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Project Name: CoBOP Coral Reefs: Optical Closure of a Coral Reef Submarine Light Field.

Principal Investigators: Charles S. Yentsch and David A. Phinney
Bigelow Laboratory for Ocean Sciences
McKown Point
W. Boothbay Harbor, ME 04575
email: cyentsch@bigelow.org; dphinney@bigelow.org
phone: 207-633-9600
fax: 207-633-9641

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SCOPE OF RESEARCH

The primary productivity of coral reefs is believed to be near the theoretical maximum for natural ecosystems on earth (see Ryther, 1959). This high productivity results primarily from a benthic system of attached macroalgae, seagrasses and algal symbionts (zooxanthellae) packaged within coral animals. Research has demonstrated that reef communities are complex ecosystems exhibiting high species diversity. It has also been shown that the photosynthetic response of zooxanthellae within individual corals is identical to that observed in terrestial plants and algae (Porter, 1980: Muscatine, 1980). High concentrations of algal exudates released by the zooxanthellae are almost entirely consumed by the coral animal host. Closely coupled to this 'packaged' photosynthesis is the process of calcification which forms the skeletal structure of the reef. Clear overlying waters are comparatively depauperate in terms of phytoplankton production due to low nutrient concentrations.

The high diversity of 'photosynthetic packages' and their spatial positioning on various substrates complicates the measurement of community production at scales greater than one meter. For areas less than one square meter, *in situ* production has been measured on individual coral formations. Whole reef estimates have been made from changes in oxygen content in waters flowing across reefs (Hatcher, 1988). We believe that optical techniques can be used to estimate productivity on scales less than one square meter to thousands of square meters by accounting for photons entering the ocean from incident solar irradiance and penetrating the overlying waters to be absorbed, reflected or re-emitted as fluorescence by benthic surfaces. To complete such a photon budget is to achieve optical closure of the reef ecosystem. In its most simple sense, the optical approach can be thought of as a measurement of the change in substrate spectral albedo which is apparent to an observer passing over a reef patch surrounded by white sand. Regions of high reflectance correspond to low productivity and the dark, high absorption areas are sites of benthic primary producers containing photosynthetic pigments. While the incident solar irradiance and spectral attenuation of the overlying waters remain relatively constant, the intensity and spectral characteristics of the upwelled light vary widely, including near-bottom enhancement due to fluorescence emission. We believe that these changes in the spectrum of upwelled light hold the key to the development of optical algorithms for primary productivity of coral reef communities.

Coral reef surface benthic communities are not only comprised of a diversity of living organisms, but also exposed rock, dead coral litter and sand bottom. The same techniques described above for determining benthic primary production will also serve to differentiate bottom types and other classifications. Additionally, it will be possible to model the benthic monochromatic light regime within depth zones to provide the background signal necessary for dectection of contrasting man-made objects placed within reef benthic communities.

BACKGROUND OF CoBOP

The Coastal Benthic Optical Properties project seeks to further research on the optical properties of benthic communities in general. Our research team has chosen to focus on coral reef environments as they constitute coastal regions of high water clarity which are of great interest to the Navy's mission and also to science in terms of global oceanic processes. In the two experimental years, sites around the Dry Tortugas in the Florida Keys were selected where diverse optical measurements were made of coral communities in 10m of water. Measurements included standard water column and laboratory techniques as well as a number of innovative diver operated and ROV, AUV mounted cameras and sensors. We performed observations of the following properties:

1) Reflectance spectra of upwelled light from benthic communities in coral reef environments including seagrasses and sand bottom as a function of increasing water depth

2) Absorption and fluorescence characteristics of the overlying waters

3) Fluorescence spectral signatures of individual coral and algal species by laboratory measurements aboard ship

4) Depth resolved current direction and velocity using a bottom mounted upward looking ADCP

5) Near bottom physical and bio-optical measurements of wind and tidally induced advection and resuspension.

Basic research will be furthered by studies of in-water and benthic optical properties of coral reef communities at small spatial scales, mapping and classification of coral reef substrates and modelling of reef reflectance as spectral albedo reaching a remote sensor.

