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Research Article

Economic analysis of loco abalone (*Concholepas concholepas*) commercial cultivation in Chile

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ABSTRACT. Loco abalone (*Concholepas concholepas*, Bruguière, 1789) represents the most important gastropod fishery from the central coast of Perú down to the southernmost part of Chile. International prices are attractive enough to motivate the development of an important body of research to bring the catch to commercial size under controlled conditions. In this study, we analyze whether the fattening of loco from the seed stage (between 2 and 3 cm of peristomal length) up to commercial size is economically attractive for a private investor. The results of this model, composed by biological, technological and economic submodels, shows that under current conditions cultivation is not convenient Net Present Value (NPV) = -198,179 US$ on t = 1,400, the day where the maximum biomass is reached). The negative result is explained by the high operational costs (mainly wages) and high initial investments requirements (mainly plastic boxes to house the *C. concholepas*). Interestingly, the model shows that feeding costs are comparatively low. At t = 1400, the accumulated disbursements for investments (US$92,209) are lower than those for the operating costs (US$299,486) and represent only 24% of the total accumulated disbursements. The latter shows that the project is not profitable due to the high operating costs other than the feed. The sensitivity analysis shows that would be required a 30-fold increase in the current biomass selling price for a positive NPV. In the future, this project would benefit if more efficient forms of production are developed, especially reducing the burden due to workers' compensation.

Keywords: *Concholepas concholepas,* net present value, culture, bio-economic model, Chile.

INTRODUCTION

The loco abalone, commonly known as false abalone, loco (in Chile) and chanque or tolina (in Perú), is a benthic gastropod inhabiting the intertidal zone. It represents the most important gastropod fishery from the central coast of Peru (6º55’S, 79º52’W) to the south of Chile (55ºS, 68ºW). *Concholepas concholepas* has a large foot, which is popular seafood and an important economic resource (Rabi & Maraví, 1997).

Up to the 1980s, loco fishery in Chile was mainly oriented toward domestic consumption and was characterized by an open-access regime so that traditional fishers migrated to places with more abundant supplies. Exports to the Asian markets (to China and especially Japan) began as a less expensive substitute of the abalone (*Haliotis* spp.) foot (Castilla & Gelcich, 2008), this brought about a rapid increase in demand and a growing pressure on the resource, with an annual peak landing of 24.800 t in 1980 (Castilla & Gelcich, 2008). Faced with an imminent collapse of the stocks of *C. concholepas*, in 1982 the Subsecretaría de Pesca, Chile introduced a three-month annual ban on its catch during the breeding season (from March 1 to May 31). The catch, however, did not diminish significantly. This period, during which the so-called "loco fever" occurred, was characterized by exorbitant overfishing of this valuable resource. Historically, the primary extraction area in Chile, with more than 50% of the total catch, has been the Los Lagos region (41°27’36”S; 72°55’12”W).

During 1988, the fishing of loco was authorized for only 15 days, with the production reaching a total of 11,180 t (Fig. 1). The clear signs of depletion of the natural populations forced the authorities to impose a complete ban on fishing from 1989 to 1992 to facilitate their recovery (Castilla & Gelcich, 2008).

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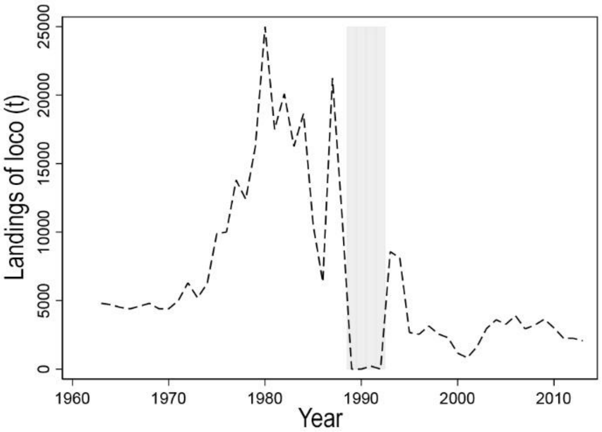

Figure 1. Landings of loco (t) in Chile. In gray, the period when the fisheries remained closed. Source: based on SUBPESCA (2008, Table 2).

However, this ban brought to the surface the delicate social problem of traditional fishermen whose survival was based mainly on the catch of the mollusk. Finally, the Chilean legislation was modified in such a way that it made loco fishery an enterprise managed through Territorial Use Rights in Fisheries (TURFs, or AMERB in Spanish), imposed a moratorium on new entrants to the fishery, and restricted artisanal fishermen to working in the area of their residence. Beginning in 2005, the landings originating in the AMERB reached practically 100% of the national catch. Currently, the geographical distribution of landings includes Coquimbo (29°53’60”S; 71°15’0”W) and Los Lagos (41°27’36”S; 72°55’12”W) as the two most important areas, with almost 80% of the national catch. Nowadays, there is a total ban on the resource extraction, running until December 2017, save for quota extractions on the AMERB’s (SERNAPESCA, 2017).

Despite the protective measures that have been adopted, it is still very common to see large amounts of loco seized, processed by clandestine factories, and ready to be shipped overseas. Very often, the preferred form of illegal trafficking is to use a false shipment manifest, declaring that containers carry either hake or cod (Bandin & Quiñones, 2014).

Market conditions make of loco a very attractive resource from an economic standpoint, encouraging the development of an important body of research to bring the cultivation of this species to its commercial size in controlled conditions, parallel to another set of investigations whose goal is repopulation, be it natural or artificial. Most of the available information about loco comprises the description of sizes in natural populations (Bustos & Navarrete, 1986; Rabí & Maraví, 1997).

Another important body of research, originated in Chile in the 1980’s, has sought the cultivation of loco through the artificial production of seeds and juveniles of the species. In this area, worthy of note are the works of the Instituto de Fomento Pesquero (IFOP) in Putemún, Chiloé, and of the Universidad Católica del Norte (UCN) in Coquimbo (Dr. Louis DiSalvo). In both cases, the success was very limited. Lack of knowledge about quality, quantity, and adequate size of prey during the post-larval stage, up to seeds of 1 cm in size, seems to be the cause of most losses because of cannibalism and starvation (Bustos & Navarrete, 2001). The repopulation was suggested by Lody (2008).

A third line of research has attempted to bring the experimental cultivation to the commercial stage, based on juveniles collected in the natural environment (Navarro & Torrijos, 1995; Bustos & Navarrete, 2001). In these cases, the juveniles are placed in special enclosures and artificially fed under controlled conditions. The results of these experiments will form the basis of the present study. Indeed, the goal of this research is the analysis of biological, technological and economic conditions under which loco cultivation, from the seed stage (peristomal length between 2 and 3 cm) up to commercial size, is feasible for a private investor.

MATERIALS AND METHODS

Description of the system: a business model for loco fattening

Table 1 allows illustrating the structure of the model we used for the bioeconomic analysis for the commercial cultivation of the *C. concholepas*. It is a dynamic model since it is focused on the evolution of their components over time, and it is a deterministic model. We work with the expected or most probable values of the parameters under the conditions that are established. Table 1 also shows that the model is composed of three submodels: biological, technological and economic. From another dimension, the model is constructed through four stages fundamentally. In the first, the value of the key parameters for each of the submodels is defined. In the second stage, the relationships between the different components within each submodel are defined, that is, the biological, technological and economic submodels are formulated. In the third phase, the interactions between the three submodels are defined, which allows building the global model, all the key variables of the model interacting. Finally, quantitative predictions are obtained about the behavior of key variables over time for each of the submodels. Here it is of particular interest to obtain estimates of the overall convenience of the culture, which corresponds to Net Present Value (NPV) estimates, which is part of the economic submodel.

