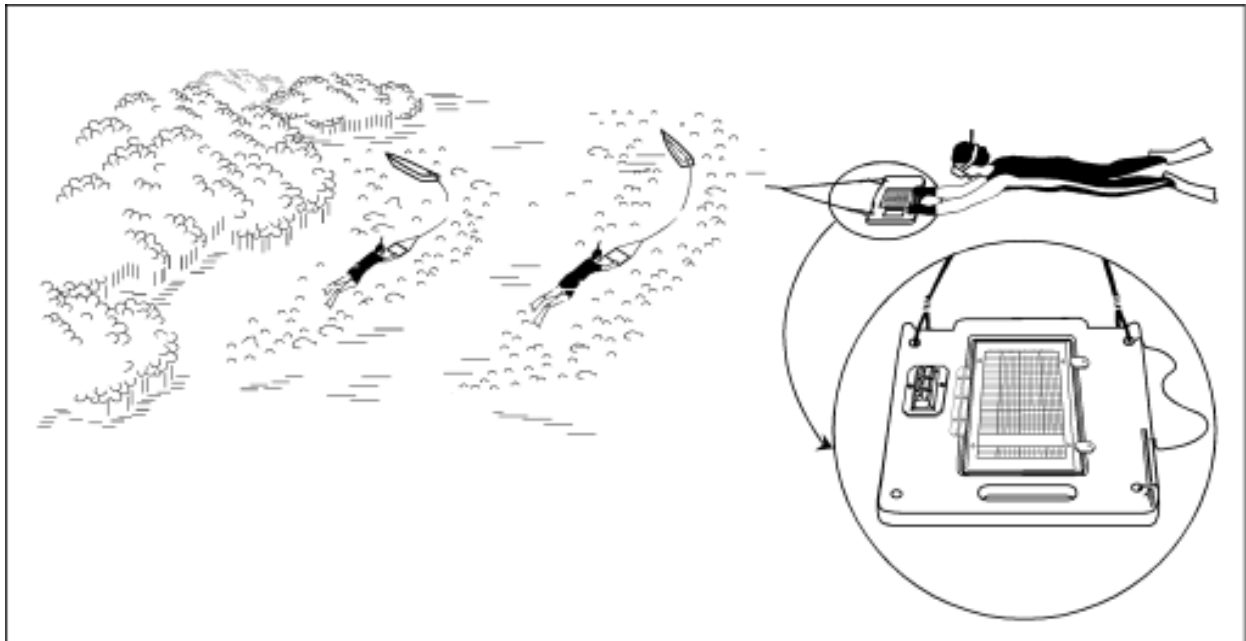


Fig. 7. Manta tow surveys. Diver in the center and on the left are being towed along reef contours. The inset image shows a typical towboard with a handhold, compass, pencil and place to attach a datasheet. Drawing from the South Pacific Regional environmental Program (SPREP) monitoring plan.

Timed Swims

A timed swim survey is a type of roving survey that allows observers to cover moderately large areas and different depths quickly and efficiently. The diver (or snorkeler in shallow water) searches within crevices, under ledges and in other habitats that would not be detected using conventional transect or quadrat surveys. Timed swim surveys are most useful to detect the patchiness and abundance of a condition that is widespread, but at too low a density or prevalence to measure using stationary transect or quadrat surveys. This method typically relies on an estimate of distance or area.

This method can be used to:

- 1) Select sites for more quantitative monitoring;
- 2) Compile species lists;
- 3) Describe the characteristics of a site or depth;
- 4) Identify cryptic and rare species; and
- 5) Obtain semi-quantitative data on the abundance of certain organisms or prevalence of a particular condition.

Methods: A buddy team selects a particular reef or habitat within that reef and slowly swims in a predetermined pattern recording the parameters of interest. To obtain abundance or prevalence data, the diver may swim for a certain time (or a predetermined number of fin kicks) at one depth, counting the organisms or parameter being examined, and then repeat the survey at a different depth. The diver/snorkeler can determine their average swimming speed by deploying a transect and recording the number of fin kicks or time required to cover the length of the transect and then use this value to the survey areas to estimate distance covered. This calculation assumes similar environmental conditions (e.g. current/wave action) and similar swimming speeds.

Equipment needed:

- Slate, underwater paper or datasheet, pencil
- Depth gauge
- Digital camera
- Underwater cards to aid in identification of specific parameter

Medium Scale Methods

Transects provide detailed quantitative information over a relatively small section of coral habitat. Transects are placed on the bottom to allow counting of objects underneath the line and/or on either side of the line, or they may be deployed behind the diver when recording fish in the water column. They can include tape measures, lead line marked at specific intervals, or chains. Transects vary in length, most typically 10 m, 30 m, 50 m, or 100 m. The length used depends on the abundance and/or size of the organism being monitored and the spatial heterogeneity of the site. Transects are usually placed parallel to shore or the reef crest, or along depth contours. In some cases, long (e.g. 100 m) transects may be positioned perpendicular to shore to examine different depths, zones or habitats along the same transect. Transect allow you to quantitatively measure or record specific parameters within a defined area. There are four primary transect-type surveys (Fig. 8):

Line intercept transect: Measurements are taken directly under the line along the entire length of the line. These focus on the horizontal plane of the reef. These can be used to measure cover, abundance and size of benthic organisms, but are not useful to assess populations of motile invertebrates or fishes. The cover of a particular organism is defined by the fraction of the line that is intercepted by that organism (Loya 1978).

Chain transect: Chain transects measure benthic cover and species composition in a three dimensional plane. They are a special type of line intercept method that allows divers to collect information on the structural complexity (substrate heterogeneity and rugosity; or flatness and steepness) of the reef. The chain follows the 3-dimensional contour of the reef and rugosity can be calculated by using the ratio of the measured chain length to the linear distance of a transect tape. Chain transects can also be used to assess cover by recording what is under each link. This is easiest using a chain with links of approximately 1 cm or larger (Lessios 1996).

Point intercept transect: Point intercept transects (PIT) measure benthic cover of plants, algae, sessile invertebrates and various substrates at specific intervals directly below the transect tape. Living cover can be recorded to genus/species, major functional group, major taxonomic grouping and growth form depending on the specific question and level of expertise. It is important to note that individual colonies are not counted or measured using this method. An individual coral may fall under a single or multiple points, or it may be in contact with the line, but completely miss the points being assessed, thus no information is obtained on density or size. Typically, for a 10 m transect, the organism and substrate is identified every 10 cm (total 100 points/transect), with multiple transects examined in each location. Longer transects and fewer points per transect may be recorded. It is important to deploy replicate transects. This method works well for estimating cover, but not abundance or size of organisms and cannot be used for motile invertebrates or fishes.

Belt transect: Belt transects are similar to line transects except the parameters are recorded in a band or swath that includes the area under the line and a certain distance from the line. The appropriate length and width depends upon what you are measuring (and its abundance and size), the water clarity, and the spatial extent of the survey area. Belt transects cannot be used to obtain quantitative measures of benthic coverage, except when using photographic methods (and subsequent laboratory analysis of photographs).

Recorded information collected in the field can include:

- 1) Abundance and size of sessile organisms;
- 2) Frequency or prevalence of specific stressors such as bleaching or disease;
- 3) Counts of motile invertebrates; and
- 4) Population dynamics (abundance/size) of fishes.

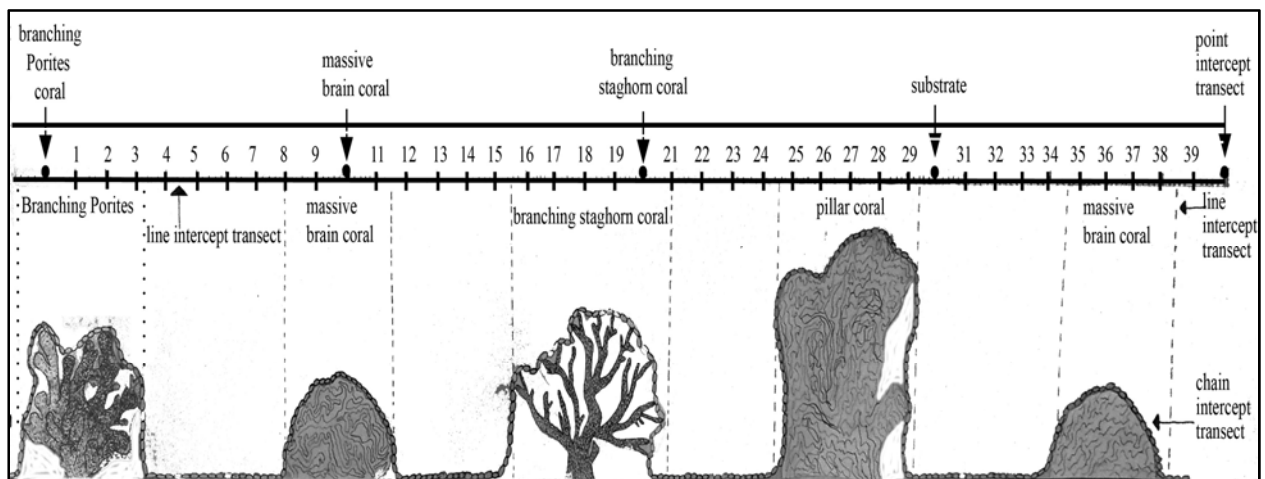


Fig. 8. A comparison among a point intercept transect (PIT), line intercept transect (LIT) and chain transect (CT) along a 40 cm horizontal section of reef. The PIT transect records organisms or substrate under individual points (in this case, every 10 cm; 4 points are coral and one is substrate), the LIT records the width of every coral under the line (indicated by the dotted lines), and the CT records the number of chain links covering each coral. Figure by Haili N. Bruckner.

Fine scale methods

Fine scale monitoring provides the greatest level of detailed data. These can detect relatively small changes and can be used for counting of small organisms that may occur in high numbers.

Quadrat: A quadrat is a square or rectangular sampling unit that is placed onto the substrate either in predetermined locations or randomly/haphazardly throughout the site. The organisms of interest are counted or measured within the quadrat. The appropriate quadrat size is dependent upon the size and spatial abundance of the organism(s) being assessed. Typically for benthic surveys, quadrats are from 0.5-1 m². Assessment of smaller organisms such as coral recruits is done using smaller quadrats (25 cm X 25 cm).

Quadrats can be assessed visually by estimating coverage of each organism and substrate categories within the entire area or by counting the number of organisms present within the boundaries of the quadrat. The quadrat can also be subdivided using a grid (e.g. 1 m² quadrat can be strung with 10 vertical and horizontal lines to create a grid of 100 squares, each 10 cm X 10 cm) to increase accuracy of visual estimates (Fig. 9). For gridded quadrats, estimates of cover can be made for each smaller square, or point samples can be recorded by assessing what is directly below the intersect of each vertical and horizontal line.

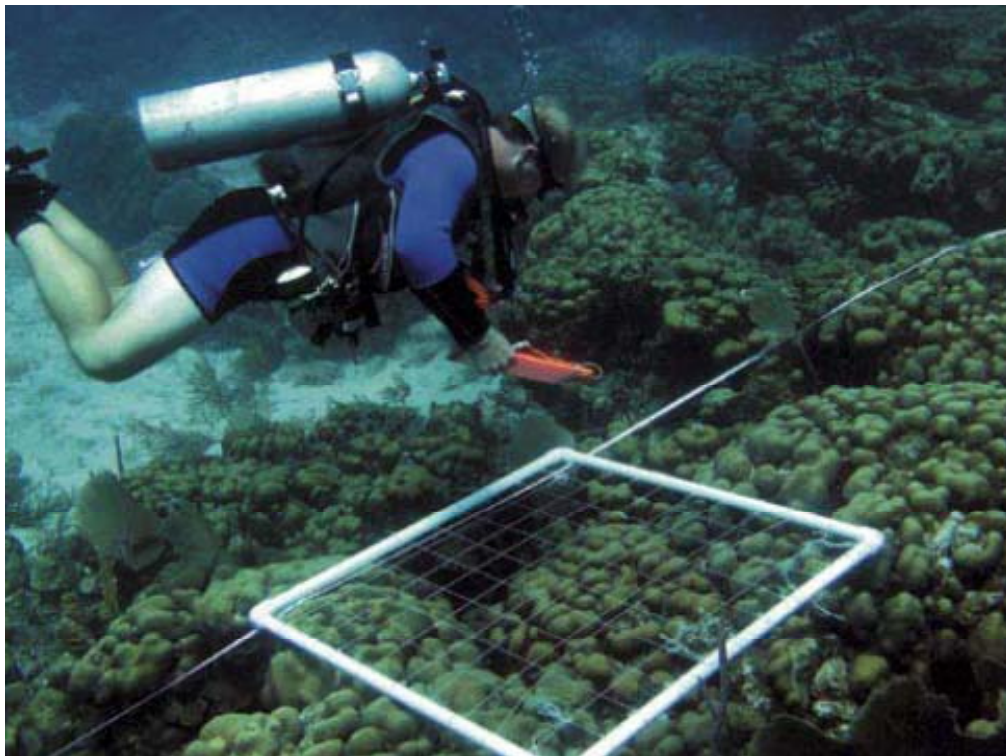


Fig. 9. Example of a diver assessing coral community structure in the Caribbean using a gridded quadrat placed at defined intervals along a transect line.

Settlement tiles or plates: Coral recruitment is an important monitoring parameter to document replacement rates of corals and patterns of recovery following disturbance and to predict future reef trajectories. The abundance of coral recruits can be determined using the quadrat methods described above. Quadrat surveys examine what has settled at a specific point in time, but unless the quadrat is permanently attached and monitored repeatedly, no information is gleaned on the patterns of recruitment, rate of recruitment over time, or the rates of survival and growth of the recruits. Artificial settlement plates or tiles made from unglazed terracotta (ceramic), slabs of volcanic rock or sections coral skeletons can be attached to the substrate to document recruitment (Fig. 10). These are placed in various locations of differing heterogeneity, different distances from the substrate and at different angles (e.g. on vertical and horizontal surfaces). For best results, these should be deployed 4-6 months prior to mass spawning events to allow them to acquire a rich fouling community and crustose coralline algae that is similar to the surrounding area. A subsample of the tiles can be removed at various intervals and examined under a dissecting microscope. Data can be obtained on the number, diversity, settlement location (e.g. top or bottom of the tile) and size of recruits. Tiles can be returned to the field after examination to monitor growth and survival of recruits over time.

Settlement plates can also be used to measure other parameters such as algal colonization and amount of herbivory. These can be placed in the open and compared with plates that are excluded from herbivores (by placing them in cages) and removed at various intervals to evaluate patterns of colonization, succession, and growth of algae.

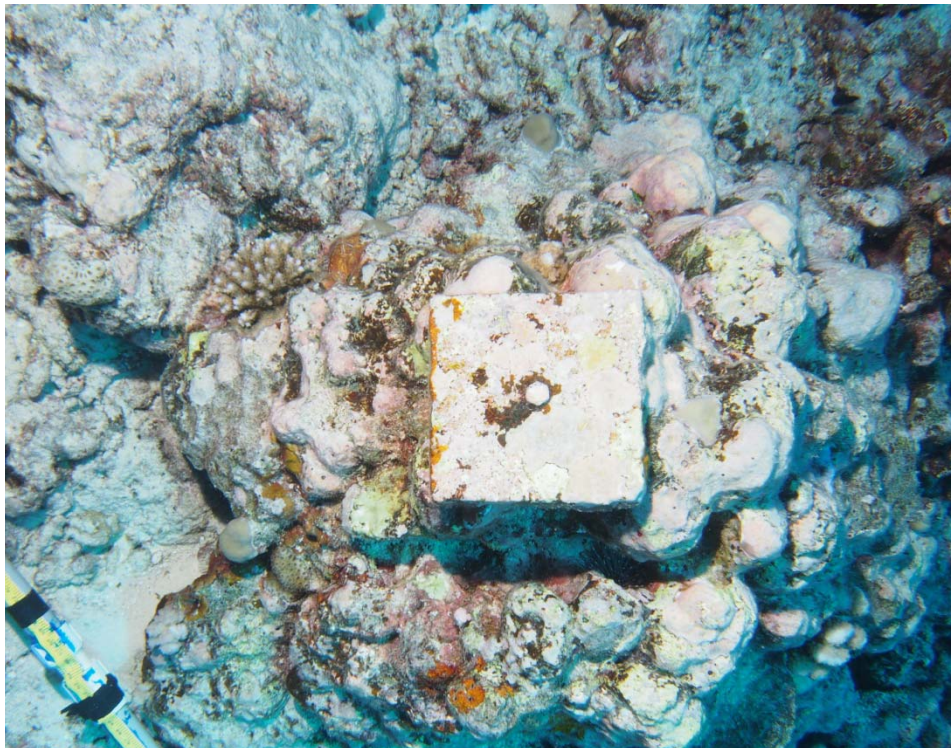


Fig. 10. Terracotta tile secured to a dead *Porites* colony to assess coral recruitment.

GALÁPAGOS CORAL MONITORING PROGRAM

A detailed monitoring program for coral communities requires the utilization of multiple methods. This can be accomplished using a small team, with individual divers focusing on a single parameter based on their expertise. For instance, one diver may focus solely on fish assessments, while a separate diver conducts benthic surveys and a third diver monitors only corals. In some cases, different surveys can be conducted using the same transect, especially when examining relationships between different parameters and to collect information that allows you to relate the occurrence of one group of organisms (e.g. fish) to another (e.g. benthic structure). One possibility is to pair the fish and benthic observer as follows: the diver assessing the fish community structure deploys a transect in the survey area as he records fish, and the second diver follows behind the fish observer recording benthic parameters along that transect. It is also possible to acquire similar information by conducting multiple (different) transects within the same area.

The methodology presented in the following section is based on the survey approach used by the Khaled bin Sultan Living Oceans Foundation during the Global Reef Expedition. These methods were applied to coral communities in the Galápagos during June 2012, with the intent on determining the community structure and health of coral communities, threats, damage associated with past disturbances, the extent of recovery that have occurred to these areas, and indicators of resilience. Methods are presented on the standardized survey approach used across the globe with additional information on the approaches used by our partners to assess sites within the Galápagos that they have been following over time.



1. Site Characterization

Objectives: Complete baseline assessments to aid in selection of long-term monitoring sites.

A pilot study can help determine the most effective sampling regime for the long-term monitoring program. Prior to establishing monitoring stations, a preliminary survey of the entire shallow marine environment will help identify coral areas. Compilation of historical information, images and data should be undertaken to obtain any past records and general information for use in the monitoring program. The following should be included:

- Characterization of the distribution and spatial extent of different habitats;
- Identification of any past disturbances and patterns of human uses; and
- Compilation of historical information, including previous data on physical and environmental parameters affecting the site.

Methods: Obtain data and information archives, evaluate, describe and map sites.

- Obtain available historical information, including satellite imagery, aerial and underwater photographs, maps (Fig. 12) and datasets for the site. This could include monitoring data, the timing, severity and duration of past disturbance events, patterns of human use and any other available information
- Take an inventory of the different kinds of plants and animals found in your site, their general population structure and health.
- Measure the abiotic factors of your site.
- Note any biotic stressors, damage or signs of disturbance.
- Describe the location of each site as completely as possible.
- Create maps of the site.

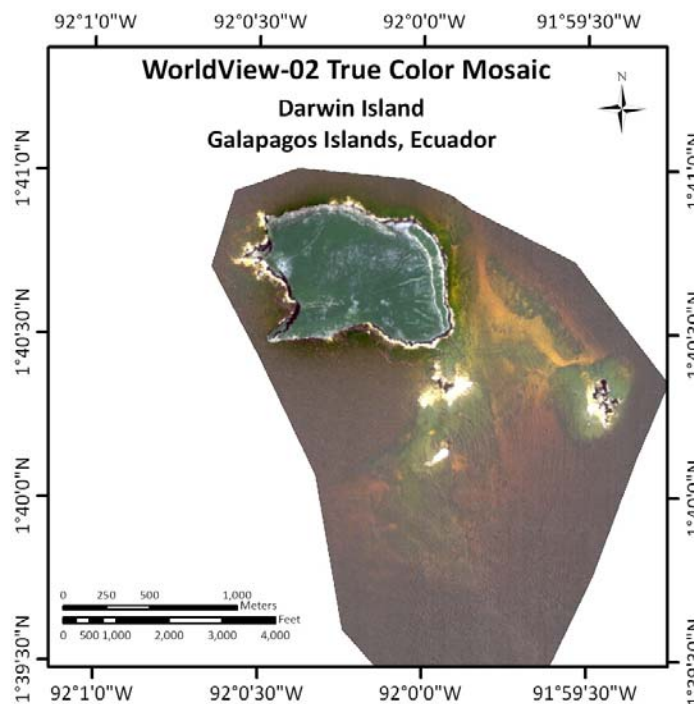


Fig. 12a. Satellite imagery for Darwin Island and the shallow marine environment.