CONCEPTS OF OPTICAL CLOSURE

Optical budgets account for all sources and sinks of photons within the submarine light field as a function of wavelength impinging on a point/surface as a function of angle.

Incident solar irradiance is the primary source, with inelastic backscattering (due to water molecules and particles) and elastic scattering (Raman and fluorescence of pigments) as additional sources. Loss terms are absorption and inelastic scattering at forward angles, collectively termed attenuation. So-called 'two flow' models have been used to describe the downwelling and upwelling light fields as a function of wavelength and angle using the inherent optical properties. Downwelling light is those photons propagating from the surface to depth, upwelling light is those photons returning from depth primarily due to backscattering. At depth, Raman scatter and fluorescence can contribute significant amounts of photons to the upwelling light (Yentsch and Phinney, 1990). Reflectance is the ratio of upwelling light to downwelling light which, for points in the water column, is typically expressed as:

$$R = E_u/E_d = 0.33b_b/a \qquad (1)$$

where b_b and a are the backscatter and absorption coefficients, respectively. In clear, shallow water columns over reefs, downwelling light reflected off the benthic surfaces and fluorescence from high concentrations of photosynthetic pigments 'packaged' in benthic animals and plants become the major components of the upwelled light. Backscatter and absorption from the relatively thin layer of overlying water and its low concentrations of dissolved and particulate constituents becomes negligible as does Raman scatter (Stavn and Weidemann, 1988).

REFLECTANCE

Two types of reflectance measurements are required to characterize benthic communities: 1) the actual *in situ* reflectance of the benthic surface given the ambient spectral light regime and 2) the apparent reflectance that is measured at the surface of the water column. We obtained both types of spectral reflectance measurements at the Dry Tortugas site in August, 1995. Nearly 100 actual *in situ* reflectance spectra of various benthic organisms and substrates was measured using a Spectrix diode array system contained in a water tight housing (K. Carder, USF). Apparent reflectance at the surface was measured using a Satlantic Total Surface Reflectance Buoy (TSRB). The buoy passively measures incident solar irradiance (E_d) above the surface and upwelling radiance (L_u) just below the surface in 7 bands (406, 412, 443, 490, 510, 555 and 665nm) at 6Hz in units of $\mu W\ cm^{-2}\ nm^{-1}$ and $\mu W\ cm^{-2}\ nm^{-1}\ sr^{-1}$, respectively. Data for downwelling irradiance in air are minute averaged, corrected for losses at the air-water interface (reflection) and refraction as a function of solar zenith angle for each band and the light propagated to the depth of the upwelling sensors (0.7m) using average k_d values at each wavelength. Remote sensing reflectance (R_{rs}) at each wavelength is calculated as the ratio of upwelling radiance to downwelling irradiance in water (L_u/E_d). Figure 1 shows the results of measurements acquired over carbonate sand and seagrass (*Thalassia testudinum*) bottoms at 5m compared to a deep water, oligotrophic ocean spectrum. Significant differences in the blue part of the spectrum can be seen, with very little blue absorption occurring over sand bottom or in the overlying water. The seagrass removes more blue and red light than a bottomless oligotrophic station with similar chlorophyll concentration as the water covering the *Thalassia*. This contrast between dark productive areas and bright white sand regions is predictive in shallow waters but is lost as water depth increases to the point where absorption due to water and its constituents becomes the dominant signal.

WATER COLUMN ATTENUATION AND FLUORESCENCE

Ideally, we would like to strip away the water in order to observe the bottom clearly. Since this is not possible, the next logical choice is to work in an area where modulation of the light field is minimized. Coral reefs were selected as an ideal environment for the first attempts to optically sense benthic substrates because of the diversity of bottom types and the clarity of the overlying waters. The effect of water column components are small in most reef areas with water depth, sea surface roughness and variability in turbidity (attenuation) at some spatial and temporal scales due to the action of tides and winds as the most important factors. Fluorescence emission from pigments contained in phytoplankton as a source of photons to the water column is a minor factor based on their low concentrations. Two major groups of pigments are observed, the chlorophylls which shift blue photons to red wavelengths, and the phycobilins (primarily phycoerythrin) which shift green photons to orange. Several individual pigments occur within each group which exhibit specific excitation and emission characteristics. Fluorescence emission from pigments contained in simbiotic phytoplankton associated with corals can be a significant source of photons to the near-bottom waters due to their extremely high concentrations.