Table 1. The business model for *C. concholepas* fattening. NPV: Net Present Value.

	Components of the model (Fig. 2)		
Stages of the model	Biological submodel	Technological submodel	Economic submodel
Definition of parameters (known or projected)	+	+	+
The relationship between components in each submodel	+	+	+
Definition of interactions between submodels	+	+	+
Prediction of ex-sample relevant results (NPV)	+	+	+

Globally, it is a model that seeks to obtain predictions based on the best available information. Because up until now there has not been an experience of taking a *C. concholepas* cohort to commercial size under artificial feeding, as we postulated here, there is no way to compare the results predicted by our model with actual ex-post data, and therefore, the latter is not part of the study.

Each submodel generates its results, which are presented separately. The results of the biological submodel are a necessary input to generate the results of the technological sub-model. In turn, the results of both biological and technological submodels are a necessary input to generate the results of the economic sub-model. That is the reason why the Results section offers not only the results of the economic submodel, which constitutes the outcome of the study but also the results of the biological and technological submodels.

The business model for *C. concholepas* fattening and commercialization is performed for a single cohort, which allows the model to be comprehensible and straightforward, and still, provide useful information. Therefore, we consider our model the first approach before elaborating a more complex model, including, for example, multiple overlapping cohorts.

The model takes into account only the so-called “fattening stage” (weight gain) shown in Bustos & Navarrete (2001). This stage begins with the acquisition of juveniles at market prices. The previous period (procurement of capsules and the cultivation of juveniles until approximately 287 days from the capsules’ hatching) is not part of the evaluation in this study. The juveniles are kept at sea and are taken care of by the fattening center. Right after harvest, the *C. concholepas* production is sold at market price. The fattening process (weight gain) of the juveniles can take place at the Chilean AMERBs, although this is not a requirement.

A conceptual model for the system

We use Stella™ software (High-Performance Systems, Inc., 2001). It provides an easy solution of the resulting differential equations, a transparent drawing of the model diagram and in a clear definition of the mathematical relationships. The fundamental idea behind Stella is to relate stocks and flows between various points of accumulation using some basic components, which comprise the fundamental building blocks for system modeling. In Stella, amounts are called stocks (rectangles) and represent accumulations. Flows (arrows with a central water valve) are defined by a rate (amount per unit time). They influence stocks, causing accumulations and/or depletions. Converters (circles) are used to input parameters, do arithmetic operations, unit conversion, or other mathematical necessities. Finally, connectors are devices that carry information flow between components and are represented by an arrow.

The complete model, in the Stella specification, (Fig. 2), including the three submodels (biological, technological and economic). Note: See in the Appendix the Stella equations of the whole model.

The biological submodel projects the biomass (B_t) to be harvested, in kg, and includes the projection of growth in length (L_t) and weight (W_t), and survival (N_t). The technological submodel estimates the rate of consumption of individual daily food (FR_t) in grams per day and the total for the cohort (FRT_t) in kg d^{-1}. The economic submodel aims to estimate the Net Present Value (NPV), and is composed of investment projections classified into four groups (Inv G1, G2, G3 and G4), six types of recurring costs (Cost A, B, C. D and E), and revenues from the sale of the biomass (Income). The other components of this diagram will be explained in the following sections.

Quantitative model formulation

Biological considerations

In Chile, several hatcheries meet conditions to offer stock of up to 100,000 juveniles yr^{-1} to a fattening center (Lody, 2013). The laboratory or hatchery becomes then responsible for the remaining conditioning stages before the fattening stage (weight gain) and hands the individuals over as juveniles of 2 to 3 cm of peristomal length.

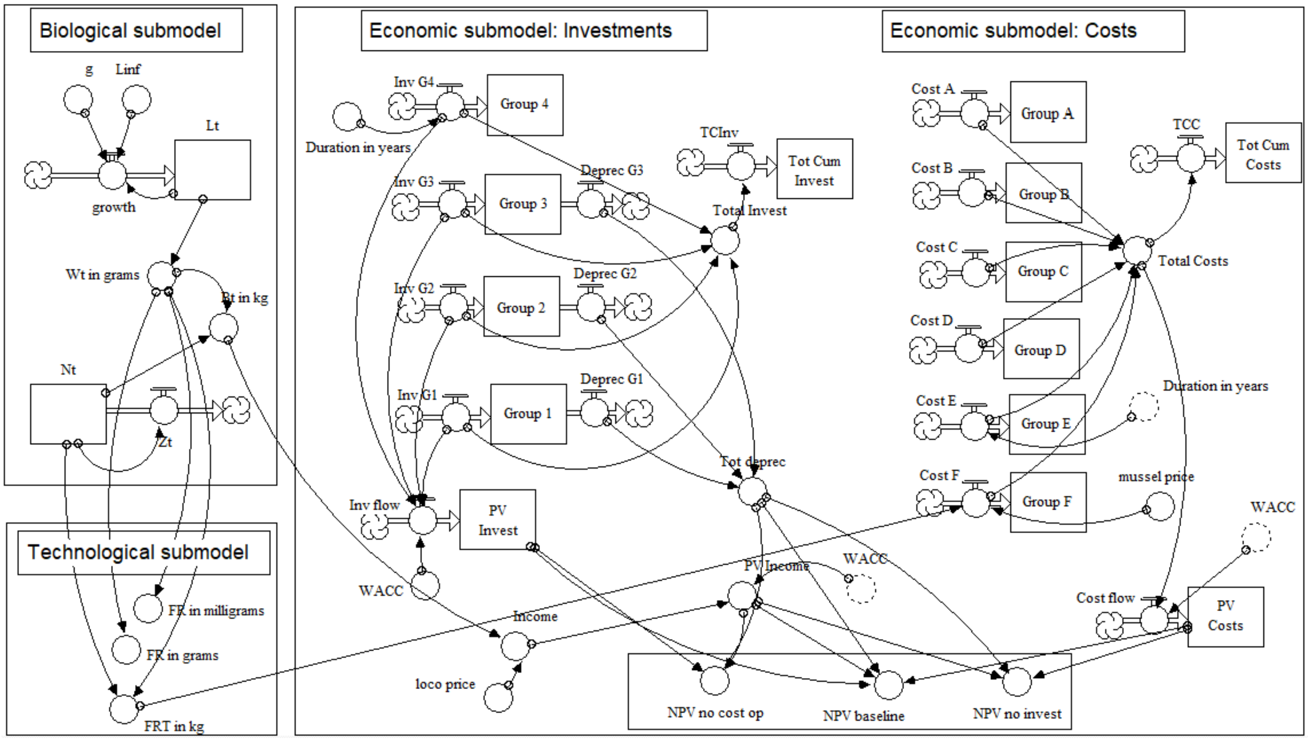

Figure 2. Global model diagram in Stella, TM.

During the fattening stage on floating cages, growth curves were fit using von Bertalanffy's equation (Wolff, 1989; Bustos & Navarrete, 1986). In its simplest functional form, the loco daily increase in length is given by the following equation:

$$\frac{\partial L_t}{\partial t} = g \times (L_{inf} - L_t) \qquad (1)$$

where time t is given in days of culture ($t = 0$, is the day when the juveniles reach the farm), L_t corresponds to the length (mm) on day t, L_{inf} is the theoretical asymptotic length (mm), and g corresponds to the daily growth rate.