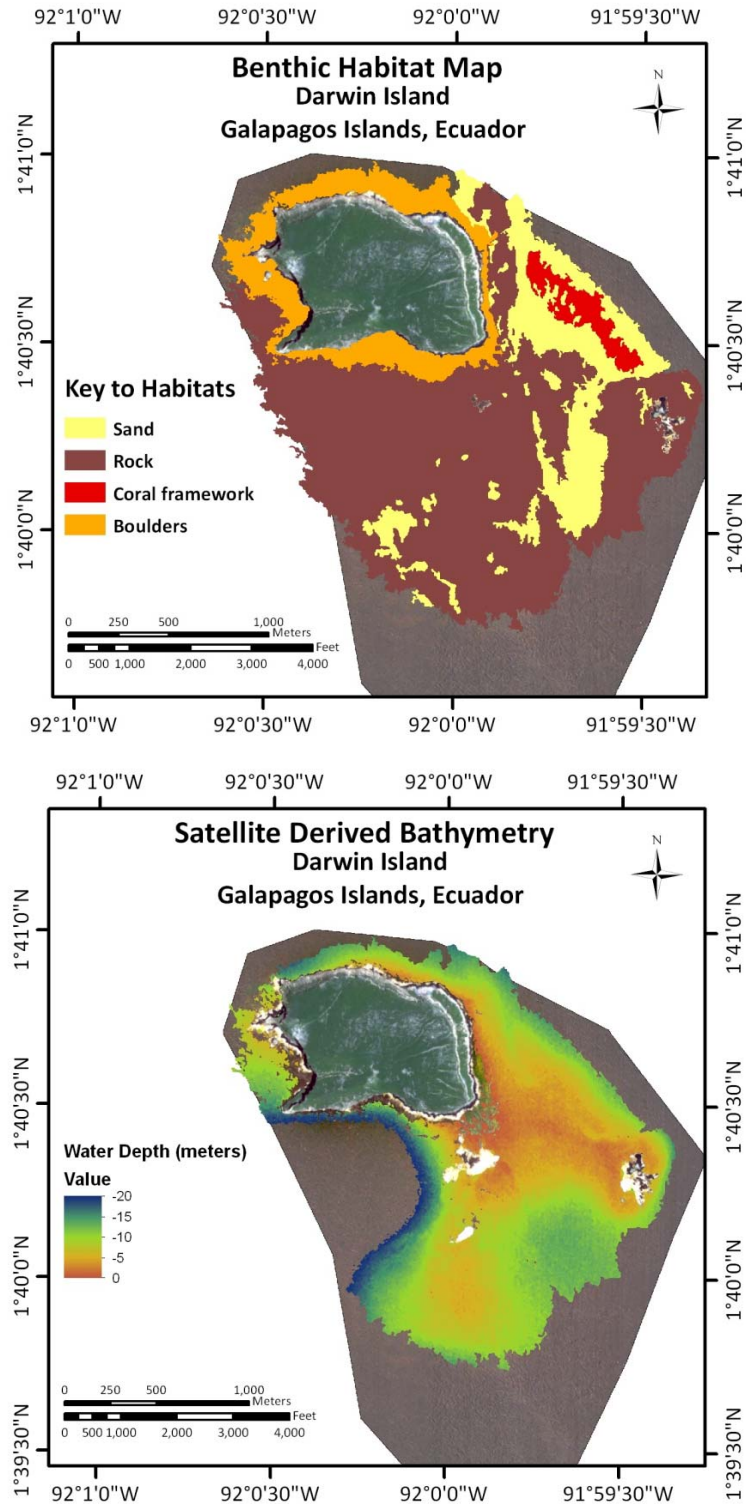


Fig. 12b. Habitat map (top) and bathymetric map (bottom) for the shallow marine environment off Darwin Island. Maps were developed by the Khaled bin Sultan Living Oceans Foundation and NOVA Southeastern University and are available for eight islands in the Galápagos.

2. Benthic Monitoring

Objectives: To assess the benthic community structure and changes over time.

- Characterization of the amount of the sea floor covered by corals and other sessile invertebrates, algae, sea grasses, and various types of substrate;
- Measurement of the diversity and abundance of coral recruits;
- Quantification of the biomass of macroalgae; and
- Determination of the abundance of larger motile invertebrates.

Methods: Conduct Point Intercept Transects.

- Choose an area that is representative of the community found at that site within each predetermined depth (e.g. 5, 10, 15, or 20 m) as your survey location.
- Deploy a 10 m transect across the bottom, attempting to stay at the same depth and in a straight line. Choose a starting point for your first transect haphazardly (e.g. drop your meter stick or a small weight from the surface of the water, or as you descend to the bottom; do not swim around and find the “best” coral area). Tie off the beginning of the line to a rock (or attach it to a 1-2 lb weight and place the weight in a crack or crevice or behind a rock/coral). Slowly swim away from the starting point, extending the line in a linear manner and straightening it as necessary. Once you reach the end, pull the line taught and tie it off to a dead coral, rock or some other firm object. Transects should target reef habitats or hardground areas, avoiding sandy areas when surveying reefal habitats. Benthic surveys can also be conducted in sand-bottom or algal habitats if these contain corals. In the Galápagos this includes assemblages of free living fungiids, *Psammocora*, and large *Pavona gigantea* colonies).
- As you return to the starting point, record the substrate type, organism and other information (see “types of data collected on benthic transects”) directly under the line at 10-cm intervals, collecting 100 data points (see Appendix II for a benthic datasheet).
- Swim back towards the end of the line, placing a 25 cm x 25 cm quadrat at 2-m intervals along the transect line (2, 4, 6, 8, and 10 m). Place the quadrats either on one side of the line, or alternate between the right and left side. Ensure that the quadrat does not land on a large live coral (e.g. it lands somewhere where corals can recruit). If >70% of the quadrat is occupied by a single coral, move the quadrat forward or backward until that coral is no longer within the quadrat.
 - For each quadrat, brush away the algae and/or sediment and carefully search for small corals. Record the species for each coral recruit or juvenile coral, dividing them into two size classes, 0-2 cm and 2.1-3.9 cm.
 - Record additional information on the substrate type (e.g. pavement, sand, rubble, dead coral, live coral) within the quadrat, as a percentage.
 - Take a minimum of 5 measurements of the height of the fleshy algae macroalgae contained within the quadrat using a 15 cm ruler (Steneck and Dethier 1994).

- Record the total number of large motile invertebrates (molluscs, sea cucumbers, sea urchins, crustaceans) within 0.5 m on either side of the line using a 1 m bar placed perpendicular to the line for scale.
- After completing all measurements, reel in the line and then deploy it in another location. You should complete a minimum of five additional transects within the same general area, ensuring they do not overlap and they are spaced apart a minimum of 5 m.
- Repeat this as needed at other depths and locations.

Types of data collected on benthic transects



Substrates: Hardground/pavement (PA), fused rubble (FR), loose rubble (LR), sand/silt (SA), live coral (LC), long dead coral (DC), bleached coral (BC), recently dead coral (RC) (Fig. 14). Sand, silt and rubble can be further classified by composition and size structure, with identification of biogenic (calcareous) sediments, volcanic rock/sediment, and various constituents of sand/rubble such as urchin spines, coral fragments, and mollusc shells (Fig. 13).

Fig. 13. Close-up of sediment collected near Devil's

Crown. The sediment contains sea urchin spines, mollusc shells, dead coral and other fragments.

Corals: Identified to species, if possible; at minimum to genus. Record growth form (Table 2). Examples of the dominant growth forms in the Galápagos, a solitary scleractinian coral and an ahermatypic (azooxanthellate) scleractinian coral are shown in Fig. 15. Record coral condition as live (LC), bleached (BC), recently dead (RC) or long dead (LD) (Fig. 16).

Other Invertebrates: Identify sponges, anemones, gorgonians, zoanthids and other sessile invertebrates to the lowest taxonomic level possible (Fig. 17). If Genus or species ID is not possible, record invertebrates by growth form. For instance, sponges can be differentiated into crustose, rope, submassive, massive, tube and barrel sponges.

Motile Invertebrates: (Table 3; Fig. 18, 19, 20). Record the number of large crustaceans, molluscs, and echinoderms within a 1 m X 10 m belt.

Algae: Characterize algal community into five functional groups: fleshy macroalgae, erect coralline algae, crustose coralline algae, turf algae, and cyanobacteria. Record Genus/species for the dominant macroalgae and erect coralline algae if possible. Measure algal height (a proxy of biomass) of macroalgae and erect coralline algae within quadrats. If turf algae or cyanobacteria are abundant, their height can also be measured to the nearest 0.1 cm (Table 4; Fig. 21, 22).

Seagrass: If present, identify to genus or species.

Coral Recruits: Identify coral recruits in quadrats to genus or species on benthic point intercept transects and coral belt transects. Recruits are divided into two categories: corals up to 2 cm diameter and larger corals, 2-3.9 cm diameter.

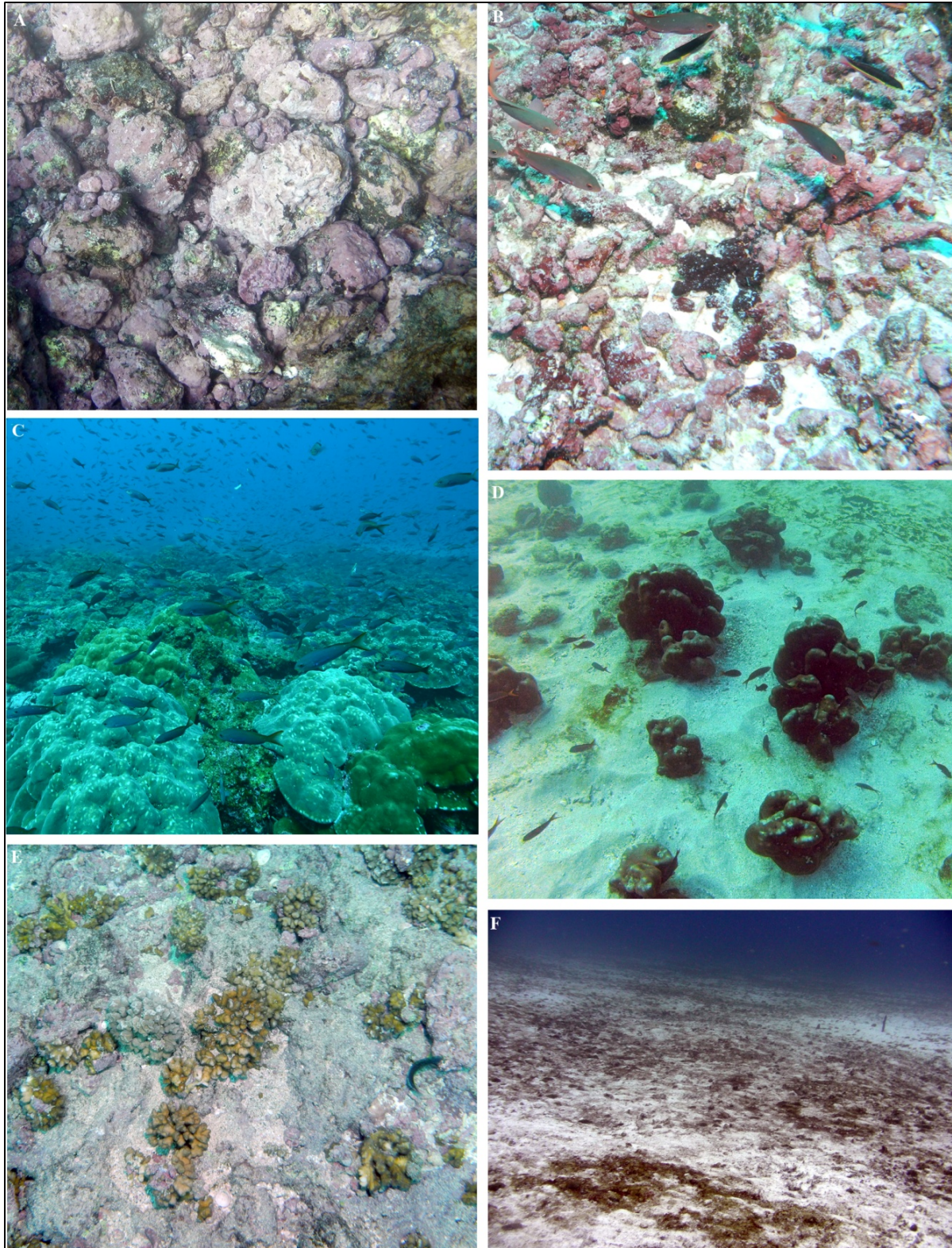


Fig. 14. Substrate types associated with coral communities and coral reefs in the Galápagos. A. Boulders and fused rubble (FR). B. Loose rubble in sand (LR). C. Live coral (LC). D. Sand with scattered coral colonies (SA). E. Pavement with coral (PA). F. Sand with algae.

Table 2. Coral morphology and growth forms.

Type of coral	Code	Description
Branching	BR	Erect colonies with branches or elongate projections. Branches may be cylindrical, flattened or finger-like, may branch in one direction or multiple directions, and may have bifurcated ends. Colonies may be low-lying, oriented parallel to the substrate or upright, forming large arborescent or tree-like growths. This growth form can be subdivided into several categories.
Massive	MA	Ball, dome or boulder –like colonies that are solid and similar in shape in all dimensions. Colony has a third dimension, extending from the substratum.
Submassive	SM	Mound-shaped or hemispherical irregular-shaped colonies with a lower surface completely attached to the substrate. Colonies are no more than 5 cm tall.
Plating/Foliaceous	PL	Thin, flattened sheets, plates or saucer-like colonies of similar thickness usually oriented parallel to the substrate, but not completely fused to the bottom. Colonies may also form upright, wavy, leaf-like plates.
Encrusting	EN	Forming a thin crust or sheet that grows laterally and is completely adhered to or attached to the substrate.
Columnar	CO	Massive hemispherical or irregular colonies forming erect, upright columns.
Free-living	FL	Corals not attached to the substrate.

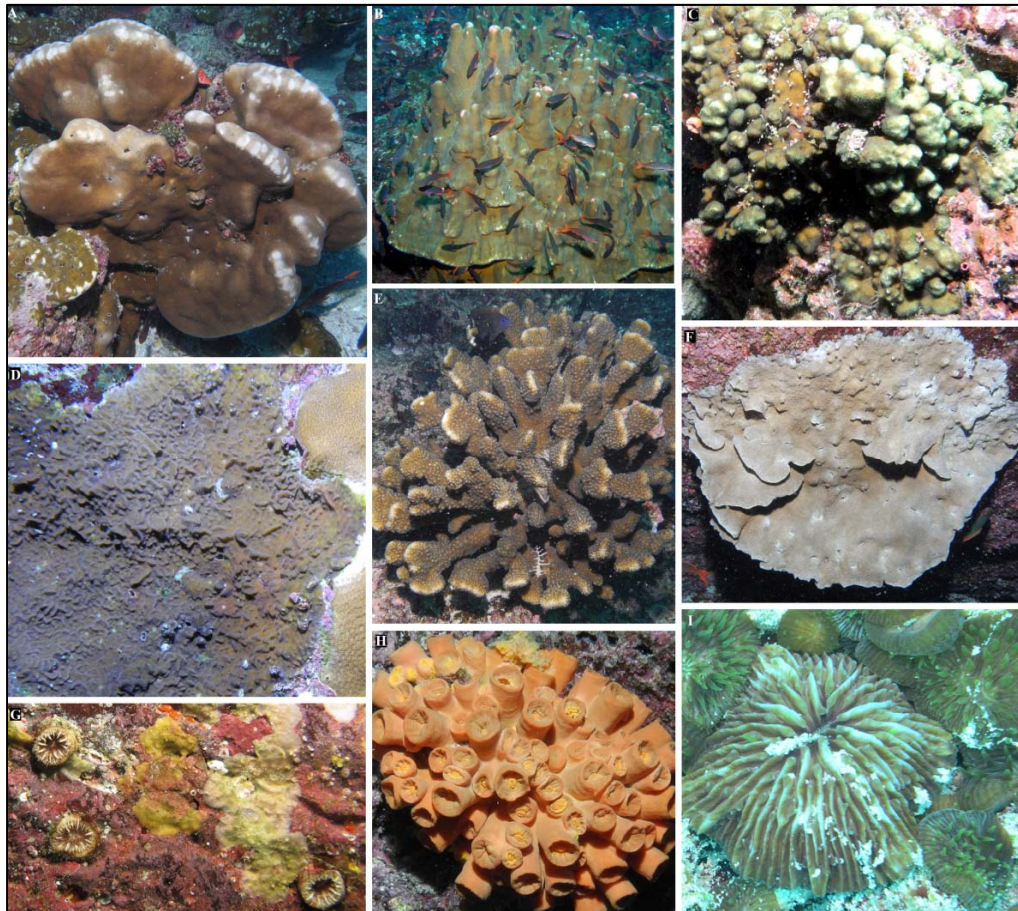


Fig. 15. Growth forms of corals. A. Massive *Pavona clavus*. B. Columnar *Porites evermanni*. C. Submassive *Psammocora stellata*. D. Encrusting *Pavona varians*. E. Branching *Pocillopora eydouxi*. F. Plating *Pavona*. G. Solitary ahermatypic coral (*Culicia stellata*). H. Submassive azooxanthellate coral (*Tubastrea faulkneri*). I. Free living *Cycloseris curvata* surrounded by *Diaseris distorta*.

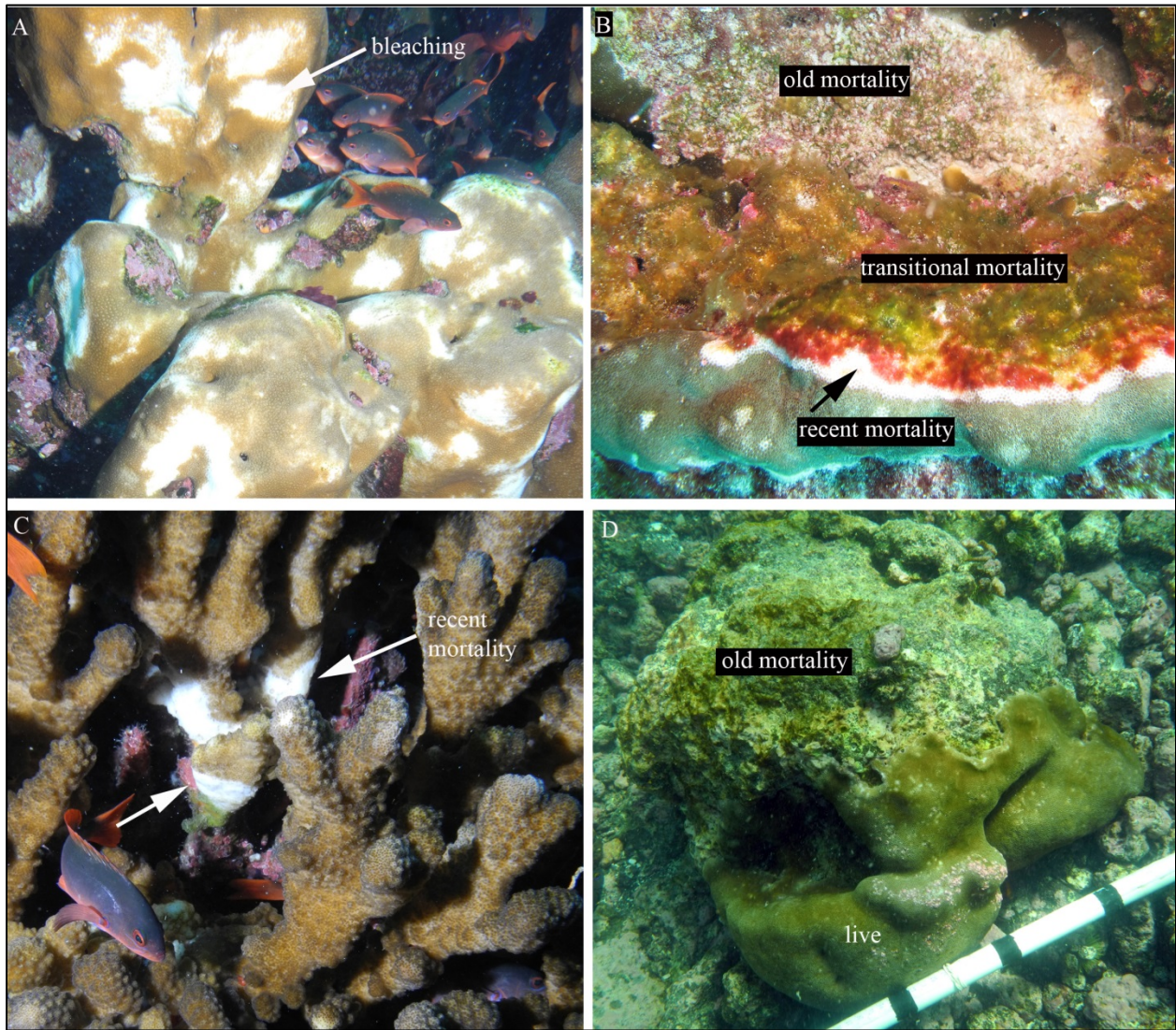


Fig. 16. Coral condition. A. *Pavona clavus* showing patchy bleaching. White areas are still live. B. *Porites lobata* with old mortality, transitional mortality and recent mortality. A narrow band of live tissue remains at the base of the coral. C. *Pocillopora* with recent mortality at the bases of the branch caused by snail predation. D. *Porites lobata* with old mortality. Approximately 50% of the coral is long dead. Distance between black bars is 10 cm.



Fig. 17. Sessile invertebrates recorded along benthic point intercept transects in the Galápagos. A. Submassive orange sponge. B. Erect gorgonian or sea fan (*Muricea* spp.). C. Encrusting sponge on crustose coralline algae. D. *Bunodosoma grandis* sea anemone. E. White tube sponge. F. *Macrorhynchia philippina* stinging hydroid. G. *Arachnanthus* spp. cerianthid (tube) anemone. H. Bushy black coral, *Antipathes galapagensis*.

Table 3. Motile invertebrates included in surveys and their rationale.

