Fish Catch and Nutrient Limitation in the South China Sea

Yafeng Zhang, and Kedong Yin

***Abstract*—**The South China Sea (SCS) is a major marginal sea with distinct variations in primary production (PP) due to the monsoon, river discharge, upwelling, eddies and typhoons. The integrated PP in the SCS is 477 mg C m^{-2} day^{-1}, which is a little higher than the global value (365 mg C m^{-2} day^{-1}), while the fish catch per square meter (FC/A) and the carbon transfer efficiency (CTE) in the SCS are respectively 6 times and 4 times higher than the global ocean. Compared with the East China Sea (ECS), lower FC/A and CTE in the South China indicated that fishery in South China Seas were burdened with a large central region of low productivity. If the productivity per square meter in the central part of the SCS did match that of the ECS, there could be 7.5 Mt/yr more sustainable fish catch.

***Keywords*—**About four key words or phrases in alphabetical order, separated by commas.

I. Introduction

THE South China Sea (SCS) is one of the largest marginal seas and located on the tropical–subtropical rim of the western North Pacific Ocean, encompassing an area from Singapore to Taiwan Strait of around 3.5×10^6 km^2, with an average depth of about 1212 m [1]. The central SCS contains a deep ocean basin that can be seen in Fig. 1. There are several major rivers discharging into the SCS, including the Pearl, Min, Jiulong, Red, Mekong, Rajang, Pahang, and Pasig Rivers. Most parts of the SCS belong to tropical oligotrophic waters with strong underwater irradiance and low nutrient concentrations that hover around the detection limits during most of the year [2]. Therefore, primary production (PP) is largely controlled by nutrient availability [3], [4]. Numerous investigations of the factors that influence PP in these oligotrophic waters revealed that any physical phenomena that increase the nutrient supply could enhance the PP. The monsoon [1], [5], river discharge [6], [7], upwelling [1], [8]-[10], typhoons [11]-[13], cold eddies [14]-[16] and nutrient advection [17], [18], can all elevate nutrient concentrations in surface waters and sustain high PP.

The SCS, stretching from the equator to 25 ^{0}N, is surrounded by nine countries with about 500 million citizens. The nutrients required to process carbon are relatively scarce leaving a niche for cyanobacteria to play an unusually import role in new PP. The small amount of organic carbon produced constrains the amount of secondary production in the SCS and consequently the food for the rising littoral human population. Fisheries are supported by the ecosystems they are embedded in [19]. Fish production is limited and influenced by various factors, but PP is arguably the most important and most fundamental [20], [21]. PP in each area is dependent on nutrient availability. Therefore, the distribution and availability of nutrients is the fundamental factor determining the fish production. As the fishing technology improved, the amount of fish caught has become mainly limited by the potential of fish production. Therefore, there is a linkage between nutrient availability and fish catch. This linkage suggests that river discharge, monsoon wind speeds, vertical mixing and a proposed index of tropical cyclone impacts are the physical forcing factors dominating the biological production by influencing dynamics of nutrients [22]. Fishery catch yields can serve as an indicator of the productivity of marine ecosystems if fishing mortality is constant. Linkage of fish abundances to ocean variability has played an important role in investigations of the production dynamics of marine ecosystems [23], [24]. Therefore, it would be interesting to compare the ratio of fish catch to PP with the global average ratio to evaluate the productivity of this marine ecosystem and to provide suggestions for management of fishery resources in the SCS.

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II. Nutrient And Organic Carbon

A. The Limiting Nutrients

The SCS is an oligotrophic body of water, located in the subtropical and tropical western Pacific. The standing stock and production of phytoplankton are very low, resulting from impoverished of essential macro-nutrients and trace metals [25], [26]. Both N and P in its euphotic layer are usually below the detectable limits when measured by conventional methods [27]. Lee Chen et al (2004) investigated the inorganic nitrogen (N) and phosphorus (P) concentrations and found that both N and P were scarce in the euphotic zone [28]. Growth in phytoplankton is limited by nutrient availability and the nutrients missing can be identified by incubation experiments. Nutrient enrichment would relieve the biomass limitation of phytoplankton by opportunistic response of taxa with low nutrient affinity in northern SCS [29]. Culture bottle studies using multi nutrients showed phytoplankton growth 48 hours after providing the nutrients to surface seawater and 31 hours for the deep chlorophyll maximum layer water from the central SCS (Fig. 2a) [30].