The allometric relationship of eq. (2) allows estimation of the weights of individual animals (in grams of loco moist meat, *e.i.*, soft tissue) based on their length, in mm [most of the biological equations can be found in Clark, (1976) and Wilen (1985)]:

$$W_t = \alpha \times {L_t}^3 \qquad (2)$$

where α is an empirically estimated conversion factor.

The number of surviving individuals on day t, N_t, is determined by the daily mortality rate, Z. Survival can be expressed by a differential equation (Lara *et al.*, 2007), with an initial number of 100,000 juveniles, as follows:

$$\frac{\partial N_t}{\partial t} = -Z \times N_t, \quad N_0 = 100{,}000 \qquad (3)$$

Then, the biomass in grams at time t corresponds to the number of individuals surviving in the cages, multiplied by their weight:

$$B_t = N_t \times W_t = \alpha \times N_t \times L_t^3 \qquad (4)$$

Biomass forecast at harvest time is the main result of the biological considerations of this study.

Cultivation technology

In the growing stage at sea, the aim is to expose the animals to natural conditions of temperature, salinity, oxygen, and light. The fattening stage begins when loco juveniles are acquired, and their size reaches between 2 and 3 cm of peristomal length (mean of 2.5 cm).

The cultivation system consisted of cages suspended by long lines. Each line is 100 m long and is anchored at the bottom. The cages are plastic boxes of dimensions 40×40×60 cm, covered by a mesh, and they are placed underwater and connected to the long lines by a vertical rope. Each vertical rope holds up to three cages allowing the free flow of seawater (Fig. 3). Each box is cleaned, and food replenished monthly, keeping under control loco growth, density and survival. Once the locos reach the expected size, they are harvested merely by retrieving the boxes from the system.

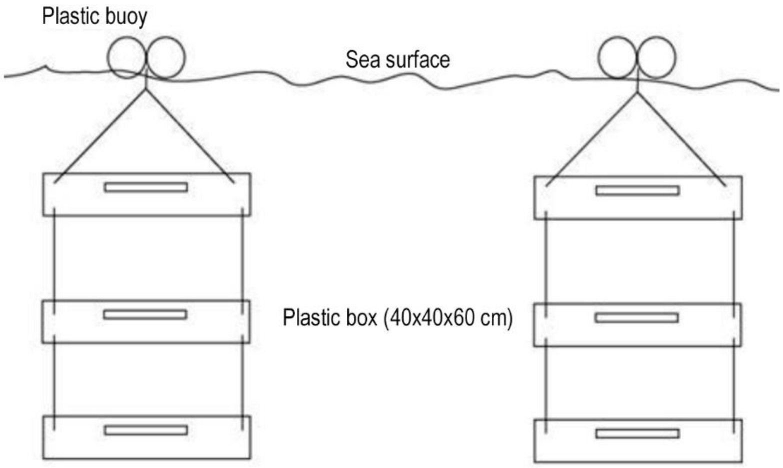

Figure 3. Lateral view of a loco fattening system under water. Source: adapted from Bustos & Navarrete (2001). Other authors have used similar systems (Navarro & Torrijos, 1995; Vejar, 2009).

Cultivation density and sowing

The densities are of 100 individuals (ind) per box when they are 2.5 cm of peristomal length, and then 50 ind per box when they are 5 cm or more of peristomal length (Bustos & Navarrete, 2001). The project evaluates an initial fattening stage with 100,000 ind. In the beginning, 100 ind are placed in each box. Each arrangement contains three vertically aligned boxes, and similar sets are placed 5 m apart from each other.

Given that a long line is roughly 100 m long, on each of them 20 sets are left hanging, that is, 60 boxes and 6,000 ind per line. In order to sow 100,000 ind, initially, 17 long lines are required, for 1,020 boxes. Long lines are in turn placed 6 m apart from each other, meaning that the sea area needed is slightly over 1 ha. A long line includes six anchors of 250 kg each, 215 m of rope (18 mm in diameter), 12 buoys (30 cm in diameter) and 60 buoy ropes (6 mm in diameter).

Feeding

The food employed for loco fattening is fresh mussel (chorito, *Mytilus chilensis*). Navarro & Torrijos (1995) show that for both small and large sizes a diet based on *M. chilensis* results in a positive energy balance for loco, and growth rates similar to those found in the wild can be achieved.

The daily feeding rate (FR_t) of loco depends on the individual's weight, and it grows at increasing rates as weight increases. The following equation can approximate this rate:

$$FR_t = a_0 \times W_t^{a_1}, 0 < a_1 < 1, \quad (5)$$

where FR_t is measured in grams per day of chorito, moist meat or soft tissue), W_t is the loco meat wet weight, and a_0 and a_1 are specific parameters.

The total daily consumption of food at the cultivation center depends on the intake rate (which in turn depends on individual weight) and on the number of individuals at the cultivation system. It is given by

$$FRT_t = FR_t \times N_t. \quad (6)$$

The cultivation program in our analysis is made up of a single cohort, which is kept under fattening until harvest time. The duration of the fattening period depends on the size and the type of market coveted.

Economic considerations

The economic dimension deals with the estimation of the initial investments, the production, and administrative costs, as well as an income forecast. In order for the cultivation to be profitable in the short term, the income from the sale should be sufficient to cover the operational outlays. In the long run, the income must cover the operational and administrative costs, including the entire investment.

The Present Net Value (NPV) is the main criterion for assessing the suitability of any investment program (Ross *et al*., 2010). When NPV >0, then the investment is feasible from the standpoint of a private investor. Formally, the NPV is defined as follows:

$$NPV = \int_{t=0}^{t=T} FCF_t \times e^{-WACC \cdot t} dt > 0 \quad (7)$$

where FCF_t is the relevant free cash flow expected from the long-term program; t is time in days, T is the harvest time for a single cohort.

WACC is the daily weighted average cost of capital, which is given by (Ross *et al*., 2010):

$$WACC = k_d(1 - Tx)\left(\frac{Debt}{Debt+Equity}\right) + k_s\left(\frac{Equity}{Debt+Equity}\right) \quad (8)$$

where k_d is the debt cost of the firm, k_s is the equity cost; Tx is the corporate tax rate, and *Debt* and *Equity* (stocks) are the market values of the debt and the equity, respectively, of a firm of similar size, risk, and leverage. In order to estimate the WACC, many authors report that in the U.S. the appropriate discount rate for startups should be at least 50%, and once a project is consolidated (exit stage), the demanded yield must surpass 30% annually (Wetzel 1981; Plummer 1987; Ruhnka & Young 1991; Bygrave *et al.*, 1999). Given that in emerging countries the discount rates must be higher than in developed countries (*cet. par.*), in this study, a 50% annual rate was considered.