Motile invertebrates	Code	Importance
Sea urchins	DIA, ECH, TRP	Urchin abundance and density are important indicators of levels of herbivory and bioerosion. They may affect survival of coral recruits and interactions among other herbivores including fishes. Key taxa monitored include <i>Diadema mexicanum</i> , <i>Lytechinus semituberculatus</i> , <i>Eucidaris thouarsii</i> , and <i>Tripneustes depressus</i> .
Molluscs	OCT	Octopuses are important invertivores, controlling populations of gastropods. These are often harvested for food.
Crustaceans	LOB	Lobsters are important predators that control populations of small gastropods, including coral eating snails, as well as pencil urchins. These are commercially harvested and their abundance is an indication of fishing pressure. Overfishing of lobsters is reported to allow <i>E. thouarsii</i> populations to boom, in turn causing the bioerosion of coral by sea urchin overgrazing (Fig. 18).
Sea cucumbers	CUC	These species are very important detritivores, helping maintain clean, well aerated sediment. In absence of sea cucumbers, sediments may harden and populations of pest species, such as cyanobacteria may colonize soft bottom habitats. Sea cucumbers are commercially valuable and are often overexploited to support the beche de mer trade. Species of concern is <i>Stichopus fuscus</i> .
Sea stars	STR COTS	Most sea stars feed on small invertebrates and do not cause damage to corals. The main exception is <i>Acanthaster</i> , the crown of thorns sea star. This animal is extremely voracious and can devastate entire reefs during population explosions. This is present in the Galápagos but has not been observed at high abundances

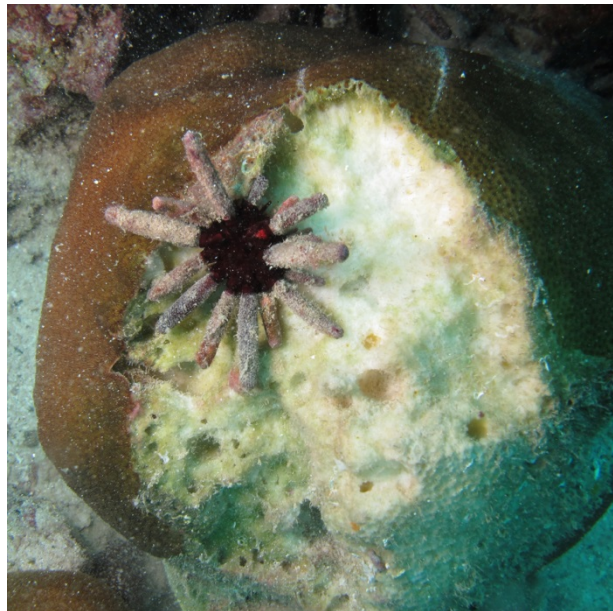


Fig. 18. Bioerosion of *Porites lobata* caused by *Eucidaris* (pencil urchin).

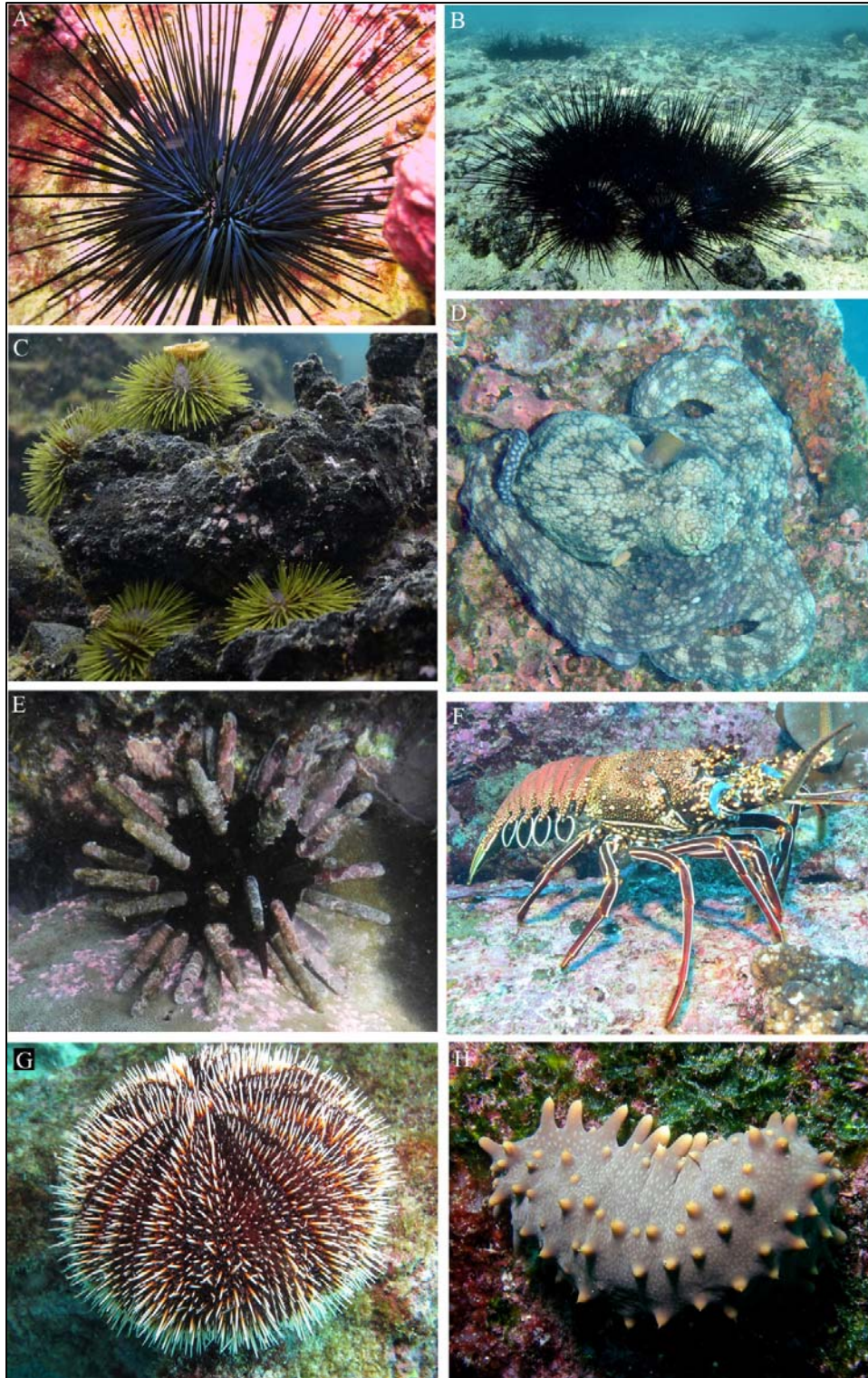


Fig. 19. Ecologically and commercially valuable motile invertebrates in the Galápagos. **A,** **B.** Long-spined sea urchin, *Diadema mexicanum*. **C.** Green urchin, *Lytechinus semituberculatus*. **D.** Octopus. **E.** Pencil urchin, *Eucidaris thouarsii*. **F.** *Panulirus femoristraga*, red spiny lobster. **G.** White sea urchin, *Tripnuestes depressus*. **H.** Sea cucumber, *Stichopus fuscus*.



Fig. 20. Ecologically relevant sea stars found in the Galápagos. A. *Pentaceraster cummingi*. B. *Nidorellia armata*. C. unidentified starfish. D. *Nidorellia armata*. E. Crown of thorns sea star (*Acanthaster planci*), a severe coral predator. F. *Pharia pyramidata*.

Table 4. Benthic algae included in surveys and rationale for inclusion in a monitoring program.

Measure	CODE	Importance
Algae		Species rich, productive and functionally important components of benthic coral reef environments that may be involved in construction of the reef, components of the food chain, or space occupiers that are not eaten.
Fleshy Macroalgae	FM	Most species are eaten to some degree by some herbivorous fishes and invertebrates but some produce deterrents (toxic compounds, leathery skin etc.). Abundance and biomass are indicators of grazing pressure, nutrients and levels of disturbance. Macroalgae should be low in areas with low anthropogenic nutrients, runoff and high herbivory. Shifts toward macroalgal dominance reflect loss of key functional groups of herbivores (urchins/fish), nutrient input, and mass mortality of corals. Certain taxa inhibit coral larval recruitment and may kill or overgrow corals; may provide refuge for corallivores or be a repository for coral pathogens.
Turf algae	TA	Eaten by many herbivorous fishes and invertebrates. Low to moderate cover of turfs reflect moderate levels of herbivory; increasing biomass of turfs and trapping of sediments within turfs may indicate poor substrate quality that reduces recruitment potential of reef-builders, and few herbivores. Turf algae mats can trap sediment, inhibit coral larval recruitment, and kill/overgrow live corals and crustose coralline algae.
Crustose coralline algae	CCA	Cover of certain species of crustose coralline algae is indicative of the suitability of substrate to support coral recruitment. CCA binds sediments and consolidates the reef, and constructs or cements the reef framework. CCA may indicate good conditions for recruitment of coral larvae.
Erect coralline algae	CM	Some taxa (<i>Halimeda</i>) produce sand that forms beaches and contribute to the infilling of reefs.
Cyanobacteria	CYAN	Indicate altered reef conditions associated with high nutrients, temperature perturbations and low herbivory. Cyanobacteria may kill/overgrow corals or prevent coral larval recruitment.



Fig. 21. Filamentous cyanobacteria overgrowing a black coral.

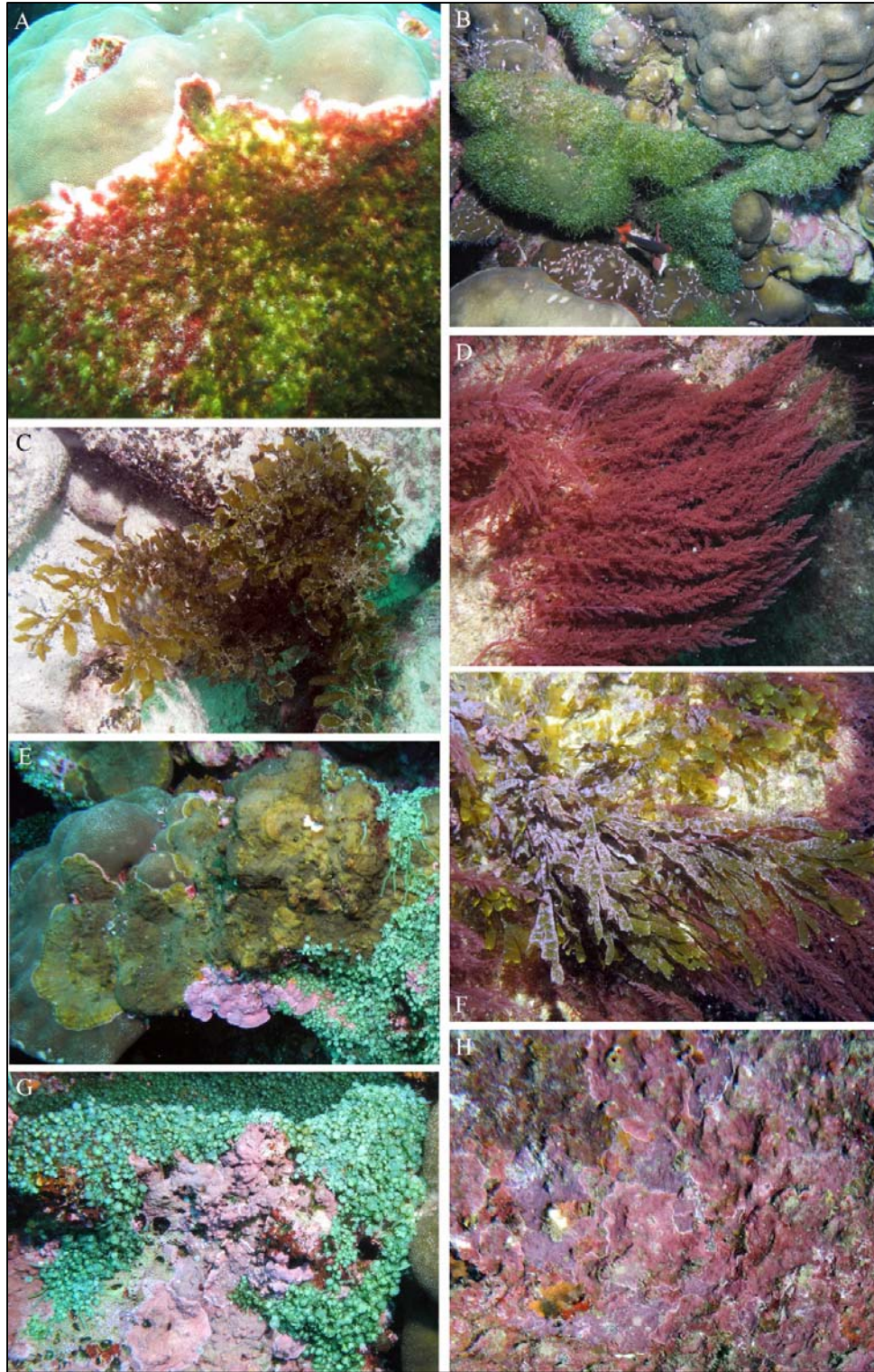


Fig. 22. Functional groups of green, brown and red algae occurring in the Galápagos. A. Turf algae (TA) on *Porites* skeleton. B Green turf algae (TA). C. Brown fleshy macroalgae (FM; *Sargassum*). D. Red fleshy macroalgae (FM; *Asparagopsis*). E. Encrusting red calcareous algae (*Peyssonnelia*). F. Unidentified brown fleshy macroalgae. G. Green fleshy macroalgae (FM; *Caulerpa*). H. Red crustose coralline algae (CCA).

Equipment needed for benthic surveys (Fig. 23)

- 10 m transect tape (a better alternative is a lead line* marked in 10 cm intervals; the lead line will sit flat on the bottom, even in high surge conditions).
- 25 cm X 25 cm quadrat
- Clipboard or slate with underwater data sheet and pencil
- 1 m PVC pipe, marked in 10 cm intervals
- 15 cm ruler attached to clipboard
- Digital camera

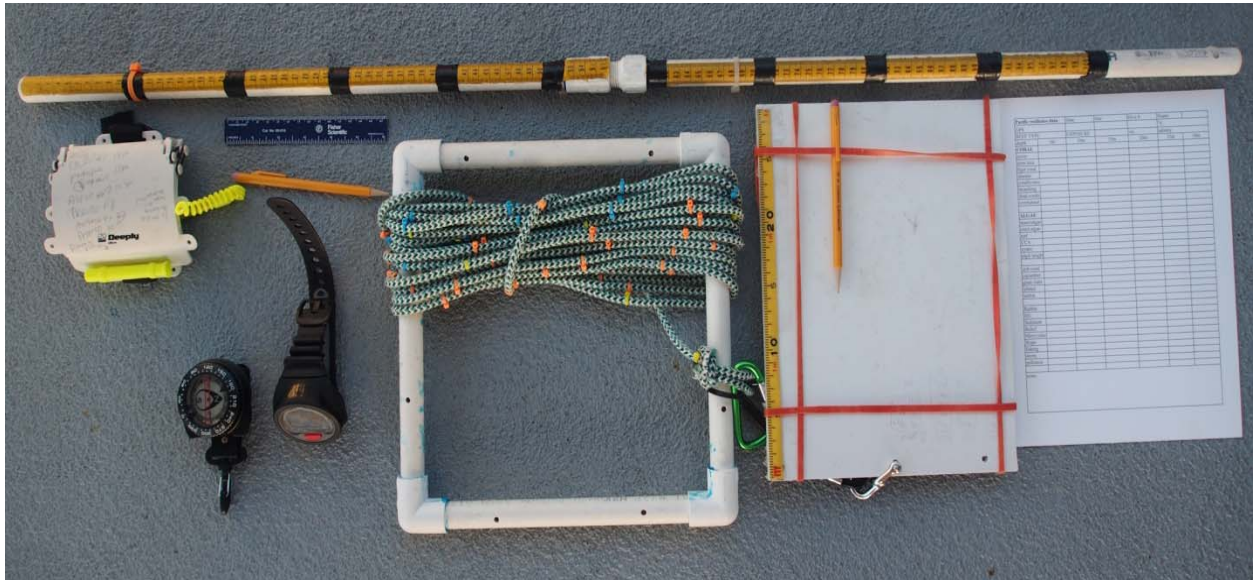


Fig. 23a. Equipment used for benthic and coral surveys. This includes 1) a 10 m lead line with colored cable ties placed at 10 cm intervals; lead line is wrapped around a 25 cm X 25 cm quadrat; 2) slate with a pencil and scale bar; 3) datasheet; 4) 15 cm plastic ruler; 5) depth gauge; 6) compass; and 7) a PVC meter stick with a 1 m tape measure and additional electrical tape markings placed at 10 cm intervals. An additional slate (top left) that can be attached to your arm is useful for recording general habitat data and other observations. The quadrat and clipboard should have a carabineer that can be attached to your BC for ease of transport when swimming.



Fig. 23b. Close-up of lead core rope showing the placement of the cable ties at 10 cm intervals.

3. Coral Monitoring

Objectives: To assess the coral community structure, health, and changes over time.

- Assess the composition, abundance and density of all stony corals (all Scleractinia and *Millepora*) ≥ 4 cm diameter;
- Assess the size and condition of each of the corals;
- Estimate percent partial colony mortality for each coral, separating measurements into recent, transitional and old mortality; and
- Identify any stressors affecting the coral and/or the cause(s) of recent tissue loss.

Corals are assessed using one of three methods, depending on habitat, community structure and coral type.

- **Belt transects:** Belt transects are used in coral reef habitats such as that seen at Darwin and Wolf Island where there is extensive coral habitat. Belt transects allow calculation of the population density, size structure and size-specific condition. These are more effective than line transects (where only corals that touch the line are assessed) which tend to oversample larger corals and under sample small colonies (Zvuloni et al. 2008).
- **Quadrats:** Quadrats are used in soft bottom areas, such as Devil's Crown to assess populations of fungiids (*Diaseris* and *Cycloseris*) and *Psammocora* because the corals are small, they occur in aggregates, and individual aggregates are separated by extensive sandy areas. In these areas, the size of the patches is too small for use of transect.
- **Individual colony monitoring:** All colonies within a defined area are assessed in locations where corals are present, but at too low a density for use of either transects or quadrats. For example, *Pocillopora* are common in hardground areas of San Cristobel, but they occur as isolated colonies or small aggregates (up to about 5 corals/patch) with extensive hardground areas between colonies. Transect surveys would be very inefficient to capture an adequate sample of the population, whereas hundreds of individual colonies can be assessed through roving surveys. Individual corals can also be tagged and followed over time.

Methods: Belt Transects

- Choose an area that is representative of the community found at that site and identify predetermined depths (e.g. 5, 10, 15, or 20 m) for your survey locations.
- Determine a starting point for your first transect haphazardly (e.g. drop your meter stick or a small weight from the surface of the water, or as you descend to the bottom; do not swim around and find the "best" coral area). Tie off the beginning of the line to a rock (or attach it to a 1-2 lb weight) and slowly swim away from the starting point, extending the line in a linear manner and straightening it as necessary. Once you reach the end, pull the line taught and tie it off to a dead coral, rock or some other firm object. Transects should target reef habitats or hardground areas, avoiding sandy areas adjacent to the

hardground or sand patches/channels within hardground areas that do not support coral communities. **In central and southern islands surveys may need to focus on soft bottom communities as these contain free-living corals (e.g. fungiids and *Psammocora*) and populations of massive *Pavona gigantea*. However, transects may not be appropriate for these types of communities (see below for quadrat and individual colony assessments).**

- Slowly swim back towards the starting point, holding your 1 m bar perpendicular to the line, with the center of the bar positioned on the transect line as a scale.
- For each coral (only colonies with a minimum diameter of 4 cm) that falls anywhere within the 1 m X 10 m area, record the species (Fig. 25) and growth form (Fig. 15).
- Measure the size of the coral (maximum diameter, width perpendicular to the diameter, and height) using a one meter bar (marked in 1 cm intervals) (Fig. 24).
- Assess the condition of the coral for: amount of partial mortality, presence of bleaching, disease, predation, or overgrowth, and/or nuisance species (see “coral condition”).
- Record and assess the next coral along the transect. Repeat this procedure until you assess all corals along the entire transect.
- Swim back towards the end of the line, placing a 25 cm x 25 cm quadrat at 2-m intervals along each transect line (2, 4, 6, 8, and 10 m). Place the quadrats either all on one side of the line, or alternate between the right and left side. Assess coral recruits as described under benthic monitoring.
- Use 1 m bar for scale and swim slowly along the line recording the species and numbers of different motile invertebrates within the 1 m X 10 m swath.
- After completing the first transect, reel in the line and then deploy it in another location at least 5 m from the first transect. Complete a minimum of 2 transects per depth.



Fig. 24.
Measuring
the height
of a *Porites*
lobata
colony
along a 10 m
belt transect
off Wolf
Island.

