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TITLE XII
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EARTH OBSERVING SYSTEM AND CORAL REEF FISHERIES

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ABSTRACT

Coral reefs could supply more than one-fifth of the fish caught in developing countries. However, the management of reef fisheries is hampered by a lack of accurate knowledge of the extent, status, and dynamics of coral reefs and their resources. Currently available satellite data is of limited utility at depths below a few meters.

The Earth Observing System (EOS) of the mid-1990's will offer a broad range of data which will be useful in studies of coral reef fisheries. The HIRIS sensor will offer data from more than thirty wavelength bands which penetrate seawater. This instrument should be able to discriminate among broad groups of photosynthetic pigments, particulate content, and a variety of benthic fish habitats. Other instruments will be useful in monitoring variability in the environments of coral reefs by quantifying wave heights, sea surface temperatures, solar incidence, precipitation, and a variety of other factors. However, the complexity of reefs, and the volume and complexity of the data require preparatory research on ways to automate the analyses. Current information on the relationships between fish habitat variables and fishery production is limited. Low-cost aerial verification survey methods are needed to enable coral reef scientists in developing countries to utilize EOS data. Some activities of

the U.S. AID Fish Stock Assessment Collaborative Research Support Program in the Philippines are focused on these problems.

INTRODUCTION

The use of satellite imagery in fisheries has generally involved seeking correlations between fish production and either sea surface temperature or inferred phytoplankton production (Amidei 1983, Cornillon et al. 1986). In tropical regions, however, an important contribution of remote sensing to fisheries management may lie in the analysis of shallow water fish habitats and the environmental variables which affect them.

Coral reefs have the potential to contribute approximately 20-25% of the fish available to developing countries (McManus 1988). Recent studies indicate that finfish may contribute only 30-40% of the food available on heavily exploited reefs (McManus et al. in press). When gathered products such as edible invertebrates and seaweeds are accounted for, the potential supply of protein from coral reefs for developing countries may be far higher. As human populations on coastal areas rise and new reefs enter the realm of the over-exploited with accelerating rapidity, it becomes increasingly important that reef resources be accurately inventoried, evaluated, and protected under optimal management schemes.

Potential harvests from coral reefs are generally determined by extrapolating known production figures to estimates of the aerial extent of reefs in a given region. This approach has been used at the local (del Norte et al. in press, Menez et al. 1988, McManus et al. 1988), national (Carpenter 1977), and global scales (Smith 1978, Stevenson and Marshall 1974, Munro and Williams 1985, McManus 1988). The usual source for estimates of reef area are maps and charts. While it is usually assumed that these sources are subject to some inaccuracies, the magnitude of these inaccuracies warrants emphasis. Reefs in tropical coastal areas are often copied onto maps from aerial photographs. This coverage is generally incidental to aerial surveys of the land, and the photographs are often obscured by sun glint from the water. The portions of reefs which appear in these photographs are often limited to the upper few meters of reef flat and reef crest, which may be poor predictors of the deeper zones of the reef. More significantly, the number of reefs which have reef flats and other shallow features may be small relative to the number of reefs which do not. These reefs are generally charted from depth soundings, which in many areas of the tropics are still restricted to data from patchy surveys of the 19th century or military surveys in selected areas during World War II. It is likely that estimates of reef area are inaccurate by a factor of two or more.

Current Coral Reef Remote Sensing Efforts

Remote sensing data can greatly improve the estimation procedures. Multispectral Scanning Sensor (MSS) and Thematic Mapping (TM) data can yield maps to a 20 m depth in clear waters. The differential depth penetration of data in available bandwidths can be used in a process of density slicing to yield crude depth contours (Bina et al. 1978, Jupp et al. 1985b). For some reefs of well-known ecological structure, it is possible to break the aerial estimates down into specific reef habitat types, such as reef flat, lagoon, reef slope, etc. (Bina et al. 1978, Bina and Ombac 1979, Jupp et al. 1985a, Jupp et al. 1985b, Jupp 1986, Claasen 1988, Reichelt and Bainbridge 1988). Given appropriate data on fish production and catch composition within a particular habitat type, evaluations of reef fishery potentials can be made at a more specific level (del Norte et al. in press).