In the Pearl River, the inorganic nitrogen (N) concentration

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is very high and the inorganic phosphorus (P) concentration is relatively low, leading to a very high N: P ratio. This leads to P limitation for phytoplankton growth in the Pearl River Estuarine and in the coastal waters of the northern SCS [31], [32]. The nutrient limitation shifts to N limitation in the seawater [33]-[35] as the results in Fig 2b demonstrated. The role of N in modulating phytoplankton growth was investigated in the South China Sea on cruises in March 2000 and March 2001 by examining the phytoplankton growth in response to nutrient enrichments [34]. They found that the ratios of N: P were much smaller than the Redfield N/P Ratio of 16:1 and the results of the enrichment experiments, Fig 2b, showed that N alone limited phytoplankton growth. Enrichment with N only resulted in a phytoplankton growth as shown by the enhanced chlorophyll a concentration. Enrichment with both N and P as resulted in a little bigger phytoplankton response, as shown, suggesting P may also become limiting if N is adequate (Fig. 2b). The low N/P ratio in the deep water confirmed the N limited in the SCS [2]. Other studies on the trace nutrients, such as iron, have shown that central SCS water has adequate trace nutrients relative to the deficient in N and P. Unlike the low abundance of eolian iron in the eastern Pacific equatorial region, the atmospheric fluxes of iron in the western Pacific region are three-orders higher in magnitude [36], [37].

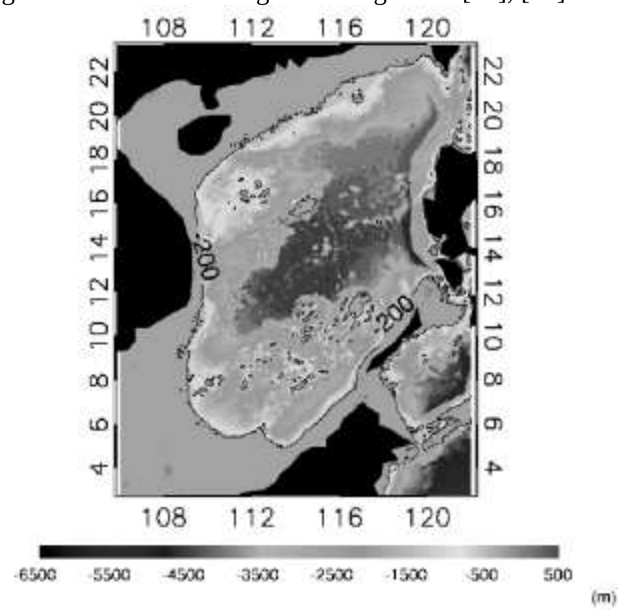

Fig. 1 The SCS showing the deep central basin

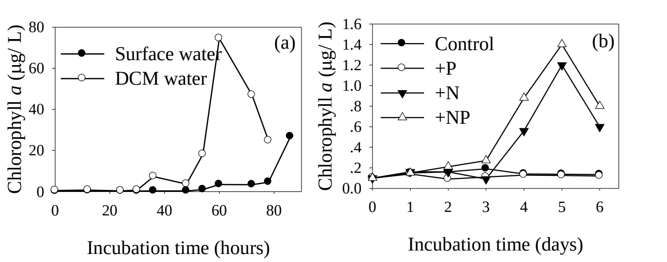

Fig. 2 (a) The incubation experiment at the station location 18^0 N, 115^0 E with the surface seawater and the deep chlorophyll maximum (DCM) layer water after nutrient addition with f/2 media in the central SCS [30]. (b) The incubation experiment in which surface water at a station in the basin of the SCS, was enriched with either 0.1 μM of phosphate (+P), or 1.0 μM of nitrate (+N), or both 1.0 μM nitrate and 0.1 μM phosphate (+NP) and incubated for 6 days during a cruise conducted in March 2000. No nutrient was added to the control group (Control) of cultures [34].

