Performance differences between scallop culture in Peru and Chile:
a bio-economical modelling approach

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PART II - Manuscript

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Abstract

Peru and Chile cultivate the same scallop species (*Argopecten purpuratus*), the former sowed and spread over the seafloor, the latter using hanging cultures. While the Peruvian scallop farming has proliferated greatly over the past decade, the scallop cultivation in Chile has greatly decreased during the same period. In an attempt to understand these changes in production, we use a multidisciplinary modelling approach, combining biology and economy. Data on growth and mortality rates, harvest size and season, cultivation costs and scallop market prices at both places were assembled and this data was fed into a newly developed bio-economic model for both sites. Using this model, the profitability of the different modes of aquaculture in both countries were estimated and compared. Main differences between both places arise due to environmental as well as economic conditions. The faster growth of the scallops to market size and lower production costs in Peru and the high seed cost in Chile are the main causes of the performance differences in both countries.

1. INTRODUCTION

The scallop *Argopecten purpuratus* (Lamarck, 1819) (Peru: *Concha de Abanico*, Chile: *Ostión del norte*) can be found in the Southeast Pacific, in both tropical and subtropical zones, from northern Peru to central Chile (Wolff and Mendo 2000). Since the 1950's, scallops have been targeted by fishermen along the Peruvian and Chilean coast, from where, in the 1980's, cultivation of the species evolved (Valdivia and Benites 1984). This filter-feeding bivalve, belonging to the family of Pectinidae, has its two valves held tightly together with a central adductor muscle (Figure 1) and can use this to swim or expel material. The products of main interest for the fishery market are that adductor muscle and its gonad (also called ‘coral’) (Molina et al. 2012). The species can be found mostly on sedimentary substrates, in infralittoral zones from 5 to 30 m (Mincetur 2015; Kluger & Wolff 2013). The larval phase has a duration of about 30 days (Mendo et al. 2011) and a period of 12 to 18 months is needed to grow to the commercial size of 65 mm (Badjeck et al. 2009). The life trait characteristics of *A. purpuratus* are favourable for aquaculture purposes: they live long, grow rapidly to commercial size, reproduce throughout the whole year and have the possibilities for mass productions in hatcheries (Disalvo et al. 1984; Navarro and Gonzalez 1998).

The culture of *A. purpuratus* is widely spread in the Sechura Bay (Figure 2), northern part of Peru (Taylor et al. 2008). The species sustains important socio-economic activities for the local and regional economy, where the bay is home to many artisanal fishermen (Badjeck et al. 2009). The popularity of these scallops in the Sechura Bay can be explained by their natural abundance, the relative shallowness of the bay and a high temperature. The high productivity in the bay is caused by offshore Ekman transport along the coast, which induces a deep marine upwelling that brings cold, nutrient-rich water to the surface. Notwithstanding the upwelling, the summer water temperature in the bay is about 22°C, which is warmer compared to higher latitudes that experience the same phenomenon. This is because Peru is close to the equator and the Sechura Bay is positioned at the transition zone of the Humboldt Large Marine Ecosystem, where the transport of southern cold water stops and meets with the warmer waters from the northern tropical equatorial region (Bakun and Weeks 2008; Taylor et al. 2008). During the warm phase of the El Niño Southern Oscillation (ENSO), sea surface temperature (SST) rose to values higher than 25°C. In the Sechura Bay, such warmer phases can be disastrous for agriculture as well as for fishery and aquaculture (Taylor et al. 2008). However, in the south of the country, Independence Bay, *A. purpuratus* can benefit from an increased temperature, shortening the time to reach a size of 65 mm in 6 to 12 months (Badjeck et al. 2009).

Along Chile's extended coast, longshore wind currents also cause the effect of cold water upwelling due to offshore Ekman transport of coastal water. Bahía Vincente (37°S), close by Valparaiso, is the furthest point from the equator where extinct beds of this species can be found. Most important local natural beds are situated in the Tongoy Bay (Figure 2), in northern...
Chile (Wolff and Mendo 2000). This shallow sandy bay has an average depth of 25 m and an average temperature of 14.6°C, with a peak in the sea surface temperatures of 19°C during summer (Wolff 1994).

1.1 Aquaculture

There are two main methods used for culturing scallop, one being on-bottom and the other off-bottom (suspended). The advantage of the first method is the simplicity of stocking, whereby scallops can just be thrown on the seafloor from the boat and, of main importance, its lower production costs as only few equipment is needed like nets, mesh, corks and buoys (FAO 2015a). For the off-bottom culture, pearl nets are used for the grow-out of very small spat which, once big enough, are transferred into lantern nets, where stocking density is higher (Molina et al. 2012). Culturing off-bottom also has a number of advantages. Excrements are able to fall out more easily. The survival rate is higher because organisms are prevented from escaping and are safe from predation, which means less loss of the stock (FAO 2015a; Emerson et al. 1994). Suspended cultures have also better oxygen and nutrient conditions than the on-bottom cultures due to the nets’ position in the open water column. This suspended method is considered as the most profitable way in terms of monetary returns, although it needs a lot of investment, so it can take a while for profits to appear (Taylor et al. 2006). High production costs are thereby one of the biggest disadvantages of this method (FAO 2015a).

One of the main challenges to scallop aquaculture is to obtain young recruits, or “seed”, as starting stock for the molluscs. One method is the extraction from natural banks (Evans and Tveteras 2011), another is the natural collection of post-larvae. The latter is done by placing ‘collectors’ in the water column of areas where scallops occur naturally, whereby a hard substrate is provided for the floating larvae to settle on. This technique often returns variable yield given the variability of exogenous factors (weather, predators, etc). The last technique used is the production of larvae in laboratories (or hatcheries). With this method, obtaining seeds at a scheduled basis is possible, but very expensive (Mincetur 2015). On top of that, bacterial infections are often associated with failures in hatcheries and the consequent losses for the economy (Jorquera, Silva, and Riquelme 2001).

1.2 Modelling

A bio-economic model was developed to compare the scallop culturing in the two countries. Models are very useful tools to test different possible scenarios or future predictions and by combining ecological and economic aspects, a very rich model can be created without a remarkable increase in the complexity of the model (Drechsler et al. 2007). Nowadays, the use of models for management purposes is more and more of importance. Taylor et al. (2006) tried to determine differences in various scallop culturing methods by modelling a combination of
biological and economic aspects, based on scientific experiments. Later, other models were developed that fishermen could use themselves. Examples are FARM (Farm Aquaculture Resource Management) (Ferreira et al. 2007) or the MARKET model (Nobre et al. 2009). Molina et al., 2012, used a combination of biological, technological and economical parameters to build up a model to simulate and investigate farming activities in Chile.

1.3 Aim of the study

The aim of this study was to compare the two situations of cultivating scallops in Peru and in Chile using a dynamic, mechanistic simulation model. Both situations will be presented with their own specifications and one typical way of working, on-bottom for Peru and off-bottom for Chile. This division is made based on a common view of both locations. The main objectives were (i) to compare typical small-scale aquaculture operation profitability between on-bottom culture (Peru case) and off-bottom culture (Chile case); (ii) to compare various starting culture sizes in terms of seed; and (iii) to explore the effects of external environmental phenomena on the profitability of the industry.
2. MATERIALS AND METHODS

2.1  Socio-economic background

2.1.1  PERU

MARKET BACKGROUND

Export of Peruvian scallops is mostly oriented towards France (60%), the USA (22%) and Belgium (5%) (PRODUCE 2011). Harvests of the A. purpuratus increased from 7,732 t in 2002 to 93,050 t in 2011 and was still rising. In 2011, more than 50 % of aquaculture activities in Peru was dedicated to the scallop cultivation (PRODUCE 2012). Whereby a total export of frozen scallops produced in Peru, was good for 142,938 Million US$ in 2013 (PROMPERU 2014).

Increased interest in the scallops began in the south of Peru, in Independence Bay in Pisco, due to their high natural abundance, especially during El Niño events with increasing fishing effort as result (Badjeck et al. 2009; Wolff and Mendo 2000). The actual culturing of the bivalves started in 1979 in that same province (Valdivia and Benites 1984). After the activity decreased, some fishermen migrated to other favourable zones like Sechura. This was possible due to the open-access nature set by the General Fishing Law (GFL), in 1992, regulating the exploitation of fishery resources in Peru. According to this law, the fish production on the Peruvian coast and all other aquatic resources are state property (Res publica) and resources and fishing grounds are ‘open access’ (de-facto open access). Citizens can get rights on the usage of the fishing grounds through licenses or permits, which enables fishermen to migrate all over the coast as they are not bound by privatisation. But also many non-local Peruvian people joined the fishermen-community to grab a share of the pie, disregarding increased pressure on the ecosystem and the threat on the resources (Badjeck et al. 2009). In 2007, size limits, gear control, closed seasons, restricted areas and licenses/fishing permits were the main management tools mentioned for almost all types of fishery in Peru (Salas et al. 2007).

