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Ecological–economic assessment of aquaculture options: Comparison between abalone monoculture and integrated multi-trophic aquaculture of abalone and seaweeds

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ABSTRACT

Integrated multi-trophic aquaculture (IMTA) possesses ecological and socio-economic advantages, relative to single-species aquaculture. The promotion of a sustainable aquaculture industry requires that decision-makers, ecosystem managers and farmers have sufficient quantitative information associated with its implementation from both public and private perspectives. The present paper applies the Differential Drivers–Pressure–State–Impact–Response (ΔDPSIR) methodological approach to an ecological and economic comparison between mono-aquaculture and IMTA. Data from a South African 240-ton year^{-1} abalone farm were used as a case study. Three operation schemes were considered: abalone monoculture in a flow-through system; and two IMTA schemes, which recycle water and replace 10% and 30% of kelp consumption with on-farm-grown seaweed. The analysis indicates a decrease in the aquaculture generated ecological pressures with the incorporation of seaweeds, mainly a reduction in nitrogen discharges into the adjacent coastal ecosystem (by 3.7 to 5.0 tons year^{-1}), a reduction in harvest of natural kelp beds (by 2.2 to 6.6 ha year^{-1}) and a reduction of GHG emissions (by 290 to 350 tons CO_2e year^{-1}). Adopting an IMTA configuration raised farm profits by 1.4 to 5%. The corresponding overall gain from using IMTA in the case study is several folds larger than the net gain in profit, and is estimated between 1.1 and 3.0 million U.S. dollar per annum. This range of values reflects the gains of adopting IMTA on (i) economic value of the aquaculture, i.e. farm's profit, (ii) value of environmental externalities, and (iii) implementation costs. The analysis suggests that the value of the benefits to the public by adopting the IMTA configurations can be larger than the gains in farm's profitability.

1. Introduction

Aquaculture has grown at an average annual rate of 8.8% since 1970 up to 2004 (FAO, 2006). Sustainability issues related to socially and environmentally irresponsible aquaculture practices reported for certain cultivation systems have generated concerns about the industry, particularly its industrialized and intensified monoculture forms (Allsopp et al., 2008; GESAMP, 2001; Islam, 2005; Paez-Osuna et al., 1999; Xu et al., 2007). Environmental impacts, their negative feedbacks on the aquaculture operations and their influence on policy makers and general public opinion often limit the expansion of monoculture farms below their technical and commercial potential (GESAMP, 2001; Gibbs, 2009; Islam, 2005). The broader public and policy makers are often unaware of the benefits that aquaculture can generate, e.g., through water biofiltration, to the environment (Ferreira et al., 2007; Lindahl et al., 2005; Newell, 2004; Rice, 2008; Žydelis et al., 2010) and to the society, e.g., through poverty reduction, employment and food security (FAO, 2005; Kaliba et al., 2007; Msuya, 2006; Robertson-Andersson et al., 2008; Troell et al., 2006). Given the importance of food security on the one hand (Ahmed and Lorica, 2002), and negative ecological–economic impacts of poorly conceived aquaculture practices on the other (Islam, 2005), an integrated planning and management of aquaculture is required (GESAMP, 2001). Furthermore, external benefits of socially and environmentally responsible aquaculture can have direct economic value. For instance, consumers have been showing increased awareness of and preference for sustainably produced seafood (FAO, 2006). The main technological approaches that have been developed to meet environmental concerns (Gutierrez-Wing and Malone, 2006; Neori et al., 2004; Refstie et al., 2001) include: (i) improved feed and water management, (ii) water recirculating systems, (iii) bacterial

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biofilters and (iv) extractive species (filter feeders, detritivores and macroalgae).

More recently, the integration of fed species and extractive species in the modern form of polyculture called integrated multi-trophic aquaculture (IMTA, also known as 'partitioned aquaculture' and 'aquaponics'), has been developed to ease environmental concerns because it addresses issues of both productivity and nutrient loading into the environment (Abreu et al., 2009; Buschmann et al., 2009; FAO, 2006; Neori et al., 2004; Troell et al., 2009; WGEIM, 2006). IMTA has been gaining recognition as a sustainable approach to aquaculture because of its combination of environmental, economic and social advantages (Allsopp et al., 2008; Ridler et al., 2007; Whitmarsh et al., 2006). A key to IMTA functioning is the plant component, usually algae: while taking up dissolved inorganic nutrients (nitrogen and phosphorus), the produced algal biomass is a renewable protein-enriched feed to other cultivated species, and a product on its own (Chopin et al., 2001).