B. Nutrient supply and physical impact factors

Phytoplankton biomass and PP is low almost all the year in the basin of the SCS. Nutrient input by terrestrial sources and nutrient flux by vertical mixing are two main sources of increased PP.

River discharges, rainfall, and nutrient advection are important pathways for the input of nutrient to the SCS. During the wet season, abundant low salinity but high nutrient waters occupied the coastal waters, resulting in a strong nutrients gradient from estuary to offshore deep waters, and hence producing a gradient of phytoplankton. The PP in the Beibu Gulf and along the coast of Guangdong is higher the whole year, since it belongs to the coast sea areas with high nutrients discharged from estuaries such as the Hong Ha and the Pearl River [38]. Phytoplankton biomass from the eutrophic Pearl River Estuary to the oligotrophic northern SCS was studied [39]. They found that nutrient replete Pearl River Estuary waters resulted in high chlorophyll concentration, whereas nutrient depleted offshore waters had low biomass [39]. This coincided with the finding that the higher phytoplankton biomass and higher PP in the Pearl River Estuary and Pearl River discharged water [7]. A red tide in Hongsha Bay of Sanya due to a large input of nutrients washed into the bay after the heavy rainfall [40]. The southward long-range transport of nutrients from the East China Sea to the northeastern SCS carried by the China Coastal Current also enhances the PP in the northeastern SCS [18].

Monsoon, upwelling, typhoons and cold eddies are all factors that influence vertical mixing of nutrient. Both in summer and winter, the monsoon deepens the mixed layer, especially in winter, and readily detectable concentrations of nutrient were found as a result of enhanced vertical mixing, resulting in a strong peak of PP in winter and a sub-peak of PP in summer in the deep ocean basin [38]. Upwelling is one related process, which moves cold and nutrient-rich water towards the surface. It is one of the most important physical processes for PP in the SCS [9]. Typhoons induce strong upwelling and vertical mixing in their wake, leading to elevated nutrient concentrations in surface waters and fueling phytoplankton growth. Tropical cyclone events could account for 20 to 30% of the annual new production in the open SCS, based on an average of 14 tropical cyclones passing over the SCS per year [41]. The phytoplankton blooms triggered by two typhoons with different intensities and translation speeds in the SCS, confirmed that the elevated nutrient triggered by typhoon-induced upwelling and mixing did fuel the phytoplankton growth [42]. There is also a report that typhoons crossings can enhance PP by up to 275% in summer in the SCS [12].

C. Phytoplankton standing stock

Satellite born sensors measure surface chlorophyll on a daily basis. The standing stock of organic carbon can be estimated from the remote signals, but there are problems with estimating the C: Chl-a ratio and the sub surface chlorophyll maximum. The yearly averaged surface chlorophyll concentration was less than 1 μg/L in most part of the South China Sea LME, particularly in the deep ocean basin where the chlorophyll concentration is even less than 0.2 μg/L.

