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Review of coral reef ecosystem remote sensing

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ABSTRACT

Coral reef communities face unprecedented pressures at local, regional and global scales as a consequence of climate change and anthropogenic disturbance. Remote sensing, from satellites or aircraft, is possibly the only means to measure the effects of such stresses at appropriately large spatial scales. In the past 30 years, remote sensing of coral reefs has made rapid progress. However, the current technology is still not mature enough to monitor complicated coral reef ecosystems. Compared with foreign research in this field, our work lags far behind. There are still deficiencies in many aspects, such as basic data collection, theoretical research and platform construction. In our nation, it is even unclear how coral reefs disperse and where they may be unhealthy. In this paper, general characteristics of coral reef ecosystems and spectral features of different reef benthos have been summarized, based initially on a review of relevant literature in recent years. Based on the spectral separability of different reef types or benthos, remote sensing can be used to monitor two aspects of coral reefs: (1) Measurement of the ecological properties of reefs. (2) Health assessment of the coral reef ecosystem. In the first part, optical remote sensing methods are widely used to map reef geomorphology and habitats or biotopes. The investigation of geomorphologic zonation has proven to be one of the most successful applications, as different geomorphologic zones are associated with characteristic benthic community structures and occur at spatial scales of tens to hundreds of meters, they are amenable to remote detection by moderate to high resolution sensors. With more and more attention on the ecological problems of coral reefs, a number of studies have used high resolution sensors to map reef communities. The number of classes distinguishable depends on many factors, including the platforms, resolution (spectral, spatial and temporal resolution) and environmental conditions (water depth, water clarity, surface roughness, etc.). Compared with deep water color remote sensing, or terrestrial remote sensing, three techniques for the measurement of reef ecological properties are examined in this paper: (1) Coral reef classification system using remote sensing. (2) Techniques of sea surface correction and water column correction. (3) Techniques of coral reef information extraction from images. In terms of the complexity of coral reef ecosystems, the current techniques still need further improvement or optimization. In the health assessment of coral reef ecosystems, there are two ways to carry out the monitoring using remote sensing: (1) Monitoring the pigment or symbiotic zooxanthellae contents in corals. (2) Measuring the environmental properties of reefs. The first way is theoretically feasible, but difficult to achieve in practice. Currently, most reef health assessments are carried out by measuring environmental parameters, including sea surface temperature, solar radiation, ultraviolet radiation, water color, wind speed and direction, rainfall, ocean acidification, sea level, etc., of which sea surface temperature has been routinely measured by NOAA to monitor coral bleaching. In addition to the contents above, this article puts forward five main prospects for development in the future: (1) Establishment of a coral reef classification system using remote sensing. (2) Satellite launch for monitoring coral reefs. (3) Theoretical and methodological development. (4) Establishment of a spectral database for different reef benthos. (5) Integrated application of multi-source remote sensing data. It is hoped that the information provided here will be a reference for subsequent similar studies.

1. Introduction

Coral reef is one of the ecosystems with the most productivity and the most abundant species on Earth. It is also an ecological key area of special value to maintain the productivity of marine resources and an important indicator of the healthy marine environment. However, in the past few decades, coral reef communities experience profound changes at a global scale as a consequence of climate change and anthropogenic disturbance. According to the data released by Global Coral Reef Monitoring Network (GCRMN) in 2008 [1], currently 54% of world's coral reefs are still

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suffering from global or regional threats. According to the "China Marine Environment Conditions Communiqué 2010" released by China's State Oceanic Administration, in the past five years, the average coverage of live scleractinian coral has shown a declining trend, with the average coverage at Xisha Island, the east coast of Hainan and the southwestern coast of Leizhou Peninsula declining 58%, 15% and 12% respectively. The overall coral reef ecosystem biomes showed a trend of degradation. Therefore, supervision of coral reef ecosystems is extremely urgent.

Since the dynamic changes of the coral reef ecosystem structure are affected by its various surrounding environmental processes on spatial scales from a few millimeters to thousands of kilometers [2], conventional monitoring methods appear to be inadequate in the study of large-scale problems, such as the effect of global climate change on coral reef ecosystems, due to a lack of access to the data in a relatively short time. The emergence and development of remote sensing technology provide a new way for the regional monitoring of coral reef ecosystems. It is characterized with rapidity, observing in a comparatively large area, repeatable observations, and thus becomes an important supplementary means to conventional methods [3–5].

