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Both riverine detritus and dissolved nutrients drive lagoon fisheries

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ABSTRACT

The net ecosystem metabolism in lagoons has often been estimated from the net budget of dissolved nutrients. Such is the case of the LOICZ estuarine biogeochemistry nutrient budget model that considers riverine dissolved nutrients, but not riverine detritus. However the neglect of detritus can lead to inconsistencies; for instance, it results in an estimate of 5–10 times more seaward export of nutrients than there is import from rivers in Chilika Lagoon, India. To resolve that discrepancy the UNESCO estuarine ecohydrology model, that considers both dissolved nutrients and detritus, was used and, for Chilika Lagoon, it reproduced successfully the spatial distribution of salinity, dissolved nutrients, phytoplankton and zooplankton as well as the fish yield data. Thus the model suggests that the riverine input of both detritus and dissolved nutrients supports the pelagic food web. The model also reproduces well the observation of decreased fish yield when the mouth of the lagoon was choked in the 1990s, demonstrating the importance of the physics that determine the flushing rate of waterborne matter. Thus, both farming in the watershed by driving the nutrient and detritus inputs to the lagoon, and dredging and engineering management of the mouth by controlling the flushing rate of the lagoon, have a major influence on fish stocks in the lagoon.

1. Introduction

There are several descriptions in scientific literature of the food web in different estuaries (see reviews in Valiela, 1995; Wolanski et al., 2004; McLusky and Elliott, 2004; Heip et al., 2011; Wilson and Luczkovich, 2011; Day et al., 2012; Wolanski and Elliott, 2015). These studies often emphasise the key role in the food web of either phytoplankton or detritus; other studies, however, recognise that both phytoplankton and detritus are important in driving the food web, especially in the presence of tidal wetlands providing detritus that the microbial loop helps make bio-available (Mann, 2000; Montague and Wiegert, 1990; Mitsch and Goesselink, 2000; McCallister et al., 2004).

An important component of estuarine detritus is particulate organic carbon (POC) and it is derived from several external sources, including riverine POC detritus (typically 3% by dry weight of SPM), fluvial plankton (both living and detrital), detritus from tidal wetlands and the benthos, and marine plankton with POC content up to 20% (Meybeck et al., 1988; Wolanski et al., 2004). Another important component of estuarine detritus is internally produced; dying organisms and excreta, become detritus that is recycled, some through the microbial loop. The fate of this detrital organic matter remains little known for most rivers and estuaries. It is known however that the detritus consumers ingest the detritus-rich sediment and the detritus-rich particles in suspension in the water column, and thus detritus consumers comprise most of the herbivores, omnivores and primary carnivores in an estuary; thus most of the estuarine biota are particle producers (microalgae and detritus derived from plant growth) and particle consumers (Knox, 1986; Wetzel, 2001; Sobczak et al., 2005).

Estuarine fisheries production varies naturally in response to variation in freshwater flows that alter the delivery of terrestrially derived nutrients and organic matter, including their anthropogenically derived fraction, into estuarine and coastal systems (Darnaude, 2005; Gillson, 2011). The relationships between nutrient-enriched freshwater and fisheries production largely

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depend on how reliant the food web of a particular estuary and coastal waters is on active biological incorporation of riverine organic matter (Sobczak et al., 2005; Darnaude, 2005; Connolly et al., 2009); in fact, this appears to vary from estuary to estuary. In some estuaries, fish feed on mobile crustaceans and/or macro-infauna (Elliott and Hemmingway, 2002; Wolanski and Elliott, 2015). In other case, estuaries, such as the Chilika Lagoon, India, clupeoids, catfishes (scavenger and omnivorous) and mullets, are dominant (contributing up to 63% of the total fish catch in the lagoon; Mohapatra et al., 2007) and their diet is dominated by detritus-based food items (dead organic-rich matter) even when other food resources are readily available in the lagoon (Rajan, 1964; Gerking, 1994; Aguiaro et al., 2003; Odum, 1970; Rao and Babu, 2013; Padmakumar et al., 2009; CDA, unp. data). Ecologically, there are two major groups of fishes in the Chilika Lagoon, namely freshwater species and saltwater species. The freshwater species prefer the less saline parts (thus they are mainly found in the northern part) and the saltwater species are found in the higher saline parts of the lagoon (Jones and Sujansingani, 1954).

The understanding of estuarine ecosystems can be facilitated by the use of models to test scenarios, provided relevant field data exist; such models combine an estuarine water and sediment circulation model with a food web model (see a review in Baird and Mehta, 2011; Wolanski and Elliott, 2015). One key question that models are asked to answer is “what is the fate of riverine nutrients on entering an estuary?”