Water depth acts to reduce the total quantity and quality of light reaching the bottom as an increase in the pathlength that a photon must penetrate which varies as a function of wavelength. Ultraviolet and red wavelengths disappear quickly while blue and green wavelengths can penetrate to great depths. As stated above, the sum of absorption (a) and scattering (b) at a wavelength equals attenuation (c). Pure water values measured by other workers are 0.168 and 0.165, for c and a respectively. Water, particles, photosynthetic pigments, colored dissolved organic material and other substances all attenuate light according to their concentration and the shape of their action spectrum. In clear, shallow waters (less than 5m) the bottom is illuminated by a substantial portion (15-45%) of incident radiation at most visible wavelengths, while at 20m only 3-5% of the surface light between 400 and 600nm (blue and green) is present.

We have observed significant optical variability on the order of 100% for spectral attenuation and 40% for spectral non-water absorption over a series of tidal cycles off the Dry Tortugas. Average spectral values of attenuation ranged from 0.25 to 0.5 (m-1) with total absorption coefficients ranging from 0.215 to 0.235 (m-1). Highest chlorophyll concentrations, spectral attenuation and spectral absorption were observed at the lowest tide of each mixed tidal cycle (tidal range 0.7m), lowest values were found at the highest tides in each cycle. Scattering represented 14% of attenuation at the low end and 53% at the high end of each range suggesting the presence of higher numbers of particles at low tide which act to increase scattering. Temperature, salinity and the spectral attenuation and absorption coefficients were homogeneous with depth, with the exception of the very near-bottom layer (0.5-1m) where attenuation increased.

If we assume that the near-bottom layer has not been disturbed such that attenuation is uniform with depth to the substrate and that 2% of the surface light between 400 and 700nm is required to interrogate the bottom by a sensor, then substrates shallower than 25 feet can be observed at low tide while the bottom at 55 feet can be seen at high tide. This can be a significant increase in benthic area for regions of gentle relief. This analysis is based on average spectral values across the visible region, better results can be obtained at blue/green wavelengths which penetrate further. The result is analogous to what an observer on a boat in 40 feet of water would see, clear to the bottom at high tide with visibility reduced at low tide to the point where the bottom was obscured due to increased turbidity.

BENTHIC SUBSTRATE CLASSIFICATION AND FLUORESCENCE SIGNATURES

The ability to classify benthic substrates builds on the concept of optical closure with basic classes differentiated by spectral reflectance, fluorescence excitation and emission characteristics within specific color bands of known photosynthetic pigments and the lack of pigment absorption/fluorescence or changes in the backscatter coefficient in the case of rock or bleached coral. In addition, two *in situ* fluorescence emission bands of unknown origin in the blue and green regions of the spectrum have been shown to occur in different species of coral (C. Mazel). Understanding the optical variability of coral reef substrates is of primary importance to this program and fluorescence excitation and emission signatures are crucial to this understanding. We have measured these signatures in the laboratory aboard ship using a fluorescence spectrophotometer and front surface techniques for a number of coral, seagrass and macroalgal species in the region of the Dry Tortugas sites (Figure 2). Chlorophyll and accessory photosynthetic pigments such as carotenoids and phycobilin pigments (phycoerythrin Types I and II) are found in different benthic organisms as well as significant signal intensity changes in the case of bleached coral or calcified seagrasses. We have not measured the unknown fluorophores found in corals as we have primarily focussed on the photosynthetic pigments. In all, the variety of available signals suggests that classification at least to major color groups (Table 1) is highly practical (Yentsch and Phinney, 1985; Topinka et al., 1990). These signals are also measurable by the Laser Line Scanner which can survey relatively large areas of reef (100's of square meters) at extremely small scale resolution (cm^2 to mm^2).

