Bioeconomic modelling and salmon aquaculture: an overview of the literature

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Abstract: Bioeconomic models can be used to assist producers and decision-makers in identifying optimal production system designs, operation management strategies, and alternative development and policy approaches. This paper reviews the literature on bioeconomic modelling in aquaculture since 1993 and builds on an earlier article by Leung (1994) which examines this literature for the 1974–1993 period. In order to identify the papers reviewed in the present study, a thorough online search in various databases and some specific journals was conducted. Observations on the general state-of-the-art of bioeconomic modelling in aquaculture are discerned based on a comparative analysis of work in the field, with specific reference to salmon aquaculture. Implications for salmon aquaculture systems in Chile and elsewhere are discussed.

Keywords: bioeconomic models; aquaculture; salmon production.

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1 Introduction

Depletion of the world's natural fish stocks will have a great impact on the world food supply in the coming years. About one billion people – one-fifth of the global population – now rely on fish as their primary source of protein. In the future, the only way to ameliorate the growing scarcity of the global fish supply will be to manage fish resources better, to adopt environmentally friendly technologies, to improve equity in the distribution of the fish supply through policy-driven interventions, and through aquaculture. At present, the rapid increase in the fish supply is due in large part to an upsurge in aquaculture.

Aquaculture is the most rapidly growing segment of agriculture. More than 220 species of finfish and shellfish are farmed. It now contributes approximately 27% of the seafood consumed by humans worldwide and accounts for 18.5% of total world seafood production. Since 1984, world aquaculture production has nearly doubled, and the UN Food and Agricultural Organisation predicts that by the year 2030, aquaculture will dominate fish production and more than half of the fish consumed will be raised through aquaculture methods. Major marine cultured species include such high-value species as shrimp and salmon (FAO, 2003).

The intensification of aquaculture, while holding great promise for increasing global fish supply and addressing concerns over food security, poverty, livelihood and income, has not been without its impacts and conflicts. Most marine and diadromous finfish, for example, are reared in floating net cages near shore. Rapid expansion and technological change in the aquaculture industry has often surpassed society's ability to manage the growth of this diverse and dynamic sector. This has led to adverse environmental impacts that often constrain the growth and development of aquaculture and affect other resource users. These impacts include release of pollutants and other wastes, degradation and destruction of ecosystems and wild populations, loss of genetic and biological diversity, disease outbreaks, and resource use conflicts. The salmon and shrimp industries, while providing economic benefits, offer the most prominent examples of the potential and real negative environmental impacts of aquaculture when management is inadequate (FAO, 2003).

Due to the complexity of aquaculture production systems and the many challenges imposed by the rapid growth of this industry, comprehensive modelling efforts are needed in order to provide technological information to producers and policy alternatives to decision makers. According to Cuenco (1989), there are several reasons that warrant the modelling of aquaculture systems, including:

- modelling serves as a powerful tool for the formulation, examination, and improvement of hypotheses and theories
- models can make intelligent predictions about the consequences of various management strategies on the system
- modelling provides a working tool to quickly conduct numerous 'what if' experiments and makes it feasible to evaluate the consequences of various hypotheses or management strategies for large and complex aquacultural systems, which are seldom possible in their natural environment
- models serve as mechanisms to identify what is not known by organising what is known within the framework of the models
- models facilitate the evaluation of complex interactions of aquacultural systems
- modelling accelerates the use of more quantitative and precise methods in aquaculture research
- models can integrate knowledge from theoretical, laboratory and field studies into a consistent whole so as to identify areas where knowledge is lacking, sparse and/or inconsistent.

Bioeconomic models are a good methodological approach to study the interaction of the various components (biological, physical, technological, economic, institutional) of aquaculture systems. Bioeconomic models can provide answers to the questions of economic feasibility, optimal system design, optimal methods of operations, and research direction (Leung, 1994). However, bioeconomic models cannot be directly extrapolated between species as each species' growth is determined by specific factors and parameters.