The expected free cash flow ($\mathrm{FCF_t}$) is the sum of the following three groups of items (Zúñiga-Jara & Marín-Riffo, 2016):

a) Revenues from sales: the biomass of loco that is periodically produced and sold ($\mathrm{B_t}$), multiplied by the ex-factory selling price of the biomass (P). For that, it was considered that the ratio of meat weight (soft tissue only) to the total weight, fresh with shell, is between 30% (Lody, 2008) and 36.5% (Pérez & Stotz, 1992). There are several ways to estimate the ex-factory price of *C. concholepas*.

b) The *C. concholepas* (meat with shell) penalty price (established by the Chilean government to punish illegal captures) is 132.6 UTM per ton, which corresponds to US$9.0 per kg (meat with shell). Thus, the penalty price of meat is around US$30 per kg.

- In Véjar (2009), *C. concholepas* price is US$1,939 per t at the factory, with shell, that is, US$1.9 per kg with the shell. From this, the most conservative estimate for Vejar is US$6.33 meat only (soft tissue).

- Lody (2008) estimates a range of prices for meat (soft tissue) between US$18.9 and US$23.1, the most probable being a price of US$21.0 per kg. This price is similar to the average of the prices quoted by the rest of the authors, and it is the price used in this work.

c) Initial investments ($\mathrm{Inv_t}$), reinvestments ($\mathrm{Reinv_t}$), rescue value ($\mathrm{RV_t}$) and tax shields from depreciation ($\mathrm{Dep_t} \times \mathrm{Tx}$); investments are initially required at t = 0, but because of depreciation, reinvestments are required during the lifetime of the project, and tax shields originate from the tax benefit of depreciation, where Tx is the tax rate, and Dep is depreciation. We assume that cultivation is undertaken by society under the "semi-integrated tax system" according to the recent tax reform in Chile, and the corporate income tax utilized is 27%.

d) Recurrent fixed and variable costs ($\mathrm{Cost_t}$), including the fixed costs of administration and sales ($\mathrm{FCost_t}$), weekly planting costs ($\mathrm{SCost_t}$) and weekly harvesting costs ($\mathrm{HCost_t}$).

In detail, the NPV formula used here is as follows:

$$NPV = \int_{t=0}^{t=N} [(B_t P - Cost_t)(1 - \mathrm{Tx}) - Inv_t - Reinv_t + RV_t + Dep_t \times Tx] \times e^{-WACC \cdot t}\, dt \qquad (9)$$

Sensitivity analysis

Because our model is a predictive one, and there is no observed real data for the final stages of the artificial culture, in this section analysis of the three scenarios is performed. The first is the baseline model, which analyzes whether the income from the sale of the biomass covers all the investments and costs. In the second scenario, it is analyzed if the culture covers only the initial investments (without operational costs). Finally, it is analyzed if operating costs are covered, excluding investments. The simulations are done using the standard tools of Stella TM.

RESULTS

Biologic results

The individual length and weight

For the eq. (1) We used the most conservative estimation (see Table 2). According to this, juveniles reach the 2.5 cm length at day 360. The fattening center will acquire them at this size. Figure 4 shows the corresponding behavior of length (peristomal) of a typical individual over time. t = 0 is the initial time of the fattening stage (stocking) when individuals are approximately one year old (around 2.5 cm in length).

We use conservative estimates for α (see Table 2). Figure 5 shows this relationship based on the size curves of Figure 4. As a reference, in Figure 4 the individuals with 100 mm of length (day t = 3,200 from stocking, *i.e.*, eight years from stocking approximately) reach a soft tissue weight of around 70 g.

Survival

We use estimations in Table 2. In Figure 6, beginning with $N_0 = 100{,}000$ ind, the number of survivors on day t = 3,200 from stocking is around 7,000 ind.

Total biomass

The estimation of the eq. (4), is shown in the Figure 7 and illustrates that total biomass on day t = 3,200 from stocking is approximately 490 kg. The same figure also shows that the expected biomass reaches its maximum beyond day 1,500 (4.2 years). If harvest occurs on day t = 1,000, the harvest would contain around 43,400 ind, measuring 68 mm on average, weighing 23 g in meat each, and the harvested biomass in moist meat is in the neighborhood of 1,000 kg.

Table 2. The biological and technological submodel's parameters.

Parameter	Equation	Parameter value	Source
L_{inf}	Eq. 1	108.0 mm	Stotz *et al.* (2000), Figure 5.5
g	Eq. 1	0.27/365	Stotz *et al.* (2000), Figure 5.5
α	Eq. 2	0.00007	Pérez & Stotz (1992), Figure 4
N_0	Eq. 3	100,000	Defined by the authors
Z	Eq. 3	0.3/365	Based on several sources (see in the text).
a_1	Eq. 5	0.02304	Navarro & Torrijos (1995), Figure 2
a_2	Eq. 5	0.56	Navarro & Torrijos (1995), Figure 2

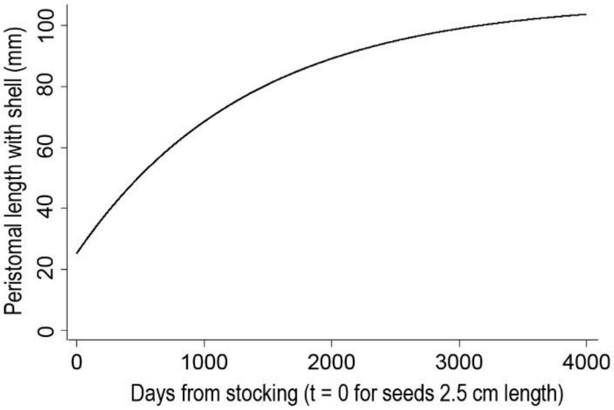

Figure 4. Peristomal length (with shell) of a typical *C. concholepas*.

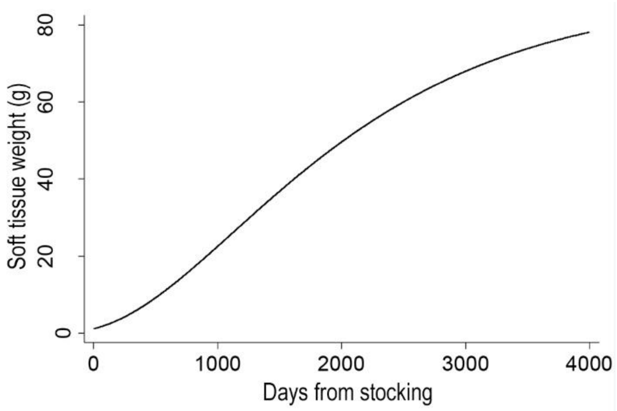

Figure 5. Soft tissue weight of a typical *C. concholepas*.

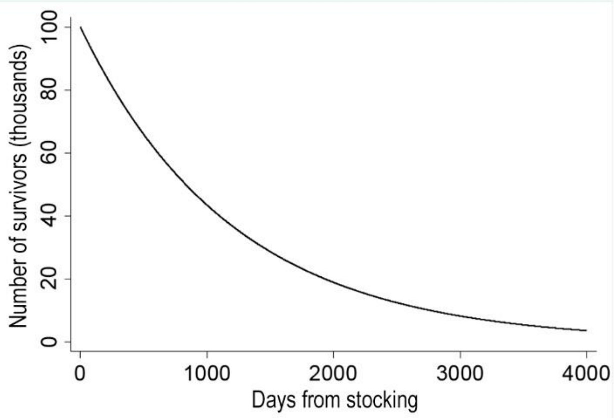

Figure 6. *C. concholepas* survivability in the fattening stage. N_t: the number of survivors.