Fish communities differ substantially between the various habitats associated with coral reefs. In its natural state, a fringing reef in Southeast Asia may include a mangrove forest along the shoreward portion of the reef flat, patches of open sand, regions of short seagrass dominated by _Thallassia hemprichii_, areas of long seagrass dominated by _Enhalus acoroides_, deeper lagoonal areas dominated by sand, seagrass, or lagoonal corals, a backreef zone with microatoll corals, brown algae zones dominated by *Sargassum* spp. or *Turbinaria* spp., a calcarious reef crest and boulder zone, a reef slope covered by patches of hard coral, soft coral, or algae, perpendicular sandy channels, a steep coralline wall, and a sand talus slope at 20-30 m. Each of these habitats supports a particular assemblage of fish species, each of which differs in its catchability, fishery production and economic return.

Reefs vary considerably in the proportional extents of each zone. Some reefs exhibit all of these features, but most reefs are missing one or more zones. Reefs in Australia have very little seagrass on the average (Maxwell 1968). Fringing reefs in the Philippines tend to be dominated by seagrass (McManus 1988). Fishery potential estimates are often based on studies of coral dominated areas (Alcala 1981, Alcala and Luchavez 1982), although a few estimates from seagrass dominated reef flats are now available (del Norte et al. in press, McManus 1989, Menez et al. in press). The problem of relating habitat types to fish composition and fishery production is a focus of the on-going U.S. AID Fish Stock Assessment Collaborative Research Program (FSA-CRSP) in the Philippines. Further work on this problem in other biogeographic areas is needed, to provide a basis for improved estimations of potential reef resources.

Ideally, one would be able to estimate the resource potential of a reef from knowledge of its fish habitats and the production expected from each. However, current remote sensing technology makes this difficult. On land, automatic clustering routines or standard algorithms often clearly distinguish among major ecological zones. On coral reefs, this procedure is often complicated by the overwhelming effect of water depth on classification procedures. In Australia, several years of research, including extensive aerial and underwater verification surveys, have led to procedures which are used to automatically map portions of the Great Barrier Reef (Claasen 1988, Jupp et al. 1985a, Jupp et al. 1985b). Part of the success of this enterprise is attributable to the high correlation between structural features and ecological zones on these reefs (Jupp et al. 1985a). A typical reef of this system includes a reef flat and lagoon surrounded by a steep reef slope and wall. Most of the horizontal area of the reef is comprised of a very shallow sandy reef flat with raised features covered by corals or seaweeds.

The FSA-CRSP study of the Bolinao Reef Complex in the Philippines reveals an entirely different situation. The reef flat in this study is covered with seagrass broken by sandy lagoonal channels and irregular patches of coral, sand, mud or seaweed. The seagrass beds are extremely patchy, varying from low to high density, and from fairly regular dispersion patterns to very clumped patterns. The designation of bottom dominance is highly scale dependent. A place which appears to have only an occasional clump of grass to an underwater observer may seem to be a continuous seagrass bed from an aerial photograph. These seagrass beds exhibit little relation to topography. Because of this complexity, automatic classification procedures generally yield confusing patterns reflecting combined effects of depth, seagrass density, and substrate reflectance. Additionally, the reef flat is less than half of the reef area in the complex. The reef slopes are hilly and irregular, extending outward in horn-like formations.

We have been able to map this area to a minimally useful level with MSS data, by using supervised clustering in conjunction with extensive surveys underwater, from boats, and from an ultralight aircraft. The latter has been invaluable in identifying mesoscale features on the images which are not discernible at small scales. The seagrass area has been successfully delineated by seeking training areas for the classification procedure which yield maps corresponding to information obtained from the ultralight. This subjective procedure of iteratively refining maps based on frequent aerial surveys is useful for purposes of local area determinations, but would not be feasible for large area classifications.

The forereef area delineated by density slicing corresponds closely with that found by supervised classification. Both have been evaluated by spot checks and chart information, and the accuracy is believed to be within a few tens of meters horizontally. This success is partly attributable to the fact that the reef edge is bounded by a wall dropping from approximately 15 m until from 25 to 30 m in most areas. Therefore, the depth penetration of the deeper band does not greatly affect the delineation of the reef slope.

We can accurately delineate mangroves, the seagrass covered reef flat, the non-seagrass reef flat, muddy areas, the lagoon, the intertidal sand areas, the reef crest, the upper reef slope to 5 m, and the lower slope to 20 m. Beyond this, we cannot yet discriminate ecological habitats.