The objective of this paper is to review bioeconomic modelling efforts since 1993. It will build on a paper by Leung (1994) that reviews the literature on bioeconomic models in aquaculture from 1984 to 1993. Observations on the general state-of-the-art of bioeconomic modelling in aquaculture are discerned based on a comparative analysis of work in the field, with specific reference to salmon aquaculture. Implications for salmon aquaculture systems in Chile and elsewhere are then discussed.

2 Literature review: data sources

Leung (1994) reviewed the literature on bioeconomic modelling efforts for aquacultural systems for the 20-year period going from 1974 to 1993. The first decade (1974–1983) relied on the work of Allen et al. (1984). The second decade (1984–1993) was based on a computer literature search and identified 32 specific bioeconomic modelling applications, as compared to 22 in the first decade.

For the current study, an online review was made of the following database: Agricola; Agris International; Ingenta; Social Science Citation Index; Agecon; and Science Direct. In addition, a complementary search was performed in the following scientific journals: *Aquaculture; Aquaculture and Fisheries Management; Aquaculture Economics and Management; Aquaculture Engineering; American Journal of Agricultural Economics; Asian Fisheries Journal; Marine Resource Economics; and Southern Journal of Agricultural Economics*. The literature search yielded a total of 28 papers using bioeconomic models; seven for aquaculture, 19 for capture fisheries, and two for artisanal capture fisheries. Table 1 presents a brief summary of these 28 papers. However, the present paper will focus only on the seven studies involving bioeconomic modelling for aquaculture.

Table 1 Studies using bioeconomic models for aquaculture and fisheries: 1994–2003

Authors	*Year*	*Specie(s)*	*Geographical region*
Aquaculture			
Aull-Hyde and Tadesse	1994	Hybrid-striped bass	USA
Gasca-Leyva et al.	2002	Seabream	Canary Islands, Spain
Hean and Cacho	1999	Giant clam	Solomon Islands
Hernández-Llamas	1997	Catarina scallop	Baja California, Mexico
Kazmierczak and Caffey	1996	Tilapia	USA
Miao and Tang	2002	Grouper	Gauxiong and Pindong Counties, Taiwan
Penney and Mills	2000	Sea scallop	Newfoundland, Canada
Capture fishery			
Cellina et al.	2003	Macroalgae	Southern Italy
de Anda-Montanez and Seijo	1999	Pacific sardine	Gulf of California, Mexico
de Castro	2001	Corvine	Southeastern Brazil
de Leo et al.	2001	Silver eel	Northern Italy
Flaaten	1998	Multispecies	Norway
Garza-Gil	2003	European hake	Iberian Peninsula, Spain and Portugal
Gillig	2001	Red snapper	Gulf of Mexico, USA
Holland	2000	Groundfish	George Banks, USA
Capture fishery			
Jerry and Raissi	2002	Theoretical model	–
Laukkanen	2001	Salmon	Northern Baltic
Lleonart et al.	2003	European hake	Western Mediterranean
Mardle and Pascoe	2000	Multispecies	English Channel, UK
Pezzey et al.	2000	Theoretical model	–
Rueda and Defeo	2003	Multispecies	Tropical Estuarine Lagoon, Colombia

Table 1 Studies using bioeconomic models for aquaculture and fisheries: 1994–2003 (continued)

Authors	*Year*	*Specie(s)*	*Geographical region*
Capture fishery			
Sanchirico and Wilen	2001	Theoretical model	–
Smith and Wilen	2003	Multispecies	Northern California, USA
Sumaila	1998	Cod	Barents Sea, North East Atlantic
Weninger	2001	Clam and quahog	Mid-Atlantic, USA
Wilen	2001	Theoretical model	–
Artisanal fishery			
Cabrera	2001	Multispecies	Yucatan, Mexico
Ulrich et al.	2002	Multispecies	English Channel, UK