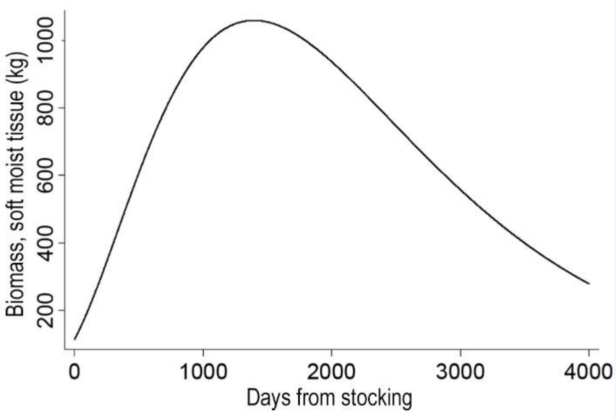

Figure 7. Expected Biomass, B_t (soft moist tissue).

Technological results

Doubling

When individuals measure 5 cm long (near day 480, *i.e.*, 1 year and four months after the fattening stage begins), there are approximately 67,000 surviving individuals. During the doubling, 50 ind are apportioned per box, and 1,340 boxes are required (67,500/50). Then an additional investment of 5 long lines and 320 boxes is necessary. This fact, in turn, increases the sea area requirements in 3,000 square meters (0.3 ha).

Feeding

We use estimations of the ingestion rates when feeding with mussels (*M. chilensis*) in Table 2. From eq. (5) and eq. (6), it can be seen that on day t = 3,200 an average individual 100 mm length and weight 70.5 g consumes on average 0.25 g of moist mussel per day (Fig. 8),

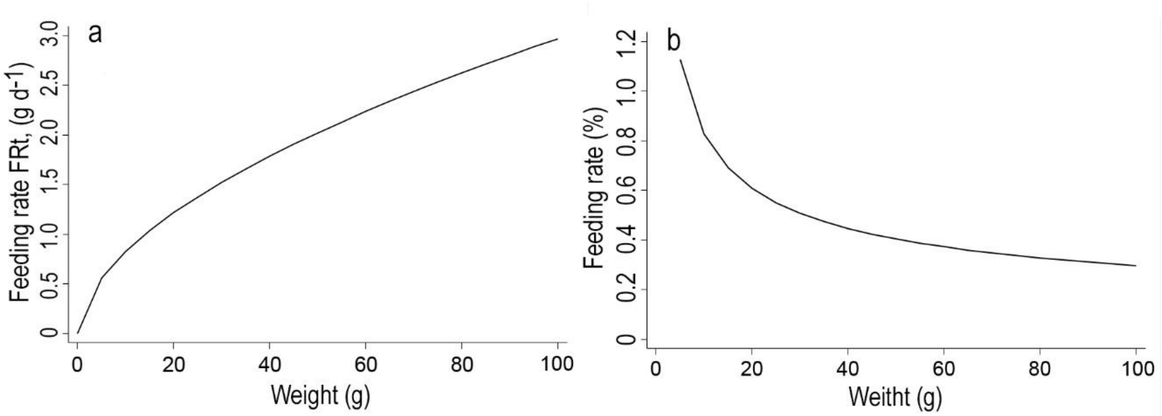

Figure 8. *C. concholepas'* fresh food consumption, as a function of its weight. a) Daily food consumption, in g of moist meat, FR_t, b) daily food consumption of moist meat as a percentage of its weight ($\frac{FR_t}{W_t} \times 100$). Source: Castilla *et al.* (1979) and Navarro & Torrijos (1995).

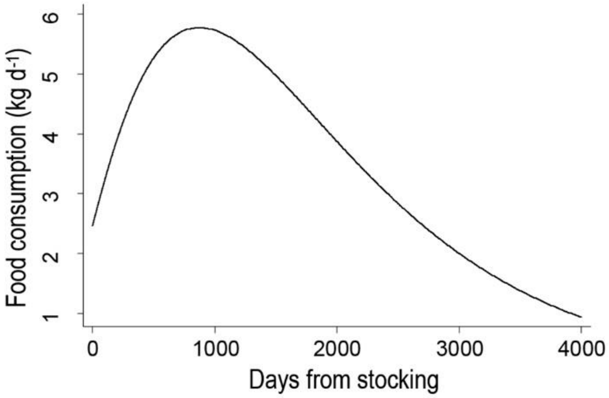

Figure 9. Food consumption (*Mytilus chilensis*), in kg per day, for a single cohort at the fattening center.

which is in agreement to what is reported by Castilla *et al.* (1979), also shows that food as a percentage of *C. concholepas'* weight ($\frac{FR_t}{W_t}$) always decreases, at rates that roughly match those of Castilla *et al.* (1979).

Since on day t = 1,000 a typical *C. concholepas* weigh W = 23 g, Figure 9 shows that total consumption of moist meat of fresh mussels at the cultivation center would be approximately 5.7 kg per day because at that time, a single *C. concholepas* consumes 0.13 g of mussel meat, and there are about 43,400 ind.

Table 2 shows a summary of the equations and the value of the parameters used for the estimates in the biological and technological submodels.

Economic results

Investments and reinvestments

The investments are organized in four groups based on their useful life and are shown in Table 3.

- Group 1 refers to the anchors.
- Group 2 contains long lines and their installation costs, and the plastic boxes with a protective mesh.

Each long line is 100 m in length, holds 20 ropes, that is, 20×3 = 60 boxes. Initially, 1,020/60 = 17 long lines are needed. After the doubling, 1,340/60 = 22 long lines are required (Table 3). Initially, 1,020 boxes are needed. After the doubling, in order to place 50 ind in each box, 1,340 boxes are needed (340 additional boxes) (Table 3). Due to the doubling, some investment is required several months after the beginning, but we assume that all of them will be made at the beginning to obtain discounts for large volumes in the purchase.

- Group 3 includes buoys and safety nets.
- Group 4 is the working capital.

Figure 10 shows the behavior of investments over time. It allows knowing the value of the investments at any time when the harvest could occur.

This moment will be defined later regarding the NPV estimations. Figure 10a shows how the stock of capital lose value due to the depreciation until a new investment increases the stock of capital, and this process is repeated successively over time. This figure shows the residual values of the investments at any time. From another point of view, the Figure 10b shows the cumulative balance of cash disbursements (payments) on investments, from t = 0 to the day indicated in the figure.

Recurring costs

Costs are classified into six groups, in accordance with the frequency of their occurrence (Table 4).

- Group A includes the lease of sea area (Government fees), and the market premium fees that have to be paid as rent for a sea area to another aquaculturist who possess that permission.
- Group B includes rent of offices and warehouses.

Table 3. Investments, in US$, on 1.3 ha of sea cultivation of *C. concholepas* (22 long lines). Source: Authors' estimates, based on interviews with experts.