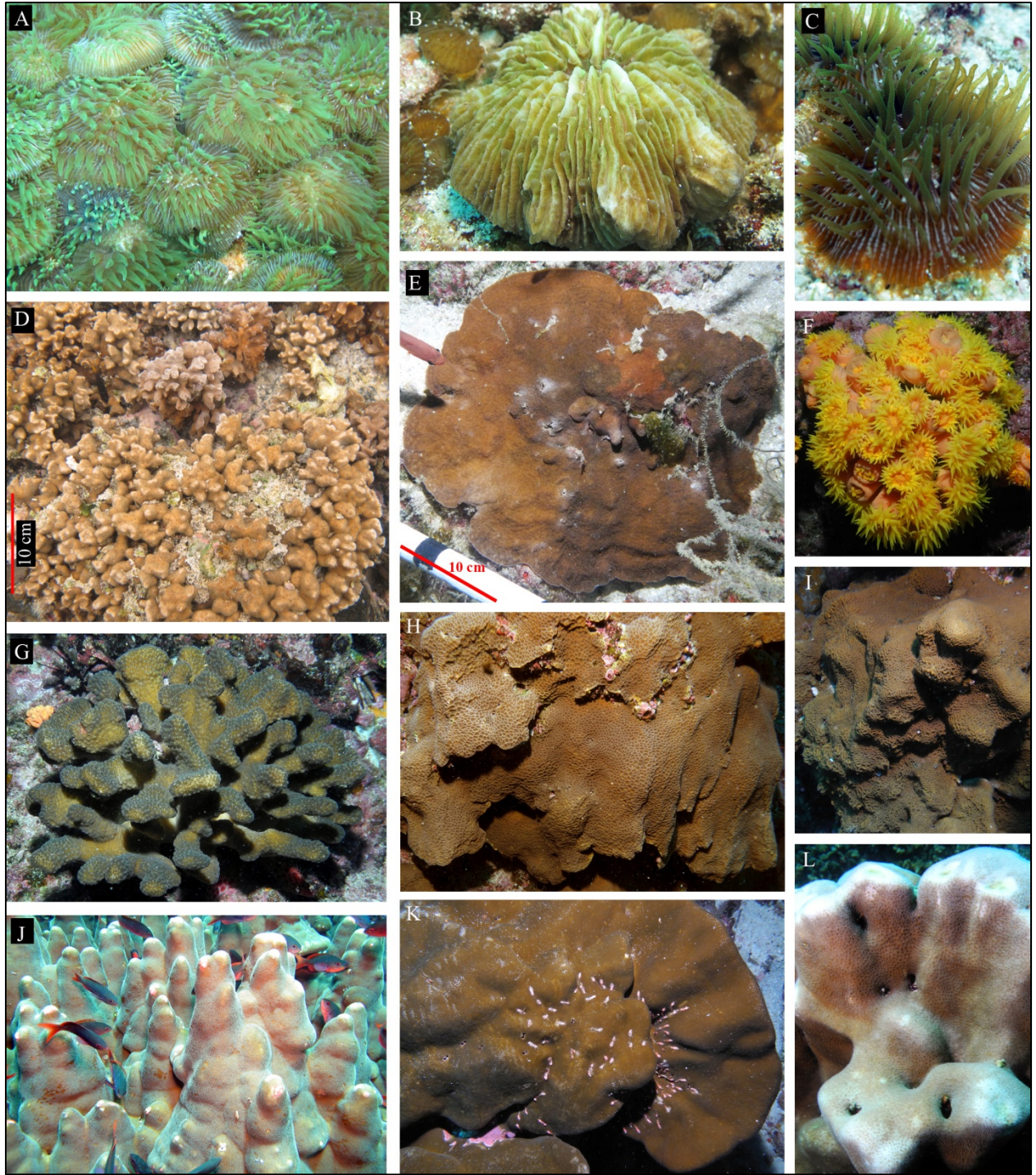


Fig. 25a. Dominant coral taxa seen in the Galápagos. A. *Diaseris distorta*. B. *Cycloseris curvata*. C. *Diaseris* with tentacles out. D. *Psammocora stellata*. E. *Leptoseris scabra*. F. *Tubastrea faulkneria*. G. *Pocillopora woodjonesi*. H. *Gardineroseris planulata*. I. *Pavona varians*. J. *Porites evermanni*. K. *Porites lobata*. L. *Pavona clavus*.



Fig. 25b. Common species of *Pavona* seen in the Galápagos. A. *Pavona clavus*. B. Close-up of *P. clavus* (top) and *P. gigantea* (bottom). Tentacles of *P. gigantea* are extended. C. Close-up of *P. clavus* (top) and *P. gigantea* (bottom). Tentacles of *P. gigantea* are retracted. D. *P. gigantea* whole colony. E. *P. varians*. F. Close-up of an encrusting *P. chiriquiensis*. G. *P. gigantea* whole colony. H. Distance photo of *P. varians*. I. Encrusting colony of *Pavona maldivensis*.

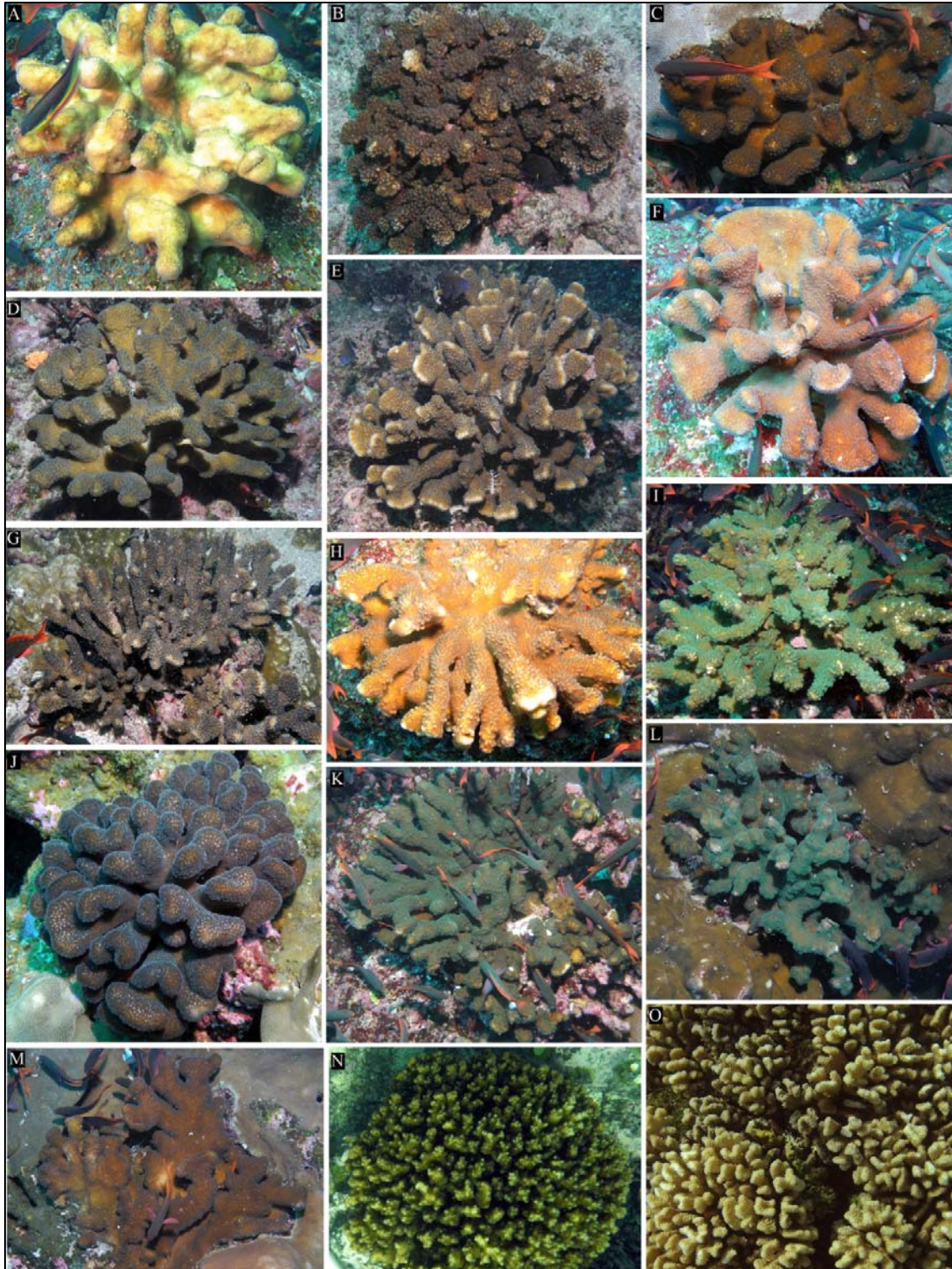


Fig. 25c. Representative photos of *Pocillopora* spp. from the Galápagos. Identification to species is difficult without specimen collection for morphometrics and genetics. A. *P. inflata*. B. *P. verrucosa*. C. unknown. D. *P. elegans*. E. *P. capitata*. F. *P. woodjonesi*. G. *P. elegans*. H. *P. effusus*. I. *P. elegans*. J. *P. verrucosa*. K. *P. effusus*. L. *P. capitata*. M. *P. inflata*. N. *P. damicornis*. O. *P. meandrina*.

Coral Condition

A. Bleaching

Corals may exhibit loss of pigmentation due to expulsion of their symbiotic algae when stressed by abnormally high temperatures and light levels (Fig. 26), unusually low temperatures and a host of other factors such as a drop in salinity or prolonged turbid conditions associated with run-off. Bleaching may be widespread, affecting all taxa and depths, it may be restricted to certain coral species or depths, or it may be patchy in distribution, affecting a small proportion of corals or a very limited area within the community. The severity of bleaching may also vary from colonies that are uniformly pale, partially bleached or fully bleached. The spectrum of bleaching can also include white corals as well as unusually colored corals (e.g. brown corals that turn blue or pink). A bleached coral is still living. Colonies with lesions characterized by a loss of tissue and prominent white bands or blotches of exposed skeleton without tissue are not bleached and should be categorized as recent tissue loss (described under “Tissue Loss”).

Monitoring of bleaching occurrence, prevalence and patterns of recovery/mortality can be achieved with belt transects, point intercept transects or quadrats, depending on the objective.

Bleached corals can be assessed in a variety of ways.

- Complete a visual assessment of the proportion of colonies that are bleached. Categorize these as 1) no bleaching; 2) low or mild bleaching (1-10%), 3) Moderate bleaching (11-25%), 4) moderately severe bleaching (26-50%), 5) high bleaching (51-75%), and 6) extreme bleaching (>75%).
- Characterize the severity of bleaching. This can include descriptive categories (pale, patchy, fully bleached); color categories (using Coral Health Monitoring Chart cards; www.coralwatch.org); or spatial pattern (e.g. apical surfaces, colony base, colony sides).
- Return to the site as frequently as possible. It is preferable to assess the corals when bleaching is first identified, at the peak of the event, once the stress (e.g. temperature) abates, and several intervals during the recovery phase to assess impacts.



Fig. 26. Coral bleaching during the 1998 ENSO event. Photo by Joshua Feingold.

B. Tissue Loss

Record a visual estimate of tissue loss for each colony (over 4 cm in diameter) using a 1 m bar (marked in 1 cm increments) for scale, and assess its condition.

- If the coral exhibits tissue loss, estimate of the amount of remaining tissue, percent that recently died, and percent that died long ago, for the entire colony surface.
- Categorize tissue loss as **recent mortality** (stark white skeleton, occurring within the last 1-5 days), **transitional mortality** (filamentous green algae and diatom colonization; dead for 6-30 days) and **old mortality** (macroalgae, CCA, invertebrate colonization; dead for >30 days) (Fig. 27).
- Diagnose lesions into four categories: **recent tissue loss**, **skeletal damage**, **color change**, and **unusual growth patterns**; an individual colony could have multiple characteristics (e.g. color change and recent tissue loss) (Fig. 28).
- For each coral with partial or whole colony mortality, attempt to identify the cause of mortality if possible. The diagnosis includes an assessment of the type of disease (Fig. 29), extent of bleaching, predation, competition, overgrowth or other cause of mortality.
- Examine each coral carefully to identify cryptic predators and nuisance species (Fig. 30). This could be small lesions caused by snails, polychaetes or echinoderms. If the underlying skeleton has been damaged see if the pattern of damage resembles the scrape marks from a fish. Look for competing organisms, such as algae or sponges at the margin of the colony. The location (apical, basal, medial) and pattern of tissue loss (linear, annular, focal, multifocal, and coalescing) can help differentiate signs of predation from coral disease.

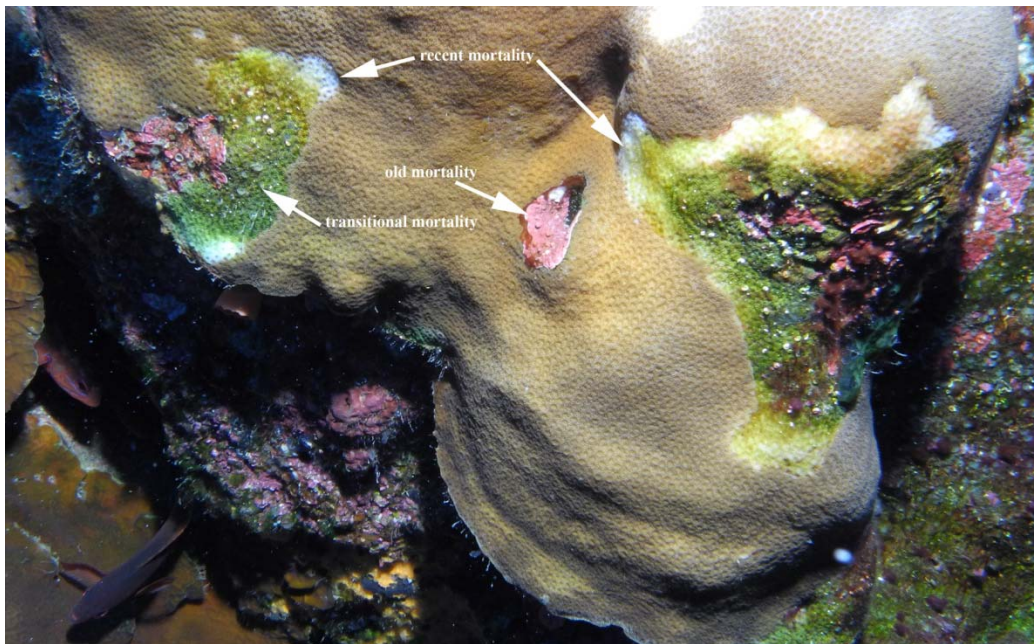


Fig. 27. Colony of *Pavona clavus* with recent mortality (white, exposed skeleton), transitional mortality (exposed skeletal surfaces colonized by fine filamentous green algae and diatoms) and old mortality (long-dead areas colonized by CCA).

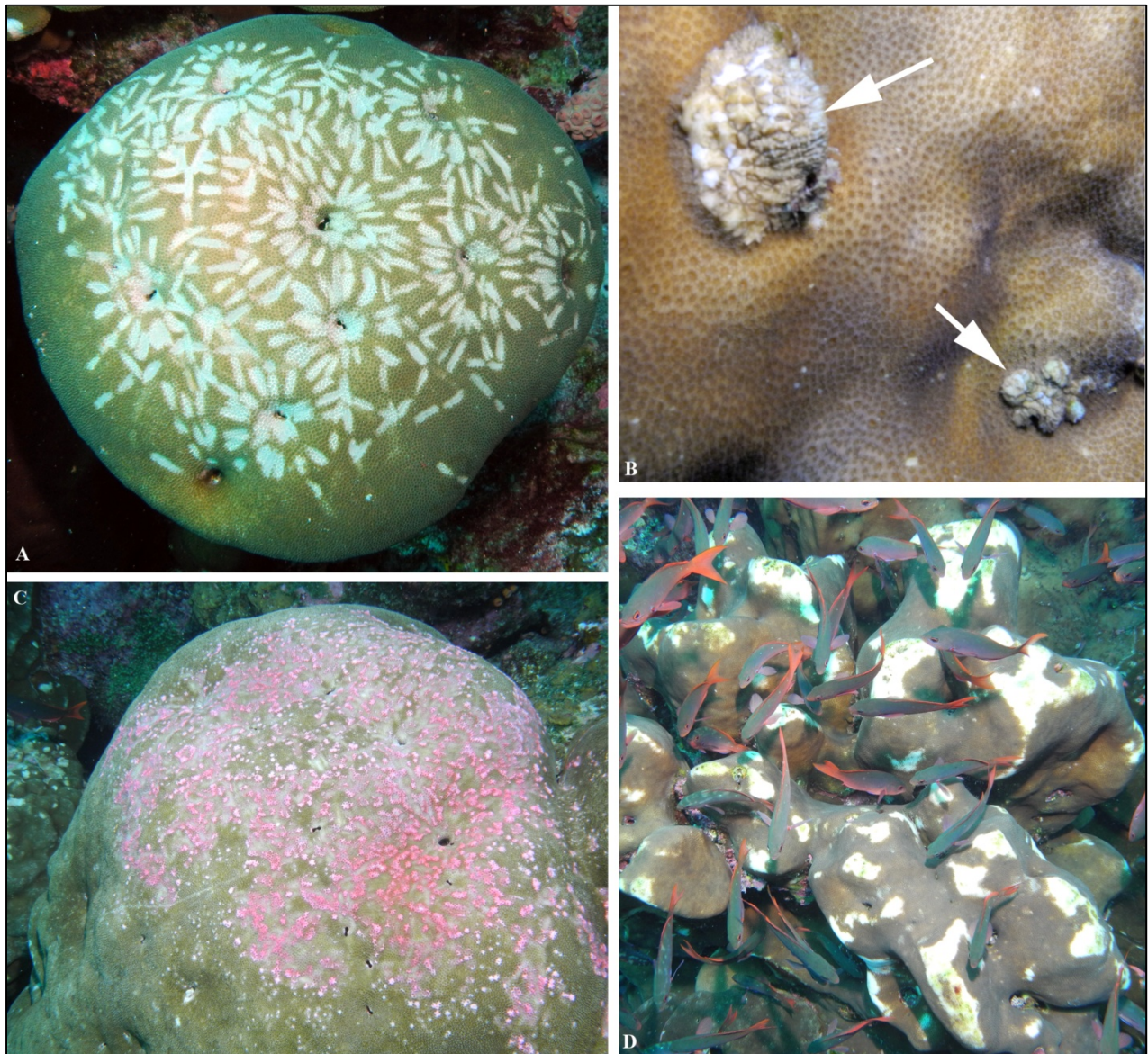


Fig. 28. Four characteristics of coral lesions: skeletal damage, abnormal growth, color change, and recent tissue loss. A. Colony of *Porites lobata* with skeletal damage from fish bites. B. *Pavona clavus* with abnormal growth. Arrows indicate two growth anomalies. C. *Porites lobata* with color change. The pink lesions are associated with *Plagioporus* sp. trematode infections. D. *Pavona clavus* with recent tissue loss. The colony has multifocal lesions dispersed over its surface.

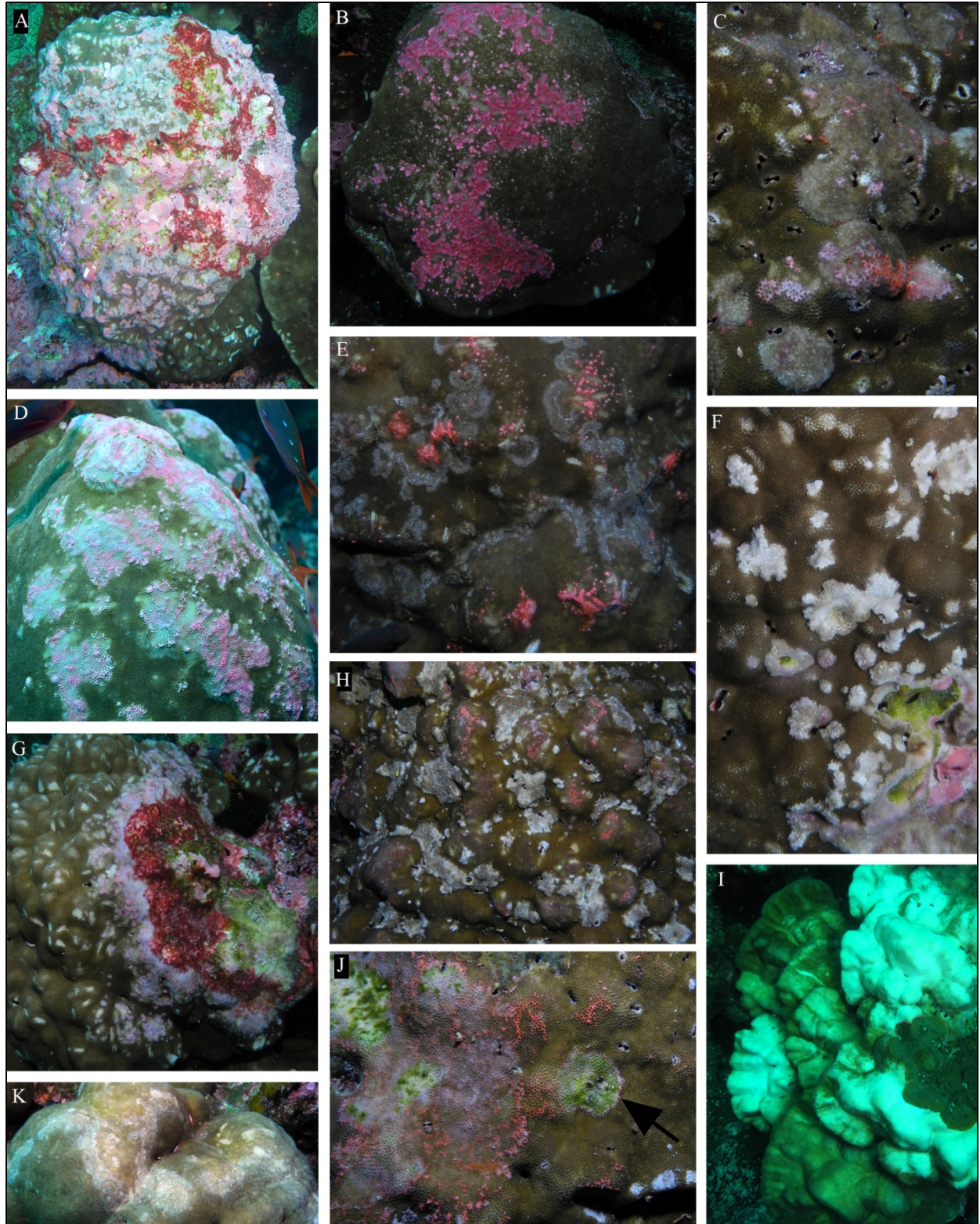


Fig. 29a. Coral diseases observed among *Porites lobata* colonies in the Galápagos. Description of each coral is on next page.