The LOICZ model is the most commonly used model to answer that question, having been applied to more than 200 estuaries worldwide. It does so by neglecting detritus and focusing on dissolved nutrients though it takes into account the partition of nutrients between the particulate and dissolved phases (Swaney et al., 2011; Xu et al., 2013, 2015). More advanced models that could be used to answer that question couple hydrodynamics, water quality and ecological sub-models. The ecological sub-models range from simple to complex in the parameterization of the processes transforming the nutrients that sustain the food web structure of the ecosystem; the most simple models stop at plankton and the most complex models consider the food web up to the fish (Baird and Mehta, 2011). However, these models commonly neglect riverine detritus; an exception however is the UNESCO estuarine ecohydrology (UEE) model that links a physical sub-model with an ecological sub-model that includes detritus (Wolanski et al., 2006a, b; Wolanski and Elliott, 2015). As a consequence, we chose the LOICZ and the UEE models to answer that question and to provide the data for the models we undertook a process-based field study in Chilika Lagoon (19°40′N, 85°20′E; Fig. 1) on the east coast of India.

The lagoon covers an area of 950 km^2 during summer and 1165 km^2 during monsoon with a mean water depth of 1.7 m. (Siddiqui and Rao, 1995). It has a monsoonal climate and it drains 19 rivers and rivulets that carry high amount of inorganic and organic load (Muduli et al., 2012). The northern sector receives most of this discharge during the southwest monsoon season (July–October). The southern sector has extensive seagrass meadows. It has one major mouth to the sea (the Bay of Bengal) and that mouth is naturally migrating northward at a rate of ~100 m yr^{-1} due to the northward longshore sediment coastal drift (RangaRao et al., 2009). As a result of this drift, in the late 1990s the lagoon was choked and the fisheries collapsed. A new mouth was dredged in 2000 close to the middle of the lagoon, and this has greatly improved water quality and the fisheries recovered (Ghosh and Pattnaik, 2006). A new natural inlet mouth has since formed about 1 km north of the dredged mouth. Since then, the lagoon is continuously evolving ecologically due to the seasonal fluctuations in the river inflow (Sila and Vora, 2005; ICMAM-PD, 2010; Jayaraman et al., 2007; Mohanty and Panda, 2009; Ramanadham et al., 1964). Fishing activities and tourism in Chilika provide sustainable support and economic livelihoods to more than 200,000 people who live around the lagoon in 141 villages. The total fish production from the lagoon in 2013–14 was 12,936 MT (fish, 7699 MT; shrimp/prawn, 4928 MT; crab, 309 MT) (http://www.odishafisheries.com/File/tender/2014/fisheries-statistics-odisha-15-revised-1.pdf). Chilika Lagoon is a Ramsar Site under the Convention of Wetlands of International importance for large aquatic birds. Among the different group of birds, long-legged waders and dabbling species are predominant. Other groups include ducks, and smaller wader flocks, shovelers, pintails, coots, gadwalls and great crested grebes, flamingos etc. Besides eating algae and insects, these birds also depend on the lagoon fishes and benthic animals for food, and some are herbivores. The lagoon also harbours the Irrawaddy dolphin (*Coryphaena* sp.).

This study quantifies through field data and modeling, the fate of riverine nutrients in Chilika Lagoon. We demonstrate an apparent pitfall of the LOICZ biogeochemical estuarine nutrient budget model as it predicts a seaward export from the lagoon of dissolved nutrients that is an order of magnitude larger than the riverine input into the lagoon. We overcome this limitation by applying the UNESCO estuarine ecohydrology (UEE) model that considers riverine detritus inflow to the estuary. The UEE model reproduced successfully the spatial distribution of salinity, dissolved nutrients, phytoplankton and zooplankton as well as the fish yield data and it suggests that the riverine input of both detritus and dissolved nutrients supports the pelagic food web. Both farming in the watershed by driving the nutrient and detritus inputs to the lagoon, and dredging and engineering management of the mouth by controlling the flushing rate of the lagoon, have a major influence on fish stocks in the lagoon.

2. Methods

2.1. Field data collection

A scientific team from the NCSCM (National Centre for Sustainable Coastal Management) was involved in the collection, analysis and processing of physico-chemical data (salinity, temperature, suspended sediment concentration, DIN, and DIP, phytoplankton and zooplankton) in May 2014 (dry season) and October 2014 (wet season), at 35 sampling stations evenly distributed within the lagoon (Fig. 1). The standard methodologies of Ganguly et al. (2015) were followed for all the biogeochemical and physical analysis.

Rainfall and wind data were obtained from IMD (India Meteorological Department). Daily river runoff and evaporation data were obtained from CDA (Chilika Development Authority). CDA also provided data on fish landings in the 4 sectors shown in Fig. 1. The areal distribution of dolphins, birds, seagrass and macrophytes, and the suspended sediment concentration (SSC) was determined from our field observations and the data provided by the CDA.

2.2. The LOICZ model

Because the waters were vertically well-mixed, the depth-averaged LOICZ biogeochemical model of Swaney et al. (2011) was applied to Chilika Lagoon to estimate the net ecosystem metabolism (NEM) of the estuarine and coastal water.

To obtain data for the model, two independent observations were carried out for a peak representative month corresponding to dry (March) and wet (July) seasons of 2014, each covering a spread of 35 stations chosen to represent the south, central, and northern lagoon and the outer channel (Fig. 1). Simultaneously, 19 major rivers/rivulets, which drain into Chilika lagoon, were also sampled.