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Research Article

Simulation model of the scallop (*Argopecten purpuratus*) farming in northern Chile: some applications in the decision making process

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ABSTRACT. Aquaculture farming is a complex system integrating several disciplines, including biology, engineering and economics, all which need to be correctly intertwined to have a profitable and environmentally sustainable activity. During the past recent years, scallop (*Argopecten purpuratus*) farmers in northern Chile have come to comprehend the hard way that aquaculture producers operate in a complex and dynamic environment where natural and economic factors are in constant change. Thus, to keep a profitable and competitive business in today's world, aquaculture farm managers are in need of relatively easy to use tools for efficient and timely decision making. Harvest size and time, mortality and growth rates, stocking rates, costs and market prices are important variables and parameters to monitor, where decisions with respect to their levels or values have to be made. In this context, non-linear and dynamic quantitative bioeconomic models should become valuable tools, for periodic decision making in the aquaculture business. This paper shows how to emulate Chilean scallop farming using a simulation model that mimics some of the industry's features. The model presented here focuses on a scallop aquaculture center that uses the common technology approach of pearl net and lanterns of the northern region of Chile, and analyses the farming strategies based on harvesting size. Also, these strategies were subject to variations in the parameters in order to identify patterns and asses the sensibility of the model to input values.

Keywords: simulation, dynamic, aquaculture, *Argopecten purpuratus*, scallop, Chile.

Modelo de simulación para el cultivo del ostión (*Argopecten purpuratus*) en el norte de Chile: aplicaciones para la toma de decisiones

RESUMEN. La acuicultura es un sistema complejo que integra varias disciplinas, incluyendo la biología, ingeniería y economía, las cuales deben ser correctamente entrelazadas para lograr una actividad rentable y ambientalmente sostenible. Durante los últimos años, los cultivadores del ostión del norte (*Argopecten purpuratus*) en Chile han comprendido de la peor manera, que las actividades de acuicultura operan en un entorno complejo y dinámico, donde los factores económicos y naturales se encuentran en estado de cambio constante. Para mantener un negocio rentable y competitivo, los administradores de los centros de cultivo necesitan herramientas que sean relativamente fáciles de utilizar para facilitar la toma de decisiones de manera eficaz y oportuna. Las tallas y tiempo de cosecha, tasas de mortalidad y crecimiento, densidades de cultivo, costos y precios de mercado son variables y parámetros importantes para controlar, donde son necesarias decisiones respecto de sus niveles y valores. En este contexto modelos cuantitativos dinámicos y no-lineales deberían convertirse en herramientas valiosas para la toma de decisiones, de forma periódica, en la industria de la acuicultura. Este trabajo muestra una alternativa para emular el cultivo del ostión en Chile, mediante un modelo de simulación dinámico que imita algunas de las características de la industria. El modelo presentado se enfoca en el proceso de engorda que utiliza el enfoque tecnológico común de pearl nets y linternas en el norte de Chile, con el cual se analizaron estrategias de cultivo basadas en la talla de cosecha. Estas estrategias fueron sometidas a variaciones en los valores de los parámetros para identificar patrones de tendencia y evaluar la sensibilidad del modelo a los valores de entrada.

Palabras clave: simulación, dinámica, acuicultura, *Argopecten purpuratus*, ostión del norte, Chile.

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INTRODUCTION

In Chile, the scallop (*Argopecten purpuratus*) farming started in the Antofagasta and Coquimbo regions back in 1982, to later extend itself to the Atacama region, reaching a total production of one ton that year (Cabrera, 2000). In 2009, shellfish farming was the second largest aquaculture activity in Chile with 188 thousand ton produced, where 16.6 thousand ton resulted from scallop production (SUBPESCA, 2010). In 2009 scallop aquaculture activities were mainly concentrated in Atacama and Coquimbo regions of Chile (SERNAPESCA, 2009).

Scallops are grown in the marine environment through various farming systems, which depend on the preferences of farmers and the different stages of cultivation for this species (Cabrera, 2000). Chilean scallop aquaculture business is usually vertically integrated with direct product flow from the farm to the processing plant, and eventually to the market, without third parties involvement (Cabrera, 2000). Scallops are mostly exported as adductor muscle or “scallop” mainly to the USA market and also as “scallop and coral” to the French market; nevertheless, a minor portion of the total production is also oriented to local and national markets (Cabrera, 2000).

After a highly profitable period during the 1990s and the first half of the 2000s, the scallop industry is currently undergoing economic problems due to a strong market price competence from countries with low production costs and massive productions, such as Peru (Gómez, 2008). This crisis has shown Chilean scallop producers that they need to rapidly improve their efficiency and competitiveness, or face even harsher times with increasing unemployment and loss of income. In this context, decision making tools that generate information to improve productivity and reduce production costs have become critical. Harvest size and time, mortality and growth rates, stocking rates, seed and other operating costs, and market prices are important variables and parameters to monitor; decisions with respect to their levels or values have to be made by farmers in order to maintain themselves in business.

The use of models as tools for decision making and efficiency improvement has been thoroughly researched, where many successful experiences have been reported. Sternman (2000) has compiled an astonishing amount of system thinking models that have been used in politics, sociology, heavy industry and agriculture. Hannon & Ruth (1994) have also developed several models for animal production, and fisheries, where model outcomes have been used to develop industry strategies (Hannon & Ruth, 1994). Aquaculture is no exception (Bjørndal *et al*., 2004), where several attempts for modeling scallop farming have been made (Hawkins *et al.*, 2002; Pelot & Zwicker, 2006; Ferreira *et al.*, 2007), but none of those have been made for the Chilean reality.

Aquaculture is a complex and dynamic activity that deals with multiple factors in order to be efficient. It is the authors’ intention to show that non-linear and dynamic quantitative bioeconomic modeling should become a valuable and relatively easy to use tool for timely and efficient decision making in the scallop aquaculture business. Thus, this paper shows the use of a deterministic bioeconomic dynamic simulation model as a strong decision making tool in scallop (*Argopecten purpuratus*) aquaculture. This model provides useful information to facilitate the evaluation of farming strategies, assisting the decision making process that will set the new competitive strategies of this business.

MATERIALS AND METHODS

Bioeconomic model of scallop culture

This section illustrates the bioeconomic model to study how different strategies might affect the economic performance of a scallop (*Argopecten purpuratus*) farming facility in northern Chile. The dynamic simulation model presented here was built using the Stella® (Version 9) interface and it is comprised by three sub-models, namely: a biological, a technological and an economic sub-model.

