



Assessment of long-term changes of ecosystem indexes in Tongoy Bay (SE Pacific coast): Based on trophic network analysis



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ABSTRACT

Quantitative macroscopic's indexes have been used to compare three trophic models of the exploited benthic ecosystem of Tongoy Bay. In this system the primary productivity and benthic invertebrates are more important in the cycling of biomass. The models were built with a similar number of compartments for the years 1992, 2002 and 2012, using *Ecopath with Ecosim (EwE)*. Odum and Ulanowicz's frameworks and ecological network analysis were then used to estimate the levels of maturity, growth and development of the system. Likewise, "keystoneness" indexes – at each time – were also estimated for the models. Our results show that Tongoy Bay exhibited an increase in maturity and development ("health") in 2012 compared to past conditions, which was reflected by (1) an increase in the total system biomass, total system throughput, AMI, and absolute *Ascendency*, (2) higher flow and increased efficiency of transferred energy and its proportion at higher trophic levels, (3) an increase of recycling (FCI), (4) a reduction of NPP/R and NPP/B ratios of the system, and (5) an increase in the number of compartments trophically linked that comprise the *keystone species complex*. We argue that these results are a consequence of reduced fishing pressure on this benthic system in recent years. This study shows that the fishing would not only have a direct impact on exploited species, but would also affect the structure and functioning of the ecosystem. The information obtained could help to improve the management of fisheries resources, evaluating surveillance indicators that can show the putative changes of intervened ecosystems.

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1. Introduction

The rapid deterioration of ecosystems worldwide has intensified the need to assess the emergent properties (as macroscopic indexes), which allow them to be monitored over time (Mageau et al., 1998; Costanza and Mageau, 1999). Sustainability indexes associated with ecological system theory focus on the ability of ecosystems to withstand natural or anthropogenic disturbances (Rapport et al., 1998; Mayer et al., 2004). It is proposed that "good" healthy ecosystems would be sustainable, if they were capable of maintaining their structure (organisation) and function (activity) over time after suffering external disturbances (Holling, 1973, 1987; Ulanowicz, 1992; Grimm and Wissel, 1997; Costanza and Mageau, 1999). Odum (1969) and Ulanowicz (1986, 1997)

developed two frameworks, which allow us to use several macroscopic indexes related to ecosystem health (Rapport et al., 1998; Costanza and Mageau, 1999; Mayer et al., 2004).

Anthropogenic influences, such as fishing and pollution, have been associated with long-term ecosystem changes in structure, organisation and functioning (Pauly et al., 1998; Gunderson, 2000; Scheffer et al., 2001; Troell et al., 2005; Petersen et al., 2008). These conclusions have focused efforts to apply procedures that allow one to quantify the changes in ecosystems. In this sense, Odum (1969) proposed that maturity of ecosystems occurs when their structural and functional characteristics are maximised, which can be measured as increments of biomass, dominant symbiosis, nutrient conservation, stability, reduced entropy, and increased information. Thereafter, Ulanowicz (1986) developed a framework called *Ascendency*, which is based on network analysis and principles of thermodynamics. *Ascendency* evaluates the degree of growth and flow coherence of an ecosystem. Likewise, *Ascendency* can be used to describe the trend of an ecosystem after natural or anthropogenic disturbances (Costanza and Mageau, 1999; Walters and

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Martell, 2004) and used to compare ecosystem trajectories at different times (Wulff and Ulanowicz, 1989; Baird et al., 1991; Monaco and Ulanowicz, 1997; Ortiz and Wolff, 2002a; Heymans, 2003; Christensen et al., 2005).

The flow of matter and/or energy through any network permits one to obtain relevant information about their structure and functioning. Based on this information it is possible to assess the influence of each component upon the entire the food web (Christensen et al., 1996; Pauly et al., 1998; Ulanowicz and Baird, 1999). The *Ecopath with Ecosim (EwE)* software was designed for the construction, parameterisation and analysis of trophic mass-balance models for aquatic ecosystems (Christensen et al., 2005). This software can quantify ecosystem macroscopic indexes with regard to its structure and dynamics, and estimate the propagation of direct and indirect effects through the networks as response to different management/harvest scenarios within marine ecosystems (Christensen and Pauly, 1993; Ortiz and Wolff, 2002a; Pikitch et al., 2004; Christensen et al., 2005; Ortiz et al., 2009, 2010). Based on this analysis, we can provide vital information for ecosystem-based management (EBM), which aims to maintain ecosystem services by conserving ecosystem structure and function (García and Cochrane, 2005).

The overall ecosystem productivity of Tongoy Bay, Chile (Fig. 1) is conditioned by the occurrence of periodic upwelling near the centre of the bay (Daneri et al., 2000). The most important components of the system are benthic invertebrates whose food intake exceeds that of pelagic fish and birds (Wolff and Alarcón, 1993; Wolff, 1994). This upwelling has led to the development of important benthic fisheries and consequent human interventions (Ortiz and Wolff, 2002b).