The present article concerns a South African farm, where a two-component abalone and seaweed IMTA configuration has operated side-by-side with an abalone monoculture. The consumption of the seaweeds produced in the farm by its own abalone component and the existence of both configurations make this farm particularly suitable for our analysis. Abalone farming is an aquaculture industry that can particularly benefit from the implementation of IMTA with marine seaweeds, which are the natural abalone food. South Africa, the third largest abalone producer in the world (Gordon and Cook, 2004), has begun implementing IMTA with the seaweed *Ulva lactuca* L. and the abalone *Haliotis midae* L. (Robertson-Andersson et al., 2008). This move has largely emerged for the following reasons:

(i) Increasingly limited stocks of and access to harvestable South African kelp (Bolton, 2006; Hwang et al., 2009; Smit et al., 2007; Troell et al., 2006).
(ii) Observed acceleration of abalone growth rate when fed diets of mixed algal species, relative to single-species kelp diets (Dlaza et al., 2008), particularly using farm-grown protein-rich seaweeds (Naidoo et al., 2006): Growth rate (body weight) of juvenile *Haliotis midae* was 32% higher with a mixed kelp and farm-grown seaweeds, compared with fresh kelp and dry prepared diets (Naidoo et al., 2006).
(iii) Cultivation of seaweeds in the farm's abalone effluent allows water recirculation and reduces nutrient discharge into the environment (Robertson-Andersson, 2007).
(iv) A land-based seaweed facility allows the abalone farm to disconnect itself from the sea for extended periods by water recirculation through seaweed ponds during red tides and oil spills (Robertson-Andersson, 2007).

Aquaculture, like other uses of marine resources where the environmental and the socio-economic systems are intertwined, requires for its sustainable development information about the ecological and economic impacts of different practices. This implies communication between the commercial, scientific, management and policy-making communities, and the integration among disciplines using mutually understandable concepts (GESAMP, 2001). The Drivers–Pressure–State–Impact–Response (DPSIR) approach is a potential analytical framework for the determination and the communication of the impacts of aquaculture options. This approach has been applied to assist in the evaluation of environmental impacts and of ecosystem management (Stanners et al., 2008). In particular, the DPSIR has been widely used to report the quantification of the impacts of human activities on coastal activities (Borja et al., 2006; Elliott, 2002; IMPRESS, 2003; Nobre, 2009). The DPSIR is a conceptual framework for integrated environmental assessment that provides (i) a systematic view of the socio-economic and environmental interactions and (ii) a reporting framework to policy makers and public (Bowen and Riley, 2003; Ledoux and Turner, 2002; Nobre, 2009). The application of the DPSIR is based on the use of indicators (Stanners et al., 2008). It facilitates the structuring of data following the causal chain D–P–S–I–R: *Drivers* are the anthropogenic activities generating *Pressures* that perturb the *State* of the ecosystem, thus causing an *Impact* on the ecosystem, which calls for management and policy-making *Responses* to improve the *State* of the ecosystem (Borja et al., 2006; IMPRESS, 2003). A recent modification of the DPSIR, the Differential Drivers–Pressure–State–Impact–Response (ΔDPSIR), establishes an explicit link between the ecological and the economic systems and screens the evolution of ecological and economic variables between points in time or simulated scenarios (Nobre, 2009). The ΔDPSIR approach provides a tool for the assessment of changes in environmental quality and consequent effects on the economic system, including on the value of anthropogenic activities and of the ecosystem itself (Nobre, 2009).

The aim of the work presented herein is to couple ecological and economic information to support resource managers in the assessment of the ecological and economic *Impacts* of aquaculture operations. The ΔDPSIR framework (Nobre, 2009) is applied in the evaluation of a case study of a South African farm that integrated seaweed production to its abalone operation in the form of IMTA. The data sets used in this study were the only ones available in sufficient detail from land-based IMTA farm. In fact, while economic analyses for two open water IMTA farms are now available (Buschmann et al., 2008; Ridler et al., 2007) this is the first detailed analysis of the economics of a commercial land-based IMTA farm.

The analysis carried out in this paper includes the following two main components:

(i) An assessment of the environmental and economic *Impacts* to the main stakeholders by the shift from abalone monoculture to IMTA with seaweeds, using data from the South African farm (Robertson-Andersson, 2007; Robertson-Andersson et al., 2008; Sankar, 2009).
(ii) Nutrient mass balance analysis for three modes of operation in the two-component South African abalone and seaweed farm and in a three-component Israeli farm with abalone, fish and seaweeds (Neori and Shpigel, 2006), to provide guidance for the sustainable management of the nutrient limitation that occurs when expanding the seaweed production.

2. Methodology

2.1. General approach

The ΔDPSIR methodology (Nobre, 2009) is applied here to compare the sustainability of different options in aquaculture farm operation. The ΔDPSIR approach uses ecological and economic variables to evaluate the *Drivers*, *Pressures* and ecosystem *State* in two or more scenarios, which differ in their configuration; these values are then used to calculate (or predict) the relevant overall *Impacts* of the scenarios, which differ from each other as a result of management *Response*, i.e., a changes to configuration and management. The economic assessment uses a cost–benefit analysis to quantify a given management *Response* (the implementation of an IMTA system) from an environmental and economic perspective.

The ΔDPSIR components are defined as follows (Nobre, 2009):

(i) *Drivers*—the anthropogenic activities that may have an environmental effect at a given moment in time; it is a socio-economic component of the ΔDPSIR that is quantified by the value of those economic activities (*VDrivers*).
(ii) *Pressures*—direct positive and negative (e.g., biofiltration and pollution, respectively) influences of the *Drivers* on the environment. The quantification uses *Pressure* indicators at the research (e.g., nutrient loads from human activities) and management levels (e.g., overall human influence index by Bricker et al. (2003)).
(iii) *State*—the condition of the ecosystem at a given moment in time. It has both ecological and economic dimensions and is influenced