There are several works that have used a dynamic approach to model aquaculture systems for shellfish, for instance Pelot & Zwicker (2006) developed a simulation model to manage the inventory systems in scallop aquaculture, and Ferreira *et al.* (2007) developed a simulation model to improve productivity and profitability reducing environmental effects for shellfish. The software Stella® has also been used several times to simulate other aquaculture systems for shellfish as the experience of Hawkins *et al.* (2002), who developed a simulation model for *Chlamys farreri* under aquaculture conditions in China, or the evaluation of different shallow culture methods using a bioeconomic model for *Nodipecten subdonosus* by Taylor *et al*. (2006), and Grant (2000) who uses simulation through Stella® to describe the growth behavior of scallops, specifically for *Patinopecten caurimus*.

In order to evaluate the dynamic characteristics of the model and its behavior throughout time, the dynamic analysis was done using Stella®’s capability of dynamic simulation. The numerical integration method used by the software to solve the dynamic bioeconomic model was the Euler's algorithm, where the integration method is described by Butcher, 2005 as:

$$y_{n+1} = y_n + hf(x_n, y_n) + O(h^2) \qquad (1)$$

where y_{n+1} represents the calculations mesh's posterior point; y_n is the mesh's anterior point, h the difference between the mesh points, and f (x_n, y_n) is the equation being analyzed. Finally, the term $O(h^2)$ describes the local truncation error of the method (Butcher, 2005).

Biological sub-model

Population dynamics

The stock behavior of scallops was modeled using Sparre & Venema (1995) relationship for fish populations and Zúñiga (2008) for individuals under aquaculture conditions. The relationship is given in the formula below:

$$\frac{d\left(N(t)\right)}{dt} = -zN(t) \qquad (2)$$

where N describes the number of individuals in the instant of time (t), where t is based on weeks. These individuals are also subject to mortalities throughout time, the proportion of individuals affected by this is determined by the coefficient z.

The farming process in northern Chile determines the mathematical approach adopted to represent the population dynamics of scallops, including the need to consider the effect of lagging in individual growth (defines the effect where some of the individuals cultured will manifest a slower growth that the average population), which is usually observed in the aquaculture systems for this species (Cabrera, 2000). Scallop farming in Chile uses the pearl net-lantern system, and the process includes three stages, namely: pearl net, initial lantern, and final lantern. The farming process begins by stoking seeds in pearl net units, to subsequently transfer them to the initial and final lantern stages as individuals grow in time until they finally reach harvest size (Cabrera, 2000). Molina (2010) suggested the following representation for a typical farming process using Forrester (1961) diagram approach (Fig. 1).

The lagging of some individuals is included in the model by defining the "G" stages. This approach means that the group of scallops that growth normally will go through the normal line of the process (*normal*). However, if some individuals at the end of the initial lantern stage do not reach enough size to be transferred into the final lanterns, they will be kept at initial lanterns, creating a second group labeled "Group 1" (*G1*). Using the same logic, *G1* will be composed by the individuals that lagged at the end of the initial lantern stage of the normal group; *G2* will be composed by the individuals that lagged at the end of the pearl-net stage of the normal group; and finally *G3* will be composed by the individuals that lagged at the end of the initial lantern stage of the *G2* group. There is no lagging at the end of the of the final lantern stage, since lanterns will be retrieved from the water once the average size has reached the harvest size (Fig. 1).

The dynamics of this process are represented by the following formula (Molina, 2010):

$$\frac{d\left(G_{ij}(t)\right)}{dt} = \begin{cases} A_i(t) - T_{ij}(t) & ;if\ (j=1) \\ Y_{ij}(t) - T_{ij}(t) & ;if\ (1 < j < 7) \\ Y_{ij}(t) - H_{ij}(t) & ;if\ (j \geq 7) \end{cases} \forall j \qquad (3)$$

The "i" and "j" indexes describe the i^th^ batch (batch defines all the individuals that are entered into the farming process in a specific week of the year), considering that every year has 52 weeks, and the j^th^ stage of that specific batch at the moment of time (t); the list of the stages (j) is shown in (Table 1). G describes the number of scallops present at the given stage. A describes the number seeds being stocked in the pearl net stage for the initial stage. T describes the scallops that are being moved to the next stage. Y refers to the number of scallops entering that specific stage. Finally, H describes the number of individuals being harvested at the final lanterns. This approach considers that dead scallops are removed only when individuals are transferred to the next stages (Cabrera, 2000).

In order to reflect differences in mortality and lagging through the whole farming process, flexibility is added into the model by specifying independent parameters in every stage:

$$M_{ij}(t) \cong z_j G_{ij}(t) \qquad (4)$$

$$F_{ij} \cong \left(G_{ij}(t) - M_{ij}(t)\right) R_{ij} \qquad (5)$$

R represents the fraction of scallops alive at the end of the given stage that do not have sufficient size to be transferred to the next stage.

Growth

Accordingly with Stotz & González (1997), individual growth for scallops in Chile can be represented using the von Bertalanffy's formulation if the appropriate parameters are estimated for a specific geographic location. This model includes von Bertalanffy's growth by using the following expressions:

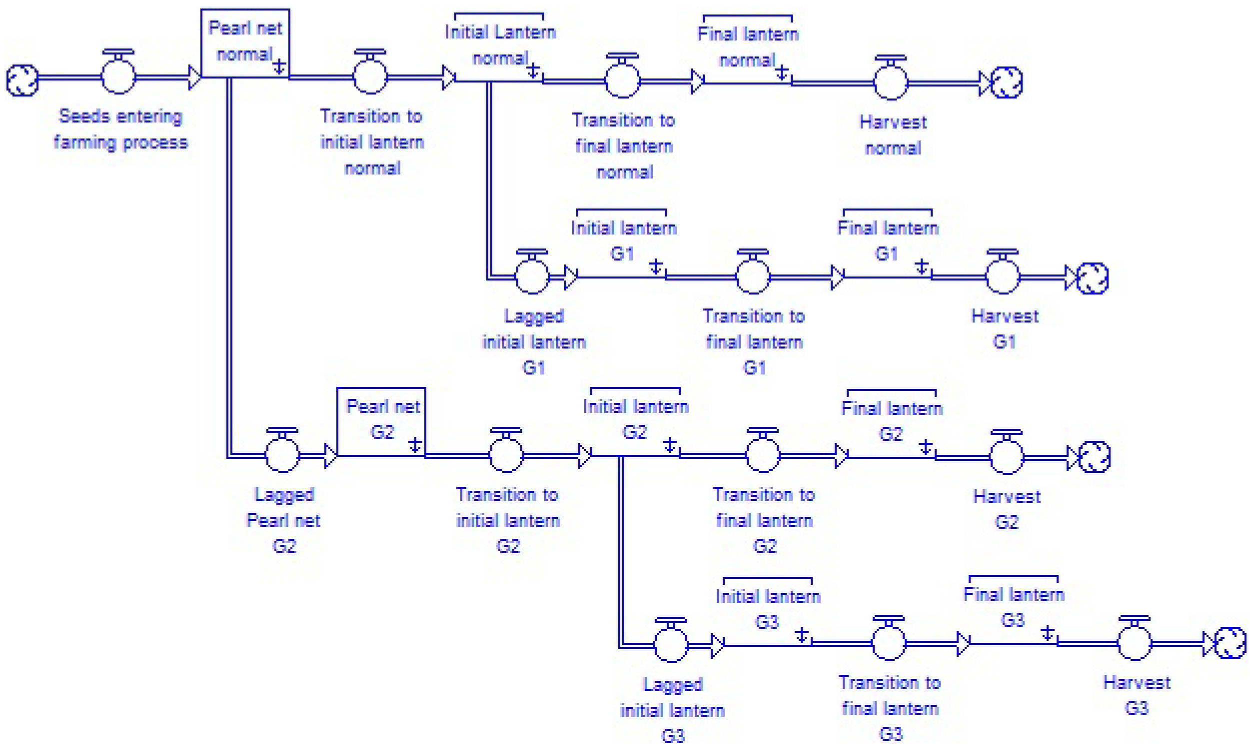

Figure 1. Forrester diagram of the scallop farming process suggested by Molina (2010).

Figura 1. Diagrama de Forrester para el cultivo de ostión sugerido por Molina (2010).

$$\frac{d\left(L_{ij}(t)\right)}{dt}=\begin{cases} l_i(t)+g_{ij}(t)-W_{ij}(t) & ;\ if\ (j=1) \\ D_{ij}(t)+g_{ij}(t)-W_{ij}(t) & ;\ if\ (1<j<7) \\ D_{ij}(t)+g_{ij}(t)-m_{ij}(t) & ;\ if\ (j\geq 7)\end{cases}\ \forall j \quad (6)$$

$$g_{ij}(t)=K\left(L_{\infty}-L_{ij}(t)\right) \quad (7)$$

where L is the mean length of scallops at the specific stage at a given moment of time. l is the mean length for seeds when a batch is introduced; D is the mean length of scallops when the subsequent stages start. g is the instant growth for individuals in every stage of the process. Finally, W is an artificial variable to reset the stage length when scallops are removed from that stage; m works in the same way, but only when scallops are being harvested. The individual growth is included using K as the von Bertalanffy's growth parameter for scallops and L_{∞} as the asymptotic length for the species.

The length of the scallops will differ between the different stages, and it will increase as the scallops proceed to the following stages. Since the model incorporates this growth increase by differentiating between the stages, the variables involved in each stage will also differ in a similar manner. The general equation for this is presented below:

$$w_{ij}(t)=\begin{cases} \phi_{j-1}W_{i(j-1)}(t) & ;if\ \{j=2,4,6\} \\ W_{i1}(t) & ;if\ \{j=3\} \\ W_{i2}(t) & ;if\ \{j=5\} \\ W_{i(j-4)}(t) & ;if\ \{j\geq 7\}\end{cases}\ \forall j \quad (8)$$

where w is the initial length of individuals at the beginning of the stage, and ϕ represents the average fraction of the normal size that lagged individuals will have at the beginning of the lagged groups. W is now used to calculate the initial length of the scallops entering a given farming stage.

Technological sub-model: farming units, lines, boats and labor

Farming inputs

The technological side of the scallop farming is modeled using the same approach as Molina (2010), where quantities of scallop at different stages and densities will determine the farming units (pearl nets and lanterns), lines, boats, and labor needed through time in a linear fashion. The following expressions will determine how many farming inputs (U_k) have to

Table 1. Indexes used in the model for each of the farming stages considered.

Tabla 1. Índices usados en el modelo para cada una de las etapas de cultivo.

Parameter	Index
Pearl net (*normal*)	1
Pearl net (*G2*)	2
Initial lantern (*normal*)	3
Initial lantern (*G1*)	4
Initial lantern (*G2*)	5
Initial lantern (*G3*)	6
Final lantern (*normal*)	7
Final lantern (*G1*)	8
Final lantern (*G2*)	9
Final lantern (*G3*)	10

be on the water at time *t*, where *k* {1,…,4} will denote pearl nets, lanterns, lines and boats respectively:

$$U_k(t) \cong \begin{Bmatrix} \sum_i \sum_j \left(G_{ij}(t)/\rho_j ; \forall \{ j \leq 2 \} \right) & ; if\ (k=1) \\ \sum_i \sum_j \left(G_{ij}(t)/\rho_j ; \forall \{ 3 \leq j \} \right) & ; if\ (k=2) \\ \left(U_1(t)/PNL + U_2(t)/LL \right) & ; if\ (k=3) \\ \left(U_1(t)/CLB \right) & ; if\ (k=4) \end{Bmatrix} \forall k \qquad (9)$$

where *ρ* refers to the farming density of every stage for all the production cycle. *PNL* will be the total pearl net units that can be set on a single line and *LL* refers to the total number of lanterns that can be set on a single line as well. Lastly *CLB* accounts for the capacity in lines that is maintained by each boat.

Farming units, lines and boats will be stored if they are not being used, further reincorporation will be done when the requirements of the farm increase again accordingly. Therefore, if there are not enough units to keep up with the requirements in the farm, new farming units, lines or boats will be acquired as necessary. When any of those three implements has achieved its lifespan, it will be discarded as well (Molina, 2010). The equations describing the inventory dynamics are presented below:

$$TUE_k(t) = TUU_k(t) + TUA_k(t) \qquad (10)$$

where *TUE* will represent the total farming inputs that are currently in the farm, as the sum of the ones in use (*TUU*), and the ones that are under storage (*TUA*). The dynamics of the lifespan of every faming unit will be considered by the following dynamics (Molina, 2010):

$$\frac{d[TUE_k(t)]}{dt} = AU_k(t) - DU_k(t) \qquad (11)$$

where *AU* represents all the farming inputs that are bought at a given point of time, and *DU* will account for those that are being discarded (Molina, 2010).