The scallop fishery development in the Sechura Bay really got off the ground in 1999-2000 due to favourable environmental conditions, development of (inter)national markets, the emission of the sanitary certificate for export to the European Union, and lower landings in the south of the country (Ysla et al. 2005). The practice employed a large part of the people in the scallop fishery sector of Piura (about 25 % of all people in working age) (INEI 2011). These practices are taking more than 145 km² of the bay in use for export purposes of their products (ITP-SANIPES 2012). In 2003–2004, 12 fishermen-associations were formally authorized by the government to develop aquaculture in the Sechura Bay. This led to an increased amount of fishermen who did not belong to such an association and involved into non-authorised practices (DIREPRO 2005). However, in time this got more organised and already 130 associations existed in 2012 (Correa 2015).

SCALLOP AQUACULTURE – METHOD

The most popular method of culturing scallops among the Peruvian fishermen in Sechura Bay is the bottom culture (Taylor et al. 2008). On an artisanal vessel with a length of 4 to 7 m, the fishermen go out several days to plant the scallops on their farming ground. This is done virtually at a single point by throwing the scallops into the water without a clear pattern (Mendo et al., 2011). Extraction of the resource is done by means of semi-autonomous diving, targeting mainly scallops over 65 mm size, according to the governmental limitations (IMARPE). Scallops in the Sechura Bay reach that size approximately after 1 year (Kluger and Wolff 2013). The scallops are collected by the diving fishermen and are counted per manojos, which are 96 individuals and are then sold per malla. Those are special nets containing, depending on the size of the scallops, two or three manojos. The products are then transported to the processing freezing plant, which is mainly operated by contracted services (Kluger and Wolff 2013).
**SEED COLLECTION**

Fishermen in Peru are mainly depending on the natural seed-stock which they extract from natural banks or buy from other fishermen (Evans and Tveteras 2011). Most of the seed is extracted from within the Sechura bay or from the island Isla Lobos de Tierra. Seed from hatcheries is not so popular among the associations of fishermen in Peru as it required a significant capital investment which is not feasible for most of the associations (Badjeck et al. 2009; Kluger and Wolff 2013).

2.1.2 CHILE

**MARKET BACKGROUND**

Export of Chilean scallops is mostly oriented towards the USA, to France and Spain. Minor market interests come from local and national parties (Molina et al. 2012). The whole market was good for an export of 11,365 t in 1996, almost a tenfold compared to 10 years earlier (Bourne 2000) and in 1999, more than 3,600 jobs were created directly or indirectly with those practices (Avendaño et al. 2001). In the northern parts of Chile, where cultivation occurs mostly, production increased to 24,697 t in 2004, followed by a decrease to only a total of 5,000 t in 2013, representing 88.23 % of the total mollusc catch for the whole northern part of Chile (SERNAPESCA 2009; SERNAPESCA 2013a).

The growth of the aquaculture industry in Chile started in 1982 in the Antofagasta and Coquimbo regions and later expanded further to, inter alia, the Atacama region (Molina et al. 2012). But it was after the fall of the dictatorship of Pinochet, that the interest in the scallops (and aquaculture) greatly increased, encouraged by the political and economical instability and an increased world demand (Lozano 2000; Barton and Fløysand 2010). The unstable environmental policy and the lack of a set-up of any protective measurements was shown by the over-exploitation of the natural banks. By 1994, the political character changed with the approval of the Environmental Law (Barton and Fløysand 2010). The regulations were implemented by the Undersecretariat of Fisheries of the Ministry of Economy and the National Fisheries Service controlled whether or not the law was being complied. There were no guidelines on how to run an aquaculture farm but the facility area has to be classified as an area, "adequate for the establishment of an aquaculture facility", whereby licenses, empowers the fishermen to manage their aquaculture production, making use of the whole water column and the surface area of the bottom (FAO 2015b; Bjørndal 2002).

**SCALLOP AQUACULTURE – METHOD**

Open water hanging cultures were most frequently used in Chile (Wolff 1994), partly by the a lack of adequate habitats for the scallops to inhabit or to set up cages on the sea bottom (Disalvo et al. 1984). The total cultivation phase is split in three different parts whereby two different types of net are used, pearl and lantern nets (Figure 3). The two types each have different mesh sizes and both are suspended a few meters under the water surface. This critical level will decide the light penetration and the amount of biofouling, but also the access possibilities of bottom dwelling predators (Leavitt et al. 2010). Pearl nets are used for the first growing stages of the juvenile scallops and have a stocking density of 30 - 50 % of surface cover for scallops smaller than 30 mm. Lantern nets, which cover the second grow out phases starting from 30 mm size, have a stocking density of 35 to 75 %. Later, stocking density in the final lanterns increases to 75 - 85 % upon harvesting at 75 mm. Harvesting is in normal conditions possible after 11 to 12 months (AECI/PADESPA and FONDEPES 2004). Pearl units and lantern units comprise each 7 to 10 levels per unit on top of each other (Figure 3). On one line, there is space for 990 pearl units and 99 lantern units (Molina et al. 2012). The diameter of a net is 50 cm and in between two units, one meter space is given for the currents to flow. Twenty meter in between the two lines enables the boat to manoeuvre (Taylor M., pers. comm.).
For many years, artisanal fishermen collected small entities of scallops that were growing on natural banks, occurring along the coast of Chile (Jorquera et al. 2001). However, the extraction of naturally occurring spat was a threat for the scallop population of the natural beds in Chile (Avendaño and Cantillánez 2008). In the '90s, other techniques were used by the Chilean fishermen to collect their seed: one was the natural collection with the floating collectors, copied from the Japanese, the other was by means of hatcheries in laboratory (Jorquera et al. 2001).

2.2 Setup of the model

Aquaculture practices have a certain impact on the natural as well as on the social environment for both the countries. Organic matter and oxygen within the water column will be used abundantly by the animals. On the other hand, the live scallops will produce huge amounts of excrements that will accumulate on the seafloor. The practice will also create a whole spectrum of employment. Much more people than the actual fishermen will be pulled in the practice and will benefit from the country’s natural resources, which will in turn benefit the local markets and cities. In Peru as well in Chile, the aquaculture of scallops took off when an export market was established (Barton and Fjøysand 2010; Ysla et al. 2005). In 2002, Peru and Chile contribute less than 1% of world production of scallops (Mincetur 2015). However, since 2009, increasing production of Peru is accompanied with decreasing production in Chile. This is remarkable, as they both cultivate the same species, and they both benefit from the favourable natural deep water upwelling along the coast. Still, total production of Peru was seventeen times higher in 2013 (PRODUCE 2012; SERNAPESCA 2013b). The aim of the model is to find out the possible reason(s) for the differences in performance of the cultivation of the A. purpuratus between Peru and Chile. The model will also be used to try optimising the farms.

The model deals with three main elements in accordance to Molina et al., 2012: (i) the ecological element, which includes the natural conditions of the grow out of the scallops; (ii) the economic element, which focuses on the investment, the costs and the profit; and (iii) the decision element, which determines the time schedule of the farm operation. The production cycle comprises all elements together. The ecological and economic elements are strongly intertwined during the production cycle while the decision element is only coming in play at the end of it, when the scallops are harvested.
Simulations start with the introduction of a new cohort of seeds and the investment costs comprising the purchase of seed. As time proceeds, animals grow in size and their density declines, while total costs accumulate according to a fixed yearly rate. Upon harvesting, the cumulative cost is compared to the monetary return of the harvest to find out the accumulated profit.

2.2.1 Data used and basic assumptions

The data used in the model was obtained from the literature (Table 1, 2 and 3). For Peru, most of it from the SASCA project, which stands for “Sustainability Analysis of Scallop Culture in Sechura bay (Peru)”, established by a cooperation between the Leibniz Center for Tropical Marine Ecology (ZMT) in Bremen, Germany and the National Agrarian University La Molina (UNALM) in Lima, Peru. The focus will be on one cultivation spot, or ‘lote’, of one fishery association (lote Nº109, 1km²). Data used for the Chilean model, was obtained from the paper published by Molina et al., 2012, which is mainly based on other experiments as well.

At the beginning of the production cycle, a starting size of the scallops is assumed. For juveniles, collected in the wild, an initial size of around 30 mm is used (Peru, Chile); when produced in the hatcheries (Chile), the initial size is 10 mm.