The most important limitation is the inability to distinguish between living and dead coral. The study area has been subjected to a considerable amount of blast fishing and poisoning, and 50-60% of the coral in some areas has been killed (del Norte et al. in press). The MSS data does not permit us to delineate and quantify this effect, which is believed to have a substantial influence on fishery estimations.

Another limitation is our inability to use satellite data to relate variations in the fish community and production with environmental factors. Ideally, we would use images from TM and SPOT data to evaluate seasonal changes. Data from the Advanced Very High Resolution Radiometer (AVHRR) and the Coastal Zone Color Scanner (CZCS) are available at resolutions approximating 0.8 - 4 sq.km., which can be useful in defining very general patterns of temperature and productivity in the area of reef.

We have so far been hindered in using this data by the high expense of obtaining repetitive imagery, and the lack of a microcomputer analysis system which can conveniently handle a broad enough range of analyses and data formats. However, a single AVHRR image which was sent to us as an advertisement has revealed an intriguing vortex pattern near the study area, which, if seasonally recurring, could have implications for entrainment of larval reef fish and the timing of reproduction as it has in other areas (Munro and Williams 1985).

The Earth Observing System

A vastly improved array of satellite sensors will be available by the mid-1990's. The Earth Observing System (EOS) is expected to include an initial configuration of 33 instruments, and later additions of at least seven others

(EarthQuest 1988). The system is part of an international effort involving principally the U.S. National Aeronautics and Space Administration (NASA), the National Oceanographic and Atmospheric administration (NOAA), the European Space Agency (ESA), and the Government of Japan. EOS has been designed to work in conjunction with a variety of other satellite systems scheduled to operate concurrently, such as the Geostationary Operational Environmental Satellite System (GOES) and the Tropical Rainfall Explorer Mission (TREM) (Butler et al. circa 1987).

This report will consider a selected subset of these instruments of particular interest in coral reef fishery management. The anticipated capabilities of each instrument in EOS are described in a series of publications available from NASA (NASA 1988, Butler et al. 1984, Butler et al. ca. 1987, Esais et al. 1986, Goetz et al. 1987, Curran et al. 1987, Carver et al. ca. 1987, Bindschadler et al. 1987). None of these instruments was designed specifically for use in coral reef research, and little or no mention is made of these ecosystems in the official documentation. However, their potential role in coral reef science can be inferred from scenarios involving other systems such as inland aquatic systems (Melack 1984, Butler et al. ca. 1987) and the open ocean (Abbott 1984, Buter et al. cal. 1987). The instrument descriptions below are summarized from the NASA references, and concentrate on aspects of interest to this study.

High-Resolution Imaging Spectrometer (HIRIS)

A major limitation of current high-resolution remote sensing systems is in the number of wavelength bands to which they are sensitive. The MSS data consists of four bands at 80 m resolution, of which only two penetrate below a few meters of water. TM data consists of seven bands at 30 m resolution, and SPOT includes three spectral bands at 20 m and one panchromatic band at 10 m resolution. This severely limits the use of these instruments for shallow water mapping. HIRIS will include 192 bands, covering virtually the entire visible spectrum. Of these, at least 30 will fall in the range of .4 to .7 micrometers, indicating useful underwater penetration. The resolution will be approximately 30 x 30 m horizontally, which will reveal many of the larger features of the reef.

One criteria for selecting the band ranges and widths was to permit discrimination among photosynthetic pigments. The instrument is expected to permit the grouping of phytoplankton into a few broad groups, and to allow the determination of the phytoplankton and non-phytoplankton components of suspended matter in shallow waters. This same feature should enable the determination of living from dead coral, by differentiating between the reflectance values of zooxanthellae in coral tissues and those of the filamentous algae which characteristically settles on dead coral. The broad range of depth penetrating bands will be useful in producing detailed contour maps through density slicing, which can be compared with data on bathymetric features available from the SAR instrument. HIRIS will produce improved analyses of features currently associated with Landsat studies, including ecological zonation, geological structure, cloud cover, and perhaps certain pollution events such as oil spills. The instrument will have a tilting capability, useful in minimizing glare.