The total landings of the benthic resources from Tongoy Bay have fluctuated substantially since 1985, reaching a peak value in 1992 of ~300 tonne. The main exploited resources are predatory crabs, such as *Romalion polyodon*, the scallop *Argopecten purpuratus*, and clams. Over the last 20 years, the fishery has experienced a downward trend accompanied by changes in the composition of harvested species. These changes would suggest that the benthic system of Tongoy Bay has experienced changes since 1992 that, in turn, could modify the energy/matter flow patterns in this bay. Wolff (1994) and Ortiz and Wolff (2002a) determined several macrodescriptors of the Tongoy Bay benthic ecosystem and evaluated the effects of different fishing management strategies. However, both contributions were independent temporal snapshots of the bay. In the current study we adopt a network analysis – as a general strategy – for examining and comparing the long-term changes of macroscopic indexes as a consequence of fishing activities in the Tongoy Bay benthic ecosystem. To achieve that, three trophic models were constructed in order to represent the “ecosystem state” of the benthic communities for the years 1992, 2002 and 2012. Based on these models, our aim was to better understand the trajectory of the performance measures of this bay.

2. Materials and methods

2.1. Study area

Tongoy Bay (Fig. 1) is located in north-central Chile (30°12' S–71°34' W). This bay has high productivity due to the presence of a seasonal (spring and summer) upwelling (Fonseca and Farías, 1987). Seasonal upwelling produces high phytoplankton biomass, which in turn supports fishing and scallop (*A. purpuratus*) aquaculture (Boré et al., 1993). Although scallop aquaculture has increased dramatically over the past 20 years, natural stocks are depleted and benthic landings have experienced a remarkable reduction. In 1998, management areas for benthic

resource exploitation were delimited in Tongoy Bay under a territorial user rights for fishing (TURF) as a measure to reduce fishing pressure (Ortiz & Wolff, 2002a)

2.2. Source of data and models assumptions

Three trophic mass-balance models were constructed for the Tongoy Bay benthic ecosystem for the years 1992, 2002 (based on Wolff and Alarcón, 1993; Wolff, 1994; Ortiz and Wolff, 2002a), and 2012 (own sampling data), using *EwE* Software 6.0 (Christensen et al., 2005). The models were fit for the trophically linked biomass pools, concentrating on the major system biomass components (Walters et al., 1997; Pauly et al., 2000; Christensen et al., 2005). Biomass groups were defined as a species or functional group in term of wet weight. Each model represented the annual average condition of the Tongoy Bay benthic ecosystem. For comparisons at the system-level, the three benthic models were constructed with the same number of compartments ($n=12$), so as to reduce any bias associated with different aggregation strategies (Gaichas et al., 2009). It is important to mention that the fishes, birds and marine mammals were not included in the models due to insufficient scientific information. Wolff (1994) suggests that in Tongoy Bay benthic invertebrate predators are more important in the cycling of biomass than demersal fishes. Although this reduces the realism of the model configuration, the most relevant interdependencies and flows are reflected. This strategy permitted to obtain comparative macronicators to benthic level over time under similar limitations.

EwE is based on a series of linear equations and assumes a mass balance system between the compartments of the model. The general equation can be expressed as follows:

$$\frac{dB}{dt} = P_i - (B_i * M2_i) - P_i * (1 - EE_i) - EX_i \quad (1)$$

where biomasses are at steady state, P_i is production ($\text{g m}^{-2} \text{ year}^{-1}$), B_i is biomass (g/m^2), $M2_i$ is predation mortality (year^{-1}), EE_i is ecotrophic efficiency (%) which quantifies the proportion of the production that is utilised in the system, $1 - EE_i$ is other mortality of i (year^{-1}), and EX_i is export i ($\text{g m}^{-2} \text{ year}^{-1}$). Production is estimated by the relationship of production/biomass (P/B) and average annual biomass (B) and is expressed as: $P_i = B_i * (P_i/B_i)$. Predation mortality depends on the predator activity, and it is defined as the sum of consumption by all predators (j) preying on a species or group (i) and can be expressed as:

$$B_i * M_i = B_j * \frac{Q_j}{B_j} * \frac{D_{ji}}{C_{ji}} \quad (2)$$

where Q_j/B_j is the consumption/biomass of predator j (year^{-1}) and D_{ji}/C_{ji} is the i fraction of prey in the diet spectrum of predator j . For each functional group and/or species, the key input parameters are B_i , P/B_i , Q/B_i , and EE_i . At least three of these input parameters must be known for each group; the model estimates the fourth. The functional groups comprised species with similar trophic roles: (1) Predatory snails (PS) (e.g., *Xanthochorus* sp. and *Priene* sp.), (2) Predatory crabs (PC), such as *Cancer* sp. and *Homalaspis plana*, (3) Seastars (SS) (e.g. *Heliaster helianthus*, *Meyenaster gelatinosus*, and *Luidia magallanica*), (4) Small epifauna herbivores (SEH) (e.g., *Tegula* sp. and *Fissurella* sp.), (5) Large epifauna (LE) (e.g., *Pagurus* sp. and *Alpheus* sp.), (6) Small epifauna (SE) (e.g., *Caprella* sp. and *Nereis* sp.), (7) Bivalves (Biv) (e.g., *Mulinia edulis* and *Ensis macha*), (8) Zooplankton (Zoo), (9) Macrophytes (Ma) (e.g., *Chondrocanthus chamosoi*, *Ulva* sp., *Rhodymenia* spp.), and (10) Phytoplankton (Phy). The crab *Romalion polyodon* (RP) and the scallop *A. purpuratus* (AP) were included as individual compartments into the model because of their commercial importance. Information about diet matrices, productivity, and consumption of these functional groups was obtained from Wolff (1994) and Ortiz and Wolff (2002a) and

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