Many of the economic data were not simply available; therefore, to be able to compare certain factors, some of the input variables were used from the other country. Firstly, the social structure of the organization of the formal and informal fishermen in Sechura (Peru) is very complex (Kluger and Wolff 2013). It is therefore very difficult to incorporate all costs relating to one ‘lote’ or an area of 1 km². Boats are passed through one another within the association, therefore the cost for a boat to operate in one ‘lote’ only is unknown (Taylor M., pers. comm.). But a boat is needed for both countries to manage the farm and to be equally treated within the model, data for the boat is taken from the Chilean example and applied in Peru. A lot of information was also unknown for the Chilean case or not investigated yet. Costs for a guard to cover 1 km² were thereby taken from the Peruvian case to apply in the Chilean case.

Table 1: Biological parameters for Peru [1] (Mendo, 2011); [2] (Kluger and Wolff 2013); [3] (Wolff 1987) and for Chile (Molina et al. 2012).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Peru</th>
<th>Chile</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>K (growth parameter)</td>
<td>1.7764</td>
<td>0.565</td>
<td>year⁻¹</td>
</tr>
<tr>
<td>L∞ (infinite length)</td>
<td>95</td>
<td>110</td>
<td>mm</td>
</tr>
<tr>
<td>L₀ (starting length)</td>
<td>30</td>
<td>10</td>
<td>mm</td>
</tr>
<tr>
<td>a.add</td>
<td>8*10⁻⁶</td>
<td>8*10⁻⁶</td>
<td></td>
</tr>
<tr>
<td>b.add</td>
<td>3.2892</td>
<td>3.2892</td>
<td></td>
</tr>
<tr>
<td>Z (mortality rate)</td>
<td>0.4</td>
<td>0.6</td>
<td>year⁻¹</td>
</tr>
<tr>
<td>N₀ (initial seed)</td>
<td>2.88*10⁶</td>
<td>15.00*10⁶</td>
<td>ind</td>
</tr>
<tr>
<td>El Niño – K</td>
<td>2.1</td>
<td></td>
<td>year⁻¹</td>
</tr>
<tr>
<td>El Niño – L∞</td>
<td>111.5</td>
<td></td>
<td>mm</td>
</tr>
<tr>
<td>El Niño – Z</td>
<td>1.41</td>
<td></td>
<td>year⁻¹</td>
</tr>
</tbody>
</table>

2.2.2 Ecological element

The first element in the model, the ecological part, includes the growth and survival of the scallops. Growth is calculated with the von Bertalanffy growth equation (von Bertalanffy 1938) that expresses the increase in shell height as:

\[
\frac{dL}{dt} = K \times (L_\infty - L(t))
\]

where (L) is the length of the animal, here expressed as the height of the shell of the scallop (see Figure 1), unit [mm], t is time, with unit [years]. L∞ is the ultimate length of the individual and K is the von Bertalanffy growth rate [year⁻¹], which determines how fast the scallop reaches its L∞.
The number of individuals (N) decreases according to a constant mortality rate (Z) [year⁻¹].

\[
\frac{dN}{dt} = -Z \cdot N(t)
\]

The differential equations are initialised with the initial length and initial starting stock \(N_0\), unit [individuals]:

\[
L(t=0) = L_0; \quad N(t=0) = N_0.
\]

Weight, unit [kg ind⁻¹], is calculated from the shell height of the scallops according to the allometric relation:

\[
\text{Weight}(t) = \left(a \cdot \text{add} \cdot L(t)^{b \cdot \text{add}}\right)
\]

Whereby the parameters \(a\), \(add\), and \(b\), \(add\) (Mendo et al., 2011) are used to convert the height of the shells into grams of the adductor muscle plus its gonad.

Total biomass [kg] at each time point is eventually constructed from the previous equations:

\[
B(t) = \text{Weight}(t) \cdot N(t)
\]

Finally, a phi value, indicating the growth performance, is calculated encompassing the relation of infinite length and the growth rate (Pauly and Munro 1984):

\[
\varphi = \log(K) + 2 \cdot \log(L_\infty)
\]

### 2.2.3 Economic element

The second element of the model focuses on the total profit of the operation. The turnover equals the price per kilogram multiplied with the amount of scallops sold. The farmer has no impact on price-setting of the scallops. This implies that the farmer is only able to strive to a maximum yield by influencing the amount. All monetary values are converted into US$ as the US is an important export market for the scallops for both countries. The convert rates for the Peruvian Nuevo Sol (S/.) and the Chilean Peso (CL), used during the time of the study, are the following: 1 S/. = 0.32 US$ for Peru and 100 CL = 0.16 US$ for Chile (15.04.2015).

Price at which the scallops are sold differs depending on the size of the singular scallop or on the amount of scallops that sum up to a weight of one kilogram. Based on Mendo et al., 2011, the price function is given by:

\[
\text{price} = b \ast \text{ind}^a
\]

where \(b\) equals 38.28 and \(a\) equals -0.366 and where \(\text{price}\) describes the price per kilogram and \(\text{ind}\) the number of individual scallops (muscle + gonad) per kilogram.

The optimum setup of a farm is at a production where Total Profit is maximum. The maximum revenue minus the minimum costs gives the maximum profit. Total costs can be split into two main categories, Total Input Costs (TIC) and Total Operation Costs (TOC). The structure of “Profit and Loss Accounts” (Bossier 2013), which is a tool to look how well the business is performing, is used to conduct the calculation of the profit over a set period of time. First, to calculate the Gross Profit (GP), the turnover, which is usually just the total sales (TS), but may include the change in valuation of the bivalve stock, is subtracted by the TIC, which represents the cost of sales such as the purchase of a certain amount of seed (S/) according to its price (CS). This variable may also include the purchase of food, chemicals... everything which enables the animals to survive and grow. The calculations are as follow:

\[
TS = \text{price} \ast \text{biomass}
\]

\[
GP = TS - \text{TIC}
\]
In Peru, the cost for the seed is depending on the area of exploitation. When seed is obtained from the Island Lobos de Tierra, they have a size of 30-40 mm. Although they are more expensive, the culture time is shorter and their mortality rate is lower, except for the stress of the transport from the island to the farm. When scallops are obtained from the bay, they have a size of 10-20 mm. According to the law, seed is only allowed to be taken from within the bay, but this is not always obeyed (Kluger and Wolff 2013).

Next component in the economic part of the model is the operating expenses which appear when running an aquaculture farm. Costs may include depreciation of equipment or other investments in materials, wages, maintenance... A summary of the cost of sales and the operating costs can be found in Table 2 for Peru and Table 3 for Chile. Operation Expenses included in the Peruvian model are the costs for materials (CM), which are very small and go mostly to the nets for the mallas which they use during harvesting and are put under that category instead. Other expenses include the costs for maintenance (mtC), such as the disposal of predators, repairing nets... In Peru, this cost is very small and is expressed in a constant value, independent of the size of the farm and the guard (GC), which is needed day and night to prevent the stealing of the scallops. For Peru, the biggest operation cost made is the cost for harvesting the stock (H). As these costs only appear once at the end of a cultivation cycle, they are only put in force at that specific moment. The costs include salary for the employees, hiring extra madrina boats, fuel for the boat and generator for the air compression and other additional costs that comes together with the harvest of the scallops. See Figure 4 for the relationship of the operation expenses with the amount of scallops cultivated.

Table 2: Technical parameters used in the model for Peru. Data from [1] (Kluger & Wolff, 2013); [2] (Mendo et al., 2011); [3] (Sanchez, unpublished data); [4] (Molina et al., 2012).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Peru</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of Sales</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seed</td>
<td>Si [1]</td>
<td>2.88*10^6 ind used in lote N°109 (1 km²)</td>
</tr>
<tr>
<td></td>
<td>CS [1]</td>
<td>0.0047 $ ind⁻¹</td>
</tr>
<tr>
<td></td>
<td>10-20 mm CS [2]</td>
<td>0.012 $ ind⁻¹</td>
</tr>
<tr>
<td></td>
<td>30-40 mm</td>
<td></td>
</tr>
<tr>
<td>Operating Expenses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Guardian</td>
<td>GC [2]</td>
<td>15,129.6 $ yr⁻¹ km⁻²</td>
</tr>
<tr>
<td>Maintenance costs</td>
<td>mtC [3]</td>
<td>2,750.72 $ yr⁻¹ per km⁻²</td>
</tr>
<tr>
<td>Harvest costs</td>
<td>H [3]</td>
<td>0.01408 $ ind⁻¹</td>
</tr>
<tr>
<td>Materials (mallas)</td>
<td>CM [1]</td>
<td>0.002 $ ind⁻¹</td>
</tr>
<tr>
<td>Boat</td>
<td>CB [4]</td>
<td>12,800 $ km⁻²</td>
</tr>
</tbody>
</table>