VELOCITY AND DIRECTION OF CURRENT FLOW

About 20 years ago, Simpson and Hunter (1974) published a tidal mixing model (log H/u^3) which provided a means to assess the influence of tidal energy dissipation in coastal waters. In its most elemental form, the model states that the transition from a region of laminar to turbulent flow is a function of the water depth (H) and the term u^3 which is the product of the velocity of the flow and a constant for bottom friction. Approximating the frictional portion of the u^3 term becomes a serious problem in regions of complex topography or high benthic diversity of sediment and habitat types across sand/mud patches, cobble fields, algal beds or coral reefs. The velocity profile changes as the bottom is approached due to increased friction such that the velocity decreases but turbulence increases as energy is imparted along the benthic boundary. This energy acts to resuspend bottom materials which affect optical properties within the benthic boundary layer. Energy from wind forcing is tranferred through the water column and increases the effect in shallow waters.

In order to assess the contribution of tide and wind induced flow to increased optical variability in the water column, we have employed a strictly empirical approach involving an upward looking Acoustic Doppler Current Profiler (ADCP) and near-bottom optics package. An Aanderaa Model DCM12 upward looking ADCP/tide gauge/wave analyzer was placed on the bottom in 20m of water off Loggerhead Key in the Dry Tortugas in 1996. The ADCP unit operates at 606.7 Hz and is designed for deployment in 3-50m of water. Three to five depth cells above the null (bottom 2m) cell were monitored for current speed and direc-tion. State of tide (water level) and significant wave height (determined as $H^{1/3}$) were measured using a quartz pressure cell. Data were logged internally at three minute intervals throughout the two day deployment.

Both current speed and direction were coherent through the water column such that depth bins were averaged to reduce noise and detect trends. Changes in current direction were most pronounced near the lowest tidal height of the mixed tides observed off the Dry Tortugas, current speed did not vary significantly, averaging 20cm/s (0.4 kts). Significant wave height varied between 0.1 to 0.15m as no major wind event occurred during the monitoring period.

VARIABILITY IN NEAR-BOTTOM BIO-OPTICAL PROPERTIES

While it is somewhat useful to categorize benthic communities as static optical regions, the optical properties of the overlying waters may be highly variable at relatively short time scales (hours to days) due to water mass advection by tides and winds as discussed above. Our objective in this work was to determine whether the optical properties of the benthic boundary layer were coupled to the rest of the water column or should be considered as a separate layer in our efforts to obtain closure. The near-bottom optics package consisted of a Sea-Bird SeaCat 19 conductivity/temperature/depth (CTD) sensor, WET Labs WETStar miniature chlorophyll fluorometer and WET Labs CStar single channel transmissometer (25cm path, 488nm) mounted to the ADCP frame (0.5m height of intake). Sample water was pumped through the CTD/fluorometer/transmissometer to ensure sample turnover and reduce fowling. The fluorometer monitored chlorophyll fluorescence as an indicator of phytoplankton specific biomass, the transmissometer monitored the attenuation at 488nm (c488) matched to the Laser Line Scanner excitation wavelength. The optical subsystem was powered by the SeaCat 19 and data logged to its internal memory as discrete time points every three minutes.

During the two day deployment at Loggerhead Key, near-bottom temperature varied by 0.7°C with minimum temperatures occurring at high tide and maximum temperatures at the higher low tide. Currents ran from 250° magnetic during the flood tide which injected deeper cooler waters from the southwest along the bottom at our monitoring site. Waters from the central portion of the Dry Tortugas region, which had warmed in the shallows, flowed across our site from 70° magnetic for short periods of current reversal centered on the lowest tides. Temperature was the main determinant of density as salinity was nearly constant throughout the cruise vertically, slowly increasing as a function of time by 0.05 PSU over two days. This pattern affected near-bottom optics by delivering higher attenuating waters to the benthic community on the flood tide which are cleared by filter feeding organisms and overwash the region on the ebb tide. Clearest waters observed at the lowest tide were similar to water column values measured from the ship. At high tide, near-bottom c488 was a factor of three to five higher than water column values. These patterns of attenuation as a function of tidal state for the benthic boundary layer and the rest of the water column are significantly different indicating that the two layers are not coupled and must be considered separately in optical models.