The full range of usefulness of this instrument is not likely to be fully explored until long after activation. This same broad utility, however, may lead to scheduling difficulties. The high resolution of the instrument and pointing capabilities are intended to facilitate periodic research work scheduled in advance. The data transmission limitations will require that only a fraction of the total band range can be active at one time. In particular, the configuration of the instrument for geological studies on land may differ considerably from an optimal configuration for marine research.

<u>High Resolution Imaging Spectrometer - HRIS</u>

This is an ESA instrument with a spectral range of have a minimum of 10 selectable bands. It will be tiltable to avoid glare. It is in many ways comparable to HIRIS except for its expected maximum data rate which will be less than half of that of HIRIS. It may be particularly useful in studies of finer scale reef features, and in avoiding scheduling conflicts with HIRIS.

Synthetic Aperature Radar - SAR

This imaging radar system will operate at 1.25, 5.3, and 9.6 Gigahertz frequencies, will provide selectable polarization and incidence angles from 15 to 55 degrees, and will offer horizontal resolutions of 25, 100 and 500 m. For oceanographic use, it is expected to provide information on current boundaries, frontal boundaries, eddy fields, cold water regions, internal waves, bathymetric features, and the surface wind field. Coral reef zonation is highly dependent on the effects of waves and currents on the reefs (Done 1983, McManus et al. 1981). Coral reef fish in some areas are suspected to time reproductive activity to coincide with oceanographic entrainment activities (Munro and Williams) or local upwelling (Pauly and Navaluna 1983). Data from this instrument will provide a basis for much further research in this area.

Moderate-Resolution Imaging Spectrometer - MODIS

This is a pair of instruments which are particularly well-suited for oceanographic studies at the meso- to global scale. The MODIS-N (nadir) covers 40 channels at 500 - 1000 m resolution perpendicular to the surface. The MODIS-T (tilt) will cover 64 visible and near infrared channels at a ground resolution of 1000 m at rotations of 50 degrees off nadir. The two sensors will provide information on distributions of sea-surface temperature, chlorophyll, dissolved organic matter and suspended sediments, as well as a variety of cloud and other atmospheric parameters. Although the resolution will be too coarse for reef mapping, the instruments will provide regular coverage of relevant oceanic conditions in the vicinity of reefs (and everywhere else) every few days. This information can be contrasted with periodic data at higher resolutions, and correlated with fish reproduction, recruitment, migration, and variability in abundance over time.

Medium Resolution Imaging Spectrometer - MERIS

This ESA instrument is basically comparable to the MODIS-T, and may replace or supplement it in the initial operational configuration (EarthQuest 1988).

Scatterometer - SCATT

This is a microwave system developed to measure wind stress at the sea surface. The data will be generalized over two parallel swaths, each covering from 120 to 700 km on either side of the satellite as it covers the earth every two days. Wind speeds will be measured to 2 m/s and directions will be resolved to 10 degree angular resolution. This instrument is of interest to reef scientists primarily in providing data on very general conditions in the vicinity of reefs and is complementary to the higher resolution data from SAR.

Altimeter - ALT

This radar system will provide data on ocean topography to within 3 cm. It is expected to measure wave heights to within 0.5 m error (or 10% if larger), and surface wind speed to within 2 m/sec for velocities of 1-18 m/sec. A knowledge of the geoid can be employed to determine bathymetry, although this is subject to local gravity anomalies which may limit its resolution.

Solar UV Spectral Irradiance Monitor - SUSIM

This instrument measures solar energy incident on the

Earth, and can be used with information on atmospheric conditions to determine energy levels incident in the general area of a reef.

Lidar Atmospheric Sounder and Altimeter - LASA

This laser system will measure a broad range of atmospheric variables important in determining the amount of solar energy reaching the Earth's surface in a given area. The system will use light detection and ranging (Lidar) technology to measure various aspects of water vapor in the atmosphere, cloud characteristics, and aerosols. This instrument is scheduled to be added sometime after launch.

Advanced Microwave Imaging Radiometer - AMIR
Advanced Medium Resolution Imagery Radiometer - AMRIR
Advanced Microwave Scanning Radiometer - AMSR
Advanced Microwave Sounding Unit - AMSU

These instruments will measure surface temperature and variables in the atmosphere important in determining the level of insulation at the sea surface. A variety of other instruments in the EOS package could also contribute to this task.