Labor

Labor is treated differently because the model considers two types of workers, permanent and temporary. Permanent workers are those who are present at all times during the farming process and thus through the simulations; temporary workers are those who will be hired when the requirements of the farm exceeds the maintenance capacity supported by the current labor force in a given instant, and they will be only hired for a short period of time; however, some of the temporary workers may be promoted to permanent status according to the hiring policy set in every simulation (Molina, 2010). The equations describing these dynamics use the index *L* {1,2} referring to permanent and temporary labor respectively:

$$\frac{d[MO_L(t)]}{dt} = CMO_L(t) - DMO_L(t) \qquad (12)$$

where *MO* will be the total workers of any of the categories at any time, stock that will change according to the number of workers being hired (*CMOP*), or the number of workers fired (*DMO*). The total work capacity of the farm will be given then by:

$$TWC(t) = \sum_L \left(MO_L(t) * CL_L \right) \qquad (13)$$

where *TWC* will reflect the total labor capacity depending on the number of lines every worker category is able to handle (*CL*). The hiring and firing policy of the farm will depend on the type of labor and the working capacity at a given time. The hiring of permanent workers will account for the initial hiring at the beginning of the simulation (*CIMO*), and the number of temporary workers that are being promoted (DMO_2) after their contract is over at rate *δ*; given their conditions they will not be fired until the end of the simulation (DC_1). Temporary workers will be hired (CMO_2) only if the current working capacity is not enough to support the current number of lines required to be maintained in the farm; they will be eventually fired (DMO_2) after the contracted time (DC_2) is over. In the case they are hired as permanent workers that will be accounted in the previous description of permanent hiring. The equations used in the model for this situation are the following:

$$CMO_L(t) \cong \begin{cases} \begin{Bmatrix} CIMO & ;if\,(t=0) \\ DMOP_2 * \delta & ;if\,(t>0) \end{Bmatrix} & \forall (L=1) \\ \begin{Bmatrix} (0) & ;if\,(U_3(t) \le TWC(t)) \\ \left((U_3(t) - TWC(t)) / CLT \right) & ;if\,(U_3(t) > TWC(t)) \end{Bmatrix} & \forall (L=2) \end{cases} \quad (14)$$

$$DMO_L(t) \cong \begin{Bmatrix} (0) & ;if\,(t < DCT_L) \\ (CMOT_L(t - DCT_L)) & ;if\,(t \ge DCT_L) \end{Bmatrix} \quad \forall L \quad (15)$$

Economic sub-model

Costs

There are several costs considered in the model: investment, fixed cost, operational costs, input costs, inventory costs, depreciation and opportunity cost. Investment (l_0) refers to the amount of capital required to establish the business previous any production activity, this cost include all previous environmental studies, construction and necessary equipment that will not be directly related to the production (Sapag & Sapag, 2000). Fixed costs (*CF*) will be related to the costs that do not vary with production output or the farming strategy and they include all administrative costs and utilities (Sapag & Sapag, 2000).

On the other hand, total operational costs (*COT*) refer to all day-to-day expenses generated in the farm; these expenses include hiring, firing, salaries, and daily operation of boats. *COT* will be a function of hiring cost (*CC*), firing cost (*CD*), salaries (*SMO*) and the operation cost for boats (*COB*) (Molina, 2010). The sum of all these specific costs will be the total operational cost:

$$COT(t) = \begin{pmatrix} \sum_L \left(CMO_L(t) * CC_L \right) + \sum_L \left(DMO_L(t) * CD_L \right) \\ + \sum_L \left(MO_L(t) * SMO_L \right) + \left(TUU_4 * COB \right) \end{pmatrix} \quad (16)$$

Input costs (*TAIC*) will be the result of the acquisition of seeds, farming units, lines and boats. These costs will be in direct relationship with the quantity of farming units and seeds that enter the systems, which is described by the following equation:

$$TAIC(t) = \sum_i \left(A_i * CS \right) + \sum_k \left(AU_k * CU_k \right) \quad (17)$$

The inventory is also a source of cost for the farm, where all the farming units that have been stored will generate expenditures (Molina, 2010). This cost (TCI) will depend on the number of units stored and the respective cost of storage (*CA*):

$$TCI(t) = \sum_k \left(TUA_k(t) * CA_k \right) \quad (18)$$

Depreciation cost (*CD*) is considered for all materials in the model, including farming units, boats, buildings, and vehicles. It will reflect the fraction (σ) on its investment that is subject to depreciation depending of the expected lifespan (*VUI*), and the depreciation of all farming units also depending on their expected life span specific lifespan (*VU*) (Molina, 2010).

$$DC(t) = \left(\sigma * I_0 / VUI \right) + \sum_k \left(U_k(t) * AU_k / VU_k \right) \quad (19)$$

The last cost considered for calculations is the opportunity cost (*CO*), which is the total cumulative investment (including acquisition of materials) depreciated and subject to an interest rate (*u*); this cost is included in order to reflect the potential loss of investing in other activity (Molina, 2010). The expression for this cost is the following:

$$CO(t) = u \int_t \left(TAIC(t) + TCI(t) - DC(t) \right) dt \quad (20)$$

Finally, the total cost in the farm (*TC*) will be given then by the last expression:

$$TC(t) = \left(COT(t) + TAIC(t) + TCI(t) + DC(t) \right) \quad (21)$$

Income

There are two sources of income considered in the model, selling harvested scallops and the possible value of the farming units once their lifespan is over selling. The income from selling scallops (*IV*) will depend directly on the size of the scallop and the price (*p*(*L*)) for that given size in the market. The mathematical expression for this income is given by:

$$IV(t) = \sum_i \sum_j \left(H_{ij}(t) * p(L_{ij}(t)) \right) \quad (22)$$

The income from selling farming inputs will depend entirely on the amount of inputs being discarded and on the discard price each of these units (*VD*). This is calculated by the following equation:

$$ID(t) = \sum_k \left(DU_k(t) * VD_k \right) \quad (23)$$

Finally, the total income in the farm (*TI*) at any time will be given by:

$$VD_k = AU_k / VU_k \quad (24)$$

$$TI(t) = IV(t) + ID(t) \quad (25)$$

Net present value

The net present value is the measure of effectiveness in the model, the formula used to calculate it, is the one proposed by (Sapag & Sapag, 2000) adapted to a continuous simulation:

$$NPV = I_0 + \int_t^T \left(TI(t) - TC(t)\right) e^{r(1-t)} dt \qquad (26)$$

where *NPV* is the net present value, *r* is the instantaneous discount rate, and T is the length of the simulation. When evaluating the result, the general rule is the higher the value of *NPV*, the better the business is in economic terms (Sapag & Sapag, 2000).