For the Chilean model, equipment cost for the off-bottom culturing is based on the total cultivated area (TCA), which is calculated from the amount of scallops cultivated (TSC) and the surface that they are taking in the nets (density is taken into account for every different phase and size of the scallops, D1-D4, see section 2.1.2. It is expressed as the percentage cover of the surface of the nets). Then, based on the size of one lantern level area (LLA) and the amount of units stacked on top of each other, the area of one whole unit is calculated, followed by the total amount of pearl nets and lantern nets (NUnit) needed and their cost (UC). The amount of Lines (NLi), used for hanging the nets on, and the costs (LiC) are calculated following the same method. Depreciation is taken into account for the investment in equipment whereby the cost is spread over the expected life period of the materials. The nets have a life span of four years, so one fourth of the purchase price is put into account annually. The boat (BC) has a life span of five years (Molina et al. 2012). The maintenance costs are expressed in terms of the amount of lines (OL) used and the salary one employer receives per year (ES), taken into account the amount of lines one employer can take care of (EW).
Table 3: Technical parameters used in the model for Chile. Data from (Molina et al., 2012); [2] (Mendo et al., 2011); [3] (AECI/PADESPA and FONDEPES 2004); [4] (Taylor M., pers. comm.).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Chile</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of Sales</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seed</td>
<td>Si</td>
<td>$15 \times 10^6$ ind</td>
</tr>
<tr>
<td></td>
<td>CS</td>
<td>0.024 $ind^{-1}$</td>
</tr>
<tr>
<td>Operating Expenses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pearl net</td>
<td>NPLi</td>
<td>990 units line$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>pP</td>
<td>10 $unit^{-1}$</td>
</tr>
<tr>
<td>Lantern net</td>
<td>NULi</td>
<td>99 units line$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>pU</td>
<td>20 $unit^{-1}$</td>
</tr>
<tr>
<td></td>
<td>SU</td>
<td>1 m</td>
</tr>
<tr>
<td>Diameter nets</td>
<td>d</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Density stocking</td>
<td>D1</td>
<td>30 % cover</td>
</tr>
<tr>
<td></td>
<td>D2</td>
<td>50 % cover</td>
</tr>
<tr>
<td></td>
<td>D3</td>
<td>65 % cover</td>
</tr>
<tr>
<td></td>
<td>D4</td>
<td>80 % cover</td>
</tr>
<tr>
<td>Line for holding nets</td>
<td>pLi</td>
<td>334 $line^{-1}$</td>
</tr>
<tr>
<td></td>
<td>SL</td>
<td>20 m</td>
</tr>
<tr>
<td>Guardian</td>
<td>GC</td>
<td>15,129.6 $yr^{-1} km^{-2}$</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Employer salary</td>
<td>ES</td>
</tr>
<tr>
<td></td>
<td>Employer workforce</td>
<td>EW</td>
</tr>
<tr>
<td>Boat</td>
<td>pB</td>
<td>12,800 $</td>
</tr>
<tr>
<td></td>
<td>BO</td>
<td>1768 $boat^{-1} yr^{-1}$</td>
</tr>
</tbody>
</table>

All this information is collected in a differential equation which expresses the cumulative cost as:

\[
\frac{d\text{Cost}}{dt} = OE
\]

\[
\text{Cost}(t = 0) = TIC
\]

\[
TOC_{\text{Peru}} = \text{Cost}(t = H) + dHC
\]

\[
TOC_{\text{Chile}} = \text{Cost}(t = H) + dCM
\]

Where \(OE\) are the constant Operational Expenses expressed per year; \(TIC\) is the initial cost at the start of every new culturing cycle, comprising investment, replacement and seedlings; \(dHC\) is the cost of harvesting in Peru and \(dCM\) is the cost for materials in Chile, both terms are depending on the amount of individuals harvested.

Profit is calculated out of the previous calculations: the total costs are subtracted from the monetary return of harvesting.

\[
\text{Profit} = TS - TOC
\]

A farm is running in Profit when the value of outputs is greater than the value of inputs, otherwise a Loss is made.

2.2.4 Decision element

The third and last element is the act of harvesting. To sell the scallops, they have to have a height of at least 65 mm according to the law, whereby harvest is done mostly after 12 to 18 months (Badjeck et al. 2009). As the price per scallop increases with scallop size, it is more profitable to sell at a larger size; however, as total density will continue to decrease, there will exist a certain optimal time of harvest beyond which profit will decline.

In the first part of the results, the focus will be on growth, mortality and cost differences, using comparable variables. The next part will simulate scenarios including the pearl-net seed
grow-out for Chile and a different number of cohorts for each country per year. The profitability of each system will be compared using the values of the Internal Rate of Return (IRR), based on the Net Present Value (NPV). Within each scenario, the elasticity of a certain parameter will be investigated in terms of its effect on the IRR. The principle of the NPV (Nagalingam 1999) is as follows: the inflow/outflow of cash in the future is discounted back to its present value with regard to a certain discount rate:

$$NPV(i, N) = \sum_{t=0}^{N} \frac{C_t}{(1 + r)^t}$$

Where \( C_t \) is the cash flow at time \( t \), \( r \) the discount rate, \( t \) the time the cash flow \([\text{yr}^{-1}]\) and \( N \) the number of years of the investment. The IRR (Mian 2011) is a measure to compare the profitability of the investment. It is the interest value for which the NPV is zero. A project will be more worthwhile if the IRR is higher. A sensitivity analysis is carried out on several parameters, increasing and decreasing the parameter with 10%, to find out its effect on the IRR.

2.3 Using R

The programming language R (R Core Team 2014) was used to create the model. The state variables in the model are: scallop size, density and integrated costs of the scallop culturing. The differential equations are solved with the use of the R-package deSolve (Soetaert et al., 2010). The package uses a number of numerical methods, which are suitable to solve the complex differential equations. Numerical solutions are preferred over analytical solutions as they can be applied to more complex models, and are more flexible (Soetaert and Herman 2009). The aquaculture model is mostly continuous as one cohort grows continuous in time, but it includes several discontinuous events, occurring at selected times. For instance, harvesting can occur when profit is at its maximum, or when organisms reach a favourable size. For that, events and roots are implemented in the differential equation model. The harvest-event, acting on the system, cannot be specified in advance as it does not occur at a predefined time, but rather at the time of maximal profit. Thus, locating the time of the event is part of the solution. To inform the model function of a triggered event, a root function is defined, and the event occurs at the root.

2.4 Parameterisation

Aquaculture space and amount of waste production is limited and need to be accounted for when striving for a realistic model. To account for the capacity of the cultivated area, an extra term was added to the growth equation. This carrying capacity equation calculates the space occupied by the scallops over the culturing area that is available for them to grow:

$$\frac{dL}{dt} = k \cdot (L_\infty - L(t)) \cdot \left(1 - \frac{N(t) \pi \left(\frac{L(t)}{2}\right)^2}{KC}\right)$$

\( KC \) is the Carrying Capacity, the total surface area available, unit [mm²] represented by lote N°109, which has an area of 1 km² and which is the example wherefrom the data for inter alia the starting stock of Peru is used (Kluger and Wolff 2013). In Chile, the stock is split at a certain time or with a certain frequency when scallops reach a non-optimal biomass (Molina et al. 2012). Therefore, the KC-formulation is not implemented in Chile, but rather the amount of nets and lines that is used to keep the scallops within the optimal biomass; it is assumed that the number of nets is such that only a certain percentage of total surface area is covered, according to their grow-out phase (see section 2.1.2). At a certain point in time, the total surface area covered by living animals decreases. Within the model, the number of nets and lines is then kept at its maximum, assuming that they don’t sell their equipment again after buying them. More time is needed to correctly incorporate the actual way of working.
Whether some costs are varying with the amount of scallops cultivated or not was investigated with the use of a data set gathered in the Sechura Bay in Peru. From Figure 4 it is clear that the maintenance cost is independent from the amount of individuals, whereas the harvest cost is definitely depending on it with a significant value of 99.98%. Per individual to harvest, it cost 0.014 US$.

3. RESULTS

The reader should be aware, the model is preliminary and features some large uncertainties. So the outcome should only be used for relative comparison, as absolute values may not be reliable.

3.1 Ecological element

With the growing conditions in Peru the commercial size of 65 mm was achieved after five and a half months, using a starting seed size of 30 mm, while in Chile it took a whole year. After one year, Peruvian scallops had a size of 84 mm and starting with a stock of 2.88 million scallops, almost 2.5 million of them survived, which is 85%. In Chile, 1.5 million of them survived, representing 53% of the initial stock. The phi value was 4.2 for Peru and 3.8 for Chile. Results with El Niño growth parameters for Peru increased the phi value to 4.4. The size of 65 mm was already reached after 4 months, while after one year, they were 100 mm high.

