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Carrying capacity simulations as a tool for ecosystem-based management of a scallop aquaculture system

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ABSTRACT

Over the past decade, Sechura Bay has become an important center for mariculture in Peru, where the Peruvian bay scallop (*Argopecten purpuratus*) is grown in bottom cultures. Currently, the business involves 5000 artisanal fishermen and yields an export value of more than 158 million US$ per year. However, intensity and area extent of cultivation activities continue to increase. Overstocking of scallops combined with critical environmental changes may cause mass mortalities and severe consequences for the ecosystem. Accordingly, the ecosystem-based assessment of the current situation and the determination of long-term sustainable limits to scallop culture for the bay are crucial. Using a trophic food web model, the further expansion of culture activities is explored by forcing scallop biomass to increase to four different levels (458, 829, 1200, and 1572 t km^{-2}) and the impact on other groups and the ecosystem are investigated. The ecological carrying capacity (ECC) is defined as the maximum amount of scallop biomass that would not yet cause any other group's biomass to fall below 10% of its original biomass. Results suggest that (a) the current magnitude of scallop bottom culture (147.4 t km^{-2}) does not yet exceed ECC, (b) phytoplankton availability does not represent a critical factor for culture expansion, (c) a further increase in scallop biomass may cause scallop predator biomasses to increase, representing in turn a top–down control on other groups of the system, and (d) exceeding scallop biomass levels of 458 t km^{-2} may cause other functional groups biomasses to fall below the 10% threshold. The applicability and potential of the here presented ECC simulations as an ecosystem-based approach to sustainable bivalve culture are discussed. Results of this study are expected to guide both local fishers and managers in their challenging task of finding sustainable long-term levels for this important socio-economic activity in Sechura Bay.

1. Introduction

Bivalves such as clams, oysters, mussels, and scallops represent valuable marine resources worldwide that have been harvested for centuries. During the last decades, aquaculture became an important means for enhancing the production of these resources for human consumption without overexploiting their natural populations. However, the development of aquaculture has often been a bottom-up process, without systematic planning, previous identification of adequate culture areas, or consideration of environmental constraints (Ferreira et al., 2013). Since intensive, industrial-scale culture may lead to changes in ecosystem structure, loss of benthic biodiversity, disease outbreaks, or may cause even mass mortalities due to self-pollution, or whole systems to collapse (e.g. Inglis et al., 2000; Ferreira et al., 2013), a system-scale assessment of bivalve aquaculture is crucial to ensure long-term sustainable usage of these important marine resources.

Along these lines, many authors have focussed on the concept of carrying capacity, which defines the maximum culture levels before unacceptable changes are incurred to the system (e.g. Inglis et al., 2000). Carrying capacity (CC) has been distinguished into physical, production, ecological, and social CC (Inglis et al., 2000; McKindsey et al., 2006), with physical carrying capacity being the area geographically available and physically suitable for the cultivation of a species in a certain location, and the production carrying capacity describing the bivalve stocking density optimizing long-term harvest. On the ecological level, carrying capacity is approached more holistically, with limits to culture that are set as to optimize production without causing unacceptable impacts on the ecosystem. The social CC considers thresholds of production in a socio-economic context (Inglis et al., 2000; McKindsey et al., 2006). Modeling approaches to carrying capacity have so far often dealt

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with hydrodynamics, food availability and production, as well as with bivalve feeding physiology (Inglis et al., 2000; McKindsey et al., 2006; Gibbs, 2007; Ferreira et al., 2013; McKindsey, 2013), thus targeting physical and production CC. Index models, as an example, have been used to evaluate the impact of bivalve culture on the respective system, comparing the filtration of seston (Dame and Prins, 1998), the production of ammonia (Gillibrand and Turrell, 1997) or biodeposits (Grant et al., 2005) with its tidal renewal as presented by a simple ratio. Other authors estimated carrying capacity as the stocking density maximizing production rates without negatively affecting individual growth rates (Carver and Mallet, 1990) or depleting available oxygen (Uribe and Blanco, 2001), or by the amount of waste production that can be assimilated, removed, or dispersed by the system of concern (e.g. Weise et al., 2009).

By definition, ecological carrying capacity describes the maximum standing stock of the cultured species that does not yet cause “unacceptable” impacts on the ecosystem (e.g. Inglis et al., 2000). The characterization of what represents such an unacceptable change is, however, difficult, and depends on both the environmental settings as well as the social context (e.g. the perception of the involved stakeholders). A holistic approach is nevertheless important, as certain carrying capacity levels may be “unacceptable” to other compartments of the system, e.g. when stocking densities result in cascade effects within the trophic structure of the system (Jiang and Gibbs, 2005). On the other hand, positive effects of culture may also be possible, when the cultured species provides a new habitat structure (Meyer, 2014) and/or an increased food source for benthic fishes and macroinvertebrates associated with bivalve culture sites (McKindsey et al., 2006). In addition to that, cultured bivalves may impact the system by an excessive partitioning of food resources (Newell, 2004), increase in water clarity (Shumway et al., 2003), competition for space (Gibbs, 2004) and increased sediment deposition (La Rosa et al., 2002). As yet, co-occurring species have not been included in most CC models, although they may be important for preservation biodiversity (Worm et al., 2006), due to their role in regulating ecosystem structure and functioning. These concerns, however, are especially important when an ecosystem-based management approach is followed to avoid surpassing carrying capacity limits with a resulting degradation of the system function (Byron et al., 2011a). Some authors used the trophic modeling (Ecopath) approach to estimate carrying capacity by a step-wise increase of the biomass of cultured bivalves, until more food is required than available in the system (ecotrophic efficiency >1, e.g. Wolff, 1994; Jiang and Gibbs, 2005; Byron et al., 2011a, 2011b). This approach, however, uses a steady-state model of constant flow rates between the compartments, and does only focus on the phytoplankton–bivalve interaction, without considering that bivalve culture may significantly impact other parts of the ecological community, or the overall system itself.