3 Bioeconomic models: an overview

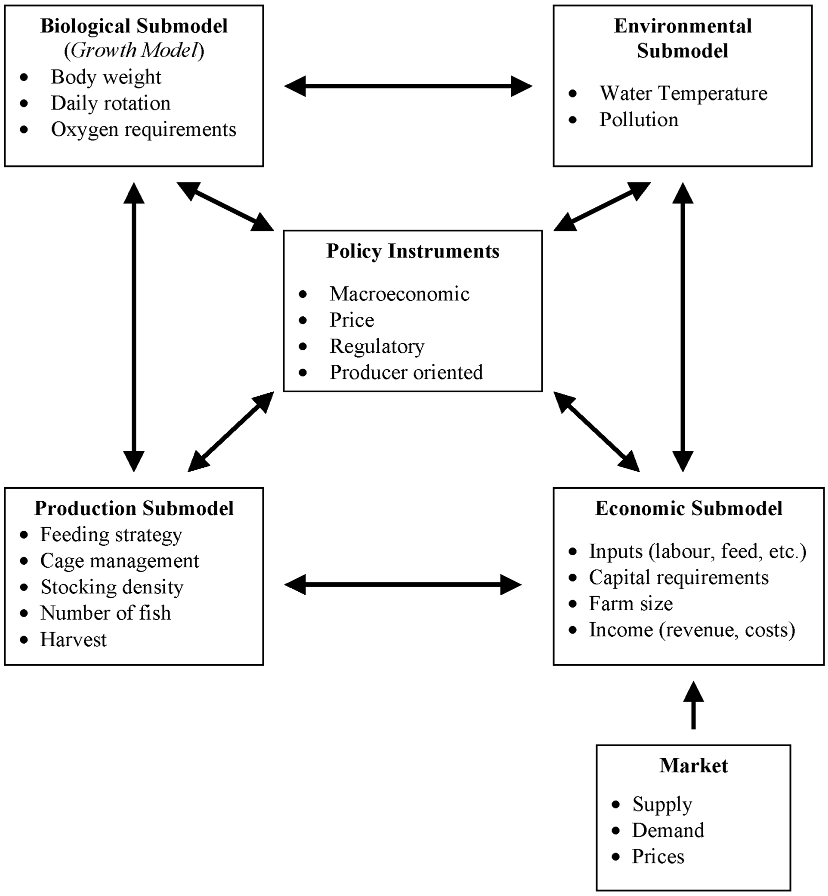
In general terms, the concept of bioeconomic models refers to the use of mathematical techniques to model the performance of 'living' production systems subject to economic, biological and technical constraints (Allen et al, 1984). Bioeconomic models address the systematic integration of biological performance and physical systems and relate them to economic considerations, which include market prices, resource allocation and institutional constraints (Cacho, 2000). Bioeconomic modelling provides an alternative method to represent the production process as compared to conventional production function analysis. It allows evaluations of a wider range of environmental conditions than would be normally possible with purely economic models, since biotechnical relationships can be more clearly defined (Leung, 1994). A diagrammatic representation of a fairly general type of bioeconomic model is presented in Figure 1.

Bioeconomic models can be used to assist producers and decision-makers in identifying optimal production system designs and operation management approaches and alternative development and policy strategies. Strategically designed bioeconomic models can provide information for developing private aquacultural strategies in response to optimal industry development and regulatory issues. In comparison to agricultural systems, bioeconomic models for aquacultural systems are still relatively limited.

The application of bioeconomic models to marine resources started as dynamic optimisation analysis for population growth (Clark and Munro, 1975). These models then incorporated optimal control and modern capital theory (Clark, 1985). In the last decade, bioeconomic models of aquaculture and fisheries have focused on developing a more realistic description of biological systems and establishing links with more complex economic models (Cacho, 2000).

Aquacultural production is a major challenge for economic modelling. The aquaculture producer cannot directly visualise the growth of the 'crop' and, therefore, must rely on indirect and subjective measures of production to formulate management decisions. Although similarities with the grow-out of other confined animals have been an important starting point for some models of aquacultural production, crucial differences – particularly in pond ecology, monitoring, and feed utilisation – require additional quantitative sophistication that is not needed for other animal production systems (Hatch and Kinnucan, 1993).

Figure 1 Basic Framework of a bioeconomic model



Given the sensitivity of aquatic species to temperature and other environmental conditions (e.g., dissolved oxygen, ammonia, salinity, and pH), the complex interaction of ecological factors can have a significant impact on the growth and profitability of aquaculture. The monitoring problems associated with the grow-out of a population that cannot be seen or handled is probably the most crucial management problem. The producer cannot determine the number of animals and their health at any given time. Aquaculture models may often need a stochastic element to represent this inability to monitor the progress of the animal population during the growing season. Feed utilisation is another source of uncertainty for the manager of an aquacultural production facility because the amount of feed actually consumed by the fish can be observed in a qualitative way as they come to the surface to feed, but cannot be known with much precision.