3.2 Economic element

Figure 5 shows that Peru had a higher profit after one year of cultivation than Chile. Chilean sea farms had an initial investment cost of 69,120 US$ for a stock of 2.88 million of seed, while Peru only paid 13,440 US$. The operation expenses to cultivate this amount of seed was 87,000 US$ for Chile and merely 20,000 US$ for Peru. The Gross Profit that the Peruvian fishermen received was 383,500 US$ for scallops of average 83 mm after 12 months. Taking into account the operation expenses, the fishermen still had 329,300 US$ left. The Chilean fishermen received no positive return after one year, which was when the scallops were 53 mm of height. Using the growth conditions of Peru in the Chilean model, a Total Profit of more than 1 million US$ was achieved after 12 months, at a height of 80 mm (Figure 8). Vice versa, putting the growth conditions that appear in Chile in the Peruvian model, Total Profit was 36,000 US$ after 12 months, at a height of 64 mm (starting with 30 mm). During El Niño environmental conditions, Total Profit for Peru increased to 275,000 US$ after one year for scallops of 101 mm. Maximum profit already appeared after 10 months. Difference in total profit decreased when starting stock of both cases were 30 mm (Figure 6) and even more for equal seed prices (Figure 7).
Figure 5: Model output for the two models (Peru & Chile) combined. L = Length (shell height) [mm], N = Number of scallop stock [ind], C = Cost for operating [US$], Weight [kg/ind], Biomass [kg], Total Sales [US$], Total Agriculture Area [km²], Gross Profit – Total Operation Cost – Total Profit [US$].

Figure 6: Model output with the two models combined with when starting size of the seed equals 30 mm. L = Length (shell height) [mm], N = Number of scallop stock [ind], C = Cost for operating [US$], Weight [kg/ind], Biomass [kg], Total Sales [US$], Total Agriculture Area [km²], Gross Profit – Total Operation Cost – Total Profit [US$].
Figure 8: Model output when using the suspended method also for the Peruvian case. L = Length (shell height) [mm], N = Number of scallop stock [ind], C = Cost for operating [US$], Weight [kg/ind], Biomass [kg], Total Sales [US$], Total Agriculture Area [km²], Gross Profit – Total Operation Cost – Total Profit [US$].
3.3 Decision element

The scallops in Peru were 83 mm height after one year, while in Chile, they were only 53 mm, which was still below the legal size of selling (Table 4). For both countries, maximum biomass and maximum profit were close to each other. Table 5 shows the IRR for both countries and the impact of certain parameters. Peru had an overall higher IRR than Chile. In Peru, the most influential parameters were the relationship of the price and the scallop its size and the purchase of the seed. In Chile, the mortality rate had the highest influence followed by the sales and purchase of the scallops. The growth constant has definitely an impact in both countries.

Table 4: Result of decision-dependable output

<table>
<thead>
<tr>
<th>Moment of harvest</th>
<th>Peru</th>
<th>Chile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Height (mm)</td>
<td>Total Profit (mill US $)</td>
</tr>
<tr>
<td>65 mm</td>
<td>65</td>
<td>0.084</td>
</tr>
<tr>
<td>1 year</td>
<td>83</td>
<td>0.314</td>
</tr>
<tr>
<td>Max Biomass</td>
<td>90</td>
<td>0.427</td>
</tr>
<tr>
<td>Max Profit</td>
<td>91</td>
<td>0.433</td>
</tr>
</tbody>
</table>

Table 5: Sensitivity analysis on limited parameters and its effect on the IRR. (H = Moment of harvesting)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\text{IRR}_{\text{Peru}}$ (%)</th>
<th>$\text{IRR}_{\text{Chile}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H = 1 year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal</td>
<td>503</td>
<td>19</td>
</tr>
<tr>
<td>Price for sales</td>
<td>565</td>
<td>25</td>
</tr>
<tr>
<td>Z</td>
<td>514</td>
<td>26</td>
</tr>
<tr>
<td>K</td>
<td>564</td>
<td>31</td>
</tr>
<tr>
<td>Guard</td>
<td>511</td>
<td>19</td>
</tr>
<tr>
<td>Maintenance</td>
<td>505</td>
<td>19</td>
</tr>
<tr>
<td>Price seed</td>
<td>517</td>
<td>24</td>
</tr>
</tbody>
</table>

4. DISCUSSION

4.1 Comparison of model with reality

The scallop production in Peru was 91,474 t in 2013, while in Chile, it was only 5,001 t (PRODUCE 2015; SERNAPESCA 2013b). A Peruvian fisherman in Sechura, in the year 2013, who cultivated an area off 1 km², had a production of 2.4 million scallops with a size between 65 and 70 mm, which returned a Gross Profit of 407,000 US$ and a Total Profit of 312,200 US$ (Kluger and Wolff 2013). When running the model with the growth and mortality conditions of Sechura Bay in Peru (Figure 5), a total amount of 2 million scallops were ready for harvest after 12 months, whereby they would have an average harvest size of 84 mm. Legal harvesting size of 65 mm is reached after 5.5 months. This shows the high productivity of the Sechura Bay. During El Niño events the commercial size was reached at an even shorter period. Even within some assumptions concerning costs and scallop mortality, total profit for a Peruvian fisherman was estimated at 314,343 US$ by the model (Table 4). This is quite close to the real case data.

A parameter which has significant impact on the outcome is the mortality rate (see also Table 5). For on-bottom cultures, the main cause of mortality is predation by gastropods, sea stars, crustaceans and fishes. This especially holds for juvenile scallops smaller than 35 mm;
therefore mortality impact could be alleviated when the Peruvian fishermen would keep the 
juvenile scallops in nurseries, until they reach the size threshold for direct predation (Leavitt et 
al. 2010). As this would imply a certain investment cost, further investigation is needed whether 
this way of working would be effective or not. The mortality parameter used in the model came 
from experiments where the scallops were put in cages, protected from bigger predators. An 
increase in the mortality rate was expected for scallops grown without any protection. However, 
this was not the case. An average mortality of 2.5-3.5% per month was estimated by the 
Peruvian iPrisco aquaculture company, which returns a Z value quite close to the experimental 
one. This is due to the fact that predation is still present in lantern nets. It occurs when larvae 
of small crabs enter in between the scallops during their planktonic life stage whereas larger crabs 
are getting on top of the nets and destroy them (Disalvo et al. 1984).

The growth constant also had a significant impact on the whole operation (see Table 5). 
However, these values cannot be taken purely since they are connected with the parameter of 
the infinite length. Therefore the phi value is an interesting parameter to compare systems and 
the growth conditions of the environment. Still, there is clearly an influence which shows that 
this is something worth investigating further.

Complete case data of Chile was lacking. However, starting stock, environmental 
conditions and operation cost are suggested by Molina et al. 2012 (Table 1 & 3). Starting from 
these parameters, a production of 8 million scallops of average 53 mm height were modelled 
after one year making a negative total profit of -218,977 US$ (see Table 4). After two years of 
growing the same cohort, 4.5 million scallops of average 78 mm height were modelled, making a 
total profit of 176,479 US$ (see Figure 5). This latter suggests the need of a later harvest in Chile 
(section 4.2). The contrast between Peru and Chile has several causes. At first, there is a large 
difference in seed price, whereby the Chilean sea farms have a much higher initial investment 
cost. The starting size of seed is also smaller in Chile (10 vs. 30 mm in Peru), additionally 
prolonging the culture period (and related costs). On top of that, Chilean fishermen have to pay 
more to keep the operation running as a suspended culture is more expensive than the on-
bottom method. Environmental growth condition aren’t as optimal in Chile either.

4.2 Harvest time and revenue

Making the optimal choice of harvest time can be seen from two perspectives. One is 
seen from a fisherman, the other from the point of view of an investor. For a single fisherman, it 
is important how much work he has to do for a certain amount of money. The investor on the 
other hand, wants to know how much his money will pay and whether other investments could 
provide better revenue. This is particularly important when the investment cost are high as the 
investor has to bring up that money to start the production. Suspended cultures have a higher 
investment price, making it is only possible for people with a certain capital to enter the 
business. This implies also that the fishermen, who are maintaining all the nets are only 
employers from the investor. In contrast, for on-bottom cultures, fishermen can more easily be 
the investors himself, enhancing self-sustainability (Taylor M., pers. comm.). The investment 
cost used is based on the purchase of seedlings. For a stock of 2.88 million scallops, a fishermen 
in Peru has to pay 13,440 US$, while in Chile one has to pay 69,120 US$. On top of that, it takes 
longer for profit to appear in Chile and the nets require a certain amount of maintenance cost, 
which isn't present for the on-bottom culture (as usually no nets are used/applied). Most of the 
maintenance work is due to fouling organisms growing on the nets. They cause a limited food 
supply to scallops as they are also filter feeders, which feed on the same food as the scallops do 
(Leavitt et al. 2010). As a result, the cost is higher for Chile. However, the occupied area of the 
on-bottom culture is much higher so that more costs need to be made for guarding the bivalves 
in the Peruvian case. This results in a maintenance cost per scallop about 1.5 times higher for 
Peru when compared to Chile.