System model and assumptions for the bioeconomic analysis

In order to illustrate how this model can help the decision maker, it will evaluate how a strategy based on harvesting size can affect the *NPV* of the farm. In order to perform such análisis, the model requires several inputs in each of the sub models described in the previous sections. Two harvesting sizes will be evaluated with differentiated prices: 90 and 100 mm. Each evaluation will be performed for a total of ten years, were the time step of the simulation (*h*) will be set in weeks, assuming that every year has a total of 52 week year^{-1}. The details for the parameters on each sub-model are described below.

Biological parameters

After conducting a literature review, two sites have been selected where growth information was available for suspended culture of scallop: La Herradura Bay, Chile and Independencia Bay, Perú, where Wolf & Garrido (1991) and Mendo & Jurado (1993) have studied growth behaviors for those sites respectively. For mortality rates, the literature reviewed provides only percentages after conducting experiments (Wolf & Garrido, 1991; Alcázar & Mendo, 2008; López *et al*., 2000; Cisneros *et al*., 2008), however the mortality in the model is treated in a continuous way in order to reflect that scallops will be affected to mortalities as long as they are kept in the farming units. That variable was selected from published natural mortality rates for this species (Wolff, 2007; Tarazona *et al*., 2007; Guzmán *et al*., 2007; Avendaño *et al*., 2010), and by making the assumption that the exclusion from natural predators (Wolff, 1994) will ensure higher survival than natural conditions, there fore the lowest natural mortality rate reported in the literature was picked (Wolff, 1987). Seed input will occur at two times for a given year as suggested by Cabrera (2000), three batches during summer and three batches during winter. Table 2 presents a summary of the biological parameters used in this evaluation.

Technological parameters

The parameters for this sub-model were extracted from three studies that analyzed technical and economic performance of scallop farming in Chile; namely Moreno (1998), Cabrera (2000) and Molina (2010). The farming area will be considered to be available and sufficient enough to keep with the production scheduled, fees and permits associated with this variable will be included in the economic sub-model as investment and fixed cost. The rest of the technological input values are presented in Table 3.

Economic parameters

The parameters for this sub-model were also extracted from the studies reported by Moreno (1998), Cabrera (2000) and Molina (2010), they account for all inputs necessary in the model when evaluating the economic performance of the simulated system (Table 4).

Note: All values were converted from Chilean pesos to US dollars using a fixed Exchange rate of: US$ 1 = $ 500 (Chilean pesos).

Sensitivity analysis

Since the data was collected from the literature and not from a validated experiment, a sensitivity analysis will be performed to identify the potential effect that changes in the parameters could have on the results of the simulation. This analysis was divided in two parts: first, variations in the *NPV* will be calculated after an increase of 15% in several input parameters of the model. Second, an expanded analysis will be performed on four of the most relevant parameters identified after the first analysis; this new analysis will allow to get deeper insights on the relationship between different input values and the financial feasibility of the system simulated.

RESULTS

Study cases

After performing a 10 years simulation for the two study cases proposed, final NPVs of US$ 2.8 million and US$ 5 million for Case 1 (La Herradura Bay) and harvesting sizes of 90 and 100 mm were respectively obtained. For Case 2 (Independencia Bay) NPVs of US$ 0.6 million and US$ 0.9 million were respectively estimated for harvesting sizes 90 and 100 mm. For both cases, it became clear that greater NPVs were obtained if greater sizes were preferred.

Survival between cases was decreased if greater lengths were preferred: 5% reduction for Case 1 and 7% reduction for Case 2. Increases in the cycle time will have positive effects on total cost and negative

Table 2. Biological parameters for the two study cases: Case 1: La Herradura Bay*;* Case 2*:* Independencia Bay.

Tabla 2. Parámetros biológicos para los dos casos de estudio: Caso 1: bahía La Herradura*;* Caso 2*:* bahía Independencia.

Parameter	Units	Case 1	Case 2
Batches per year	ba year^{-1}	6	6
A (initial seeds)	ind ba^{-1}	2.5x10^{6}	2.5x10^{6}
z (mortality rate)	year^{-1}	0.6	0.6
L_∞ (asymptotic length)	mm	220	110
k (growth parameter)	mm year^{-1}	0.35	0.565
R (lagging fraction of individuals)	%	35	35
φ (lagging fraction of lengths)	%	70	70

Table 3. Technological parameters used to evaluate the harvesting strategies.

Tabla 3. Parámetros tecnológicos utilizados para evaluar las estrategias de cultivo.

Parameter	Units	Value
Densities		
ρ_1 (Pearl net)	ind unit^{-1}	50
ρ_2 (Initial lantern)	ind unit^{-1}	500
ρ_3 (Final lantern)	ind unit^{-1}	250
Distribution in lines		
PNL (Pearl net per line)	unit line^{-1}	990
LL (Lanterns per line)	unit line^{-1}	99
Capacities and hiring		
CLB (Boat's capacity)	line boat^{-1}	100
CL_1 (Permanent labor)	line person^{-1}	35
CL_2 (Temporary labor)	line person^{-1}	20
δ (Temporary recruitments)	%	5

effects on survival and income, as it was expected to reflect with continuous mortality of the individuals. Results from both study cases using the parameters specified in the previous sections are presented in the sensitivity análisis.

After conducting a sensitivity analysis in parameters *z*, *k*, *p(L)*, *r*, *CS*, *FC*, CU_k, *COT* and *TCI*, we identified different impacts on both cases (Tables 5 and 6). Case 1 remained relatively stable to changes in the parameters by maintaining all changes in *NPV* below 3%. The four parameters with the greatest effects were price (*p*) with 2.68%, growth parameter (*k*) with 2.25%, mortality rate (*z*) with -1.45% and seed cost (*CS*) with -0.76% change per every increased percentage point respectively (Table 6).

For case 2, the effects on *NPV* were more drastic and were over 11% change per each point increased in the parameter. The four parameters with the greatest effects were growth parameter (*k*) with 11.28%, price (*p*) with 8.93%, mortality rate (*z*) with -5.52% and seed cost (*CS*) with -3.37% change per every increased percentage point respectively (Table 7).