The present work aims at addressing ecological carrying capacity of the Sechura Bay ecosystem in northern Peru, which is subjected to an intensive and growing scallop bottom culture, in a more holistic way. The possible impact of a further increase in culture activities on other species groups and possible ecosistemic changes is evaluated by the use of Ecosim. Based on scallop production trajectories of the last years, it was hypothesized that current biomass levels of scallops are already close to the ecological carrying capacity and that phytoplankton standing stocks will soon be depleted if culture activities are expanded at the current pace. The potential of using the definition of stock collapse (after Worm et al., 2009), i.e. if any group biomass falls below 10% of its original biomass, as an approach for defining “unacceptable” ecosystem-based thresholds is explored. Possible management (adaptations) scenarios are discussed in order to ensure the long-term sustainable use of this marine ecosystem and its valuable (fisheries) resources.

2. Methods

2.1. Description of study site

Sechura Bay is located in the North of Peru (5.6°S, 80.9°W) in a transition zone between the northern edge of the Humboldt Current and the southern end of the tropical equatorial region. Due to this geographic position, the bay's sea surface temperatures (SST) are usually higher than those of the central region of the Humboldt system to the south. The bay's inner part is shallow, containing a large area with depths between 5 and 10 m, with depths greater than 30 m found further offshore. The bay, which extends over an area of 400 km^2, has in recent years developed into a hotspot for scallop (*Argopecten purpuratus*) bottom culture. The species has been extracted along the Peruvian and Chilean coastline since the 1950s, and its fishery represents one of the economically most important bivalve species of the Pacific coast of South America. Due to its comparatively fast growth rate and high productivity, it represents an important portion of the aquaculture exports from Peru, with an export value of about 158 million US$ per year (in 2013, ADEX Association of Exporters Perú, 2014). In Sechura Bay, approximately 5000 artisanal fishers and 20,000 additional personnel are currently involved in the scallop production and subsequent processing. At present, about 41% of the bay's area (165 km^{-2}) is assigned to different associations of artisanal fishermen allowing them to conduct scallop bottom culture (PRODUCE–Ministery of Production, 2015). This is done without the use of large nets or substrate structures, by placing newly recruited individuals (“seed”) onto the ground at densities sometimes up to 300 ind. m^{-2} (Mendo et al., 2011). Seed is collected at natural banks within the bay or at a nearby island called *Isla Lobos de Tierra* (ILT, see Fig. 1).

2.2. Model description and data input

A trophic model of Sechura Bay was constructed using the software Ecopath with Ecosim (EwE) 6.4.3 (Christensen and Walters, 2004a), and was based on a previous model by Taylor et al. (2008), which represents the pre-aquaculture conditions of the year 1996. The updated model is comprised of 19 functional groups, representing both benthic and pelagic species groups (Fig. 2).

Input parameters for the different functional groups were obtained from various sources including regional catch statistics, empirical relationships shown in other studies or models, and assumed estimates (after Taylor et al., 2008; see Table 1). Values for production/biomass (P/B), consumption rate (Q) and conversion efficiency (GE) were based on former estimates of Taylor et al. (2008).

Phytoplankton biomass was calculated from remote sensing estimates of sea surface Chlorophyll *a* (Chl *a*) (mg m^{-3}) from MODIS (MODIS-Aqua 4 km satellite, taken from http://disc.sci.gsfc.nasa.gov/giovanni) for the region 5.17–5.89°S, 80.798–81.25°W. Annual values were first transformed into wet weight using conversion ratios from Brush et al. (Brush et al., 2002; Chl *a*: Carbon - 1:40) and Brown et al. (Brown et al., 1991; Carbon: wet weight - 1:14.25) and were then multiplied by a mean water depth of 15 m to convert values to a m^2 basis, assuming a well-mixed water column (after Taylor et al., 2008). Phytoplankton biomass was averaged for the years 2008–2012, to diminish the effect of inter-annual variability. Estimates of zooplankton biomass were taken from surveys conducted by the Peruvian Marine Research Institute (IMARPE) for the region (5°–6°S, <82°W, $n = 60$; after Taylor et al., 2008) between 1995 and 1999, as more recent data was not available. Benthic macrofauna biomass estimates, including scallops, were based on data of a benthic survey in Sechura Bay conducted during December 2010 by IMARPE. Hereby, epifauna and infauna was sampled at 124 stations using replicated quadrants of 1 m^2 each. Abundance and