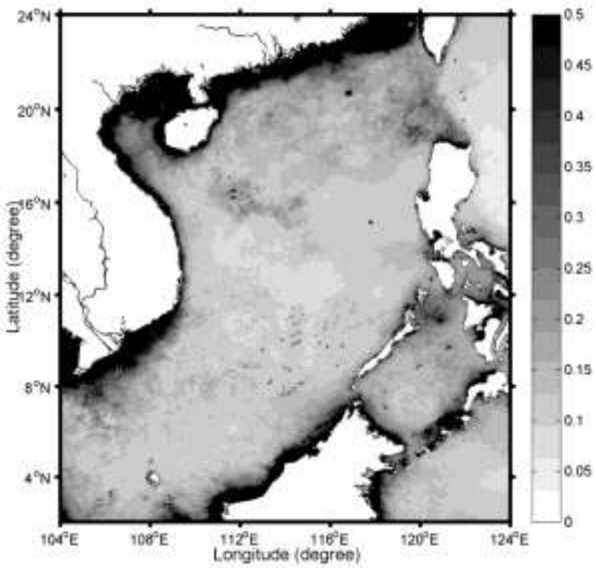

Fig. 3 Yearly averaged chlorophyll contribution in the SCS LME in 2013.

D. Primary production

There have been some investigations relevant to integrated PP in the SCS and these can be divided into culture bottle studies and remote sensing algorithms. Some measurements in the SCS have been performed using ^{14}C. Reference [5] showed the integrated PP was 546 mg C m^{-2} d^{-1} in winter and 389 mg C m^{-2} d^{-1} in summer in the SCS [5]. The integrated PP measured in the basin was higher in winter than in summer (530 versus 350 mg C m^{-2} d^{-1}) and the integrated PP on the shelf showed little temporal variation (820 in winter versus 840 mg C m^{-2} d^{-1} in summer) [32]. While the integrated PP in northern SCS during summer and found the value ranged from 189 to 976 mg C m^{-2} d^{-1} on the shelf [7].

Though culture bottle studies can be accurate, it is hard to measure the spatial and temporal distribution of integrated PP in the whole SCS in this way. Compared with the measurement, remote sensing algorithms for estimation of the PP over the whole SCS seem more feasible, even if it is less accurate. The difficulty arises in that the standing stock of organic carbon can be estimated from the remotely sensed surface chlorophyll and numerically modeled mixed layer depth, the rate of production of particulate organic carbon depends on the temperature, light level, and the concentration of nutrients in the photic zone. The integrated PP for the whole basin was estimated with an annual mean of 280 mg C m^{-2} d^{-1} derived from SeaWiFS data [1]. With an increasing number of observations in the SCS that may be used to check the validity of the previous approach, the coupled model of the SCS mentioned above was improved by employing a photo-adaptation scheme for the phytoplankton growth and using the simplest bottom boundary condition of an inert benthic layer [8]. The improved model predicts a mean annual integrated PP value of 406 mg C m^{-2} d^{-1} for the SCS, with 390 mg C m^{-2} d^{-1} for the basin region (> 200 m in depth) and 429 mg C m^{-2} d^{-1} for the shelf region (< 200 m). The integrated PP value of the SCS provided Sea Around us Project 2011 was 477 mg C m^{-2} d^{-1}.

TABLE I
COMPARISON OF INTEGRATED PRIMARY PRODUCTION (IPP, MG C M^{-2} D^{-1}) BETWEEN REMOTE SENSING ALGORITHMS (RSA) AND IN SITU MEASUREMENT (ISM) IN THE SCS.

	Methods	IPP in basin	IPP on shelf	IPP in the whole SCS
Liu et al., 2002	RSA	280		
Liu et al., 2007	RSA	390	429	406
Sea Around us Project 2011	RSA			477
Ning et al., 2004	ISM			389 - 546
Lee Chen. 2006	ISM	350-530	820-840	
Liu et al., 2011	ISM		189-976	

III. FISHERIES IN THE GLOBAL OCEAN AND THE SOUTH CHINA SEA

A. Global fish catch and mean trophic level

It was estimated using a variety of methods that upper limits for sustainable marine fisheries catches which range from 100 to 140 million tonnes (Mt) per year (Fig. 4a) [21], [43], [44]. Global landings reported have stagnated around 80 Mt per year since 1995, with perhaps another 20 Mt of additional illegal catch [45]. Catches taken per unit of fishing effort have actually declined [46], which suggests that, in general, global sustainable harvest limits have already been exceeded [47]. Fisheries have long been thought inexhaustible but over time, fishing technology has advanced and targeted marine species of lower trophic levels [21]，[48], [49]. This phenomenon was described as “fishing down the food web”. There are also researchers who do not agree that a general decline in mean trophic level of marine is likely have occurred in many regions [50]. The mean trophic level for the global ocean did show a slight decline over the past 60 years (Fig. 4b).