MODELLING OPTICAL CLOSURE IN CORAL REEFS

The premise for our approach is that all photons entering shallow coastal waters are either absorbed or scattered. Absorbed photons are converted to heat or used in photochemistry. Scattering takes many forms including fluorescence and reflectance. Photons backscattered out of the water column are lost from the system, thus, the ratio of water leaving radiance to incident solar irradiance is a measure of total absorption by coastal waters. This approach can be further refined by using optical closure techniques whereby all photons in the system are accounted for, as in a photon budget. The budget is determined for each optical interface and layer that a photon at a given wavelength must penetrate when propagating in either the downwelling or upwelling light fields. We have identified two interfaces and two layers that are important in coral reef environments:

1) Air-water interface - Sources are incident solar irradiance and total upwelling radiance just below the surface. Downwelling irradiance just below the surface is determined by losses due to reflection and refraction according to solar angle, wavelength and index of refraction of the water. Internal reflection of upwelling light affects magnitude of water leaving radiance. Wave height is an important factor.

2) Water column - Homogeneous layer where absorption and scattering by water, particles and dissolved substances reduce the quality and quantity of photons as a function of depth (downwelling) or altitude (upwelling). Scattering from adjacent water columns and reflectance from the bottom are significant sources. Other sources such as fluorescence and Raman scatter are not considered significant. Temporally and spatially variable as a function of wind stress, tides and other factors.

3) Benthic boundary layer - A layer which is probably non-linearly variable as a function of altitude which attenuates light in a fashion similar to the water layer above it but at different temporal and spatial scales. Sources are photons penetrating the water column, scattering from adjacent water columns and reflection from the bottom, the latter is highly variable and dependent on the benthic substrate. Fluorescence and Raman scatter may be significant sources as a function of the concentration of pigments per unit area of the benthic inter-

face and depth, respectively. This layer is strongly influenced by the effects of wind stress and tides.

4) Benthic interface - The sources to this surface are the impinging photons from above and internal reflections from the top millimeter of the underlying matrix (carbonate sand, coral skeleton or tissue). Absorption by pigments is the major factor affecting the reflectance of the surface which converts downwelling photons into upwelling photons.

Two flow models are appropriate for handling all of the sources and sinks for photons at a given depth increment as a function of wavelength and angle. The major differences between this hypothesis for coastal waters compared to open ocean waters are the quantities and sources of light backscattered through the surface layer and the diversity of optically active materials responsible for absorption. In shallow water with a highly reflective bottom, it is not uncommon to find as much as 25-30% of the light entering the ocean upwelled back through the surface. A bloom of coccolithophores would be required to produce similar values in the upper layer of the open ocean where, generally speaking, values range from 3-5%.

SUMMARY

We have measured input values and coefficients for each interface and layer such that a simple implementation of the model can be tested at several wavelengths throughout the visible spectrum. We argue that with knowledge of the in-water optical properties, spectral reflectance and fluorescence signatures of benthic organisms, water leaving radiances from shallow coastal waters contain ecological information concerning benthic community biomass, primary production and diversity. In addition to the measurements needed to obtain optical closure in shallow coastal waters, we believe that the flow measurements provide a means of predicting when water column optics dominate benthic boundary layer optics. If the waters overlying benthic communities are very shallow and/or transparent, this will not be difficult. However, in deeper water or anywhere that relatively opaque waters are present due to resuspension or horizontal transport, the problems become quite formidable. The spectral signatures of major species of benthic organisms fall into several catagories based on known pigment groups, UV stimulated fluorescent compounds contained in corals offer the ability to increase the specificity of a classification scheme. Remotely sensed primary production based on solar induced fluorescence has the potential to provide us with a means to approach the problem of total production of diverse benthic communities. Finally, the change in optical characteristics of man-made materials as they are colonized by benthic organisms will determine our ability to detect objects placed in benthic communities based on contrasting spectral signatures.