It is difficult to compare the two culture systems when their time frame is not the same. 
In Peru, large profits maybe already appear after one year and in Chile only after two years. 
Therefore, in Figure 9, total profit is presented as an annual value assuming a harvest cycle of a
vast period of time (x-axes). For the case of Peru, maximum profit appears when harvesting 1 year after seeding. This returns 311,000 US$ per year for a starting stock of 2.88 million scallops (Figure 9 a). For the same starting stock size, cultivated in Chile, maximum profit of only 19,400 US$ per year is found when harvest is done after 2.4 years (Figure 9 c). However the peak is much less distinct here. Harvesting after 2 years would return about 16,300 US$ per year, which is not that much different. For an investor it is interesting to compare the revenue with the interest that would be acquired if the money would be put on the bank or another investment. The yearly interest follows the same pattern as the yearly profit curve (Figure 9 a-b & c-d). For Peru, the maximum interest is around 500 % for harvest after one year and for Chile 24 % after 2.4 years (Figure 9 b & d). It is thus considerably better to harvest later in Chile than in Peru. However, this implies a certain risk for the whole operation with an increased chance on failure of the cohort due to for instance environment catastrophes or negative evolution in the external or internal market.

Spawning of the A. purpuratus takes place throughout the year, although two mass spawning events occur during spring and summer (Wolff 1983). This implies that it might be better for the fishermen to set up a regular seeding and harvest of yearly cycles. The exact moment for the fishermen to harvest is normally based on an empirical decision of the fishermen themselves, preferably during the maturation of the gonads, when the quality of the meat is best. The gonad will look full, inflated, turgid and with a red or deep orange colouration (Mendo et al., 2011). For the model, harvest of the Peruvian scallops was done after one year after Kluger & Wolff, 2013. Although decision moments in the Chilean case were even more unknown, a period of 2 years was chosen, because profits were still negative after one year. Figure 10 represents a total profit model for multiple cohorts during 4 years whereby Peruvian fishermen would harvest after 1 year and Chilean after 2 years.

Figure 9: Model output for the Total Profit per year [US$] for every moment of harvesting (a: Peru; c: Chile) and the yearly interest for that moment (b: Peru; d: Chile).
Biomass peaks in both countries have an offset in comparison with their profit peaks, of 1.5 months in Peru and 4 months in Chile. The reason for that is the fact that larger scallops are worth more than smaller ones and the larger that difference, the more profitable it is for the fishermen to wait for harvesting. Therefore, the peak offset in Peru is smaller, as the scallops grow faster and start with larger seed. When applying a function of which prices for the scallops would have less differences between the smaller individuals and the bigger ones, the lag of the two peaks even diminishes.

A sensitivity analysis on the price that fishermen would get for their scallops shows a significant impact on the monetary success of the farm (Table 5). Ideally, maximum biomass and market prices merge in a maximum profit. In practice though, the only variable that can be managed by the fisherman is the density. Other variables, such as the size at harvesting after one year and the market price at a certain period or the effect of El Niño, are defined by environmental or external market conditions. Although this may also be an indication to carefully pick out the location of the farm. Pre-investigation of the natural conditions may be useful.

![Figure 10](image-url)

**Figure 10:** Multi-cohort simulation of 4 years: a. Peru with a starting stock of 2.88 million scallops, harvesting each 1 year; b. Chile with a starting stock of 15 million scallops, harvest each 2 years

### 4.3 Optimisation

The second part for which the model can be used, is to optimise the scallop production and its profitability. The ideal harvest is one that gives the maximum benefit. This means that one can get maximum profits in a sustainable manner based on maximum biomass production of a crop and market prices. Sometimes, when a practice is done for many years, you see that local fishermen can be close to the ideal, as is seen in the Peruvian case.

When Chile would grow their scallops in better environmental conditions, like they appear in Peru, maximum profit already appears after 17 months instead of 29. When they would start with a seed size of 30 mm (Figure 6), less costs would be made as no pearl nets would be necessarily and less time would pass upon harvesting, implying less material cost and less loss of stock. After 1 year, profit would be 71,000 US$. The fact that Chilean fishermen mainly use seed of 10 mm size is because they are depending on seed production in hatchery/laboratories. In the area of Sechura (Peru), a high natural stock is present, while in Chile, natural stock of scallops is much lower. Efforts are made by the Chilean government to create a protective spawning area where seed would be able to be collected by means of the Japanese collectors. Unfortunately, the area suffers from environmental variability and illegal harvesting (Avendaño and Cantillán 2008). The use of hatcheries creates a possibility for the fishermen to grow enough seed as well, but unfortunately, the price for the seed then increases. Effort is put in prevention methods to deal with big losses of spat in hatcheries due to bacteria
present in seawater. Although a lot of these methods have disadvantages wherefore governmental institutions need to put restrictions in to prevent harmful effects on the consumers. An effective and economically attractive alternative that showed positive results in disinfecting culture water is the use of electrolytic release (Jorquera et al. 2001). All this results in a price which is ten times as high as the Peruvians pay for their seed. A run with the model, for which Peruvian prices are applied for the Chilean case, shows that total profit in Chile would increase to 72,000 US$ after one year and 443,000 US$ after two years (Figure 7). Also the IRR showed an important influence by an increase of the seed price (see Table 5).

Interesting to see is what would happen if the fishermen in Sechura (Peru) would start an off-bottom cultivation, using nets. Figure 8 shows the Chilean model, but with the growth and mortality conditions of Peru and with the starting conditions of the suspended method, including its cost. Maximum biomass of the scallops is reached twice as fast as in Chile and also, the Peruvian fishermen would get a total profit of more than 1 million US$ after one year, using the suspended method. However, the process whereby the cohort are split, as is done with the suspended method (Molina et al. 2012), is much more complex than is represented here in this study. Batches are split three times from pearl net to initial lantern net to final lantern net. Besides that, they are also separated in fast growing scallops and slower growing encouraging a better growth. With this process, also a lot of material is in the running or is stored in a warehouse when there is no need for. Further research is needed to test how this would affect the model outcome.

Another important limiting factor for the size of the farm, with regard to the amount of individuals per unit area, is the effect a culture can have on the environment. At too high biomass, food and or oxygen may become scarce creating higher mortalities within the stock and reduce growth and muscle weight. Experiments to derive at which growth of the scallops is optimal result in an initial stocking size of 30 ind/m² (Mendo et al. 2011). For suspended cultures, the planning of the different densities is much more complex (AECI/PADESPA and FONDEPES 2004). Which density is used, is also determining how big the area of cultivation will be. In the output of the model, it is clear that an on-bottom culture takes much more space than the suspended culture (fifty times more according to the model). This has an influence on for instance the payment of the guardian (see section 4.2) or on the administrative cost for occupying parts of the sea bottom. Besides, on-bottom cultures, whereby the scallops can move freely, do not favour higher densities as the swimming activity will increase and a wider area will be taken in by the bivalves themselves (Leavitt et al. 2010). In enclosed structures, scallops can harm each other’s mantle by clapping their shells trying to move or expel materials, also known as the ‘biting disease’.

Further research is needed to investigate the carrying capacity of the two places, the import and export of nutrients, the circulation... It is worthwhile to note that the model developed here is solved numerically, and the economic part is also written as a differential equation. This is in contrast to the typical bio-economical modelling practice which originated in spreadsheet, and that uses analytical solutions of simplified equations. Due to the way the model is built and solved, additional parts like direct interactions with the environment can be merged with the existing parts quite easily.

From an economic point of view, optimising the farm requires some additional information to calculate for instance the marginal cost and revenue of the last produced unit, whereby the farm strives to reach to the point where both terms are equal (pers. comm. Prof. Dr. ir. Stijn Steelman). This means that the farms’ production will increase until profits don’t continue to rise anymore, which is the point where marginal costs exceed the marginal revenue. The profitability of each system can be compared for a multiple year simulation with different number of cohorts being introduced based on the values of the Net Present Value (NPV) and the Internal Rate of Return (IRR). An estimate is made for the two cases within their normal conditions whereby an IRR was calculated at 503 % (Peru) and 19 % (Chile), showing again the better situation of Peru (see Table 5). However, due to time constraints in this work, only a preliminary implementation of the IRR could be done, so these numbers may still change. The specific parameters, used in this model, are sometimes not that straightforward to find in the
literature. Ideally, a sensitivity analysis should be conducted based on the range of the different values of the equivalent parameters.

4.4 Social structure

Many people are directly or indirectly dependent on the scallops. Already in the 1950's, artisanal fishermen would collect small quantities from natural banks (Valdivia and Benites 1984; Jorquera, Silva, and Riquelme 2001). Natural disasters are therefore a real threat to many fishermen. In 2011 a catastrophic earthquake in Japan triggered a massive tsunami that even reached the East-Pacific coast, causing, according to local Chilean fishermen, a loss of 50 to 100 percent of total scallop production (Abramovich 2011). Many structures which held juvenile scallops were destroyed. These were put in the water to try and increase the production as wild catches were over-exploiting the natural stocks (Navarro and Gonzalez 1998).