Fishing now expands further offshore and into deeper waters in many of the world’s fisheries [51]-[53]. This happens in tropical fisheries, especially as fishermen struggle to find new grounds because of reduced catches inshore. In addition, Watson and Pauly’s analyses (2014) showed that the mean depth of fishing started increasing mainly in the late 1960s, corresponding to the expansion of the fisheries catch into deeper waters below 600 m. By early 1980s, fisheries operations occurred down to 1500 m depth and close to 2000 m by 2004 [54]. In addition, as the FAO 2010 in Page 85 stated that, in 1940, the total catch from the Tonlé Sap in Cambodia of 125,000 t consisted mainly of large and medium-sized fish; while in the1995–96 catch of 235,000 t contained hardly any large fish and was dominated by small fish. In the Asia-Pacific region, the increasing demand for low value/trash fish as feed for mariculture drives unsustainable fisheries on already overexploited marine resources and leads to growth in the overfishing of the fish stocks used as feed [55]. Juvenile overfishing occurs and many small fish are caught [56].

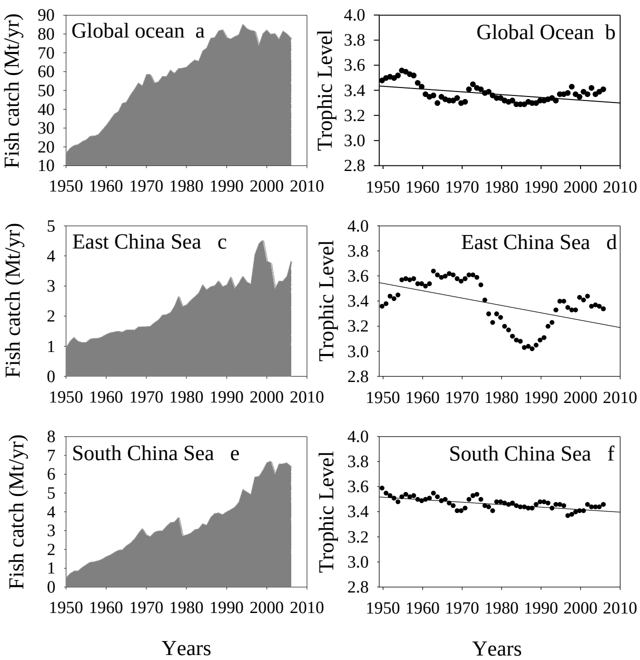

Fig. 4 Fish catch per year and mean trophic level for global ocean (a, b), East China Sea (c, d) and South China Sea (e, f).

B. Fish catch and mean trophic level in the SCS

The fish catch from the SCS is mostly from small fish over the continental shelf. Squid and their predator, tuna, populate the deep basin area. The biomass of squid is order 2.3 Mt [57] but contributes little to the SCS fish catch. The East China Sea and South China Sea showed the same pattern as the global fish catch with inter-annual fluctuations after 2000 (Fig. 4c, 4e). The total fish catches was 12.6 Mt in 2012 as reported in the China fishery statistical yearbook (2013). The fish catch by Chinese fishermen made up only part of the total fish landing in the China Seas, particular in the SCS. Fish catch in the SCS was reported as less than 3 Mt in the China fishery statistical yearbook (2013), which was just about a half of the total fish landing of the SCS, and which was consistent with the value provided by Sea Around Us Project 2011. The pattern of fish catch was found in the SCS to be essentially constant since 2000 with a value around 6.5 Mt in 2006 and also 6.5 Mt in 2010.