Leung provides a good review of economic models for aquaculture, which we find useful to quote, *in extenso*, here:

> "*The choice of appropriate economic models for economic evaluation of aquacultural systems depends on the problems to be solved and the compatibility with the biological models. Following Allen et al. (1984), economic models can be generally classified as optimizing versus non-optimizing. Optimizing models refer to techniques which seek the best value of an objective function expressed in terms of a set of control variables in aquacultural systems. Differential calculus is used when there is no constraint, or Lagrangian is used when the constraints are equalities. In the event that analytical solutions cannot be derived, numerical (search) methods are used. In this paper, these techniques are referred to as classical optimization techniques. The Faustmann model (Faustmann, 1968), originally developed for optimal forest rotation, can be applied to solving the question of optimal harvesting age or rotation period for a single growing population of aquatic organisms. In this paper, the Faustmann model is grouped together with classical optimization.*
>
> *When the constraints are inequalities, mathematical programming techniques are used. By far the most commonly used mathematical programming technique is linear programming. Linear programming is the process of determining the values of variables, which optimize the linear objective function while satisfying a set of linear constraints. Linear programming has been widely used in farm planning for choosing a profit maximization combination of production alternatives that is feasible with respect to a set of fixed farm constraints. Risk programming models are standard methodology for extending the linear programming framework to include farm risk (Hazell and Norton, 1986). Commonly used models include quadratic programming which minimizes the return variance of a farm portfolio, and MOTAD (minimization of total absolute deviations), which minimizes the absolute deviation. Target MOTAD extends the MOTAD model to include a minimum return target (Anderson et al., 1977). To include this type of safety-first feature is most appropriate when the risk of catastrophe is large, either because of an inherently risky environment or because the farmer is poor and has minimal reserves to fall back on in a bad year.*
>
> *Integer and mixed integer programming models are called upon when decisions involve indivisible objects such as tractors, buildings, ponds and tanks. When optimizing over time is desired, multi-period linear programming or dynamic programming can be used. Both are particularly suitable for aquaculture production because decisions are usually time-dependent (Bertsekas, 1995). As most of the biological and economic relations in the real world are highly nonlinear, nonlinear programming provides a more realistic alternative to model aquaculture production systems. As more reliable nonlinear programming software becomes available, nonlinear programming will gain popularity. Optimal control theory extends the classical techniques to cover both nonlinear and linear optimization problems and inequality constraints. It provides a powerful analytical tool for handling dynamic (time-dependent) systems and possesses valuable economic interpretations. The dynamic programming model is oftentimes viewed as the discrete time version of optimal control model. Dynamic programming is better suited to study more realistic stochastic problems. In other words, optimal control theory provides the theoretical basis while dynamic programming provides the tool for empirical analysis.*

Optimization techniques require tractable, functional forms; therefore, the realism of the situation being modeled is often sacrificed. Simulation techniques can be used when it is not possible to express the interrelationships in a convenient mathematical form because the system is too complex or because responses are subject to random variations. Simulation merely describes the output behavior of different combinations of inputs, control variables, and parameter values. Simulation, which is generally non-optimizing, can be classified as budget simulation and process simulation. Budget simulation usually uses a very simple biological model with extensive financial analysis capabilities such as enterprise budgeting and cash flow or capital budgeting. Process simulation, however, provides a rather detailed biological process simulation using either general purpose or special purpose simulations.