The low material costs for on-bottom cultures imply a very low threshold to enter the business in Peru. While in Chile a high investment cost is only attracting those people who are capable of investing. This creates another relationship between the fisherman and the farming activities in both countries, where more fishermen own the farms in Chile. In both countries informal activities played also a role. For example illegal fishing or for the case of Peru where those activities were an important aspect of the social structure of the fishing activity in 2002 (Kluger and Wolff 2013). Not only is this difficult to have an overview of the cultivation activity in social and biological perspectives, in terms of how many people are involved, how much scallops are really harvested/extracted. But it also forms a challenge to create a constructive management plan in which all additional stakeholders are integrated. For both countries, aquaculture represents a welcome alternative enabling much more people to work in a certain area. However, this increases the stress on the environment of the bays and the limits to the carrying capacity of the ecosystem. A significant increase of the activities within the Sechura Bay and the rest of the country during the last few years, caused the price to drop from 15 US$/kg in 2006 to only 8.30 US$/kg in 2011, according to Franklin Munoz, from the Chilean Sacmar shellfish company: “The price of Peruvian scallops is kept low thanks to a cheaper labour force and better sea conditions for raising the shellfish” (Abramovich 2011). This interaction is important to follow up as the price has a large influence on the outcome of the model (see section 4.2). Peru has a major export market in Europe and interest may still increase with the implementation of certificates based on sustainable aquaculture operations. In March 2015, AcuaPesca Group, a Peruvian scallop producer, was the first company in the world to receive a certification for scallop production by the Aquaculture Stewardship Council (ASC), which indicates that their farms, of which some are situated in the Sechura Bay, are environmentally friendly and socially responsible (UndercurrentNews 2015).

5. CONCLUSION AND RECOMMENDATIONS

The overall better growth conditions in Peru are an important factor for the difference in performance of the production of scallops. However, this is nothing Chile could change. A second important point is the price for scallop seed. Further research is needed to find a solution for that problem as wild stocks will stay very limited and hatcheries are the only reasonable solution if Chile wants to increase its production. For both countries, the market price determines the economic value of the species and has a significant impact on the return of the whole operation, e.g. on harvest size and time. Although Chile is having a hard time to keep up with Peru, even with the higher investment costs, the suspended culture seems to be more profitable according to the model, and the area of cultivation is much smaller, i.e. more organisms can be cultured in an area. It is therefore important that the possible impact on the environment is investigated in further detail. The higher costs will of course only attract people capable of investing, and even when it is creating a large employment, the low budget system in Peru and its large production will make it more difficult for the Chilean fishermen to compete.
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References


Salas, Silvia, Ratana Chuenpagdee, Juan Carlos Seijo, and Anthony Charles. 2007. “Challenges in the Assessment and Management of Small-Scale Fisheries in Latin America and the Caribbean.” *Fisheries Research* 87: 5–16.


Appendix – R-script

# Model for Scallop culture in Peru,
# Implementation: Sieme Bossier, 01-06-2015
# Karline Soetaert

# require(deSolve) # R-package to solve differential equations

Scallops <- function(t, state, parameters){
  with (as.list(c(state,parameters)),{
    dL <- K*(Linf-L)*(1-((N*pi*((L/2)^2))/KC)) # [mm]
    dN <- -Z*N # [ind]
    weight <- (a.add * L^b.add)/1000 # [kg ind-1]
    biom <- weight*N # [kg]
    ind <- 1/weight # [ind kg-1]
    price <- 38.28*(PO/weight)^-0.366 # [$ kg-1]

    # TURNOVER - Total sales
    TS <- price*biom # [$]

    # Total investment cost
    TIC <- CS*Si

    # Operation expenses - maintenance,harvest,equipment
    TAA <- N0/Nlote # [km²] Total Agriculture Area
    OE <- (GC*TAA) + (pB*0.20) + (mtC*TAA) # [$ yr-1]
    DC <- OE # [$]
    HC <- (H+CM)*N # [$] depending on the varying amount of individuals
    TOC <- C + HC # [$] = Cost + one time cost made when harvesting

    # Gross profit = turnover - cost of sales
    GP <- TS - TIC # [$]

    # Total profit
    profit <- TS - TOC # [$]

    return (list(c(dL,dN,DC),
                  Weight = weight,
                  Biomass = biom,
                  Operation_Expenses=OE,
                  Total_Sales = TS,
                  Gross_Profit = GP,
                  Total_Profit = profit))
  })
}

# Specify the parameters
parameters <- c(K = 1.776449186, # [yr-1] Growth rate; 2.1 for El Nino;
                Linf = 95, # [mm] Assymtotic length; 11.5 for El Nino
                Z = 0.4, # [yr-1] Exponential mortality rate; 1.41 for El Nino
                a.add = 8E-6, # Allometric coeff for adductor muscle
                b.add = 3.2892, # Allometric coeff for adductor muscle
                CS = 5000, # $ per kg
                PO = 200, # $ per kg
                GC = 50, # $ per kg
                pB = 0.02, # $ per kg
                mtC = 0.01, # $ per kg
                Si = 5000000 # $ per kg
)
\[ CM = \frac{0.48}{240}, \quad \text{Cost for materials, price original per malla} \]
\[ Si = 2.88e6, \quad \text{Initial amount of seed} \]
\[ GS = \frac{1.12}{240}, \quad \text{Seed cost, price original per malla} \]
\[ N\text{note} = 2.88e6, \quad \text{value used to calculate the area of cultivation} \]
\[ N0 = 2.88e6, \quad \text{value used to calculate the area of cultivation} \]
\[ GC = 1260.8*12, \quad \text{Guardian Cost} \]
\[ pB = 12800, \quad \text{Price boat (life duration of boat = 5 years)} \]
\[ mtC = 8596*0.32, \quad \text{Maintenance costs} \]
\[ H = 0.044*0.32, \quad \text{Harvest cost} \]
\[ PO = 0.45359237, \quad \text{Pound-kg converter} \]
\[ KC = 1e12 \quad \text{Carrying capacity} \]

# Specify the initial conditions
\[ \text{state} \leftarrow \text{c}(L = 30, \quad \text{Initial scallop size} \]
\[ N = 2.88e6, \quad \text{Scallop starting number} \]
\[ C = 13440) \quad \text{Investment cost (purchase of seed)} \]

# Specify the timespan used
\[ \text{outtimes} \leftarrow \text{seq}(0,4,\text{length.out}=100) \]

# Solve the equation
\[ \text{out} \leftarrow \text{ode}(\text{state,outtimes,Scallops,parameters}) \]

# EVENT - MOMENT OF HARVEST
\[ H \leftarrow 26 \quad \text{time of harvesting} \]
\[ \text{rootf} \leftarrow \text{function(t,y,parameters)} \{ \quad \text{trigger at time of harvesting (H) is reached in the model} \]
\[ \text{return(t-outtimes[H])} \}

\[ \text{eventf} \leftarrow \text{function(t,y,parameters)}\{ \quad \text{defining the changes that come with the event} \]
\[ \text{with (as.list(c(y,parameters))},\{ \quad \text{with (as.list(c(y,parameters))},\{ \]
\[ \text{return(y <- state)} \}
\}

# Solve the equation with the calculations of the trigger incorporated
\[ \text{outH} \leftarrow \text{ode}(\text{state,outtimes,Scallops,parameters, method = "radau"}, \]
\[ \text{events = list(func=eventf,root=TRUE),} \]
\[ \text{rootfunc = rootf}) \]

# PLOT GRAPHS
\[ \text{plot(out,outH,xlab="Time (year)", mfrow = c(3, 3))} \]
\[ \text{abline(h=0)} \]
\[ \text{plot(0, type = "n", xlab = ", ylab = ", axes = FALSE)} \]
\[ \text{legend(x = "center", col = 1:2, lty = 1, legend = c("no ", "yes"), title = "harvest")} \]
# ==============================  
# MULTIPLE COHORTS  
# ==============================  

```
# at what point in the out-sequence is the profit max
opt <- H

out1 <- out[1:opt]  # out is shortened to the time constrain until Harvest is reached
out2 <- out1

out2[,1] <- out1[,1] + opt
out2[,"Total_Profit"] <- out1[,"Total_Profit"] + (out1[nrow(out1),"Total_Profit"] - out1[1,"Total_Profit"])

out3 <- out2

out3[,1] <- out2[,1] + opt
out3[,"Total_Profit"] <- out2[,"Total_Profit"] + (out2[nrow(out2),"Total_Profit"] - out2[1,"Total_Profit"])

out4 <- out3

out4[,1] <- out3[,1] + opt
out4[,"Total_Profit"] <- out3[,"Total_Profit"] + (out3[nrow(out3),"Total_Profit"] - out3[1,"Total_Profit"])

outx <- rbind(out1,out2,out3,out4)

optx <- out[,"Total_Profit"][outtimes[opt]]

outtimesx <- seq(0,(outtimes[opt]*4),length.out= (opt)*4)

plot(outtimesx,outx[,"Total_Profit"],xlab="Time (year)",ylab="Total Profit (US$)", mrow = c(1, 1))
abline(h=0)
```