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Fluorescence Spectral Characterization
Benthic Organisms

Corals	Emission
Montastrea sp. (2) and Staghorn	Chl a only
Porites sp. and Brown encrusting	Chl a + PE
Red encrusting	PE only

Macroalgae	
Thallassia, Halimeda, Pennicillis and Turtle grass	Chl a only
Dictyota, Gracilaria (brown), Mixed and Green Epiphytes	Chl a + PE

Significant fluorescence intensity changes

Montastrea w/zooxanthellae vs. bleached coral
Clean vs. calcified Thallassia

Significant fluorescence spectral changes

Unhealthy Gracillaria exhibits only PE fluorescence (pink)

Table 1.

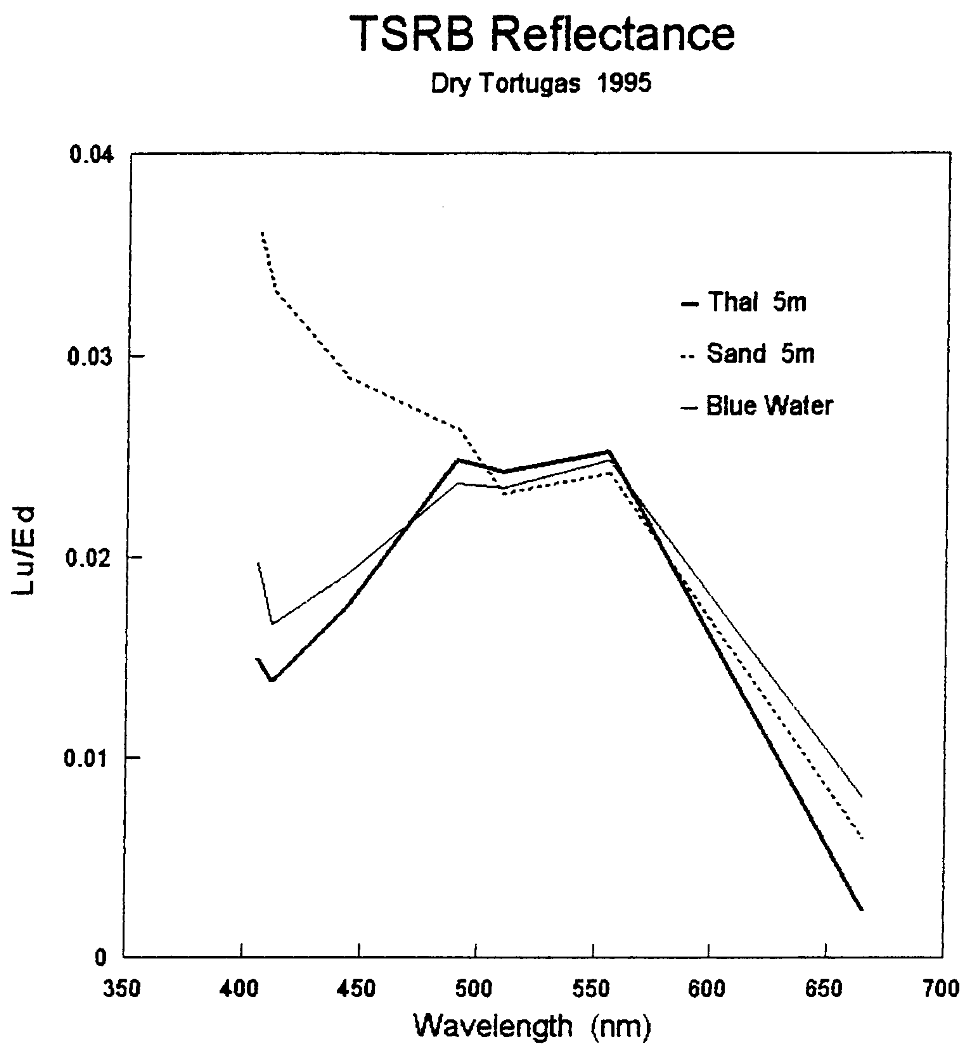
TSRB Reflectance
Dry Tortugas 1995
0.04
0.03
0.02
0.01
0
Lu/Ed
350
400
450
500
550
600
650
700
Wavelength (nm)
Thal 5m
Sand 5m
Blue Water

Fig 1.