Remote sensing of coral reef ecosystems includes monitoring ecological and environmental properties of coral reefs, of which the former is mainly carried out for the monitoring of coral reef itself to obtain the information about reef distribution, geomorphology, benthic substrate composition, reef health condition, etc. The latter is mainly the parameter inversion of atmosphere or water environment in which coral reefs exist, to evaluate or predict the health condition of coral reefs. In the past 30 years, the technology has developed from simple range monitoring to today's complex reef benthic substrate classification, investigation and assessment of coral reef health, making considerable progress in terms of remote sensing data source, spectral characteristics analysis of coral reefs, remote sensing recognition technology, health assessment methods, etc. However, the current technology is still not mature enough to monitor complicated coral reef ecosystems, being in urgent need of further improving the underlying theories. Particularly in China, no such relevant research work has been fully carried on, with only a small amount of literature involving how to use remote sensing data to monitor reef range or geomorphology [6–11]. There are still deficiencies in many aspects, such as basic data collection, theoretical research and platform construction. In our nation, it is even unclear how coral reefs disperse and where they may be unhealthy.

China's "Twelfth Five-Year" Marine Science and Technology Development Plan clearly puts forward to "focusing on the ecosystem survey of seaweed beds, marine algae, mangroves and coral reefs", and regards the development of marine stereoscopic observation technology as an important task. Coral reefs remote sensing information, as an important strategic resource for our country, is significant to the sustainable utilization of China's marine ecological resources, to improve marine cognitive competence and the competitiveness in South China Sea. This article summarizes the progress in coral reef ecosystem remote sensing techniques and the existing main problems by analyzing characteristics of coral reef ecosystems, coral reef spectral properties, recognition technology of coral reefs from images, remote sensing monitoring and evaluation techniques for coral reef ecosystem health, and suggests future development trends. It is hoped that the information provided here will be a reference for subsequent similar studies to promote the protection and management of China's marine environment.?>

2. Characteristics of coral reef ecosystems

Coral reef ecosystem is composed of coral reef biome and its surrounding marine environment [12]. As the most important part of the ecosystem, scleractinian corals usually have a lot of symbiotic zooxanthellae in vivo supplying nutrient material for scleractinian corals. The zooxanthellae, the ectodermal and entodermal tissues of polyps contain a variety of pigments, including chlorophyll a, chlorophyll c, peridinin, diadinoxanthin, diatoxanthin, β-carotene, green fluorescent protein, etc. [13]. The composition and content of these pigments jointly determine the optical characteristics of corals, which becomes an important information source for coral reef remote sensing. In addition to the scleractinian corals, a variety of benthic algae, zoobenthos, plankton, fish, and bacteria provides the coral reef ecosystem with high biological diversity [14], of which benthic algae attached to the reefs usually spread mingled with scleractinian corals, together with seaweed, sand and other substances, forming a substrate distribution pattern with high spatial heterogeneity.

Scleractinian corals are generally fit to survive in warm environment with water temperature between 20 and 30 °C. Currently, the world's coral reefs are mainly distributed in two regions of Atlantic–Caribbean and India–Pacific between Tropic of Cancer and Tropic of Capricornin [1]. China's coral reefs are mainly distributed in South China Sea, including the mainland coast of southern China, Hainan Island, Taiwan Island, and reefs of South China Sea islands [15]. In addition to water temperature, scleractinian corals have more demanding requirements on the environmental conditions in terms of water depth, sea salinity, transparency, light, sea level, and pH etc. For example, water depth is generally not more than 50 m. Optimal salinity is within the range of 32–35. Seawater should be clear and transparent to ensure that there is preferable light transmittance, etc. [14]. It is because of the coral's sensitivity to changes of these environmental conditions that makes remote sensing technology an effective way for coral reef health monitoring and coral bleaching early warning.

3. Spectral characteristics of coral reefs

The spectral characteristics of coral reefs generally depend on absorption and scattering properties of their benthic substances. Coral reef communities are largely mosaics of coral, algae and sand. Both coral and algae contain chlorophyll and other photosynthetic pigments. Their spectral magnitude and shape show a certain similarity, and largely depend on absorption and fluorescent characteristics of different pigment compositions [16]. In contrast, spectral curve values of sand are higher. In all bottom-types, spectral curves at 600–650 nm are characterized by a double-peaked pattern recorded by Hochberg and Atkinson [17] (Fig. 1). Corals have a reflectance peak around 570 nm. Hochberg et al. [16] further classified corals into brown, blue, and bleached corals. In brown corals, spectral curves had a triple-peaked pattern between 570 and 650 nm. The blue corals had an absorption peak at 580 nm

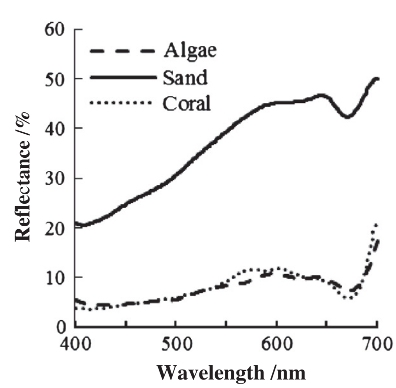

Fig. 1. Spectral curves of different reef benthos [17,19].