The second sensitivity analysis was performed for the mortality rate (*z*), growth parameter (*k*) price (*p*) and the seed cost (*CS*). These parameters were decreased and increased in 50% and changes on *NPV* were recorded. In general, we observed non-linear relationships between biological parameters (*z* and *k*) and linear relationship for the economic ones (*p* and *CS*). All analyses showed that harvesting at greater sizes will produce greater *NPV*. Case 1 showed a strong differentiation between harvesting sizes, except for extreme decreases in the growth parameter, were *NPV*s tend to merge together (Fig. 2). Case 2 responded differently at the same changes by showing significantly less differentiation between sizes, it became clear that changes in the systems conditions could drive Case 2 financially unfeasible (Fig. 3).

DISCUSSION

After evaluating the model and its performance under different conditions, it became clear that final results will be highly susceptible to biological and economical parameters. Moreover, relevant patterns can be observed in the second part of the sensitivity analysis, where these patterns can provide useful information when analyzing a given strategy for farming scallop. Therefore, in order to improve results and the utility of the model, more research related to scallop perfor-mance in aquaculture is needed, at least for the conditions in the Chilean coast.

Table 4. Economic parameters used to evaluate the harvesting strategies.
Tabla 4. Parámetros económicos utilizados para evaluar las estrategias de cultivo.

Parameter	Units	Value (US$)
Initial investment		
I_0 (Initial investment)	$	26,000
Fixed cost		
CF	$ year^{-1}	90,000
Operational		
CC_1 (permanent hiring)	$ person^{-1}	40
CC_2 (temporary hiring)	$ person^{-1}	16
CD_2 (temporary firing)	$ person^{-1}	100
SMO_1 (permanent salary)	$ person^{-1} week^{-1}	160
SMO_2 (temporary salary)	$ person^{-1} week^{-1}	100
CBO (boat operation)	$ boat^{-1} week^{-1}	34
SMO_1 (permanent salary)	$ person^{-1} week^{-1}	160
SMO_2 (temporary salary)	$ person^{-1} week^{-1}	100
CBO (boat operation)	$ boat^{-1} week^{-1}	34
Inputs		
CS (seed prince)	$ ind^{-1}	0.024
CU_1 (pearl net price)	$ unit^{-1}	10
CU_2 (lantern price)	$ unit^{-1}	20
CU_3 (line price)	$ unit^{-1}	334
CU_4 (boat price)	$ boat^{-1}	12,800
Inventory		
IU_1 (pearl net storage)	$ unit^{-1} week^{-1}	0.04
IU_2 (lantern storage)	$ unit^{-1} week^{-1}	0.04
IU_3 (lines storage)	$ unit^{-1} week^{-1}	0.04
IU_4 (boats storage)	$ boat^{-1} week^{-1}	0.20
Depreciation & opportunity		
σ (depreciable % of I_0)	%	10
u (opportunity investment rate)	%	4
VUI (lifespan depreciable I_0)	year	10
VU_1 (lifespan pearl nets)	year unit^{-1}	4
VU_2 (lifespan lanterns)	year unit^{-1}	4
VU_3 (lifespan lines)	year unit^{-1}	4
VU_4 (lifespan boats)	year boat^{-1}	5

Overall performance and suggestions

Growth parameters used in the model were one of the most relevant factors for economic feasibility in the farm. It calls our attention that the parameters reported for Peru showed such a low performance in growth, given that stakeholders (Gómez, 2008) assure that Peru has better growth conditions than Chile. The discrepancies between values could be a result of diverse environmental conditions (Navarro & González, 1998; Tarazona *et al.*, 2007), metho-dology and assumptions for the calculations of parameters such as *k* and L_∞.

To improve performance in the model, it is necessary to have more research related to growth performance of scallop farming in Chile, this matter becomes crucial given that different locations, times, environmental conditions (temperature, oxygen, food availability and ENSO) and farming densities can

Table 5. Simulation results for the two study cases. Case 1: La Herradura Bay, Case 2: Independencia Bay, HS: harvest size in mm; p: price for a given harvest size.

Tabla 5. Resultados de la simulación para los dos casos de estudio. Caso 1: bahía La Herradura, Caso 2: bahía Independencia, HS: tamaño de cosecha en mm, p: precio por talla.

		Case 1		Case 2	
Parameter	Units	*HS* = 90 *p = US$ 0.2*	*HS* = 100 *p = US$ 0.3*	*HS* = 90 *p = US$ 0.2*	*HS* = 100 *p = US$ 0.3*
Production Results					
Average survival	%	55	50	45	38
Average harvest	ind (mill) year^{-1}	1.23	1.11	0.96	0.75
Economic Results					
Total income	$ (mill)	7.68	10.06	5.76	6.62
Total cost	$ (mill)	4.82	5.06	5.12	5.68
Net present value	$ (mill)	2.86	5.00	0.64	0.94

Table 6. Results of the sensitivity analysis for the financial performance in the farm considering two harvest sizes in Case 1: La Herradura Bay.

Tabla 6. Resultados del análisis de sensibilidad para el rendimiento financiero del cultivo de ostión considerando dos tallas de cosecha en el Caso 1: bahía la Herradura.

	HS = 90 mm		*HS* = 100 mm	
Parameter	NPV[a] (US$ mill)	Variation[b] (%)	NPV[a] (US$ mill)	Variation[b] (%)
NPV Base case	2.86		5.00	
z (mortality rate)	2.26	-1.40	4.10	-1.20
k (growth parameter)	3.82	2.25	6.41	1.87
p (scallop price)	4.01	2.68	6.51	2.01
r (discount rate)	2.55	-0.72	4.49	-0.68
CS (seed cost)	2.54	-0.76	4.68	-0.43
FC (fixed cost)	2.78	-0.20	4.92	-0.11
COT (total operational cost)	2.67	-0.45	4.78	-0.29
TCI (total inventory cost)	2.77	-0.21	4.90	-0.13

[a] New net present values when increasing the parameter value in 15%.

[b] Increment in percentage in the net present value per each incremental point in the parameters.

have significant impacts on scallop growth (Navarro & González, 1998: Avendaño & Cantillánez, 2005; Tarazona *et al.*, 2007). In Chile, there are only a few growth studies conducted (Thébault *et al.*, 2008), and further research should be done under different times of the year and under different environmental conditions (Thébault *et al.*, 2008; Uribe & Blanco, 2001) throughout the farming process (Hawkins *et al.*, 2002).