__Tropical Rainfall Measuring Mission - TRMM__

This package of instruments is not included in the EOS package, but will be contemporaneous and highly complementary to it. The package will produce a set of 30-day average rainfall measurements over 5 x 5 km areas. It will consist of a cross-track scanning multichannel passive microwave radiometer, a cross-track scanning two-frequency precipitation radar, and an AVHRR (EarthQuest 1988). Rainfall is suspected to be an important variable in the timing of marine reproductive cycles, particularly in tropical areas where seasonality is often determined by rainfall more than by temperature. The periodic flooding of shallow water marine areas may also be of importance in fishery studies.

__Geostationary Operational Environmental Satellite System (GOES)__

This package is distinct from the EOS system, but complimentary in that it provides data from platforms which are stationary with respect to the Earth. This system is of interest here because it hosts a variety of instruments which provide data for the calculation of insulation, and precipitation over portions of the surface.

Preparing for EOS

The satellite sensors described above will provide an unprecedented ability to inventory coral reefs, to evaluate fish habitats associated with the reefs, and to investigate the environmental conditions affecting the reefs and their fish communities over time. One possible approach is summarized in Table 1. However, the array of projected sensors is broad enough that only post-launch experimentation will lead to the use of optimal combinations.

In the remaining years before the Earth Observing System is implemented, there are a variety of research tasks which will enable coral reef fishery scientists to make better use of the system. These tasks involve improving fishery estimations, data processing, and verification procedures.

Any evaluation of the dynamics of an ecological community should be based on data gathered over a period of time which is long relative to the life spans of the organisms in the community (Connell and Sousa 1983). The life spans of coral reef fish range from a few months to a few decades, but the average fish probably lives one or two years. Maturity is generally reached in less than a year, and spawning often occurs once or twice annually (Munro and Williams 1985, Longhurst and Pauly 1987). In a heavily exploited reef, population turnover times can be as high as twice a year (del Norte and Pauly in press). Thus, the dominant component a reef fish community can pass through as many as one or two generations each year. In order to understand the dynamics of the fish populations and communities with a reasonable degree of confidence, it would be necessary to evaluate each community for at least five to ten years.

Table 1. Applications for Earth Observing System and other future satellite sensors in coral reef fishery research. Abbreviations are in the text.

Task	Instruments
High Resolution -- Measurements by Arrangement	
Inventory of Reef Areas	HIRIS, HRIS
Bathymetric Mapping	HIRIS, HRIS, SAR
Ecological Zonation	HIRIS, HRIS
Bottom Cover Estimation:	HIRIS, HRIS
Coral, Seagrass,	
Red, Brown, Green Algae	
Sand, Rock, Rubble, Silt	
Adjacent shore vegetation	
Bottom Heterogeniety	HIRIS, HRIS, SAR
Suspended Matter	HIRIS, HRIS
Dissolved Organic Matter	HIRIS, HRIS
Phytoplankton Production	HIRIS, HRIS
Pollution events (oil, etc.)	HIRIS, HRIS
Local cloud cover	HIRIS, HRIS
Wave Action	SAR
Low Resolution -- Coverage Every Few Days	
Phytoplankton Production	MODIS, MERIS
Particulate Content	MODIS, MERIS
Sea Surface Temperature	MODIS, MERIS, AMIR, AMRIR, AMSU, others
Wave Action	SAR, ALT
Surface Wind Stress	SCATT, ALT
Currents	ALT
Insulation	SUSIM, MODIS, MERIS, AMIR, AMRIR, AMSU, LASA, GOES, others
Rainfall	TREM, GOES, others

There is a vast array of reef types and forcing functions, and a high probability that combinations of habitats have effects on the fish community in addition to those predictable from aerial estimates of the habitats alone. This means that a broad variety of reef types subjected to a range of different forcing functions must be evaluated before confident extrapolations can be made. This is as important for extrapolations of simple properties, such as the mean biomass of fish on a reef, as it is for more complex properties such as the production of a set of assemblages given a set of fishing gears. Before the satellites are to be used effectively for evaluating the resource potentials of reefs, it would be important to have a more reasonable pool of long-term fishery studies on which to base early extrapolations. Once the satellites are in place, they will provide a basis for further long-term and broad area studies to improve our conceptual and quantitative models of the dynamics of fish and fisheries on reefs. This may lead us ultimately to the ability to manage the catch composition and fishery production of reefs, and to find the optimal balance between the needs for conservation and exploitation.