Group	Item	Unit	Quantity for one long line	Quantity for 22 long lines	Unit value (US$)	22 long line value (US$)	Useful life (years)	Residual value (%)
G1	Anchors 250 kg	unit	6	132	123.34	16,281	20	0
G2	Rope long line 18 mm in diameter	m	215	4730	0.79	3,737	5	0
G2	Installation system service in sea	each	1	22	149.03	3,279	5	0
G2	Plastic boxes (40×40×60 cm)	each	60	1340	40.00	53,600	5	0
G3	Buoy 30 cm in diameter	each	12	264	7.66	2,022	1	0
G3	Buoy rope 6 mm in diameter	m	60	1320	0.09	119	1	0
G3	Safety net (black)	m2	60	1320	0.74	977	1	0
G4	Working capital	unit				2,840	Infinite	100
	Total					82,855		

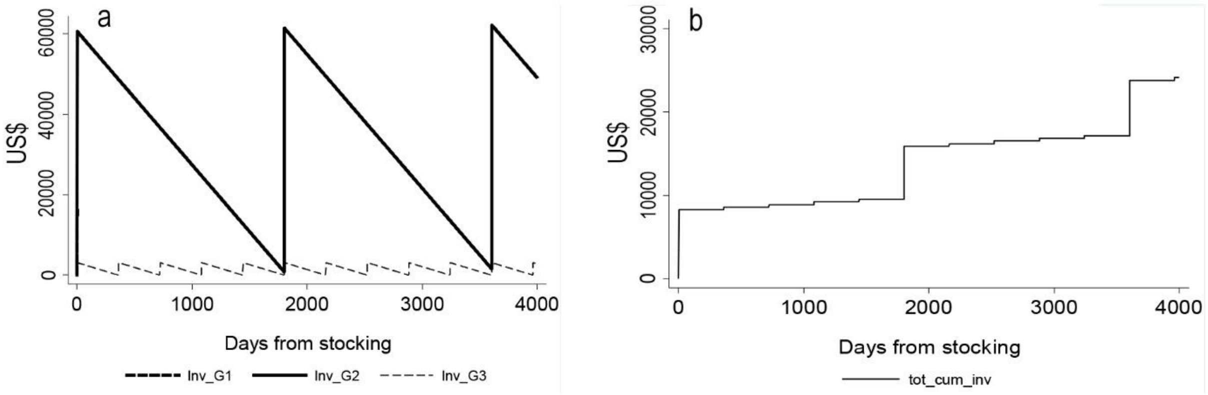

Figure 10. a) Capital stock (investments and reinvestments) of each group of investment through time (US$), b) trend of total cumulative investments (US$).

- Group C corresponds to salaries and administrative expenses. The security guard item corresponds to three guards in daily shifts of 8 hours each.
- Group D corresponds to all expenses related to the marine cultivation system, including feeding, cleaning, and operations.
- Group E corresponds to the acquisition of *C. concholepas* seeds (2.0-3.0 cm),
- Group F is the *C. concholepas* feeding cost, that is, the purchase of mussels' moist meat.

Figure 11 shows that the most important recurring costs are wages and administrative costs, the latter including a security guard on the site to prevent possible theft.

Concerning feeding costs (Group F), in Figure 11 we included the mussel requirements for the whole cohort. The market price of mussel, using the penalty price (established by the Chilean government to punish illegal captures), is 3.8 UTM (1 UTM is an inflation adjustable currency unit used in Chile, equivalent to around US$70) per ton. The price of fresh mussel with the shell is US$0.27 per kg with shell, around US$0.89 per kg of clean meat (30% yield). On this basis, the recurrent cost related to feeding varies daily following the biomass evolution. For the first years, the cost of food is as follows: year 1: US$1,214, year 2: US$1,735, year 3: US$1,863, year 4: US$1,746, year 5: US$1,515. On average, the annual feeding cost is of the order of US$1,615. Comparatively, it is a relatively low cost compared to the cost of the other groups (Fig. 11).

Harvested biomass and income

We reported the expected amount of biomass (soft tissue, without shell) to be harvested (Fig. 7). This quantity reaches its maximum approximately on day t = 1,400 and it is 1,059 kg. No differential price of sale per caliber is considered. Figure 12 shows the revenues from the harvest of the entire *C. concholepas* cohort as a function of harvest time.

Table 4. Annual operating costs, in US$, of 1.3 ha of sea cultivation of *C. concholepas*.

Group	Item	Unit	Frequency	Quantity for the frequency	Unitary cost (US$)	Total cost (US$)	Total yearly cost (US$)
A	Lease of sea area (Gov. fees)	ha	yearly begin	1.3	1,767.7	2,298.0	2,987.4
A	Lease of sea area	ha	yearly begin	1.3	883.9	1,149.0	1,493.7
B	Rent of offices & warehouses	monthly	monthly begin	1	528.6	528.6	6,343.3
C	Administrative expenses	monthly	monthly end	1	176.2	176.2	2,114.4
C	Manager salary	monthly	monthly end	1	881.0	881.0	10,572.0
C	Secretary salary	monthly	monthly end	1	616.7	616.7	7,400.5
C	Security guard	monthly	monthly end	3	596.1	1,788.3	21,459.6
D	Boat rent and fuel	hours per week	weekly begin	10	15.2	152.0	7,904.0
D	Operator salary	hours per week	weekly begin	8	8.8	70.5	3,665.0
D	Diver	hours per week	weekly begin	8	22.4	179.2	9,318.4
E	*C. concholepas* seed (2-3 cm)	unit	once per culture cycle	100,000	0.2	15,000.0	15,000.0
	Subtotal						88,258.3
F	*M. chilensis* wet meat (feed)	kg	Daily	varies daily	$0.89	varies daily	varies daily

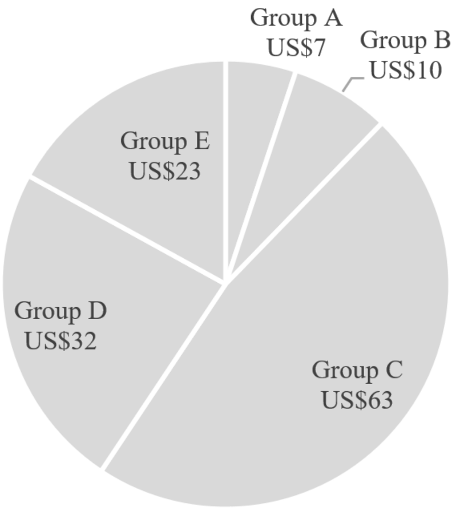

Figure 11. The total annual expenses (first year only, excluding feeding costs) distribution.

Figure 13 shows income and outlays as a function of harvest time. As an example, if harvest occurs on day t = 1,000, income would be US$20,544 (income is generated only at harvest time), cumulative investments would be US$89,091, and cumulative costs US$219,315. If harvest occurs on day t = 1,400, income = US$22,247, cumulative investments = US$92,209, and cumulative costs = US$299,486. The figure shows that costs and investments exceed by far the budgeted income, which appears in the lower line.

Net Present Value (NPV)

Figure 14 helps confirm what was reported in Figure 13, namely, that income is insufficient to cover either the investments or the costs required to set in motion the sea cultivation of *C. concholepas*. Indeed, the baseline model for day t = 1,000 produces a negative NPV of US$-183,393. However, if harvest occurs later, then the NPV is even more negative (on day t = 1,400, NPV = US$-198,179). Consequently, for the baseline model, there is no optimal harvest time.

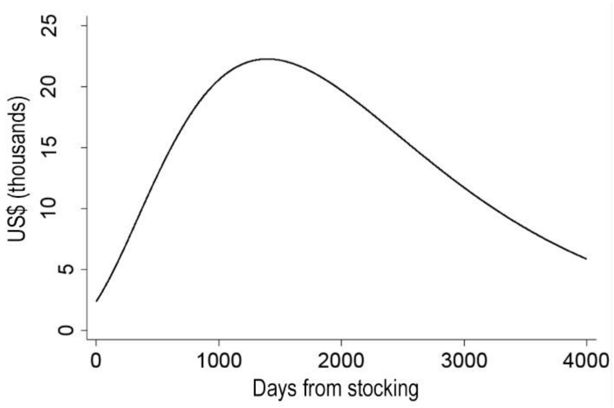

Figure 12. Income (US$), from the sale of *C. concholepas* biomass (soft tissue) as a function of harvest time, in days.