Fig. 29a. Coral diseases on *Porites lobata*. Most of these have not been fully described or examined using histology or microbiology, but they were unusually widespread at Darwin and Wolf in 2012.

- A. Unidentified syndrome characterized by multifocal pink discolorations that have spread across the colony surface. Dark red areas are exposed skeleton colonized by CCA.**
- B. Prominent pink lesions on a colony resulting from infection with a trematode *Plagioporus* sp.**
- C. Unidentified white lesions associated with tissue thinning.**
- D. Large multifocal lesions associated with tissue thinning and pink discolorations, possibly associated with *Plagioporus* sp. trematode infections.**
- E. Unidentified spreading lesions on *Porites lobata*.**
- F. Multifocal growth anomalies characterized by enlarged patches that have lost normal polypar structures.**
- G. Prominent pink lesion resembling “pink line disease” The wide pink band is advancing across the colony. A dark red band of CCA and exposed skeleton colonized by filamentous green algae and diatoms are observed to the right of the pink band.**
- H. Growth anomalies scattered over the colony surface, primary in depressions.**
- I. Bleached and pale tissues.**
- J. Large patches of discolored pink tissue, an advancing pink line and elevated pink blotches. The arrow points to a narrow band that is advancing to the right; denuded skeleton colonized by green algae is behind the arrow.**
- K. Irregular blotches of pale tissue.**

Fig. 29b. Coral diseases and syndromes observed in the Galápagos in June 2012.

- A. *Porites lobata* with an unidentified white syndrome.**
- B. *Pavona varians* and *P. clavus* with a white syndrome. A very thin band of white, recently exposed skeleton separates live tissue from algal colonized skeleton.**
- C. Large growth anomaly on *Porites lobata*. Polyp structure is normal, but tissue is bleached. Colony surface is also covered with fish bites.**
- D. Tissue loss in *Pocillopora damicornis* associated with a white syndrome. The disease advanced from the base of the branches to the tips.**
- E. Growth anomalies in *Porites evermanni*. The white enlarged areas have normal but enlarged polyps and are bleached.**
- F. Multifocal lesions in *Pavona gigantea*. The white areas are devoid of tissue. Areas first killed have been colonized by green algae.**
- G. White syndrome on *Pavona clavus*. The disease started at the border with the *P. varians* colony and is advancing across the colony.**
- H. Tissue loss in *P. clavus*. The disease started at the top of the colony and is spreading down. Areas that died long ago are colonized by CCA; exposed skeletal surfaces adjacent to live tissue are colonized by green algae. The progression of the disease has slowed considerably as evidenced by a lack of a recent white exposed skeletal band.**
- I. *Psammocora stellata* with a large lesion of unknown origin. The lesion is several days to weeks old; no recently exposed white skeleton is visible.**

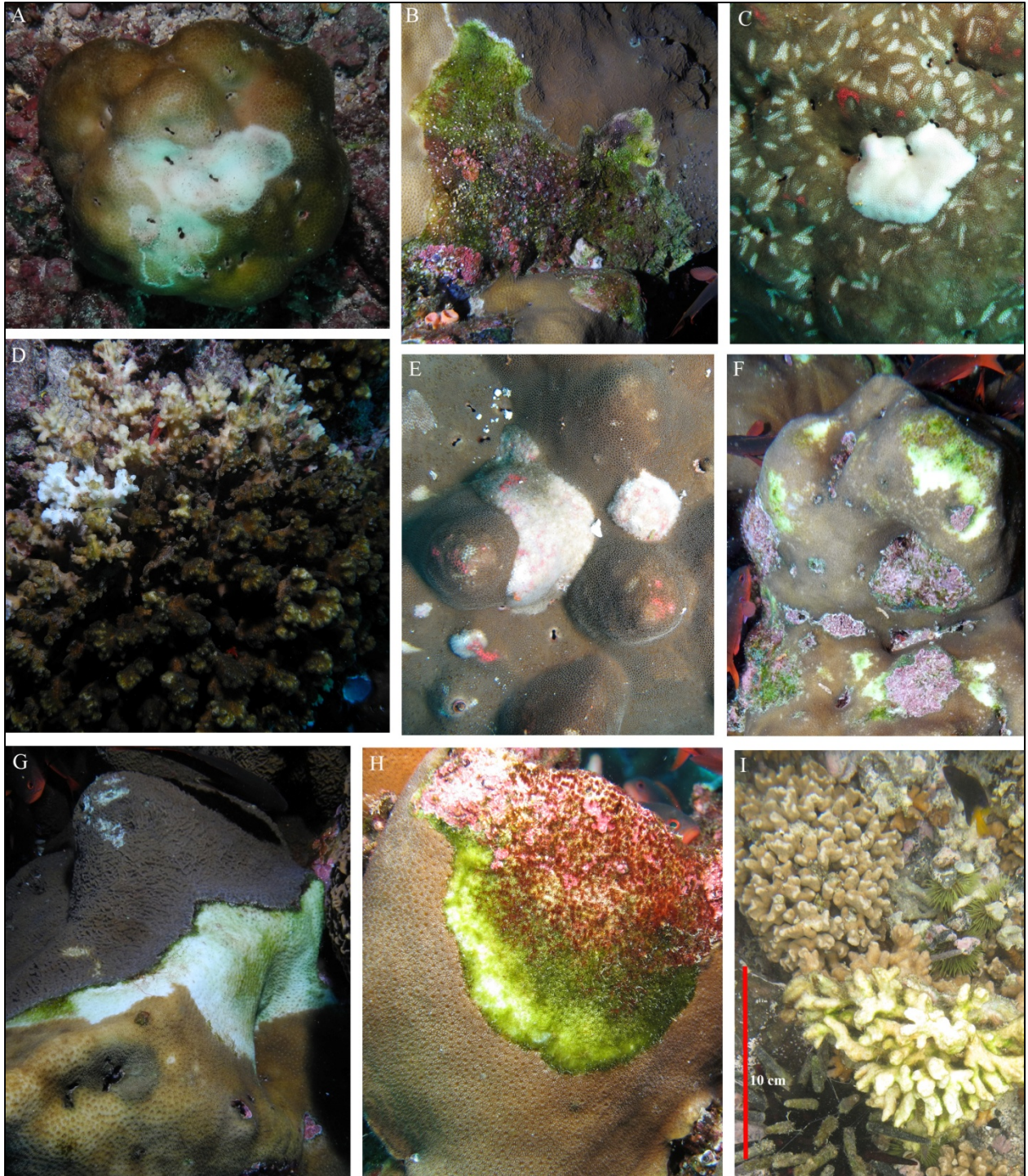


Fig. 29b. Coral diseases and syndromes observed in the Galápagos in June 2012. Description of the conditions affecting each coral is on the previous page.

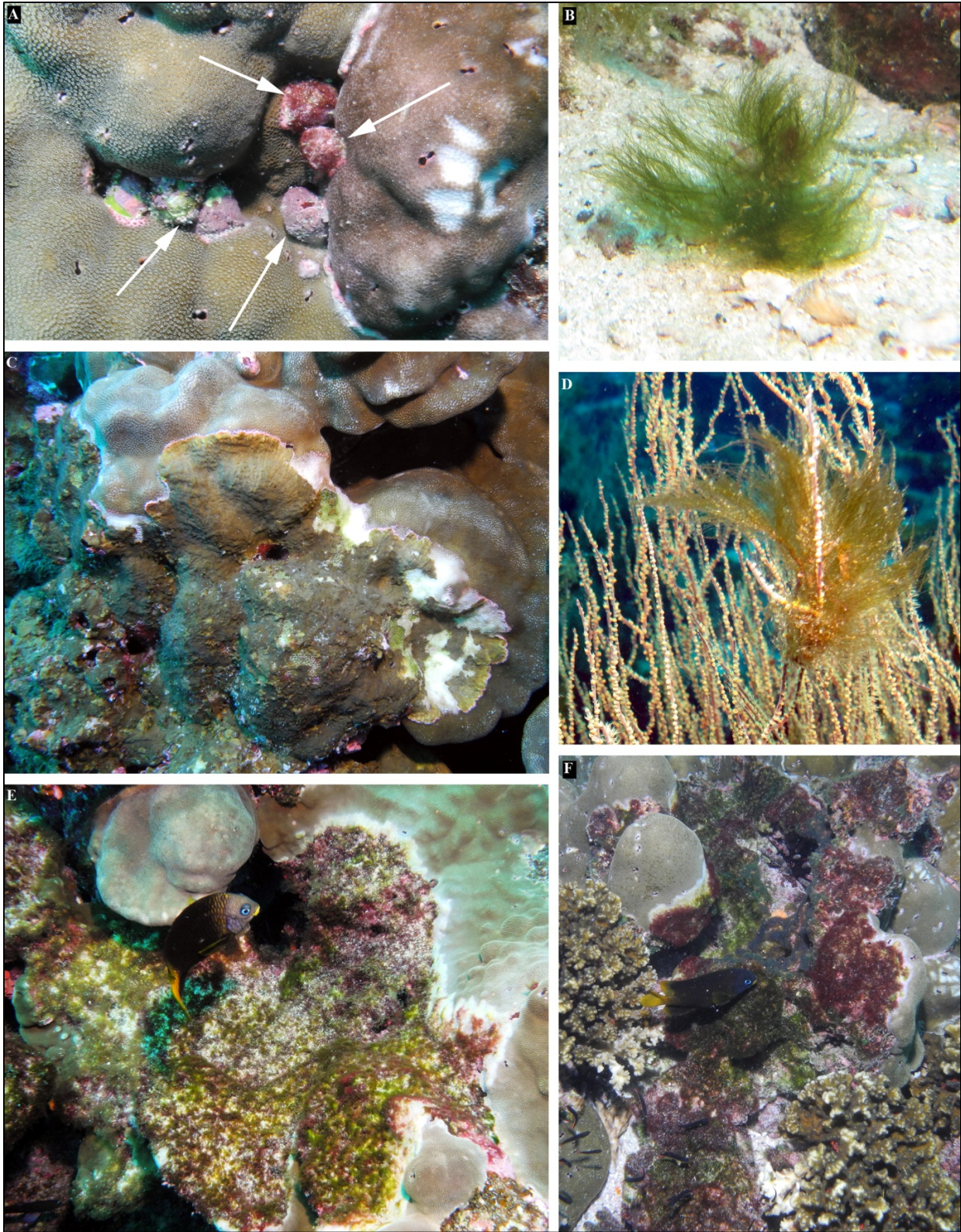


Fig. 30. Nuisance species affecting corals. A. Corallivorous snails. B. Cyanobacteria. C. *Peyssonnelia* overgrowing a colony of *Porites lobata*. D. Cyanobacteria. E & F. Damselfish algal lawns. The territorial damselfish can be seen within its territory.

Methods: Quadrats

Quadrats provide data on the population sizes of various organisms within the site. They can also provide information on cover (see benthic survey approaches), density, size structure and condition. Quadrats provide data on the horizontal plane of the reef and cannot be used in areas with high relief or scattered large coral assemblages (e.g. habitats with large *Pavona gigantea* colonies). In mixed coral communities, colonies that are small, free living or plate-like may be overrepresented, while larger boulder corals may be underrepresented.

Quadrats can be haphazardly or randomly deployed throughout a site, placed along a transect line, or they can be permanently installed or marked to allow monitoring of the exact same area. To mark the location for a permanent quadrat, concrete or stainless steel nails can be inserted at the four corners; the quadrat can also be permanently attached to the substrate.

Quadrats should be made of aluminum, PVC or stainless steel and not rebar (which rusts and is very heavy). Quadrats must be heavy enough to stay on the bottom, and can be weighted with small pieces of rebar or lead weights placed at the borders if necessary. For PVC pipes, small holes should be drilled into the plastic to allow them to fill with water. The PVC pipes that make up the quadrat can be permanently attached using PVC cement, although some researchers prefer not to glue the parts together to allow disassembly and easy transport. If PVC cement is not used, a bungee cord can be inserted into the quadrat to avoid losing parts.

- Determine the most suitable method to deploy the quadrats. Quadrats should be placed far enough apart so their boundaries do not overlap. Depending on the size of the site, the spatial distribution of the corals, and the type of corals, quadrats can be deployed along a transect or randomly/haphazardly throughout the coral assemblage.
- For relatively small defined populations, the entire population or a subset can be sampled. Ensure that quadrats are dispersed throughout the site and not concentrated in one area (Fig. 31). This can be achieved by marking the boundaries of the site and preselecting the locations of the quadrat (using a random number table, for instance) or by randomly tossing the quadrat into the site.
- For very small or extremely abundant organisms, counts may be made for only a portion of a quadrat that is subdivided into smaller sections using monofilament or nylon line.
- Measurements can include visual estimates of percent cover, and abundance, size and condition of invertebrate species, as described for benthic and coral transects (Fig. 32, 33).

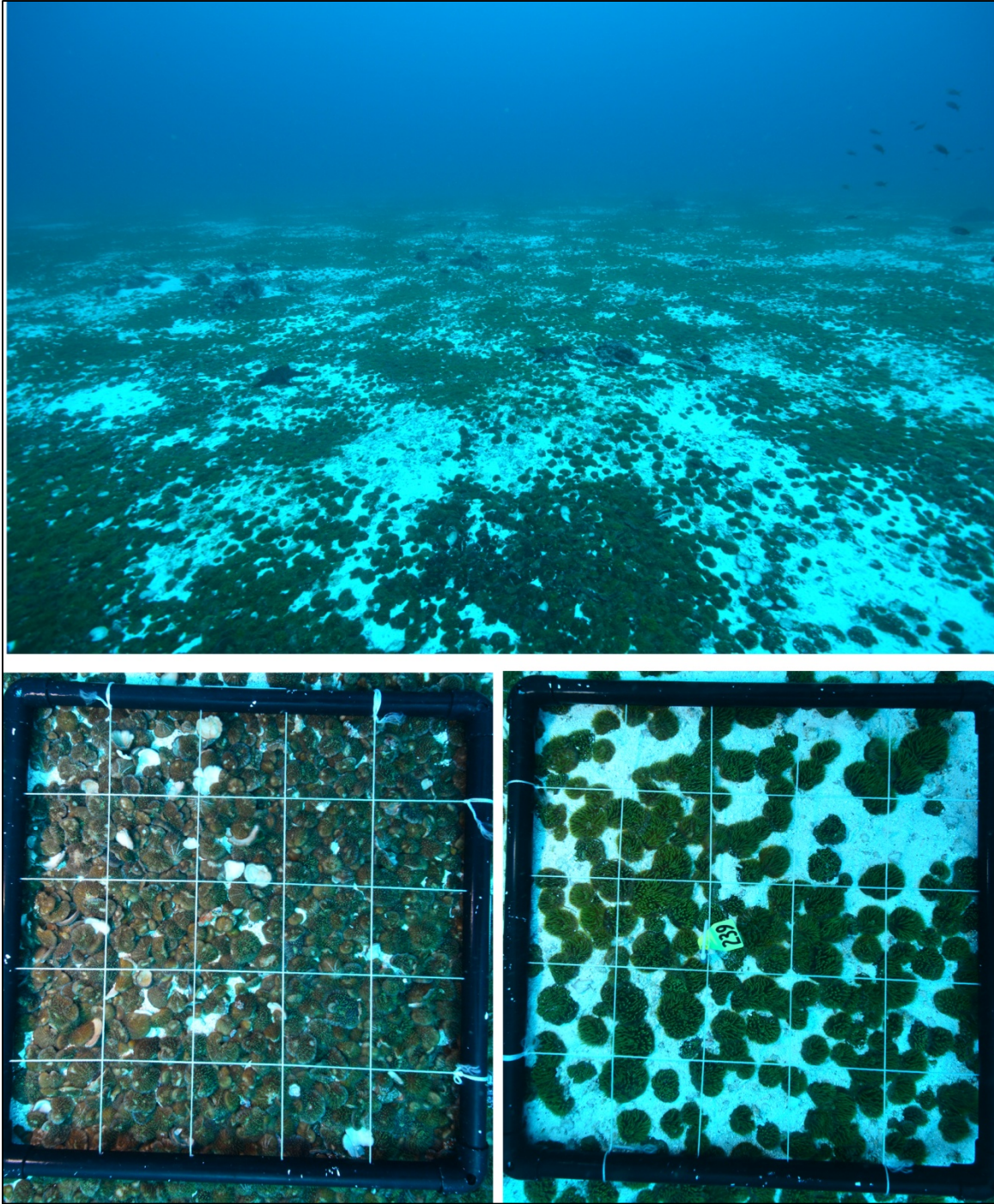


Fig. 31. *Diaseris distorta* (free-living fungiid corals) populations off Devil's Crown. Top photo taken from the center of the assemblage at 17 m depth. The lower photos show two 0.5 m quadrats from different areas within the population. Because the corals are patchy, very small in size and very abundant a belt transect method would not be feasible in this area. As an alternative, 0.5 m quadrats subdivided into 25 squares are used to obtain density estimates of the population. Different locations within the population are sampled, including dense (left) and less dense areas.

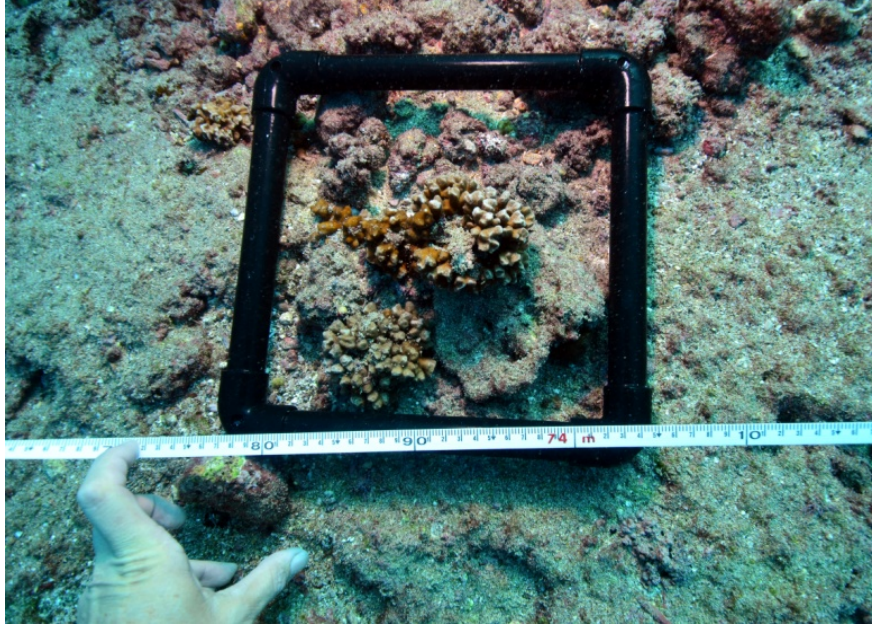
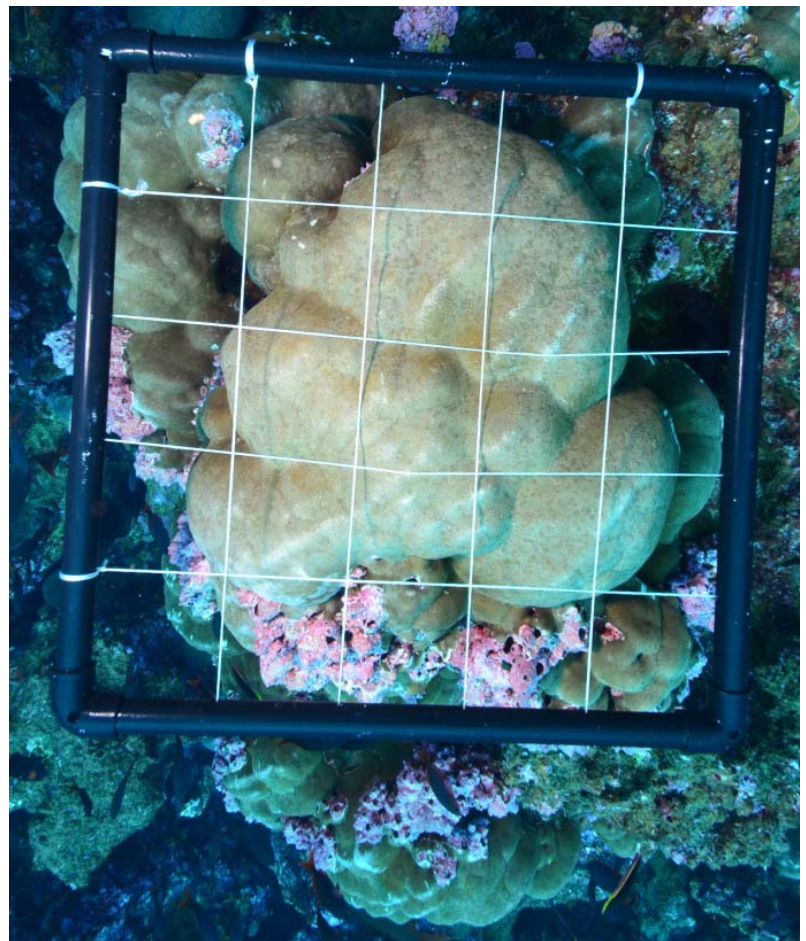


Fig. 32. A small (25 cm X 25 cm) quadrat placed along a transect line to record size and abundance of free-living *Psammocora stellata* colonies off Devil's Crown.

Fig. 33. Small (50 cm X 50 cm) quadrat subdivided into 25 squares used to assess the amount of living tissue of individual corals. In the example, about 85% of the *Porites lobata* colony is live, while CCA encrusted barnacles occur on the coral within in three squares and *Peyssonnelia* algae has overgrown the coral in one square.



Methods: Monitoring Individual Corals

Individual corals can be monitored overtime to assess growth and survival, the impacts of various stressors such as bleaching, disease and predation, and recovery through resheeting.