Mortality was also a key factor determining the performance of the model, where variations in the mortality had different effects for both cases (growth conditions). This effect is basically due to the continuous nature of the mortality used in the model and its dependency on how long it takes the scallop to reach the harvesting size. Well aware of the limitations of using values for natural banks, it is strongly believed that continuous mortality instead of percentage (Wolf & Garrido, 1991; Alcázar & Mendo, 1998; López *et al.*, 2000; Cisneros *et al.*, 2008) is the proper way to reflect the reality of the farming process. In order to improve the performance of the model is necessary to gather more accurate information about mortalities throughout the farming process (Hawkins *et al.*, 2002; Nobre *et al.*, 2009). This poses a major challenge for research, especially

Table 7. Results of the sensitivity analysis for the financial performance in the farm considering two harvest sizes in Case 2: Independencia Bay.

Tabla 7. Resultados del análisis de sensibilidad para el rendimiento financiero del cultivo de ostión considerando dos tallas de cosecha en el Caso 2: bahía Independencia.

	HS = 90 mm		*HS* = 100 mm	
Parameter	NPV[a] (US$ mill)	Variation[b] (%)	NPV[a] (US$ mill)	Variation[b] (%)
NPV Base case	0.64		0.94	
z (mortality rate)	0.11	-5.52	0.22	-5.13
k (growth parameter)	1.73	11.28	2.51	11.04
p (scallop price)	1.50	8.93	1.93	6.97
r (discount rate)	0.49	-1.56	0.74	-1.47
CS (seed cost)	0.32	-3.37	0.62	-2.29
FC (fixed cost)	0.56	-0.88	0.86	-0.60
COT (total operational cost)	0.41	-2.38	0.67	-1.97
TCI (total inventory cost)	0.54	-1.02	0.81	-0.93

[a] New net present values when increasing the parameter value in 15%.

[b]Increment in percentage in the net present value per each incremental point in the parameters.

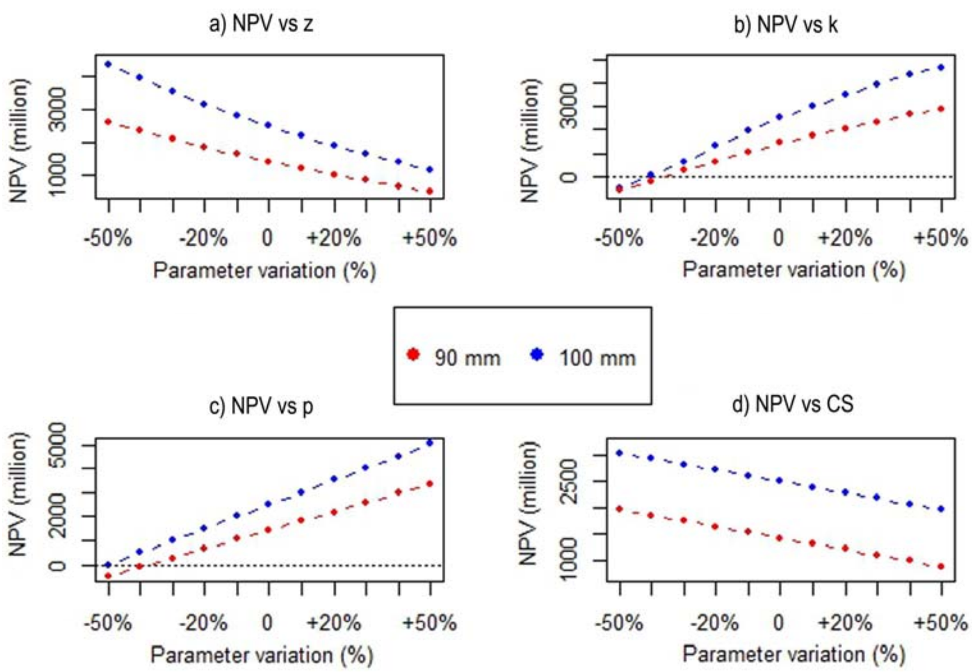

Figure 2. Expanded sensitivity analysis for Case 1: La Herradura Bay after variations in a) mortality rate (*z*), b) growth parameter (*k*), c) price (*p*), d) seed cost (*CS*).

Figura 2. Análisis de sensibilidad expandido para el Caso 1: bahía La Herradura luego de variar a) tasa de mortalidad (*z*), b) parámetro de crecimiento (*k*), c) precio (*p*), d) costo de semilla (*CS*).

because mortalities will vary between geographical locations and environmental conditions (Navarro & González, 1998; Tarazona *et al.*, 2007).

As the information on both growth and mortality is scarce for Chile (Thébault *et al.*, 2008; Uribe & Blanco, 2001), modifications in the model could be done in order to obtain results that can incorporate uncertainty and environmental variability at some extent. A risk analysis of the outcomes from this modification can provide a better insight for the