# npv & IRR - from Marc Taylor

```
V <- 26  # variable to change moment easily

# function to calculate the NPV, according to a set discount rate
npv <- function(net, time, discountRate=0.02){ cumsum(net/(1+discountRate)^time) }

# calculate the
revenue <- rep(0, V); revenue[V] <- out[V,"TotalSales"]
costs <- diff(c(0,out[1:V,"TOC"]))
net <- revenue-costs

time <- outtimes[1:V]  # the time period
npvt <- npv(net, time, 0.05)  # calculate NPV with the cash flow calculated,

# over a period of time, with a set discount rate

plot(time, cumsum(net), t="l")
abline(h=0, col=8, lwd=3)
lines(time, npvt, lty=2, col=4)
```
# the IRR function that loops through a range of discount rates to find the one, which returns a NPV of zero or close to zero

```r
irr.opt <- function(state, outtimes, Scallops, parameters, int = c(0, 20)){
  FUN <- function(discountRate = 0.05){
    out <- ode(state, outtimes, Scallops, parameters)
    revenue <- rep(0, V); revenue[V] <- out[V,"TotalSales"]
    costs <- diff(c(0, out[1:V,"TOC"]))
    net <- revenue - costs
    time <- outtimes[1:V]
    npvt <- npv(net, time, discountRate)
    (0 - npvt[length(npvt)])^2
  }
  opt <- optimize(f = FUN, interval = int)
  opt
}

# execute the function and find the value for the lowest NPV
irr.tmp <- irr.opt(state, outtimes, Scallops, parameters, int = c(0, 20))
irr.tmp$min
```
Model for Scallop culture in Chile, Implementation: Sieme Bossier, 01-06-2015
Karline Soetaert

```r
require(deSolve) # R-package to solve differential equations

Unit <- 1 # Tool to count the amount of units in the running
Line <- 1 # Tool to count the amount of lines in the running
Scallops <- function(t, state, parameters){
  with (as.list(c(state,parameters)),{
    dL <- K*(Linf-L) # [m] Growth
    dN <- -Z*N # [m] Number of starting seed
    W <- (a.add * L^b.add)/1000 # [kg ind-1] Weight of one scallop
    B <- W*N # [kg] Biomass
    ind <- 1/W # [ind kg-1]
    price <- 38.28*(PO/W)^-0.366 # [$ kg-1]
    # Total sales - Turnover
    TS <- price*B # [$]

    # Operation expenses - maintenance, harvest, equipment
    # calculation of the amount of space taken by the scallops
    LLA <- pi*(d/2)^2 # [m²] Lantern Level Area = pi*radius
    UA <- LLA*10 # [m²] Unit Area = area taken by one unit (10 lantern levels)
    TSA <- pi*((L/(2*1000))/2)^2*N # [m²] Total Scallop Area = area taken by the scallops
    # small spat need other net
    if (L<20){
      TCA <- TSA/D1 # [m²] Total Culture Area = area taken by pearl or lantern nets
    } else if ((L>20)&(L<30)){
      TCA <- TSA/D2
    } else if ((L>30)&(L<40)){
      TCA <- TSA/D3
    } else TCA <- TSA/D4

    # calculation of the amount of nets and lines needed based on the amount of scallops cultivated
    NUnit <- round(TCA/UA) # Number of Units (pearl or lanterns)
    Unit <<- max(Unit,NUnit) # Hold on to the maximum amount of units
    if (L<30) UC <- Unit*pP*0.25 # [$ yr-1] Units Cost pearls (with depreciation)
    else UC <- Unit*pU*0.25 # [$ yr-1] Units Cost lanterns (with depreciation)
    if (L<30) NLI <- round(TCA/(UA*NPli)) # Number of Lines; 990 pearl units per line
    else NLI <- round(TCA/(UA*NULi)) # Number of Lines; 99 units per line
    Line <<- max(Line,NLI) # Hold on to the maximum amount of lines
    LiC <- (Line * pLi)*0.25 # [$ yr-1] line Cost (with depreciation)
    TAA <- ((d+SU)*NULi)*((d+SL)*NLI)/1e6 # [km²] Total Agriculture Area = the total area
    # of the sea that the farm is taking
    BC <- (1*pB)*0.20 # [$ yr-1] cost boat (with depreciation)
    OL <- (NLI/EW)*ES # [$ yr-1] Operation costs lines
    OB <- 1 * BO # [$ yr-1] Operation costs boat
    GC <- GC*TAA # [$ yr-1 km-2]

    # Total investment cost
    TIC <- CS*Si
  })
```

V
# Total operation cost

OE <- GC + (pB*0.20) + OL + OB  # [$ yr^{-1}]
dC <- OE  # [$]
CM <- UC + LiC  # [$]
TOC <- C + CM  # [$]  = Cost + one time cost made when harvesting

# Gross profit = turnover - cost of sales

GP <- TS - TIC  # [$]

# Total profit

profit <- TS - TOC  # [$]

return(list(c(dL,dN,dC),
            Weight = W,
            Biomass = B,
            Total_Sales = TS,
            Total_Scallop_Area = TSA,
            Total_Culture_Area=TCA,
            Total_Agriculture_Area=TAA,
            Total_Operation_Cost=TOC,
            Gross_Profit = GP,
            Total_Profit = profit))

#specify the parameters and the initial conditions

parameters <- c(K = 0.565,  # [yr^{-1}]  Growth rate
                Linf = 110,  # [mm] Assymptotic length
                Z = 0.6,  # [yr^{-1}] Exponential mortality term
                a.add = 8E-6,  # Allometric coeff for adductor
                b.add = 3.2892,  # Allometric coeff for adductor
                d = 0.5,  # [m] Diameter lantern net
                D0 = 0.4,  # Density cover pearl
                D1 = 0.3,  # Density cover lantern
                D2 = 0.5,  # Density cover lantern
                D3 = 0.65,  # Density cover lantern
                D4 = 0.8,  # Density cover lantern
                Si = 15e6,  # [ind] Initial starting seed
                NULi = 99,  # [units line^{-1}] Amount of units per line
                NPLi = 990,  # [units line^{-1}] Amount of pearl units per line
                pU = 20,  # [$ unit^{-1}] Price units of lantern nets
                pP = 10,  # [$ unit^{-1}] Price units of pearl nets
                pLi = 334,  # [$ line^{-1}] Price line
                CS = 0.024,  # [$ ind^{-1}] Cost seed
                ES = 8320,  # [$ person^{-1} yr^{-1}]  
                EW = 35,  # [lines person^{-1}]
                pB = 12800,  # [$ boat^{-1}]  Price boat
                BO = 1768,  # [$ boat^{-1} yr^{-1}]
                GC = 1260.8*12,  # [$ yr^{-1} km^{-2}] Guardian cost
                PO = 0.45359237,  # Pound-kg converter
                SU = 1,  # [m] Space between two units
                SL = 20)  # [m] Space between two lines
# Specify the initial conditions
state <- c(L = 10, # [mm]
    N = 15e6, # [ind km^-2]
    C = 360000) # [$]

# Specify the timespan used
outtimes <- seq(0,4,length.out=100)

# Solve the equation
out <- ode(state,outtimes,Scallops,parameters)

# EVENT - MOMENT OF HARVEST
H <- 51 # time of harvesting
rootf <- function(t,y,parameters) {
    return(t-outtimes[H])
}

eventf <- function(t,y,parameters) {
    with (as.list(c(y,parameters)),{
        sc <- Scallops(t,y,parameters)
        y <- state
        Unit <<- 1
        Line <<- 1
        return(y)
    })
}

# Solve the equation with the calculations of the trigger incorporated
outH <- ode(state,outtimes,Scallops,parameters, method = "radau",
    events = list(func=eventf,root=TRUE),
    rootfunc = rootf)

# PLOT GRAPHS
plot(out,outH, xlab="Time (year)", mfrow = c(3, 3))
abline(h=0)
plot(0, type = "n", xlab = "", ylab = "", axes = FALSE)
legend(x = "center", col = 1:2, lty = 1, legend = c("no ", "yes"), title = "harvest")

# MULTIPLE COHORTS
# NPV & IRR - from Marc Taylor
Same as the model for Peru