In summary, optimization models require tractable functions but yield the best solution, while simulation can use more realism but may not find the best solution. A hybrid of these two classes of models can be helpful in some cases."
Leung (1994, pp.120, 121)

4 Application of bioeconomic models to aquaculture: a review

In his analysis of the use of bioeconomic models in aquaculture, Leung (1994) found that mathematical programming models, especially risk programming, were commonly used in the 1984–1993 period. He felt that this trend could be due to several reasons including an increase in whole farm applications, the popularisation of risk programming in the early 1980s, and the availability of more powerful computer programs, such as GAMS, which promoted the application of non-linear and integer type models. The increase in the use of dynamic programming models during the 1984–1993 period was primarily due to the increase in production scheduling applications. There were fewer optimal control applications in the same period due to the shift in modelling species in less controllable culture environments. More budget simulators were developed over the 1984–1993 period, but fewer process simulators were developed. This change could be due to a shift toward more whole farm analyses.

The literature review for the current study identified seven published papers on bioeconomic analysis of aquaculture since 1993. A brief summary of those studies can be found in Table 2. This represents a significant decrease compared to the number of papers (54 in the two decades from 1974 to 1993) identified by Leung (1994), but the reasons for this decrease in the number of published studies are difficult to pinpoint. Four of the seven studies shown in Table 2 used budget simulation models. The remaining three studies made use of mathematical programming models, while only one study explicitly accounted for risk. There were no applications of optimal control models. The majority of the studies relied on experimental data or a combination of commercial and experimental data.

Table 2 Some key features of bioeconomic models for aquaculture: 1994–2003

Authors (Date)	*Principal application*	*Economic model*	*Risk*	*Time dimension*	*Level of analysis*	*Stage of analysis*	*Data used**	*Species*	*Location*
Aull-Hyde and Tadesse (1994)	Decision support model of agricultural diversification	Non-linear mixed integer programming	Expected earnings	Annual	Whole farm	Grow-out	E	Hybrid striped bass	USA
Kazmierczak and Caffey (1996)	Bioenergetic and producer decision making	Simulation	NC**	Annual	Closed system	Grow-out	E	Tilapia	USA
Hernandez-Llamas (1997)	Optimal stocking density and culture period	Simulation	NC	Annual	Bottom culture in trays	Grow-out	E	Scallop	Mexico
Hean and Cacho (1999)	Optimal production cycle	Classical optimisation	NC	Annual	Bottom culture	Grow-out	C; E	Giant clam	Solomon Islands
Penney and Mills (2000)	Economic viability	Simulation	NC	Annual	Net-Pen	Grow-out	E	Sea scallop	Canada
Miao and Tang (2002)	Management productivity	Two-way multivariate	NC	Annual	Pond	Grow-out	C	Grouper	Taiwan
Gasca-Leyva et al. (2002)	Optimal grow-out system	Simulation	NC	Annual	Floating cages	Grow-out	C; E	Sea bream	Canary I. Mediter-ranean

*Data used: C: Commercial; E: Experimental.

**NC: Not considered.

Considering the dearth of papers focusing on bioeconomic models since 1993, it was deemed useful to go back to the older papers focusing on bioeconomic studies of salmon aquaculture. Some key features of four of these papers are presented in Table 3. The first is by Johnson (1974), which applied linear programming analysis to schedule release dates and choice of stocks in a hatchery. Gates et al. (1980) applied dynamic linear programming to optimal fish culture decisions in a water reuse system and financial feasibility analysis for salmon grow-out in the New England region of the USA. Bjorndal (1988) applied optimal control theory and the Faustmann model to optimal harvesting of salmon grow-out in Norway. Bjorndal (1990) published the first book on the economics of salmon aquaculture, which included more detailed analysis and information on salmon farming. Sylvia and Anderson (1993) published a book chapter on optimising public and private net-pen salmon aquaculture strategies in the US Pacific Northwest, which utilised a dynamic multilevel programming model. This last paper is of particular relevance here because it developed information for both private and public salmon aquaculture policy strategies, including environmental issues.