Sensitivity analysis

Figure 14 includes two sensitivity analyses, as we said in the methodology section.

a) In the first place, when recurrent costs are not included and harvest occurs on day t = 1,000, the NPV equals -81,616 US$ (on day t = 1,400, the NPV equals -83,882 US$). When only the investment are included (operating costs are excluded), the NPV declines over time but very slowly indicating that these costs are very relevant in the result (Fig. 14).

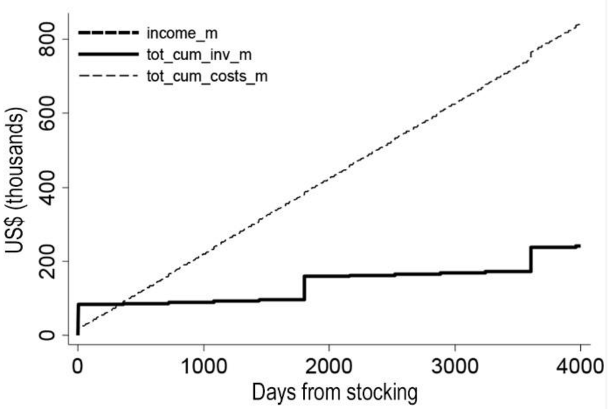

Figure 13. Income (US$), compared to recurrent costs and cumulative investments as a function of time. Recurrent costs include feeding costs.

b) On the other hand, when neither initial investments nor reinvestments are included, if harvest again occurs on day t = 1,000, the NPV equals -97,632 US$ (on day t = 1,400, the NPV equals -111,715 US$). NPV shows a behavior very similar to the NPV of the baseline model, although with a difference (distance) that increases gradually in the time (Fig. 14). The former implies that the operating costs mainly explain the form of the NPV baseline model.

Both analyses show that expected revenues fail to cover separately operating costs or the necessary investment. Then, we are quite far from the income to cover both items simultaneously.

Finally, compares the NPV for different selling prices of the *C. concholepas*. In the Figure 15, "NPV_baseline_m" refers to the results using the baseline price, of 21.0 US$ k^{-1}. Besides, "NPV_p_10" is the result when the baseline price is multiplied by 10, that is to say, US$ 210 k^{-1}. The same way for the others lines in the figure. This result shows that in the current conditions (the baseline model), for this culture to be profitable, the selling price would be required to be at least 630 US$ kg^{-1} (*cet. paribus*).

DISCUSSION

An attractive international price has made *C. concholepas* cultivation under controlled conditions a matter of permanent interest for research centers and government institutions in Chile. A relevant number of experimental studies aimed at *C. concholepas* fattening in artificial cultivation systems has been made recently in Chile (Castilla *et al*., 1979; Bustos *et al*., 1986; Lody, 2008, 2013; Stotz *et al*., 2000; Bustos & Navarrete, 2001). The results of these efforts seem to have been successful from a biological standpoint, in the sense that it was possible to grow the animals from seed to commercial size. This fact would make feasible the avoidance of the closed seasons and the capture size limitations, among other benefits. However, little is known about the economic viability of this type of cultivation. The experimental investigations provide information on the critical parameters, which would aid in the assessment of the monetary convenience of such an enterprise for a private investor, which was the primary goal of this investigation.

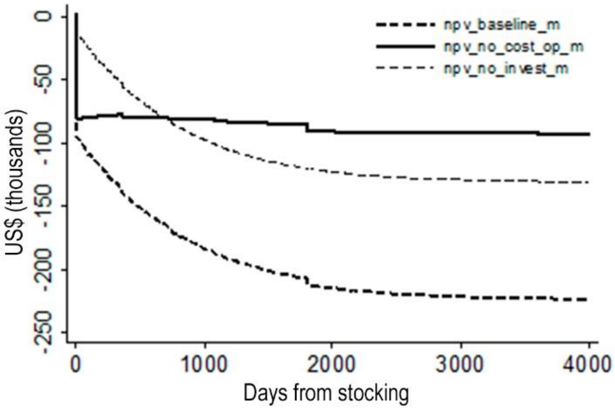

Figure 14. Net Present Value for the cultivation of a *C. concholepas* cohort, (US$), as a function of harvest time. NPV no cost op: It does not include recurrent costs. NPV no invest: It includes neither investments nor reinvestments.

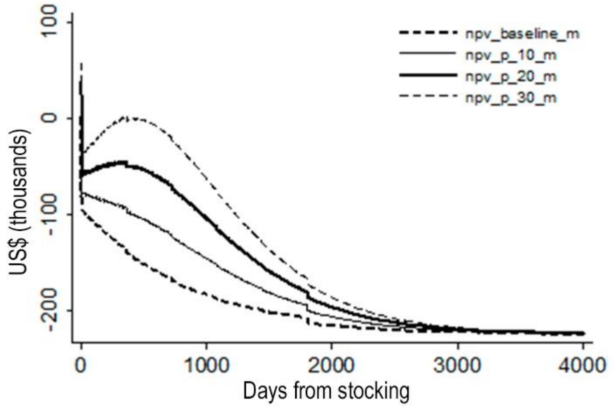

Figure 15. Net Present Value for various prices (US$) of *C. concholepas* cohort, as a function of harvest time.

Estimations of *C. concholepas* growth until harvest time under controlled conditions of cultivation are scarce (*e.g.*, Navarro & Torrijos, 1995; Bustos & Navarrete, 2001). However, there are some estimations of von Bertalanffy curves from natural loco populations. Growth estimates by Bustos *et al.* (1986), and Stotz (2000) exhibit results that are very similar to each other. The most conservative estimate is that of Stotz (2000) and concerns the species of the northern Chile.

As a reference at six years of age (2,160 days), Navarro & Torrijos (1995), Table 7 report lengths of 92.5 mm. For that same age, Stotz (2000) reports lengths between 80 and 130 mm. Bustos *et al.* (1986), Table 11 report 103.57 mm. Pérez & Stotz (1992) have studied the relationship between peristomal length Lt (in mm) and fresh individual total weight of soft tissue Wt (in g). For different locations in Chile, they obtained that the weight of soft tissue is on average close to 34% of total weight, including the shell (Pérez & Stotz, 1992, Fig. 5). Our growth estimates are based on the estimates of the cited studies and were reported in Table 2.

C. concholepas' survival varies across cultivation phases. Due to the lack of studies on the species survivability up to harvest time, it was concluded that it was superior to that of the Japanese abalone cultivated in Chile, a species on which there is plenty of information. Zúñiga (2010) used an annual survival rate of 32% for *Haliotis discus hannai* (annual mortality rate of 68%). Unlike abalones, *C. concholepas* it is a native endemic species in Chile, then it was assumed that could reach a survival rate of Z = 70% per year (mortality rate of 30% per year).