- **Identify the species.** Of the 22 species of corals found in the Galápagos, efforts should be targeted towards the long-lived massive corals including *Porites* and *Pavona*, as these have the potential to achieve a large size and live for many decades. Individual colonies of other taxa, such as *Pocillopora*, *Psammocora*, and free-living fungiid corals are more difficult to follow over time, as these tend to fragment, have shorter life-spans, are smaller, and/or are more likely to be removed by storms and bioerosion.
- **Mark the colonies.** Colonies can be tagged with plastic numbered cattle tags which are attached to a dead portion of the colony or secured to the substrate next to the coral with a stainless steel nail, hardened masonry nail or cable tie. These tags tend to become overgrown by algae and invertebrates, and should be placed with the number facing down. When tagging multiple colonies in one area, all the tags should be placed on the same side (e.g. N, S, E or W side of the coral) to facilitate relocation.
- **Assess coral condition** as described for belt transects. The coral should be measured (length, width and height) and assessed for partial mortality and any signs of disease, predation, overgrowth, competition or other stressor should be identified if possible. For colonies with recent and ongoing tissue loss (e.g. those with disease), rates of loss can be monitored by placing masonry nails in the skeleton adjacent to live tissue and measuring the progression of the lesion over time.
- **Map the tagged colonies.** To aid in relocation of the tagged corals, draw the tagged corals to scale on a grid and add other recognizable features (e.g. large outcrops, crevices, sand channels).
- **Photograph the colonies.** Photograph the colony from different angles and from a planar (top) view. For a large massive boulder coral take a minimum of four photos from known compass bearings (e.g. north, south, east and west) and same distance, to facilitate matching the photos from subsequent monitoring. Include a scale bar and a slate with the tag number in the photos. Additional macro-photographs should be taken of a lesion.
- **Reexamine the corals over time.** The frequency of monitoring depends on the condition of the colony. When documenting progression of a disease, the coral may need to be re-examined weekly for virulent, fast spreading diseases such as a white syndrome, and less often for diseases that cause minimal mortality such as growth anomalies. To document the effects of bleaching, colonies may need to be monitored very frequently during the period of high temperatures, and progressively less often once the colony begins to recover and temperatures have declined.

Table 5. Types of coral data and rationale for inclusion in a monitoring program.

Measure	Importance
Stony coral	Genus or species level identification, growth form, abundance, cover, size structure, condition, and level of recruitment for each scleractinian coral within representative habitats. Corals are important because they construct coral reefs and provide habitat for other species; they are a universal reef condition indicator.
Species composition	The diversity and structural complexity of a site. Communities with higher numbers of functional groups (e.g. branching, plating, massive corals) and redundancy of these groups may support more associated species and be more resilient.
Cover	Measure of amount of living coral, but provides limited information on population dynamics. Small changes in cover are difficult to document, but abrupt changes may reflect a major disturbance. Useful metric for comparison among reef habitats with a managed area.
Size structure	Maturity and ecological state of the taxa. Large numbers of large corals may be a sign of stable environmental conditions and long term persistence of the community; a dominance by small corals suggests frequent disturbance or recovery from a recent disturbance.
Recruitment	Abundance of recruits reflects the reef's potential for growth and recovery after major disturbances and the influx of genetic diversity.
Fragmentation	Level of physical disturbance and potential for asexual propagation. Locations of fragments (accumulations in sand channels or on reef) and fragment condition (no tissue loss; fusion to the substrate; presence of new growth) reflect the potential survival and contribution of fragments to recovery.
Dead standing coral	Amount of dead standing coral can be used to hindcast past disturbance events up to a decade or more, provided there were no major hurricanes and overgrowth and bioerosion are not too high.
Old mortality	Presence of dead areas on corals that are colonized by other biotic agents (e.g. skeleton is not white) provide evidence of past disturbances. Species specific differences partially reflect the life history strategies, population dynamics and susceptibility to various physical and biological factors. Old mortality may increase with colony size.
Recent mortality	Overall extent of recent mortality (white skeleton) reflects the severity (e.g. rates of tissue loss) and duration of a stressor. The rate of transformation from recent mortality (white, uncolonized skeleton) to old mortality is influenced by sedimentation, nutrient levels, depth, exposure, herbivory, bioerosion, competition and other factors. Rates of mortality may allow prediction of rates of turnover of corals.
Bleaching	Reef-wide bleaching may be associated with recent or ongoing temperature anomalies; extent of recent mortality in bleached corals may indicate the duration and severity of the temperature stress.
Disease	Spatial patterns of disease occurrence reflect potential for spread and level of contagion. Distinction can be made between background mortality (chronic stressors) and acute mortality caused by disease outbreaks. Presence of isolated small lesions reflect a variety of low-intensity stressors that are within the ability of the coral to regenerate new tissue, provided the colonies are large enough, while larger lesions are more likely to be colonized by other competitive organisms and may affect the normal functioning of the coral (e.g. reproductive potential).
Corallivores	Abundance of coral predators (<i>Drupella</i> and <i>Coralliophila</i> snails, <i>Acanthaster</i> seastars) indicative of the amount of recent mortality and possible changes to coral community structure and species diversity due to chronic high level infestations or outbreaks.
Competition & overgrowth	Negative factors inhibiting the growth and recovery of corals and causes of chronic mortality (e.g. algal competition) and bioerosion (e.g. sponges) of skeletons. Extent and composition of competitive organisms may reflect status of fish communities (herbivores), nutrient loading and sedimentation.
Coral associates	Obligate corallivores (butterflyfish) provide an indication of the health of the coral community or a particular taxa.
	Abundance and diversity of fishes and invertebrates within coral branches are indicative of the topographic complexity and health of the site.
	An abundance of territorial damselfish within branches and large algal lawns indicate possible overfishing of piscivores.
	High densities of sea urchins may be associated with extensive bioerosion of reef substrates and low recruitment and survival of newly settled corals; macroalgae may increase in absence of sea urchins, especially sites with few herbivorous fishes.

4. Photographic Monitoring of Benthic Communities

Photographic assessments can be used to document the community structure and condition of the seafloor bottom and the population dynamics and condition of the stony corals and other benthic organisms. These assessments can include 1) **photographs of quadrats** to document algal community structure, cover, coral recruitment, a stressor (e.g. disease) on a coral, or interactions and competition; 2) **photographs of individual corals** from different angles to assess growth, patterns of tissue loss and patterns of regeneration (see above); 3) **continuous photographs of a wide swath or band of reef** (along a transect line) to document community structure and cover; or 4) **overlapping photographs of a large area of reef** (e.g. a 10 m X 10 m quadrat) to create a mosaic. As in other measures, these can be taken in random locations or at permanently marked stations.

Methods: Photo-transects

- Extend a 10 m long transect tape along a depth contour (e.g. 20, 15, 10 and 5 m depth).
- Take continuous digital still photographs of the underlying substrate along the transect line. For best results the camera should be approximately 0.6-0.75 meters above the substrate, and the same distance should be maintained for the entire transect.
- Place a one meter bar, divided into 5 cm increments, perpendicular to the transect tape to serve as a scale bar. Using a wide angle lens, approximately 20 photographs need to be taken per transect to allow for overlap between adjacent images.
- As an alternative, a 1 m X 1 m quadrat can be continuously flipped over in a straight line to photograph a continuous 10 m band. In Photoshop or other photo-editing program, issues with photos taken at different angles or parallax problems can be corrected (e.g. an oblong image can be made square) if the photo contains four right angle corners of known distance from each other.
- Replicate transects should be photographed (a minimum of 5 m apart) at each depth.

Transect locations can be recorded by deploying a buoy to the surface and taking a GPS reading. For repeat monitoring of the same area, the beginning and the end of the transect line can be marked with a stainless steel rebar inserted into the substrate.

Download images onto a computer for analysis. Types of information that can be acquired from phototransects include benthic community composition, cover of corals, other invertebrates, and algae, substrate type and cover, and planar surface area of corals. One approach for analysis involves the use of free software developed by the National Coral Reef Institute (NCRI). This Coral Point Count (CPCE) software allows you to place a specific number of points onto each image in a random or predefined pattern, and record what is under each point to determine the cover (Fig. 34). All data can be exported to an excel file for further analysis. This software also allows you to trace the outline of individual corals and other objects to calculate surface area of live tissue (or amount of partial mortality) as a 2-dimensional projection of the digital photographic image.

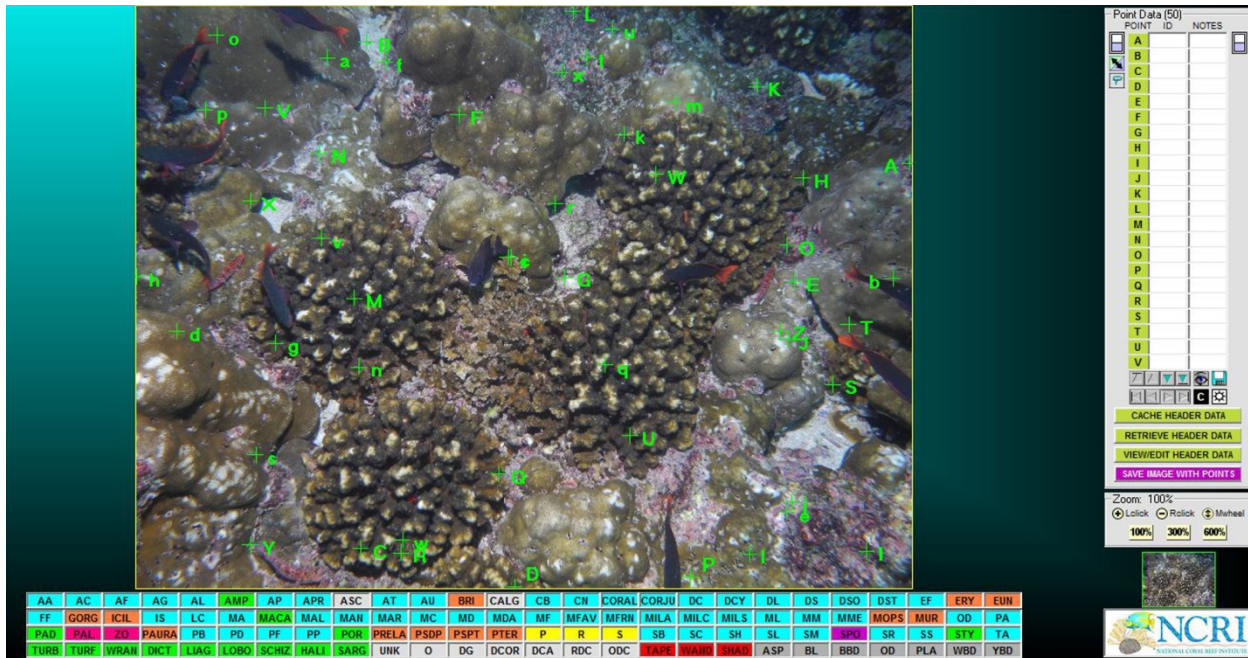


Fig. 34a. Example of a photoquadrat imported into CPCE. 50 Points are overlaid onto the photograph in a random pattern. You can modify the number of points and the placement of the points. To analyze data, a text file of the categories is imported into CPCE (shown in the lower portion of the photo). For each point, you click on the category and data are automatically compiled into the two columns on the right. This can then be exported for analysis.

The sizes and dimensions of individual corals can also be determined using CPCE. Provided that each coral has a scale bar, CPCE can be used to measure the diameter, planar surface areas and/or the amount of living tissue vs. the amount of old mortality and recent mortality.

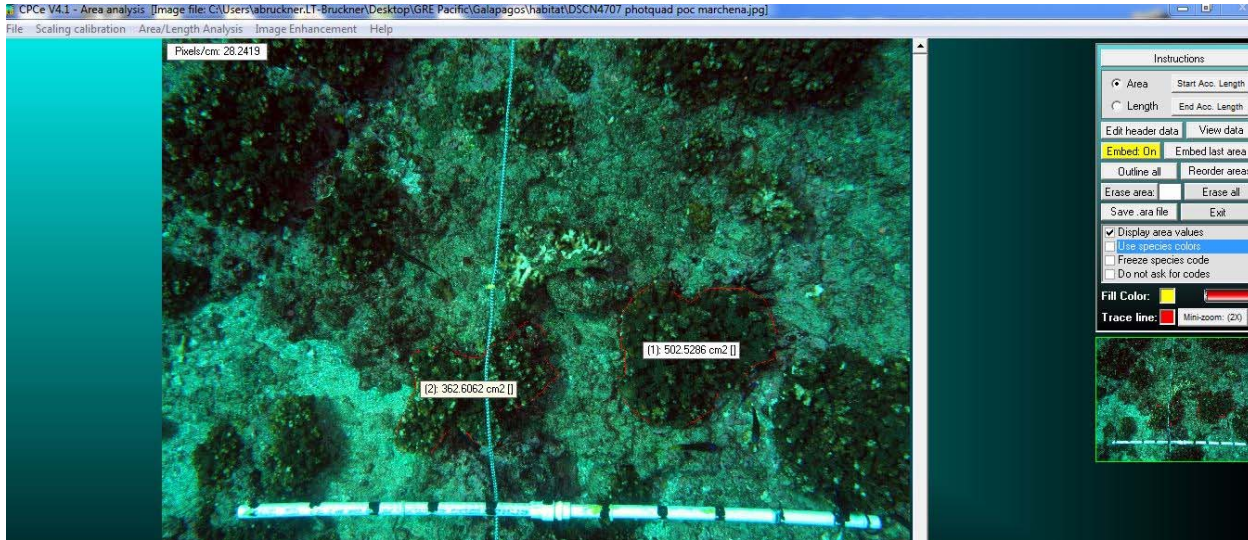


Fig. 34b. Measurement of the planar surface area of individual corals located along a belt transect. 1. Select Area/length analysis. 2. Perform image scaling/calibration by clicking two points on scale bar; 3. Enter spanned distance; 4. Click on area/length analysis; 5. Trace outline of coral (for planar surface); 6. Click right button on mouse to calculate area. Data are automatically compiled into a spreadsheet.

5. Fish Monitoring

Objective: To assess fish community structure and changes in fish assemblages over time.

Visual censuses of fishes should be completed in the same habitat as the benthic surveys and coral transects. Fish can be assessed using belt transects, stationary point counts (within an imaginary “cylinder”) and roving surveys. Each has specific advantages and drawbacks. Because many fishes are wary of humans, transects should be spaced apart a minimum of 5 m whenever possible. They should also be conducted before other divers enter the water and away from the benthic or coral surveys unless the same line is used to assess fish and benthos. In this case, fish surveys should be completed first, followed by benthic surveys. While coral/benthic transects can be deployed and then assessed while swimming back over the line, it is best to deploy the transect behind you as you swim forward recording fish (using the line primarily to judge distance). Ideally, fishes should be surveyed between 1000 and 1400 hours when visibility underwater is at a maximum due to overhead sunlight (and to avoid the crepuscular movement of fish so as not to bias fish abundance estimates). Line-of-sight issues, which are especially acute in high-rugosity habitats, and errors beyond a diver’s focal range in estimating fish sizes or the location of the belt boundary, are minimized by constraining assessments to a target group of species and maintaining a transect width of 1-4 m. A narrow belt (e.g. 1 m) is most appropriate for species associated with the benthos that are small (e.g. wrasses, damselfish, blennies, gobies) while wider belts must be used for medium-large fish. A 2 m belt is appropriate for very murky water and high numbers of small to medium fish (e.g. 5-15 cm), while a 4 m belt is more appropriate for moderately clear water with medium to large fishes as the target.

Species selected. Fish species chosen for the Galápagos surveys include ecologically important carnivores, detritivores, and herbivores; as well as species that are commercially significant as food items, export species and fishes that are collected for marine aquaria (Fig. 35). These fish play an important ecological role in maintaining the stability and sustainability of coral reefs.

- Fish that consume algae (herbivores such as parrotfishes, rabbitfish, surgeonfishes and damselfishes) control the proliferation of algae that might otherwise overgrow corals. The particular species and their size is an important determinant of the amount and type of algae that is consumed. Some herbivores are browsers (feeding on turfs) while others are scrapers and excavators removing algae and some of the underlying substrate.
- Predatory fish are critical to include because they help maintain a trophic balance across the reef ecosystem by preventing a population explosion or imbalance of certain species. Certain invertivores (e.g., file fish, trunkfish, pufferfish) aid in balancing the proliferation of corallivores (e.g., snails), which consume coral tissue and also help prevent population explosions of sea urchins. Larger piscivores such as groupers control the abundance of small-bodied fish such as damselfish which may become pests, killing coral as they farm algae. Overfishing of all these trophic groups are major threats to the persistence of coral reefs and could provide mechanisms for ecological phase shifts, for example, from coral to algal-dominated communities.

Table 6. Functional groups of fish and rationale for inclusion in a monitoring program.

Measure	Description
Fish	Fish community structure within sites can be attributed to environmental conditions, habitat complexity and quality, connectivity with other sites and intactness of adjacent habitats, fishing pressure, and management regimes.
HERBIVORES	Suppress the growth of algae. Herbivore biomass is negatively correlated with macroalgal biomass and amount of cropped habitat. Different functional groups of fish prefer different taxa and functional groups of algae and their impact to substrates and corals is a measure of the abundance and size of fish taxon, the size of bites and frequency of feeding.
Browsers	Feed on fronds of fleshy and filamentous macroalgae, controlling overgrowth and shading of corals by algae. Examples: <i>Calotomus</i> , <i>Leptoscarus</i> , <i>Naso</i> .
Grazers	Remove epilithic algae from reef surfaces without removal of underlying reef substrate. Examples: <i>Acanthurus</i> , <i>Zebrasoma</i> , <i>Siganus</i> .
Scrapers	Remove algae and small pieces of underlying reef substrate. Examples: <i>Scarus</i> , <i>Hipposcarus</i> .
Excavators	Consume coral and large pieces of reef substrate and play a key role in bioerosion and sand production. Examples: <i>Bolbometapon</i> , <i>Chlorurus</i> .
OMNIVORES	These species will consume small invertebrates including larvae, fish and fish larvae, some consume phytoplankton, benthic algae and seagrass, and some consume detritus.
Detritivores	Feed on organic material in the sediment and on reef substrates. High numbers may reflect conditions of eutrophication. Examples: <i>Ctenochaetus</i> .
Zooplanktivores	Feed on zooplankton. Indicative of the level of plankton in the water column, including larvae important for reseeding the reef; secondary indication of water column nutrient levels. Examples: fusiliers, some triggerfish, creolefish.
PREDATORS	Predator density, size and biomass are sensitive indicators of the intensity and type of fishing pressure; these species are important in controlling abundances of lower trophic level fishes.
Invertivores	These species may control populations of corallivores and bioeroders including snails, sea stars and urchins. Examples: triggerfish, snappers, sweetlips, wrasses, pufferfish, and angelfish. Some species (angelfish) also feed on sessile invertebrates like soft corals and sponges which compete with stony coral for space. Some species (e.g. goatfish) also feed in sediment around the reef on infauna, such as worms, crustaceans and small mollusks.
Obligate coral feeders	These species may provide indication of the health of the coral, especially species that are not generalists like certain butterflyfish.
Piscivores	Important control of lower trophic level fish; they are the first indicators of overfishing. Examples include sharks and groupers.



Fig. 35a. Examples of piscivores from the Galápagos included in assessments. Left: *Sphyrna leweni* (scalloped hammerhead shark; tiburón martillo); center: *Mycteroperca olfax* (bacalao; bacalao); right: *Dermatolepis dermatolepis* (leather bass; mero cuero).



Fig. 35b. Examples of Invertivores from the Galápagos including in fish assessments. Left: *Bodianus echanteri* (harlequin wrasse; vieja arlequin); center: *Arothron hispidus* (stripebelly puffer; botete panza rayada); right: *Zanclus cornutus* (Moorish idol; idolo moro).



Fig. 35c. Example of an important herbivore from the Galápagos included in reef fish assessments, *Prionurus laticlavus* (razor surgeonfish; cochinito barber).

Methods: Belt Transects

Belt transects are used to document the species, numbers and sizes of coral-associated fishes and can be used to determine diversity and population structure over a large census area. Data are used to estimate abundance, species richness and biomass for the fish populations, which can be subsequently classified by taxonomy and trophic guilds (Table 7).

The appropriate length and width of the transect varies depending on the environmental conditions and the type of fish being assessed. For small, cryptic fish, and very complex habitats, a 10 m X 1 m belt transect length may be appropriate, while large reef associated fish can be best assessed using longer and wider transects (20, 30, 50 or 100 m X 2-6 m width). For the Galápagos, we assessed fish within a 30 m X 4 m belt. It is important to avoid a belt transect that is too narrow, as the data may be biased against large schools and highly mobile fishes. In areas with low visibility, very high diversity, and unusually high abundances the transect width should be reduced to facilitate accurate identification and recording. However, for comparative purposes, all surveys in a location should rely on the same length and width.

- The transect tape should be on a reel that can be easily deployed and recovered. Secure a 30 m transect reel to your BC. Attach either a bungee cord or a small (1-2 lb) led weight to the beginning of the line. Either tie off the beginning of the line to a rock or some other dead object or place the weight at the starting point in a small crevice.
- Swim slowly parallel to depth gradients holding the t-bar in front and recording the selected species of fish within the chosen “window” (e.g. 2 m on either side of the line from the bottom to the water’s surface). Record the total number of each species and their sizes.
- Swim at a constant rate such that the measuring tape is deployed in about 15 minutes. Longer or shorter swimming periods could affect comparison of results across stations.

Methods: Stationary point counts

Stationary visual census focuses on relative abundance, size structure and frequency of occurrence of all species of fish at the site. Fish observations are recorded within an imaginary cylinder of fixed diameter from the bottom to the surface.