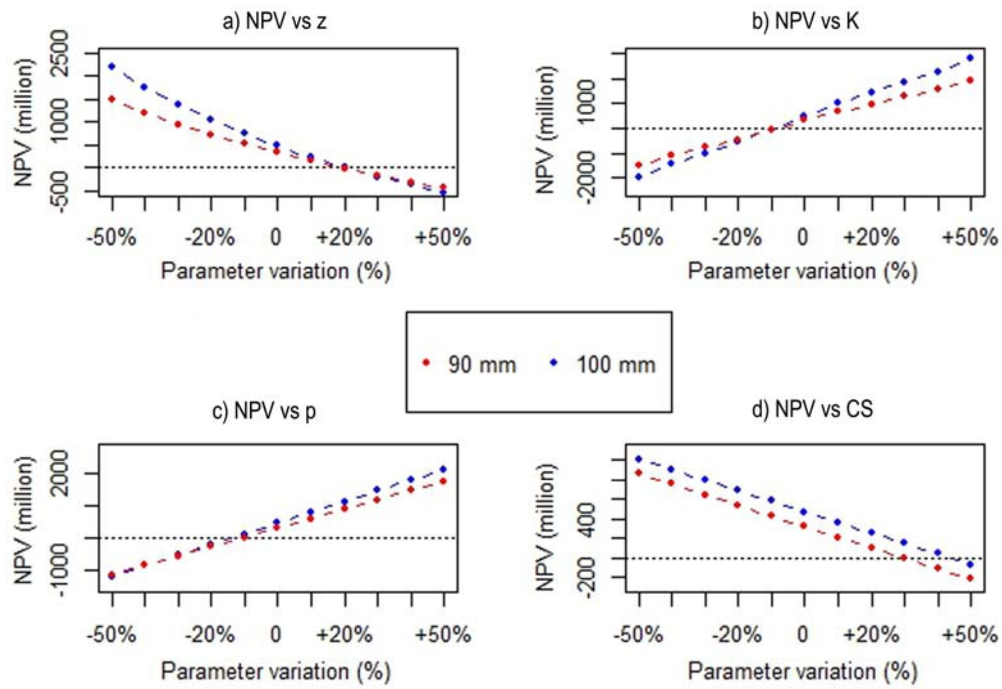

Figure 3. Expanded sensitivity analysis for Case 2: Independencia Bay after variations in a) mortality rate (*z*), b) growth parameter (*k*), c) price (*p*), d) seed cost (*CS*).

Figura 3. Análisis de sensibilidad expndido para el Caso 2: bahía Independencia luego de variar a) tasa de mortalidad (*z*), b) parámetro de crecimiento (*k*), c) precio (*p*), d) costo de semilla (*CS*).

implications of environmental variability in the economic feasibility of scallop farming. Random shocks could be the first attempt to introduce such variables in the model. Another important factor that should be considered is the inclusion of gonadal development (Cantillánez *et al.*, 2005), and its impact in the quality and price of the harvest. This could be included by establishing relationships between yearly cycles and individual length, so spawning can occur if certain conditions are met; this type of relationships are interesting and could be of great value in order to improve the overall performance of the model.

Prices were the main factor driving *NPV* from the economic parameters, which is consistent with other experiences for similar models (Pelot & Zwicker, 2006; Taylor *et al.*, 2006). The actual effect of price variation varied between cases, where its effect was greater when poor growth parameters were entered into the model. Seed cost also had a significant effect in the *NPV*, revealing that it could be a determining factor for economic feasibility of scallop farming, this is also recognized in other attempts to model this industry (Adams *et al.*, 2001). Some improvements to the performance of the model in the economic perspective could be to include seasonal variability, and stochastic processes that reflect real variation of prices and costs in the market. Some of this future approaches were also proposed by Molina (2010) for price variability, and future attempts to model this industry should consider including that type of variables.

Decision making using the results

Most of the value from this type of models is not represented by the numerical results, but from the patterns a given variable shows (Hannon & Ruth, 1994; Sternman, 2000). After the simulation of the two cases and the extensive two step sensitivity analysis, we can identify several patterns that could be useful for scallop farmers when making decisions about locations and strategies.

Regardless of the value and location of the parameters, we can treat Case 1 and Case 2 as two locations with different growing conditions, higher (HGP) and lower (LGP) growth performance respectively. HGP will have better economic performance by decreasing mortality and total cost, this is basically by decreasing the time that scallop will take to reach to harvest size and therefore the resources needed to maintain individuals during the farming process.

Given the relationships between growth performance, mortality and environmental conditions (Tarazona *et al.*, 2007), precaution must be taken before driving conclusions out of the results from the model; nevertheless, the most valuable information is provided by the trends of the sensitivity analysis. In both locations can be seen that high mortalities drive the two harvesting sizes together, which can be interpreted as if the loss in individuals is not compensated by the increase in price, it will be preferred to harvest sooner. This may seem redundant or obvious, but it could play a relevant role on how farmers produce and market their product. For instance, if an environmental event that is expected to increase mortalities is approaching, it may be a wise decision to stimulate markets for smaller sizes, implement protection technologies or to abandon the business venture, all of this depending on the expectations and the risk the farmer is willing to take. Nevertheless, HGP locations are expected to be more resilient to that type of variations.

Growth parameter analysis has to be carefully interpreted, since it there is an intrinsic relationship between the *k* value and L_∞ (Wolff & Garrido, 1991; Mendo & Jurado, 1993; Cisneros *et al.*, 2008) that cannot be ignored before driving any conclusions. Having acknowledged the limitations, it is noticed that for both sites the preferred harvest size will depend almost entirely on growth performance. The trend is actually more obvious for LGP, where *NPV* trajectories intersect each other with slight decreases in the *k* parameter (Fig. 3b). In a similar way with mortality, expected growth variability has to be consider when planning faming strategies; with LGP for instance, if environmental events are expected to decrease growth as low as 5%, it becomes a better strategy to harvest at 90 mm. The implications of this potential effect make farmers highly susceptible to any phenomena that could affect growth performance in their sites; if this is the case precautive measures should be taken such as growth monitoring, environmental conditions monitoring, better farming technologies and a more controlled farming sequence.

For price, in the case that a HGP site is available larger sizes will be preferred over the minimal harvesting size; nevertheless, this is only true for conditions where the price is large enough compared with the alternative size. Taking the results from the detailed sensitivity analysis for price in this case (Fig. 2c), if 90 mm price remains constant and 100 mm is reduced by 15% the preferred option will be to harvest at the minimum size in order to get a greater *NPV*. With LGP this conclusion is also true, but the threshold between which size is preferred is actually lower, if 90 mm price is constant reductions of just 5% in 100 mm price will render the minimum size as the optimal harvest size.

Seed cost has a different behavior since is not affected by harvest size. However, this cost will have direct effects on *NPV*, where LGP will be subject to significant effects if there is variability in the seed cost. This information could of great use if a given site is evaluating to buy, collect or produce the seed in a hatchery (Cabrera, 2000). The rule of thumb would be to choose the alternative that provides the greatest *NPV*, where this model could be used to perform those types of analyses in order to establish the best investment option.

CONCLUSIONS

This model is a first approach to develop decision making tools to improve competiveness in the Chilean scallop farming system. Its application and utility will be highly dependent on input values such as growth, mortality and cost, where the information generated from the outcomes of the model could allow decision makers to compare between locations and different strategies for variety of biological, technological and economic conditions. Moreover, for some conditions the business may render economically unfeasible and withdrawal from the industry should be an option if farming factors don't allow farmers to recover investment after setting the business.

Future attempts for modelling scallop farming should take into account stochastic processes and biological dependence on environmental conditions. More research is needed, especially in biological indicators for aquaculture in Chile. It is suggested that future efforts should be focused on providing relevant information that could help researches to improve competiveness and efficiency for scallop farming.

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