The trends in mean trophic level for catches in the East China Sea showed a similar pattern with a slightly stronger trend of "fishing down the food web" in the past 60 years (Fig. 4d). There was a particular low mean trophic level for catches in late 1980s at the dawn of fishing moratorium policy in the East China Sea. The mean trophic level in the SCS, when compared with the East China Sea, showed almost no downtrend in the past 60 years (Fig. 4h). The present trophic level is about 3.4, which was similar to the global ocean value.

C. Comparison of fishery resource and exploitation between China Seas and the global ocean

The East China Sea LME and South China Sea LME around China from north to south appeared to have undergone temporal and spatial shifts from shallow to deep seas. We measured catch per square meter and the carbon transfer efficiency for the LMEs and the global ocean (see table II). The East China Sea LME is moderate efficiency fisheries. The South China Sea LME is a poor fishery in comparison with Humboldt Current LME, but all are more productive than the global ocean. This is consistent with the PP level, which in turn is limited by the supply of nutrient. However, the fish catch per square meter is quite high, which indicates fishing intensity is high in the East China Sea and South China Sea LMEs. The same situation was also found when the fishing intensity between the South China Sea LME and other LMEs was compared [54].

Carbon transfer efficiency roughly estimates the efficiency of carbon removed from marine ecosystem by fisheries landings. It is higher in the two LMEs around China than that in the global ocean, even equal to or more than half of that the Humboldt Current LME, which is a highly productive system with ocean currents and rich nutrient upwelling [58].There are some probable reasons to explain the relatively high carbon transfer efficiency in the South China Sea given its low nutrient supply. One possibility is juvenile overfishing in the SCS. In the Asia-Pacific region, the increasing demand for low value/trash fish as animal feed leads to overfishing of the fish stocks used as feed [55]. The Beibu Gulf ecosystem in the SCS changed from large groundfish to small species due to overfishing from 1960s to 2000s when the ecosystem structure was compared before and after the collapse of fish stocks [59]. Trends of offshore extension of fisheries on pelagic and demersal fisheries can be clearly seen in the world's fisheries statistics [52], [53]. No doubt, it occurred in the South China Sea, and this expansion trend may have covered the entire LME [54], [60].

TABLE II
INTEGRATED PRIMARY PRODUCTION (IPP, MG C M^2 DAY^{-1}), AREA (10^{12} M^2), FISH CATCH IN WET WEIGHT (FC, MT YR^{-1}), FISH CATCH PER SQUARE METER (FC/A, G $YR^{-1}M^{-2}$) AND CARBON TRANSFER EFFICIENCY (CTE, 10^{-4}) IN GLOBAL OCEAN AND THE THREE LARGE MARINE ECOSYSTEMS IN 2006.

	IPP	FC	FC/A	CTE
East China Sea	891	3.5	3.5	10.8
South China Sea	477	6.5	1.2	6.7
Humboldt Current	876	10.0	3.8	12.0
Global ocean	365	80.0	0.2	1.7

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D. The fish production opportunity

The fish catch per square meter in the SCS is much less than that in the East China Sea. A partial reason for this is the deep basin in the SCS in which has a low integrated PP. Squid seem to populate this region over the deep basin and they are a negligible contributor to fish catch [57]. Fish are not caught in low chlorophyll regions. Fish catch is shown to be proportional to the chlorophyll level in the west coast of North America. Extrapolating the regression line, the fish catch expected is zero when the chlorophyll concentration is less than 1 μg/L [61]. Averaged over the year, chlorophyll levels are much below 1 μg/L (Fig 3b). The SCS is a poor fish producer. PP over central basin is too low and chlorophyll level is below a fishery threshold. The potential fish catch over the basin with an area 2 $\times 10^{12}$ km^2, is 7 Mt/yr what if the fish production in the SCS had the same level as in East China Sea. While we do not choose to investigate how this might be done, Jones has discussed concepts for providing additional micro or macronutrients to oligotrophic waters [62]. Consideration of such technologies, discussed by Jones and Harrison, may lead to the ocean providing more of China's increasing protein demand [63].

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