- Sites for stationary point counts are randomly selected in the habitat of interest.
- The dive hovers in the water, just above the bottom at the center point of the cylinder and makes several slow 360° turns first examining fish near the bottom and gradually working up the column.
- The diver identifies each species and records its abundance and size
- Continue recording fish that come inside the cylinder for a predetermined time interval (Bohnsack and Bannerot 1986).

Methods: Roving surveys

This plotless method provides information on total species richness. It can be used to assess the presence, frequency and relative abundance of all fish species within a specific zone or depth, but actual density estimates are not possible because the exact size of the survey area is unknown.

- The diver swims along specific depth gradients, in a certain compass direction, through an area of a known size, or along some identifiable habitat feature and records the species (and or abundance/size) of each fish observed within a set amount of time.
- This method does not require deployment of transects and allows the diver to census a larger area and cryptic habitats that are likely to be missed using conventional transect methods.
- Species are usually recorded as rare, common or abundant. Accurate quantification of density of a species is difficult, unless a known area is monitored. Typically this method provides an estimate of density per unit time.

Estimating size: Each fish should be scored into 5 cm size classes for fish up to 30 cm in length by estimating their total length (length from the tip of the mouth to the tip of the fins) or (less preferably) fork length (tip of mouth to the fork at the base of the tail or caudal fin). For fish over 30 cm in length an estimate of the actual size is recorded.

Methods: Capture techniques

In some situations transect, roving surveys and stationary point counts do not provide the level of detail desired. These methods can be problematic under very turbid conditions. Juveniles, nocturnal species and cryptic organisms can also be difficult to see and count, especially in high relief habitat. These methods also will not work to document recruitment patterns, or when attempting to determine the total biomass of a given area. As an alternative, scientists often use trap sampling, poisons, nets and other capture methods.

- For biodiversity assessments, the most common capture techniques involve the use rotenone, quinaldine or other poisons to identify the diversity or to collect a new species. These methods are not recommended for large areas, deep water and in high current areas. Consideration must be given to the type of poison and its effect on the flora and fauna and potential human interactions. Also, poisons may be ineffective in high relief complex habitats or in areas with strong currents.
- Traps can provide useful information on the presence of certain species that would be undetected using conventional methods, and also can detect timing of certain events (e.g. recruitment or seasonal migrations/emigration of certain species). The effectiveness of traps depend on their size, mesh size, location of placement, type of bait and other factors. Traps may target certain species over others. It is difficult to quantify the area fished by a trap.
- Nets (e.g. gill nets, tremel nets) that are set in one location and left for a defined period (e.g. overnight) can be useful to measure movement patterns of fish between habitats.
- Bottom trawls can be used to characterize fish species that live in sand, algal, or seagrass habitats and are especially useful in turbid areas where conventional visual assessments are not possible. These can cause considerable habitat damage and should only be used in low relief habitats where entanglement and breakage of sessile organisms is not likely.

Equipment

- Fish Survey Data Sheets printed on underwater paper
- Fish species codes
- Underwater slate or clipboard
- Underwater pencil attached to slate
- Flexible fiberglass metric measuring tape at least 30 m in length on a reel
- T-bar with attached clipboard and a scale bar (Fig. 36)
- Underwater digital camera
- Additional equipment is necessary for capture techniques (e.g. traps, nets, poisons).



Fig. 36. T bar with attached slate and transect line for fish surveys. The PVC bar is marked in 10 cm intervals with electrical tape. The PVC pipes are connected with bungee cords and can be folded up for ease of transport.

Table 7. Types of information determined from fish monitoring data.

Measurement	Definition	Unit	Calculation
Species richness	# species in a location	Margalef's species richness (d)	$d = (S - 1) / \log(N)$, where S= number of species; N = number of individuals
Abundance	Total number of fish	n	Total # fish observed
Density	# fish in a defined area	#/100 m ²	(Total # fish/total area surveyed)*100
Size	Total length	cm	1-5 cm, 6-10 cm, 11-15 cm etc.
Biomass	Total weight of fish per defined area	g/100 m ²	$W = aL^b$, where W= weight in grams, L= total length and a and b are growth constants*
Diversity	Index of richness	Shannon weiner diversity index (H')	$H' = - \sum i p_i (\log p_i)$
Evenness	How close in abundance each species is. Index of biodiversity. A higher J' = less variation.	Pielou's evenness (J'), a number between 0-1	$J' = H' / \log(S)$

- Growth constants, a and b, can be obtained from FishBase (Froese and Pauly 2013).

6. Resilience Monitoring

Objectives: Characterize a reef's ability to resist change or the likelihood and timing of recovery.

Resilience monitoring provides information on the ability of a system to resist change, or if it undergoes change the potential for it to return to its previous state. Ecological resilience relates to the entire scope of positive and negative factors affecting a community, such as resource extraction, pollution and invasive species. Resilience monitoring involves assessment of specific indicators that are beneficial and deleterious to the community (Obura and Grimsdith 2009). There are four levels of analysis of resilience considered in this manual:

- 1) The primary biotic components that make up the reef community - corals, algae, large motile invertebrates and fish communities (assessed using methodology described in previous sections);
- 2) The ecological interactions that drive dynamics within and among these groups;
- 3) Habitat and environmental influences that directly affect the reef associated organisms and the interactions between them; and
- 4) External drivers of change, including anthropogenic and climate factors.

The biological monitoring program already discussed will address the primary biotic components. Through literature studies, detailed information on ecological interactions can be compiled. The physical site parameters and habitat information, such as reef dimensions, topographic complexity, rugosity and spatial arrangement of the community, distance to deep water and other habitat types (Table 8) help dictate what organisms can live in an area, and how they are likely to be affected by certain anthropogenic and natural stressors. Most of these can be measured directly from satellite imagery or determined when the monitoring sites are established, and are not specific monitoring parameters as they are unlikely to change need to be calculated a monitoring program. Measurements of selected environmental parameters, such as temperature, salinity, pH, light and turbidity should be included in a monitoring program, as these will vary and in some cases may provide information on the causes of certain changes documented in the community. In some cases these can be monitored using deployable meters, while others require direct measurements. Certain parameters, such as nutrients, may be important indicators of health especially near urban areas, but they require sophisticated tools and frequent measurements.

Table 8. Physical and environmental resilience indicators.

Parameter		Importance
Physical and environmental attributes		
	Tides	Large tidal change may reduce thermal stress and increase nutrients in subtidal areas; corals in areas exposed at low tide may be more resistant to high thermal stress, salinity and light.
	Currents	Likelihood of connectivity with other sites; helps maintain cooler water temperatures.
	Wave action	Affects distribution of species and growth form; enhance exchange of water and may maintain cooler temperatures.
	Deep water	Deep water adjacent to reefs may be associated with upwelling of cool, nutrient rich waters; pelagic fish that migrate and feed on reefs.
	Inter- reef distances	Potential for connectivity with adjacent sites.
	Distance from mainland and urban centers	Gradient of anthropogenic stressors and exposure to open ocean conditions. This can be measured using satellite imagery.
	Associated habitats	Proximity, connectivity and size of associated habitats, including grassbeds, mangroves, and algal flats are important in stabilizing sediments, reducing run-off to reef habitats, feeding grounds for reef-associated species, translocation of nutrients, habitat used during different life stages of reef species, and the provision of shelter for juvenile fishes and invertebrates.
Reef attributes		
	Substrate type and quality	Reflects the potential for recruitment and survival of juvenile corals; measures include extent of sedimentation, turbidity, presence of rubble, smooth vs. rugose hardground.
	Reef slope	Proximity of deep water and potential for refuge populations; extensive shallow reef flats may heat up during calm periods and hot, hypersaline water may flow down the reef slope.
	Shading	Above water features and canopy corals that may shade understory corals, enhancing their hesitance to temperature-related stressors.
	Turbidity	Reduces penetration of UV, potentially reducing stress from thermal anomalies; may restrict vertical distribution of corals; turbidity due to resuspension vs anthropogenic run-off have different implications.
	Depth	Affects abiotic parameters (light, temperature, wave exposure), coral composition and growth form and habitats available for reef-associated fishes.
	Compass direction	Angle of incidence of the sun and diurnal changes affect amount of radiation the reef is exposed to; easterly facing reefs may exhibit more light stress than westerly facing reefs.

Oceanographic and Water Quality Measurements

Many key oceanographic parameters can be measured using loggers that are deployed at the habitat of interest. These loggers allow continuous measures for extended periods. Sensors should be deployed in areas of potentially contrasting thermal conditions (e.g., windward and leeward sides of an island). Periodic measurements can also be taken using simple hand held devices, such as a CTD which will provide an instantaneous profile of temperature and salinity from the surface to the bottom. Some CTDs also are capable of recording dissolved oxygen, pH, turbidity, and chlorophyll (fluorometrically) profiles.

- **Temperature:** One of the most common sensors is a temperature meter, which can be deployed for up to 5 years depending on the number of recordings per day (more frequent measurements require more frequent downloading of data (Fig. 37). These are usually deployed on the substrate near coral communities, but can also be deployed on vertical thermistor strings to measure temperature at the surface and different depths and to detect upwelling. The Hobo Water Temp Pro v2 is a reliable and low cost submersible temperature recorder available from Onset Instruments (www.onsetcomp.com/). It can be deployed for up to five years (shorter periods allow more frequent measurements). A sensor capable of recording pressure (depth) can provide useful information on the influence of tidal dynamics on thermocline fluctuations.

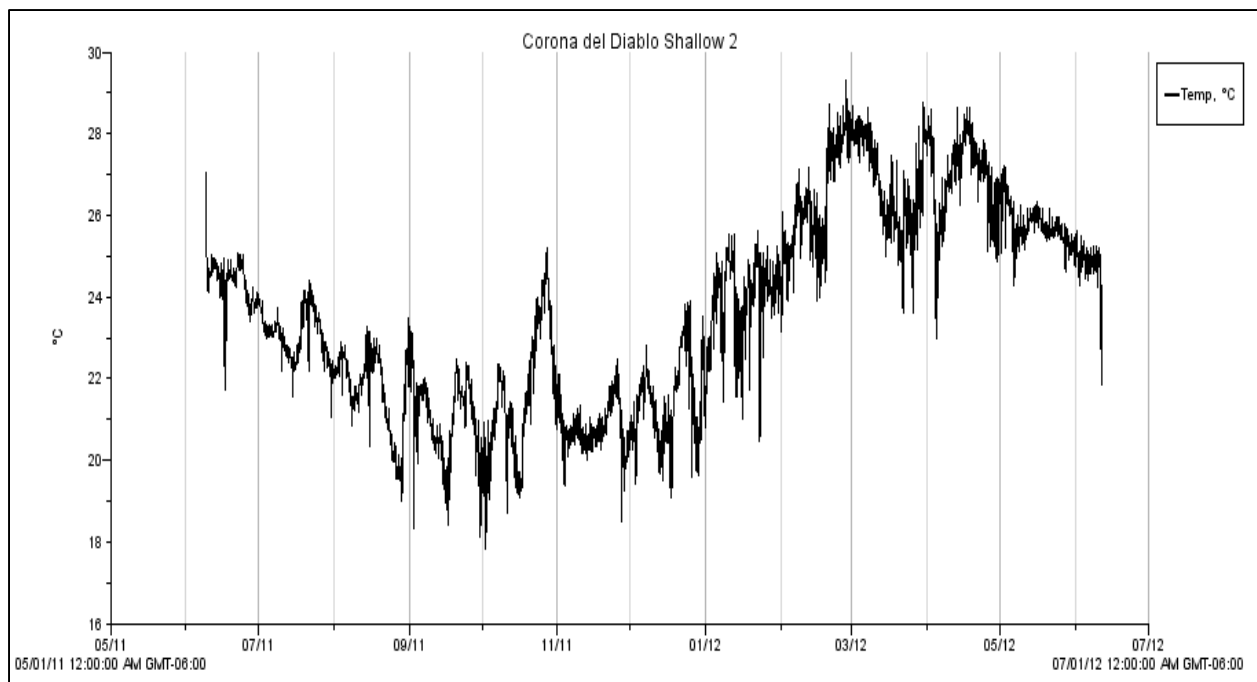


Fig. 37. Variation in temperature at Devil's Crown at 5 m depth over a one year period (June 2011-June 2012). Data provided by Joshua Feingold.

- Light and Chlorophyll:** Sensors to measure light and chlorophyll can be placed on thermistor strings or on the benthos. An inexpensive light data logger (Hobo pendant temperature/light data logger, UA-002-64) available from Onset instruments records relative light intensity on the full, yellow, green and blue spectrums (Fig. 38). Deployed light meters require frequent maintenance to avoid fouling.

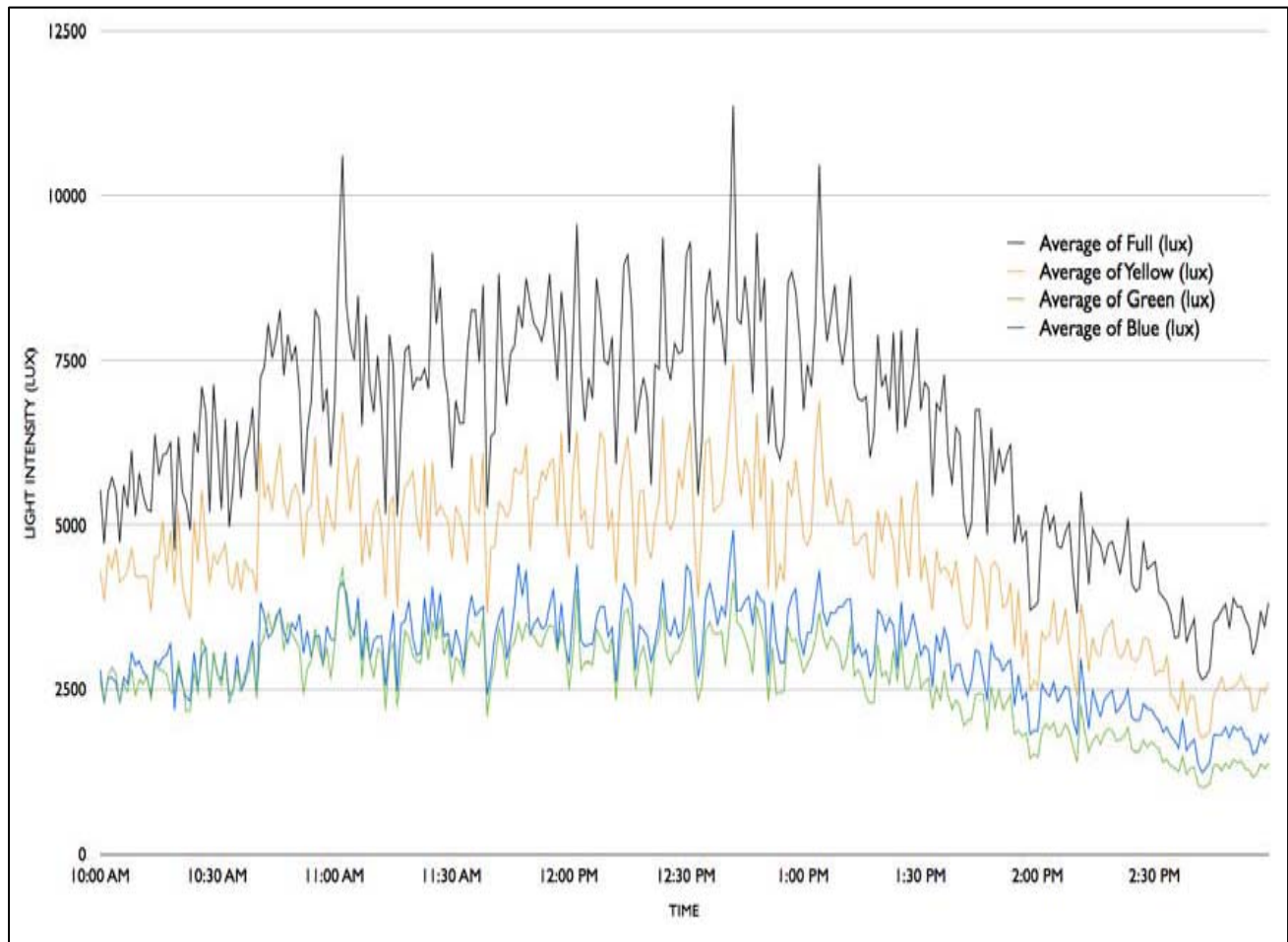


Fig. 38. Average light intensity between 10:00 AM and 02:59 PM on full visible, yellow, green and blue spectrums in Darwin, between 3-7 June, 2012 at 10 m depth. Data from Joao Monteiro, KSLOF Global Reef Expedition.

Salinity: Coral reefs are found in areas with relatively constant salinity that ranges from 29-42 parts per thousand. Surface salinity can drop quickly after extreme rainfall events, and it can increase during unusually warm, calm, doldrum-like conditions due to evaporation. Salinity may also be too low near river discharges and in areas with industry. Salinity can be measured using a refractometer, with samples collected near the surface and within survey locations using plastic bottles. YSI (<http://www.ysi.com/productsdetail.php?CastAway-CTD-49>) makes an inexpensive handheld Deployable CTD with Integrated GPS that provides instantaneous profiles from the surface to the sea floor of temperature, salinity, and sound speed.

- pH:** The acidity of the water is known to affect calcification rates of corals, and the porosity and density of their skeletons. Recent short term measurements of pH show large differences between northern and southern locations (Fig. 39) and even greater differences may occur seasonally in central and southern locations that experience upwelling. including the Sensor to measure pH can be placed on the bottom. A SeaFET Ocean pH sensor (<http://satlantic.com/seafet>) can be deployed for short periods (hours to days) or for extended durations (weeks to months) to depths of 70 m to monitor these variations. The SeaFET is an ion selective field effect transistor type sensor for accurate long-term pH measurements in salt water. It reports pH determined potentiometrically in two different ways. The ISFET potential is measured against a reference electrode bearing a liquid junction (internal reference) and against a solid state reference electrode without a liquid junction (external reference). This provides the user with the ability to assess instrument performance and ultimately achieve a greater understanding of the state of acid/base equilibria in seawater.

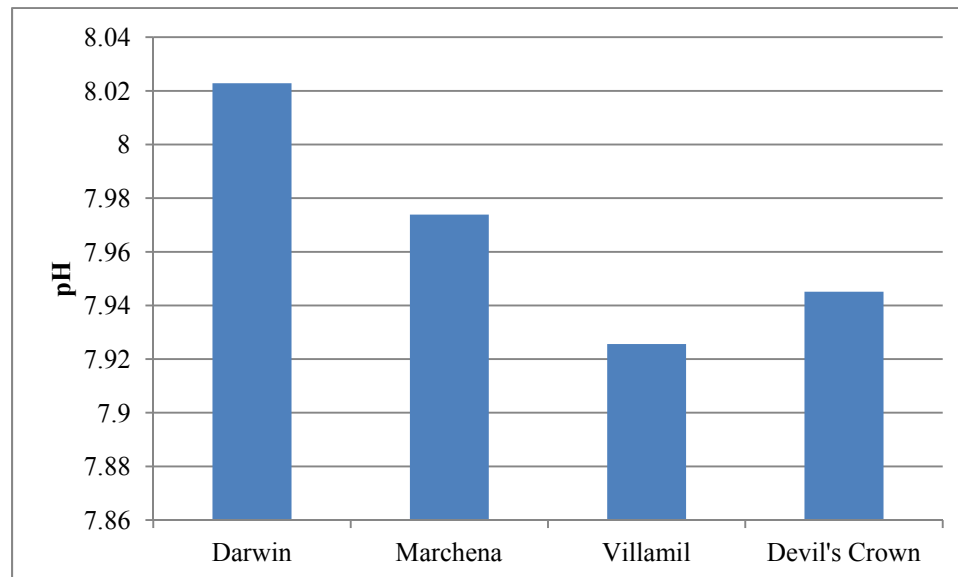


Fig. 39. Variation in pH measured in four locations in the Galápagos at 10 m depth during June 2012 measured with a SeaFET ocean pH sensor.

- Water quality:** Assessment of nutrients (nitrogen and phosphorus compounds), heavy metals, toxic chemicals, pesticides, organochlorine wastes and other pollutants requires sophisticated equipment and high levels of expertise. It can also require frequent measurements and may be very expensive. Due to the complexities associated with water quality monitoring, methods are not described here.
- Turbidity:** Turbidity is affected by the amount of suspended sediments and plankton in the water column. Turbidity increases following storms due to run-off from land and also during

periods of high wave action due to resuspension of fine sediments. A simple estimate of turbidity can be made using a secchi disc. A secchi disc is a round flattened thick sheet of PVC divided into 2 white and 2 black sections. The disc is attached to a rope marked off in 1 meter intervals. The disc is lowered into the water until it can no longer be seen. The length of line deployed into the water is a measure of turbidity. Measurements should be taken at the same time each day (between 10 AM and 2 PM), optimally when it is sunny.

- **Sedimentation:** Sedimentation rates (load of sediment arriving to the reef) can be monitored using sediment traps. These can be made simply from a rebar with attached plastic containers to trap sediment, or with 5 cm diameter PVC pipe that is sealed at the base. The rebar or pipe is inserted into the substrate and a screen is placed over the top to prevent entry of unwanted organisms. It is left in situ for several weeks to months. The jars or PVC pipe are capped and brought into the lab for analysis. The sediment can be dried in an oven, weighed to determine the number of grams of sediment deposited per unit time. The sediment can also be assessed for composition and grain size. More details are provided in English et al. 1997.
- **Currents:** Effect the amount of mixing of water, transport of pollutants, pathogens and larvae, and flushing of a site. General circulation patterns and large scale water current patterns can be determined from the primary literature. Short term semi-quantitative measures can be determined through measurement of dissolution of plaster of Paris (gypsum; CaSO_4) blocks. Blocks can be glued to pieces of PVC or Plexiglas and attached to various substrates at different depths and exposures. The blocks are pre-weighed, immersed in water for 24 - 72 hrs, dried, and reweighed. The loss in weight provides a relative measure of water motion at a site. Measurements of weight loss can be converted to water velocities by using a standardized calibration curve. A curve can be obtained by immersing blocks in standing sea water of the same temperature and salinity and the same water exposed to known velocities, for a defined length of time. It is important to note that this method provides a relative measure of water velocities and direction. For best results multiple blocks must be deployed and each block should have the same shape. Factors affecting dissolution also include temperature, salinity, abrasion from sediments and bioerosion from grazers (Jokiel and Morrisey 1993).

