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Response of microalgae to large-seaweed cultivation as revealed by particulate organic matter from an integrated aquaculture off Nan'ao Island, South China

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ABSTRACT

Large seaweed cultivation has proven an effective means to inhibit harmful microalgae at experimental scales and battle eutrophication in Chinese coastal waters, but essentially there is a lack of field-scale studies to explore the underlying mechanism. Here we present a 1.5-year-long time series of particulate organic matter (POM) and settling particulate matter (SPM) concentrations from an integrated aquaculture of *Gracilaria lemaneiformis* off the coast of Nan'ao Island, South China from April 2014 to August 2015. The microscopic examination and geochemical characteristics show that the POM mainly consisted of microalgae. The mean POM concentration increased 99.8%, 71.2%, 45.8% and 111.9% at the four sampling sites during the non-cultivation period, while decreased 25.5%, 17.3%, 12.2% and 20.3%, respectively, during the seaweed cultivation period. These results suggest that the large scale seaweed cultivation can remove excess nutrients and inhibit microalgal growth, thereby contributing to the improvement of coastal marine aquaculture environment.

Rapid economic development has led to an accelerated, intensified eutrophication in Chinese coastal waters (Qu and Kroeze, 2012; Yang et al., 2015; Dai et al., 2017), and as the leading country in aquaculture food production (FAO, 2014), the rapid expansion of animal farming in China has aggravated the environmental problem (Li et al., 2011). As a result, the frequency of harmful algal blooms (HABs) and the economic loss associated with algal toxins have increased significantly (Morand and Merceron, 2005; Anderson, 2009; Hiraoka et al., 2011; He et al., 2014). For instance, the frequency of HABs has increased three times every decade since the 1970s, and 322 HAB events were observed in Chinese coastal waters from 1952 to 1998, causing devastating damage to the aquaculture industry, coastal ecosystem and even human health (Zhou et al., 2001; Tang et al., 2006; He et al., 2014; Brooks et al., 2016).

To combat coastal eutrophication and control HABs, many physical, chemical, and biological remediation measures have been proposed by researchers (Anderson et al., 2001). As evidenced by world-wide field practice over the last few decades, artificial fishing of algal bloom or using solar ultraviolet radiation (UV-B) cannot completely reduce the reoccurrence of red tides (Sugawara et al., 2003); using chemicals is only effective within weeks, but some chemicals remain in the environment and the food web for years (Anderson, 1997), causing secondary environmental pollution. In contrast, biological remediation, such as using macrophytes or microorganisms to reduce water pollution (Furusawa et al., 2003), has proven to be environmentally friendly and sustaining, and the cultivation of large seaweeds as nutrient strippers in integrated aquaculture has been demonstrated as an excellent example of ecotechnology (Neori et al., 2004; Yang et al., 2015), in which the food production system is designed in partnership with nature.

Previous studies have revealed that there are quite a few advantages in using large seaweeds to control eutrophication and restore the marine environment (Schramm, 1999; Fei, 2004; Neori et al., 2004; Xiao et al., 2017). For example, Gracilarioid species (mainly *Gracilaria* but also *Gracilariopsis*) can contribute to the efficient removal of dissolved P and N wastes from intensive fish farms, increasing the economic output of the industry (Buschmann et al., 1996; Alcantara et al., 1999; Jones et al., 2001). Co-existence culture system experiment results demonstrated that *Gracilaria lemaneiformis* had obvious inhibitory

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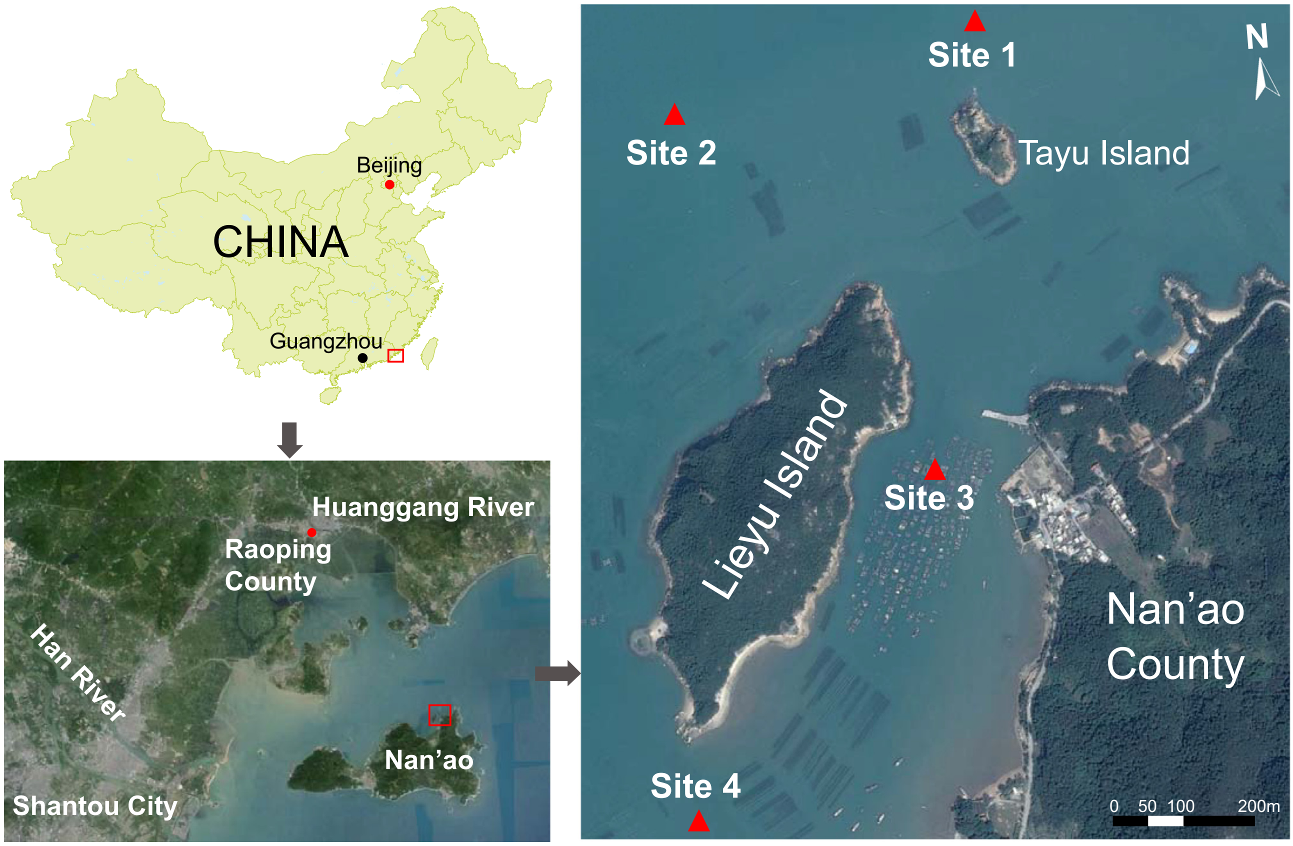