Two major concerns of the Eos program are that means be found to optimally extract useful information about the Earth from the data, and that the large and complex data sets be processed in such a way as to make the information available to the scientific community as a whole. From the analytical side, coral reef remote sensing is still in its infancy. There is a need for a concerted effort to develop effective algorithms to define reef parameters, so that we can avoid the vagaries of applying classification procedures to individual reefs as though each was an entirely new problem. In particular, the effects of water depth and composition must be more knowledgeably separable from the effects of benthic reflectance. This will require both field observations involving radiometers, and further work on the reflectance and transmissal properties of shallow marine waters.

The data handling problems of Eos in general are immense. Those involved in assimilating large amounts of highly focused data from scattered areas of the tropics will be staggering. The data base systems must be designed to permit the distribution of a broad variety of data to a coral reef scientist on a large number of very small, specifically delineated areas. In most cases, this must be done at a level of cost to the researcher which will be negligible by U.S. standards. Most coral reefs are in developing countries, and most coral reef scientists operate on extremely low budgets. One of the major factors currently limiting the use of remote sensing data is the cost, which for a single SPOT or TM image often exceeds a researcher's annual salary (1500 to 3000 USD in many countries). The data must be analyzable on a microcomputer, because in many countries the annual budget for marine research is roughly equivalent to or less than the cost of a reasonable mainframe computer. With the right combination of data preprocessing and reduction (Cornillon et al. 1987), expert systems and high-density media, the data distribution problem can be minimized. However, current microcomputer packages for analyzing satellite data by no means incorporate the current state of the art in processing data, and much work must go into keeping the state of the art accessible to a wide range of scientists through user-friendly systems.

With regard to on-site verification, the fact that most coral reefs are in developing countries is again significant. In a given country, the cost of operating an average commercial airplane is prohibitively high. However, while most commercial aircraft exceed 150,000 USD in purchase cost, there are aircraft, generally homebuilts or ultralights, for 5,000 - 50,000 USD. The initial experience of the FSA-CRSP with the use of an ultralight indicates that an engine of 50 hp is a minimal requirement for use during 50% of an average month. This limits useful aircraft to a minimal cost of approximately 8,000 USD.

It is worthy to note that the most popular production model airplane of all time was constructed of Irish linen and doping compound on a simple aluminum frame, and had a 40 hp engine. The modern ultralight with space-age sailcloth, aircraft aluminum alloy frame, and a 50-65 hp engine is far safer. However, the availability of ultralights without these features has caused insurance companies worldwide to be distrustful of the aircraft, and the unavailability of insurance is one of the greatest obstacles to their use by government institutions. Studies by the FSA-CRSP have indicated that an ultralight with floats is an excellent platform for aerial verifications of satellite maps. The aircraft is regularly operated at 50 kph at altitudes from a 10 to 1,000 m. This capability can be surpassed only by helicopters, which cost at least two orders of magnitude more to operate and maintain. Unlike helicopters, ultralights can be fitted with ballistic parachutes to bring down the entire aircraft safely in the event of a mishap.

At even further cost reductions, researchers requiring only limited aerial survey work can use kites or balloons to carry cameras.

Conceivably, a remote controlled aircraft with water take-off and landing capabilities would be more flexible in its applications. Feasibility experiments under the FSA-CRSP demonstrated that a one-quarter scale aircraft on floats could be used to take photographs from altitudes of a few hundred feet. However, the skill in operating such an aircraft was much greater than that required for operating an ultralight. Remote-controlled aircraft are used increasingly in forestry and military reconnaissance work, and a more suitable model could probably be adapted to coral reef work given a budget of a few thousand dollars and at least a year of development time.

As low-cost aerial survey work becomes more generally available to coral reef scientists, work on the remote sensing of coral reefs will be greatly facilitated. Aircraft are essential to provide the intensive on-site verification needed for confident satellite analyses of reef features. They could also be used to obtain radiometric readings on which to base algorithms for automatic analyses of coral reef resources. This automation will be essential in the application of data from the Earth Observing System to broad-area long-term studies of coral reef fisheries.

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