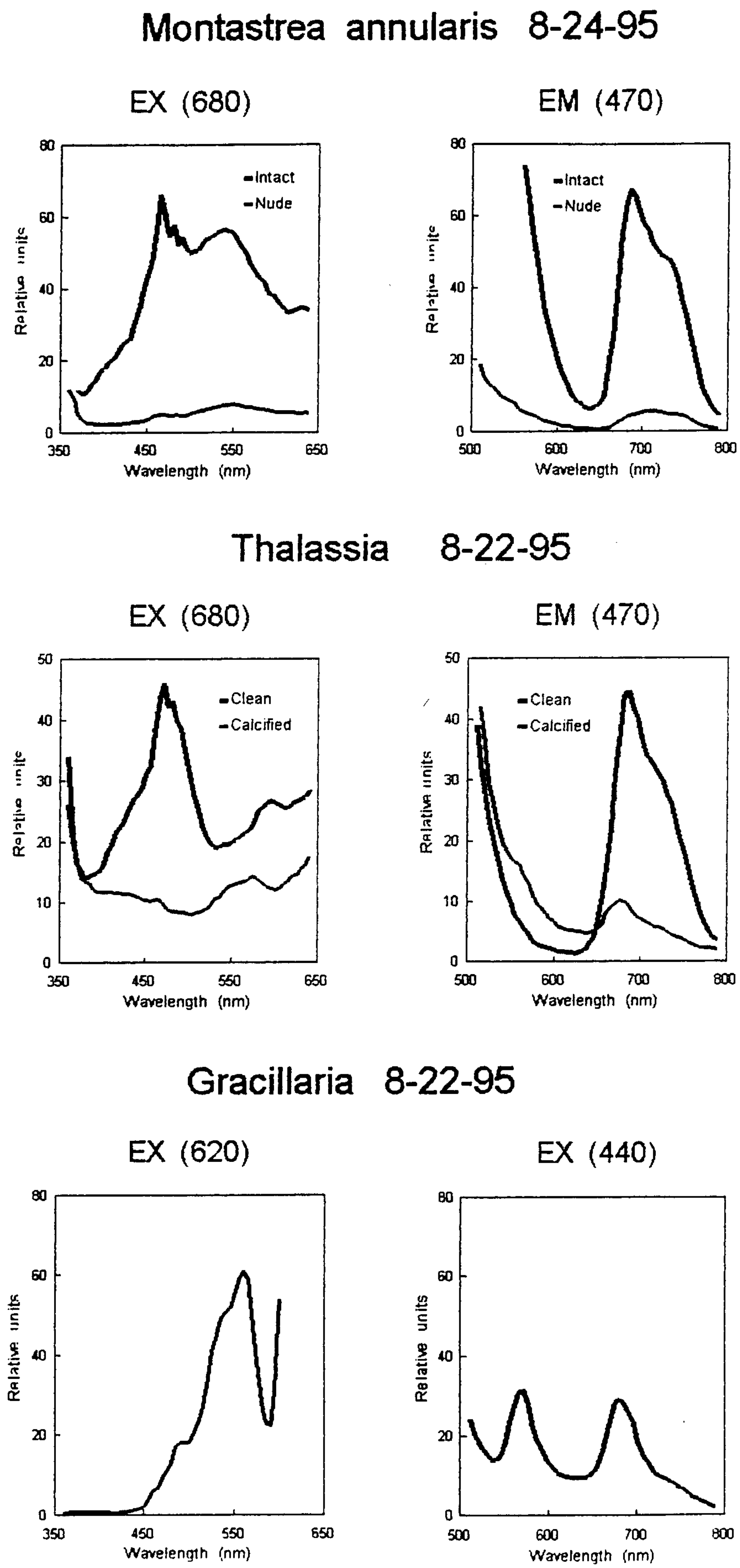
Montastrea annularis 8-24-95
EX (680)
EM (470)
Intact
Nude
Relative units
Wavelength (nm)
Thalassia 8-22-95
EX (680)
EM (470)
Clean
Calcified
Relative units
Wavelength (nm)
Gracillaria 8-22-95
EX (620)
EX (440)
Relative units
Wavelength (nm)

Fig 2.