More accurate measurements, including direction and flow rates can be made using an Acoustic Doppler Current Profiler (ADCP) or a Recording Doppler Current Profiler (RDCP). An ADCP measures the water current velocities over a depth range using the Doppler effect of sound waves scattered back from particles within the water column. Data illustrated in Fig. 40 were collected using an Aanderaa RDCP 600 which also allows addition of sensors to measure tides, wave height and period, conductivity, pressure, oxygen, temperature and turbidity.

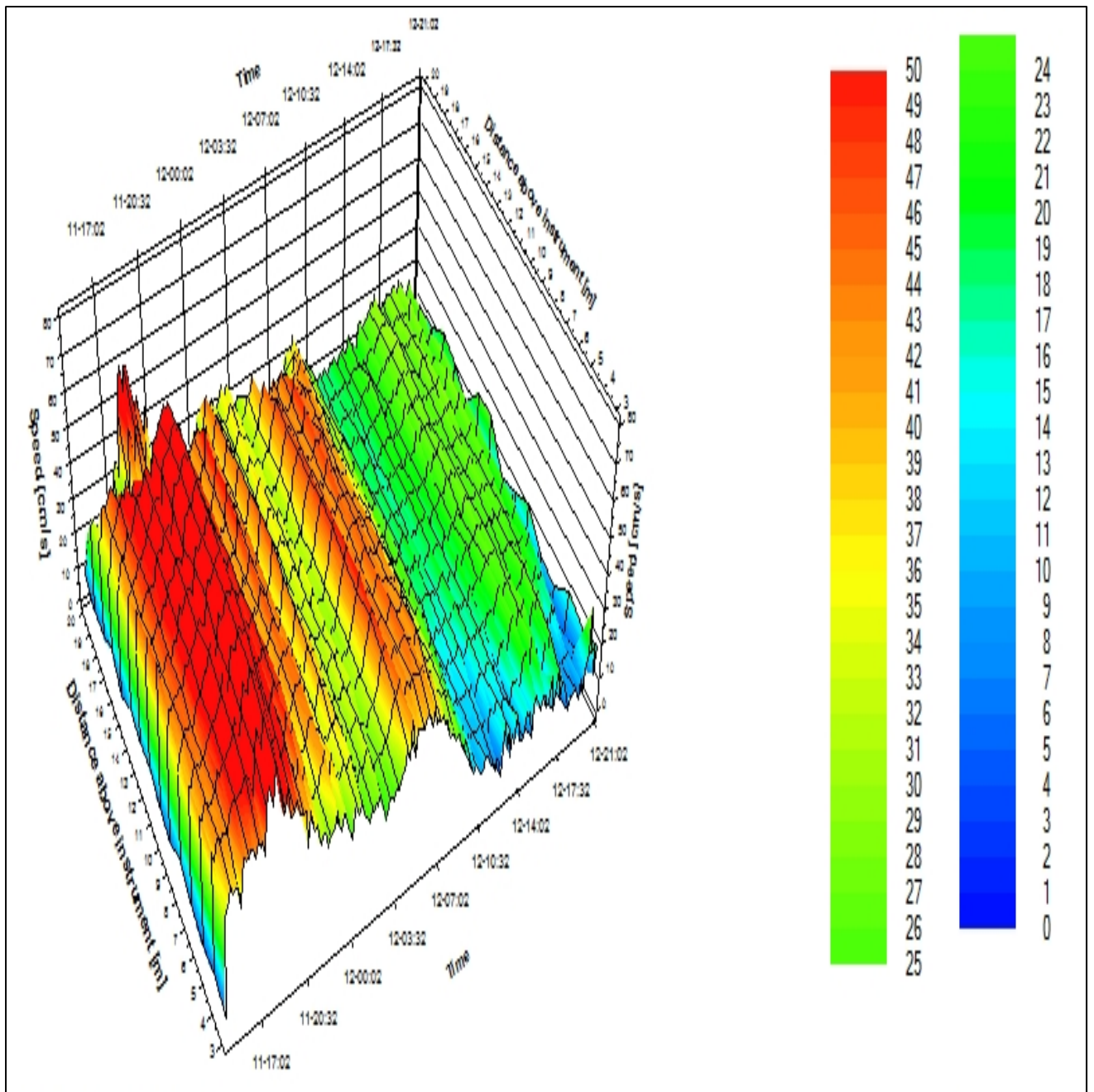


Fig. 40. Current profile (horizontal speed) from the surface to 20 m depth at Darwin Reef, June 2012.

7. Assimilating data

After each dive, the researchers must review datasheets for completeness, legibility, and correct use of codes. All datasheets should include pertinent information such as the observer, date, location, depth, transect number and other metadata necessary to link the information to a particular location or survey. Photographs associated with the recorded data should be labeled and archived to allow direct linkage with the survey location and the specific datasheet.

Data should be entered initially into an Microsoft Excel spreadsheet (or some other spreadsheet) and compiled in a manner to allow exchange between statistical software. All data are initially summarized, and outliers, errors and inconsistencies are identified and corrected. Initial summary statistics and various line, bar and box plots can be created using Excel or a simple graphics package.

Examples of basic information that can be easily calculated to describe the community composition:

- **Abundance:** Total number of colonies (coral) or individuals (fish or motile invertebrate) for all species in a particular group (e.g. all corals).
- **Species abundance:** Abundance of a selected species or proportion (percent) of the total population of all species of the group. These can be graphed using simple bar plots showing number of colonies of each species per unit area.
- **Density:** Number of colonies per square meter of benthos (or # individuals/m²).
- **Species richness:** Number of species occurring in a sample area (e.g. a reef or region). Margalef's species richness (d) can also be calculated as follows: $d = (S - 1) / \log(N)$, where S = number of species; N = number of individuals.
- **Frequency of occurrence:** Proportion of sites where a species is present.
- **Species diversity:** Index of richness and relative abundance. One measure is Shannon Weiner diversity index (H') calculate as follows: $H' = - \sum_i p_i (\log p_i)$.
- **Species evenness:** How close in abundance each species is. This is another index of biodiversity. Pielou's evenness (J') can be calculated from: $J' = H' / \log(S)$, whereas a higher J' = less variation.

Additional information can be calculated on the population structure of the different organisms:

- **Size structure of individual species:** This can include the mean, mode, median size and the variation in size for all individuals in the population. It can be plotted as a distribution of colony (for corals, or individuals of fish and motile invertebrates) abundance versus size using a simple bar graph or box plots.
- **Community structure:** Size distribution of colony abundance or other attribute for all coral species, calculated and plotted as above, including all corals (or fish). This can be plotted as a above showing the percent (or number) of colonies in each size class.

- **Average colony surface area:** Planar surface area can be determined using photoquadrats or photos of individual corals and various software, such as NOVA Southeastern University's CPCE software. Rough approximations of size can also be determined from diameter measurements [$\pi \cdot (0.5 \cdot \text{diameter}) \cdot (0.5 \cdot \text{diameter})$] if the colonies are roughly circular. More accurate measurements require multiple measurements (e.g. length, width and height) and use of formulas based on colony shape (see Bythell et al. 2001; Santavy et al. 2012), although this is quite tricky for branching corals.
- **Percent cover:** For benthic invertebrates and algae, the amount of the bottom covered by a particular organism or group of organisms can be determined from point intercept surveys or phototransects as the total number of points of a certain species divided by the total number of points in the sample.
 - More accurate estimates of coral cover can be determined from phototransects using the sum of the actual measurements of the planar surface area of each coral divided by the total area examined.
 - A second measure of the amount of the reef covered by coral can be determined from the size measurements. Converting the diameter to area allows a calculation of the total area covered by one or all the species of corals. Simple line plots can be made which illustrate the number of colonies (abundance) in each size class versus the area occupied by each size class.
- **Biomass (of fish):** Using length and abundance data from the census, fish biomass of each species at a particular size estimate may be calculated using the formula $W = aL^b$, where **W** is the weight (grams), **L** is the total length (cm), and **a** and **b** are growth constants derived from species-specific length-weight relationships (Kulbicki et al. 1993; Letourneur 1998; Letourneur et al. 1998) and those listed in FishBase (Froese and Pauly 2013). For fish species encountered with no known **a** and **b** values, the constants for their closest relative with the most similar body shape should be used instead. Where fish sizes are estimated as size ranges (i.e. 1-5cm, 6-10cm, 11-20cm, etc.), the mid-point of each size class may then be used as the total length estimate.
- **Biomass (of algae):** A proxy of biomass can be determined from the measurements of algal cover and algal canopy height for macroalgae, cyanobacteria or turf algae simply by multiplying the average cover by the average canopy height.
- **Coral condition:** The amount of partial mortality for corals can be calculated from visual estimates and presented as mean total partial mortality, or the percent partial mortality for each size class (e.g. using a box plot). This can be further subdivided into recent, transitional and old and presented for the entire community or by species to determine if certain taxa are being affected to a greater degree by particular stressors.
- **Prevalence and incidence:** Estimates of the percent of the population affected by a certain stressor (e.g. bleaching, disease, corallivory) can be calculated and plotted by species or community. The total number (percent) affected at a given time (prevalence) or number of new occurrences (incidence) can be determined from monitoring data. Certain acute

stressors (e.g. disease) may require frequent monitoring during the presence of an outbreak to detect new cases (Woodley et al. 2008).

Basic information on reef attributes can also be calculated:

- **Rugosity:** Rugosity can be measured from chain transects. Rugosity is the ratio of the overall length of chain draped over the reef contour divided by the straight horizontal distance between the beginning and the end of the chain. Rugosity is always greater than 1. For example, If a 10 m chain covers 5 m of horizontal distance, the rugosity is $10 \div 5 = 2$.
- **Relief:** Relief is an approximation of rugosity. A rough estimate of relief can be determined by averaging multiple measurements of the height from the substrate to the top of the corals.

Examining relationships between benthic, coral and fish attributes

Clustering of benthic data, coral composition and fish biomass/abundance by site can be examined using multi-dimensional scaling (MDS) followed by similarity profiles (SIMPROF) analysis to determine the factors that contribute most to a particular grouping. Individual contribution (e.g. fish taxa, fish functional groups, coral species) to the similarity of resulting groups (and dissimilarity between groups) can be estimated using the similarity percentage (SIMPER) analysis (Clarke and Warwick 2001; Clarke and Gorley 2006). SIMPER analysis results were visually inspected and biotopes were determined based on similarities, dissimilarities, taxa distribution and relative abundance (semi-quantitative data).

Analysis of Similarity (ANOSIM) testing can also be employed to evaluate the relationship between benthic and fish attributes recorded in different sites. These tests compare sites based upon ranked, species similarity measures. Coral species abundances need to be log transformed to create a Bray-Curtis dissimilarity matrix (d). The greater the dissimilarity between sites, the larger d. The tests yield R-statistics, which serve as a measure of site separation. R-values can range between -1 and 1. R values > 0.75 show complete separation between sites; R values > 0.5 show overlapping but clearly different sites; and R values < 0.25 shows sites that are barely distinguishable from each other. P-values are calculated for each R-statistic using a permuted test of random rearrangement, and comparing the true R-value with the randomly generated distribution. Similarity percentages (SIMPER) were subsequently calculated to examine the percent contribution of each coral or identified category to the measured ANOSIM differences (Clarke and Warwick 2001).

ANOSIM results can be graphically presented using non-metric, multi-dimensional scaling (MDS) (Clarke and Warwick 2001). MDS is an ordination procedure that projects a dissimilarity matrix into two-dimensional space while preserving as much of the variation (distance) between sites as possible. A low stress value is an indicator of low error, similar to a measure of standard deviation (Clarke and Warwick 2001).

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Appendix 1. Research Equipment

1. Recording data underwater

The simplest way to record data underwater is to write with a pencil on waterproof paper. A typical #2 pencil will work, but these often dissolve and are difficult to sharpen underwater. A short golf pencil holds up slightly longer. More preferable are mechanical pencils or plastic pencils containing multiple leads. Data can be recorded directly onto a styrene or polyvinylchloride slate, but this limits the amount of information that can be recorded and requires transcribing the data. The use of waterproof paper allows easy transfer of information. Use of multiple sheets per dive, and a permanent record. The paper is typically attached to the slate (or clipboard, but these rust and the clip deteriorates quickly unless made of aluminum or stainless steel) with rubber bands, stainless steel clips and/or electrical tape.

Pencils: Cost approximately \$4.50 per dozen for mechanical pencils, or \$5.00 for 144 golf pencils. Pencil can be attached to the slate using Latex Rubber Surgical Tubing - 1/4" ID, 5/16" OD, 1/32" Wall

- Paper Mate® Sharpwriter™ Mechanical Pencil # 303-01
- Universal Golf & Pew Pencil, HB, Yellow Barrel, 144 per Box

Paper: Paper can be purchased for \$50-\$80 per 100 sheets, less when bought in bulk. Specific datasheets can also be printed directly onto the paper using a laser printer. Please note that waterproof paper varies – several brands are difficult to write on underwater and pencil is very light. Also water resistant paper will not work well underwater. The recommended brands are:

- XEROX Premium never tear 8.5 x 11" 3.7 mil polyester paper, # 3R12414
- Rite in The Rain #6511 DuraCopy Paper

Rubber bands: Used to attach paper to slate. Conventional rubber bands break easily underwater. Use heavy duty bands such as:

- Alliance Red Packer Band - Size #170 Heavy Duty Rubber Band (7 x 1/4 Inches)

Slates: Slates can be purchased from dive shops, or can be made more cheaply from larger pieces of white PVC plastic. PVC sheets come in a variety of thicknesses and are easily cut with a hacksaw, table saw or circular saw. Home-made slates can be modified to have handles, a hole to attach the surgical tubing or rope for the pencil, rulers, compass, and other modifications. Slates can also curve around your arm. These can be fabricated from two halves of a piece of PVC tubing attached



with Velcro. Ocean Plastic Products also makes slates commercially that are designed to hold two full sheets of never-tear paper, one on the front and one on the back. These slates are a three part construction made from white high density styrene. The two outer panels have openings that are approx 8 X 10 inches. These are attached to the solid middle part of the slate with stainless steel screws and wing nuts. The hold the paper securely in place and allow easy removal of the paper while underwater.

http://oceanplasticproducts.com/Underwater_Dive_Slates.html

2. Conducting transects and quadrats

Transects can be done using fiberglass tape measures, lead line or chains. Conventional open reel fiberglass tape measures are used for fish transects and can be used for benthic/coral transects. The disadvantage of a fiberglass tape for benthic surveys is that it moves around under conditions of surge and it may not lay flat on the bottom. A lead line conforms more to the substrate.

Fiberglass tape measures: For fiberglass tapes ensure the parts are made of plastic, the tape is heavy duty, and there are few metal parts (that rust). It should have a large, well made handle. They are preferably all metric, with metric labels on both sides. If used for benthic surveys, ensure that it is not inches on one side and centimeters on the other as the tape will frequently flip over. Lufkin has a well-made transect tape measure for about \$20 (30 m) or \$30 (50 m).

- Lufkin FM030CME 2-Sided Metric/English 13mm 1/2-Inch Hi-Viz Orange Fiberglass

Lead core line: Lead line should be pre-measured and marked in 10 cm intervals with a permanent marker. Small cable ties of different colors can be secured to the tape measure. Generally, one color is used to mark each meter, and a separate color is used to mark the 10 cm intervals between meters. The ends of the cable tie are cut off close to the line so it does not interfere with deployment or get caught onto other gear. For benthic transects, we usually use a 10 m lead line, with 30-50 cm extra at each end which is tied into a loop to provide a place to secure the line to the substrate. To facilitate storage, deployment, and retrieval, the line is wrapped around a small quadrat (25 cm X 25 cm) which is used to assess recruits.

#20 (20 lb lead, 3/16 inch diameter) or #30 (30 lb lead, ¼ inch diameter) lead core rope. Sold in 300 ft rolls for \$50-\$60. Can be purchased from Nylon Net Company, 845 N Main, Memphis, TN 38107. 901-526-6500; 800-238-7529 ; www.nylonnet.com

Quadrats and meter sticks: Quadrats and meter sticks can be made out of ½ inch PVC pipe, attached with PVC cement and elbows. A 1 m piece of a transect tape can be secured to the PVC pipe with PVC cement for a scale bar. PVC quadrats should have holes drilled into them so they are negatively buoyant, and carabineers can be attached to the quadrat with cable ties (through these holes) to attach to your BC when swimming underwater.

Appendix II. Benthic Data Sheet

Surveyor:		Site:		Date:		Time:		Temperature: °C/ °F					
Record macroalgal heights for a total of 2 transects/site.													
Compass Bearing:		Start Depth: ft/ m				End Depth: ft/ m							
motile invert													
Transect #.	0 m	1 m	2 m	3 m	4 m	5 m	6 m	7 m	8 m	9 m	#	≤ 2 cm	2-4cm
0 cm											1		
10 cm											2		
20 cm											3		
30 cm											4		
40 cm											5		
50 cm													
60 cm													
70 cm													
80 cm													
90 cm													

Compass Bearing:		Start Depth: ft/ m				End Depth: ft/ m							
motile invert													
Transect #.	0 m	1 m	2 m	3 m	4 m	5 m	6 m	7 m	8 m	9 m	#	≤ 2 cm	2-4cm
0 cm											1		
10 cm											2		
20 cm											3		
30 cm											4		
40 cm											5		
50 cm													
60 cm													
70 cm													
80 cm													
90 cm													

Compass Bearing:		Start Depth: ft/ m				End Depth: ft/ m							
motile invert													
Transect #.	0 m	1 m	2 m	3 m	4 m	5 m	6 m	7 m	8 m	9 m	#	≤ 2 cm	2-4cm
0 cm											1		
10 cm											2		
20 cm											3		
30 cm											4		
40 cm											5		
50 cm													
60 cm													
70 cm													
80 cm													
90 cm													

Substrate codes	Coral codes	Algae codes	Algae genera	Invert	Motile invert
DC = dead coral	use first letter of genus	M = macroalgae	BRY = Bryopsis	GORG = seafan	GAS=Gastropoda
RDC = recent dead coral	and three letters of species	T = turf	CAU = Caulerpa	OCTO = soft coral	AST=starfish
BL = bleached coral	PSTE=Psammocora stellata	CCA = crustose coralline	COD= Codium	ANM = anemone	CUC=sea cucumber
HG = hardground	PDAM= Pocillopora damicornis	E = erect coralline	DER = Derbesia	SP = sponge	URC=sea urchin
FR = fused rubble	PCLA=Pavona clavus	CY = cyanobacteria	CHA = Chaetomorpha	RSP = rope sponge	LOB=lobster
R= loose rubble	PLOB=Porites lobata	TS = turf + sed.	CLA = Cladophora	TSP = tube sponge	CRB=crab
S = sand			RHI = Rhizoclonium	BSP = barrel sponge	
C = live coral	Condition		SAR = Sargassum	ESP = encrusting sponge	
I = invert	ID disease, predation, bleaching, or other compromising feature		ULV = Ulva	ANT = Antipatharian	
				ZOAN = Zoanthus	

Appendix IV. Fish Survey Sheet

Location:		Date/Time:					Name/Buddy:	Dive No:					
Depth:	Transect No.							0-5	6-10	11-20	21-30	31-40	>40
Min:	0-5	6-10	11-20	21-30	31-40	>40	Seabass						
Angelfish							Bacalao						
King							Barred Serrano						
Butterflyfish							Flag Cabrilla						
Barberfish							Leather Bass						
Threebanded							Mottled Soapfish						
							Pacific Creolefish						
Grunt							Panama Graysby						
Burrito													
Galapagos							Snapper						
Mojarra							Amarillo						
							Barred						
Parrotfish							Blue-and-Gold						
Azure							Glasseye						
Bicolor							Pacific Dog						
Bluechin													
Bumphead							Surgeonfish						
							Razor						
Damselfish							Yellowtail						
Gal Ringtail							Goldrim						
Giant													
P. Sergeant Mjr							Panamic Soldierfish						
Scissortail							Mexican Hogfish						
Yellowtail							Mexican Goatfish						
							Pelican Barracuda						
Hawkfish							Cortez Sea Chub						
Coral							Pacific Porgy						
Giant							Moorish Idol						
Longnose							Reef Cornelfish						
							Chinese Trumpetfish						
Jack							Balloonfish						
Almaco Jack							Porcupinefish						
Bigeye Trevally							Seahorse						
Black Jack													
Bluefin Trevally							Puffer						
Green Jack							Bullseye						
Rainbow Runner							Guineafowl						
Steel Pompano							Spotted Sharpnose						
Wrasse							Stone Scorpionfish						
Chameleon							Eels						
Cortez Rainbow							Finespotted						
Spinster							Panamic Green						
Sunset							Galapagos Garden						
							Ray						
Triggerfish							Diamond						
Black Durgon							Marbled						
Finescale							Spotted Eagle						
Orangeside							Shark						
							Galapagos						
Hamlet							Sc Hammerhead						
Seabream							White-Tipped Reef						
Unicornfish													