Table 3 Some key features of bioeconomic models for aquaculture of salmon: 1974–2003

Authors (Date)	*Principal application*	*Economic model*	*Time dimension*	*Level of analysis*	*Stage of analysis*	*Data used**	*Species*	*Location*
Johnson (1974)	Schedule of release dates and choice of stocks in hatchery	Linear programming	Monthly	Whole farm	Hatchery	E	Salmon	USA
Gates et al. (1980)	Optimal fish culture decisions in a water reuse system and financial analsysis	Dynamic linear programming	Bi-monthly	Whole farm	Grow-out	E	Salmon	New England, USA
Bjorndal (1988)	Optimal harvesting of farmed fish	Optimal control, Faustmann model	Annual	Pond	Grow-out	C	Salmon	Norway
Sylvia and Anderson (1993)	Optimising public and private net pen salmon aquaculture strategies	Dynamic multilevel programming model	Annual	Whole farm	Grow-out	E	Salmon	Pacific Northwest USA

*Data used: C: Commercial; E: Experimental.

5 Issues in bioeconomic modelling of salmon production in Chile

Since the start of its salmon aquaculture in 1986, Chile has become the largest producer of exported salmonids worldwide. In 2001, Chilean salmon exports totalled US $973 million, accounting for 3.5% of Chile's total exports and approximately 35%

of fishing-related exports. Total export earnings for the country in that year reached US$ 1.8 billion (EMS, 2003). Southern Chile is an ideal location for the aquaculture industry. Its moderate climate, undeveloped and extensive fresh and salt-water areas, absence of ice cover on its vast lakes and protected saltwater resources provide year-long secure growth environments for aquaculture species. Nevertheless, existing aquaculture practices in Southern Chile have been the subject of significant controversy with respect to environmental impacts on both fresh water and saltwater systems (Buschmann et al., 2002). Environmental problems include benthic pollution, water column pollution, disease control, genetic impacts, exotic introductions, toxicants and antibiotics, impacts on marine mammals and birds, noise pollution, and aesthetics. In addition, logging, mining and municipal and industrial wastewater discharges compete for resources and/or endanger salmon aquaculture (Weber, 1997; Goldburg and Triplett, 1997).

Salmonid aquaculture begins with a three to five month egg hatching stage in land-based tray systems. Once hatched, the juvenile salmon are placed in freshwater net pens until smolt stage 2 is reached. The juvenile fish are then transferred to grow-out pens in the marine environment. Both freshwater stages of salmon aquaculture result in the release of nutrients (particularly nitrogen and phosphorous), organic compounds associated with feeds (carbon, growth hormones, anti-parasitic drugs, disinfectants and antibiotics), and bioaccumulated metals or hydrophobic organic compounds associated with the fishmeal-based food fed to the hatchlings and not retained in fish tissue. Many of these environmental effects are well documented worldwide, but the underlying ecosystem processes are not well known and require more detailed attention (Buschmann et al., 2002). Therefore, the sustainability of these practices and the long-term impacts of intensifying aquaculture on the fresh water lakes and coastal zones are not well understood.

The environmental problems in the salmon aquaculture industry worldwide and in Chile have impacted firm-level production strategies and regional industry development. In some cases, environmental problems have posed direct production costs to producers by impacting salmon growth or mortality rates, or indirect costs resulting from the implementation of public policies designed to reduce environmental externalities by controlling private production practices. Different countries around the world have taken differing approaches to dealing with the environmental problems of salmon aquaculture. Environmental policies in Japan and Norway have supported the expansion of salmon aquaculture, while Scotland, Ireland, USA and Canada have developed stricter controls on industry behaviour to reduce or minimise environmental externalities. In the USA, salmon aquaculture has resulted in conflict and controversy, leading to moratoriums and in some cases outright banning of the industry (Goldburg et al., 2003).

Environmental issues in net pen salmon farming have remained especially problematic. These problems have impacted firm-level production strategies, production costs, and industry development. A paramount challenge for the Chilean salmon aquaculture industry is to determine how to co-develop both private and public strategies which could reduce externalities while allowing responsible aquacultural development to proceed in a cost effective path. Strategically designed economic models can provide information for developing private aquacultural strategies in response to optimal industry development and regulatory issues. Information can be used to address firm-related decisions and to inform decision-makers about alternative development scenarios and the potential impacts of alternative regulatory strategies. In our review of bioeconomic models related to aquaculture the most relevant work dealing with these topics is by Sylvia and Anderson (1993), discussed below.