Fig. 1. Location of the study area in Shen'ao Bay, Nan'ao County, Guangdong Province, China. Sampling sites are shown on right panel by red triangle. During the monitoring period, Sites 1 & 4 had no large seaweed cultivation or animal farming; Site 2 had *Gracilaria* cultivation during April–May 2014 and February–May 2015; and Site 3 fish farming operated all the time. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

effects on the growth of two red tide microalgae, *Chaetoceros curvisetus* and *Scrippsiella trochoidea* (Liu et al., 2006).

In addition, the cultivation of these seaweed species does not require supplementary feeding, but removes large amount of nutrients and only small amounts of organic matter and dissolved nutrients are released to the environment, in contrast to intensive-feeding fish and shrimp farms (Hopkins et al., 1995; Yang et al., 2015). To use this advantage to balance the nutrients produced by animal-fed aquaculture, integrated multi-trophic aquaculture (IMTA) was proposed in which the wastes of one resource user become a resource (fertilizer or food) for the others (Chopin et al., 2001). Since the 1990s, many studies related to multi-trophic culture have been carried out in Canada, Japan, Chile, and the United States (Hirata et al., 1993; Petrell and Alie, 1996; Troell et al., 1997; Chopin et al., 1999; Wartenberg et al., 2017). Actually, co-culture had been practiced for decades in Asian countries, especially in China, in order to meet the large demand for food and decrease the waste of resources (Li, 1987; Qian et al., 1996; Ponte et al., 2014). In general terms, IMTA is an innovative and responsible practice in mariculture.

However, many studies focused on laboratory simulation systems, small scale tank systems and short-term field monitoring (Buschmann et al., 1996; Troell et al., 1997; Alcantara et al., 1999; Jones et al., 2001; Tang et al., 2004; Carmona et al., 2006). Few studies demonstrated the long-term effectiveness of seaweed cultivation in coastal IMTA areas (see Xie et al., 2017 for an exception). In this study, we attempt to reveal the long-term variation of particulate organic matter (POM) and settling particulate matter (SPM) in a near-shore IMTA system which combines animal-fed aquaculture species (such as *Epinephelus akaara* Temminck and Schlegel, *E. awoara* Temminck and Schlegel), with an inorganic extractive aquaculture species (*Gracilaria lemaneiformis*).

In the coastal environment, POM mainly consists of phytoplankton, bacteria, invertebrates, fish and zooplankton fecal pellets and detrital particles (Volkman and Tanoue, 2002). The quality and quantity of the POM produced by phytoplankton depend on the nutrient status of the natural waters, and phytoplankton composition and growth phase. POM is of considerable biogeochemical and oceanographic importance in the aquatic environment and plays an important role in the carbon cycle, because it transports as settling particulate matter (SPM) or 'marine snow' - a primary component of export production from the surface ocean down to the ocean floor (Alldredge and Silver, 1988). When euphotic zone-derived POM sinks through the water column, it acts as a food source to marine biota (Kiørboe, 2001) and also scavenges smaller particles (Stolzenbach, 1993), while the seasonal deposition of POM on the seabed can provide essential nutrients to benthic organisms (Lampitt, 1985). Furthermore, POM and SPM on the seabed can be resuspended in the water column due to tidal influence and bio-turbulence (Wainright and Hopkinson, 1997). Therefore, POM plays a key role in coastal ecosystems, and its temporal and spatial variations can shed light on the effect of seaweed cultivation in coastal IMTA areas.

The shallow sea area around Nan'ao Island, Guangdong Province is one of the largest marine aquaculture bases in China. Since the 1980s, the animal-fed aquaculture industry has developed extensively. Due to decades of practice with mono-species cultivation and high-density fish cages, coastal water eutrophication was significantly accelerated and caused the outbreak of HABs in 1997 and 1999 (Huang et al., 1999). In the 1990s, *G. lemaneiformis* was transplanted from Qingdao to Nan'ao Island successfully. Due to the social-economic benefits, large-area cultivation of *G. lemaneiformis* has been generally promoted by the local