Regarding the technological submodel, the food of the *C. concholepas* consists mainly of live mussels (*M. chilensis*) bought at market prices. The size of these mussels is from 3 to 8 cm in length (Díaz *et al.*, 2011). Castilla *et al.* (1979) employed small mussels (*P. purpuratus*) of an average length of 20 mm, and they found that daily food consumption is in ranges on average from around 0.16% to 0.39% (as a percentage of the *C. concholepas'* weight). We use estimations of the ingestion rates when feeding with mussels (*M. chilensis*) from Navarro & Torrijos (1995). The food as a percentage of *C. concholepas'* weight decreases, as expected, at rates that roughly match those of Castilla *et al*. (1979).

The economic submodel shows that, under current circumstances, the cultivation is not attractive for a private investor. The main explanation of the negative economic result is that the projected earnings are, by far, less than the projected outlays. The main limitation is found not in the magnitude of the investments, but rather in the magnitude of the operating costs (Fig. 14). This result has important implications in order to consider more than one cohort and a larger scale of production. In our case, investments and fixed costs have a low relevance in the disbursements of the project. Then most of the production costs are almost constant in unitary terms (unitary variable cost of production almost constant) then increasing in the production scale would have a limited effect on the economic results. Then, increasing the scale of production is expected that generates a small impact on the final result.

On the other hand, to analyze if a higher number of cultivation lines would have a relevant impact on the result, we think it would be more appropriate to formulate a new model with that focus. However, our results suggest that given the low relative impact of investments, advantages can be obtained only up to extremely high production volumes. However, this will probably affect market prices, and new situations will arise that would lead to a different analysis. Furthermore, Véjar (2009) points out that it is difficult to project large production levels due to unfavorable experiences in controlled cultivation and the current knowledge about natural larvae capture.

Regarding different feeding systems for *C. concholepas*, the actual studies of feeding are based fundamentally on *M. chilensis*. There is a lack of reported experiences using food, performing better in cost-benefit. However, for now, this does not seem to be a key element, since our results indicate that the cost of feeding is much less important compared to other production costs.

Our simulations suggest that the *C. concholepas* selling price should be around 30 times the price considered in the baseline model (US$630 per kg) in order for the cultivation to become attractive, but the likelihood of this happening in the future is very slim. The prices of *C. concholepas* and red abalone show some stabilization and even an inevitable downward trend (Castilla *et al*., 2016), perhaps as a result that in Asian markets these mollusks are considered of inferior quality compared to the Japanese abalone (*Haliotis discus hannai*), see, for example, Gordon & Cook (2013).

Another element that affects cultivation profitability is the high costs of both, security and operation of the site, which translates into important requirements of labor (workers), also needed for everyday chores such as feeding, cleaning, and mending of the cultivation system. The results also show that the profitability of the project is strongly more affected by operational costs than by investments.

Finally, notwithstanding the negative recommendation of the results, it should be understood that this conclusion is valid only under the current state of the art, which translates into the specific parameter values employed here. Because of this, it cannot be ruled out that, in the future, new cultivation systems, cheaper alternative food supplies, for example, may make the cultivation of this species under controlled conditions a desirable option for a private investor. This endeavor must be accompanied with the development of techniques for a reduction in *C. concholepas* mortality rate and an increase in its growth rate.

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Appendix: Stella equations of the whole model.

```
Group_1(t) = Group_1(t - dt) + (Inv_G1 - Deprec_G1) * dt
INIT Group_1 = 0
Inv_G1 = pulse(16281, 1 , 360*20)*1
OUTFLOWS:
Deprec_G1 = 16281/(20*360)
Group_2(t) = Group_2(t - dt) + (Inv_G2 - Deprec_G2) * dt
INIT Group_2 = 0
Inv_G2 = pulse((3737+3279+53600), 1 ,360*5)
Deprec_G2 = (3737+3279+52800)/(5*360)
Group_3(t) = Group_3(t - dt) + (Inv_G3 - Deprec_G3) * dt
INIT Group_3 = 0
Inv_G3 = pulse( (2022+119+977)  , 1 ,360*1)
Deprec_G3 = (2022+119+977)/(1*360)
Group_4(t) = Group_4(t - dt) + (Inv_G4) * dt
INIT Group_4 = 0
Inv_G4 = pulse(2840 , 1 , 360*Duration_in_years)
Group_A(t) = Group_A(t - dt) + (Cost_A) * dt
INIT Group_A = 0
Cost_A = Pulse( 2298+1149 , 1 ,360)
Group_B(t) = Group_B(t - dt) + (Cost_B) * dt
INIT Group_B = 0
Cost_B = Pulse(528, 1 ,30)
Group_C(t) = Group_C(t - dt) + (Cost_C) * dt
INIT Group_C = 0
Cost_C = Pulse(176.2+881+616.7+1788.3 , 30 , 30)
Group_D(t) = Group_D(t - dt) + (Cost_D) * dt
INIT Group_D = 0
Cost_D = Pulse(152 + 70.5 + 179.2,  1, 7)
Group_E(t) = Group_E(t - dt) + (Cost_E) * dt
INIT Group_E = 0
Cost_E = Pulse(15000, 1 , 360*Duration_in_years)
Group_F(t) = Group_F(t - dt) + (Cost_F) * dt
INIT Group_F = 0
Cost_F = Pulse(FRT_in_kg*mussel_price, 0, 1)
Lt(t) = Lt(t - dt) + (growth) * dt
INIT Lt = Linf*(1-EXP(-g*360))
growth = g*(Linf-Lt)
Nt(t) = Nt(t - dt) + (- Zt) * dt
INIT Nt = 100000
Zt = 0.3/360*Nt
```

```
PV__Costs(t) = PV__Costs(t - dt) + (Cost_flow) * dt
INIT PV__Costs = 0
Cost_flow = Total_Costs*exp(-WACC*time)
PV__Invest(t) = PV__Invest(t - dt) + (Inv_flow) * dt
INIT PV__Invest = 0
Inv_flow = (Inv_G1+Inv_G2+Inv_G3+Inv_G4)*exp(-WACC*time)
Tot_Cum__Costs(t) = Tot_Cum__Costs(t - dt) + (TCC) * dt
INIT Tot_Cum__Costs = 0
TCC = Total_Costs
Tot_Cum__Invest(t) = Tot_Cum__Invest(t - dt) + (TCInv) * dt
INIT Tot_Cum__Invest = 0
TCInv = Total_Invest
Bt_in_kg = Nt*Wt_in_grams/1000
Duration_in_years = 10
FRT_in_kg = (0.02304*Wt_in_grams^0.56)*Nt/1000
FR_in_grams = 0.02304*Wt_in_grams^(0.56)
FR_in_milligrams = 0.02304*Wt_in_grams^(0.56)*1000
g = 0.27/365
Income = Bt_in_kg*loco_price
Linf = 108
loco_price = 21
mussel_price = 0.89
NPV_baseline =
 -PV__Invest+(PV_Income-PV__Costs)*(1-0.19)+0.19*Tot_deprec
NPV_no_cost_op = -PV__Invest+(PV_Income)*(1-0.19)+0.19*Tot_deprec
NPV_no_invest = (PV_Income-PV__Costs)*(1-0.19)+0.19*Tot_deprec*0
PV_Income = (Income)*exp(-WACC*time)
Total_Costs = Cost_A+Cost_B+Cost_C+Cost_D+Cost_E+Cost_F
Total_Invest = Inv_G1+Inv_G2+Inv_G3+Inv_G4
Tot_deprec = Deprec_G1+Deprec_G2+Deprec_G3
WACC = 0.50/360
Wt_in_grams = 0.00007*Lt^3
```