The models developed need to integrate biological, engineering, and environmental processes to assess the viability of alternative technologies and policy options for balanced ecosystem management. These models should make it possible to assess the potential costs and benefits of alternative production strategies and sites, as well as policy and regulatory frameworks. The results should contribute to the formulation of both management practices that maximise economic returns to producers, and policy recommendations that ensure a sustainable development of the aquaculture industry. The results should also be incorporated into educational programs dealing with sustainable development of aquaculture.

Since practical mathematical programs that can solve all salient issues have not been fully developed, a multi-level and multi-objective model, solved using a multi-stage procedure, may be most appropriate. The use of multi-level and multi-objective analysis can address both the private and public problems in aquaculture when environmental externalities are a concern. Optimal strategies can be developed to explore the potential costs and benefits of alternative production strategies or alternative site locations. Production strategies can be evaluated in response to alternative public regulatory policies. In addition, the multi-level approach can be used to address social and economic issues and impacts of alternative regulatory policies rather than solely biological or environmental impacts.

Sylvia and Anderson (1993) developed a multi-level and multi-objective model for net pen salmon aquaculture in the Pacific Northwest of the USA. In the model, the producers were assumed to maximise profits and the public policy makers were faced with four policy objectives including revenue, benthic quality, profits and tax revenues. The policy instruments in their study include the number of allowable sites and the effluent tax. The two-level problem cannot be solved in one step; thus, an approximation was obtained by using iterative simulation techniques and response functions.

Furthermore, Sylvia and Anderson state:

> "*The development and operation of a multilevel dynamic economic policy model, whether for use by the private or public sector, involves a six-step approach:*
>
> 1 *Determine the regional policy issues, goals, and potentially feasible policy instruments;*
>
> 2 *Determine the major geographical and environmental factors;*
>
> 3 *Develop an appropriately specified dynamic behavioral model for the private sector net-pen salmon aquaculture industry which includes prices, costs and environmental data;*
>
> 4 *Repetitively solve the private sector's problem for relevant ranges of feasible policy instruments and determine the response function;*
>
> 5 *Repetitively solve the policymaker's dynamic objective function for different sets of weights in linear combinations of policy goals subject to appropriate constraints including the response function calculated from the private sector's problem; and*
>
> 6 *Construct the dynamic policy frontiers and analyze results.*" Sylvia and Anderson (1993, p.23)

In addition, we believe that some specific issues that need to be incorporated into bioeconomic models for salmon farming in Chile include: (1) Alternative stocking densities; (2) Animal behaviour; (3) Health; (4) Use of antibiotics and vaccines; (5) Disease resistance; (6) Precise nutritional requirements; (7) Conversion of feed into flesh; (8) Growth rates; (9) Fertility; (10) Genetic modification; (11) Tolerance to cold and poor quality water; (12) Water quality; (13) Impact on the environment; and (15) Regulation.

6 Concluding remarks

In aquacultural systems, environmental problems have led to increased production costs for the firm, and indirect costs resulting from environmental externalities. The challenge for the Chilean salmon aquaculture industry is to determine how to develop both private and public strategies that reduce externalities in a cost-effective way, while promoting responsible aquacultural development. Properly designed economic models can provide information that can be used to make effective firm-related decisions and to inform policy decision-makers about different development scenarios and the potential impacts of alternative regulatory strategies.

Bioeconomic modelling can assist the salmon aquaculture industry in addressing both private and public policy issues when environmental externalities are a concern. Bioeconomic models can provide answers to the questions of economic feasibility, optimal system design, optimal methods of operations, and regulatory policies. Optimal strategies can be developed to explore the potential costs and benefits of alternative production strategies or alternative site locations. This type of information can guide the policy process, focus debate, and evaluate policy alternatives to maximise private profits as well as social welfare. Multi-level and multi-objective bioeconomic models can serve to address private and public policy issues affecting salmon production by incorporating biological, environmental, economic and institutional dimensions.

Long-term growth of the aquaculture industry requires both ecologically sound practices and sustainable resource management. Such practices can be encouraged by the development of best management practice guidelines for salmon aquaculture in Chile which include best practices in terms of site selection, technology, production and fish health for the private producer, as well as policy and regulatory strategies for the public sector. These best management practice guidelines can be developed, in part, through the results of the bioeconomic models.

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