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Revisiting the economic profitability of giant kelp *Macrocystis pyrifera* (Ochrophyta) cultivation in Chile

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ABSTRACT

The demand for seaweed biomass for hydrocolloid industries and novel products for the food, pharmaceutical, cosmetics and agro-industry has been steadily increasing during the last decade. This trend is expected to continue into the future as new uses are discover and the ever-increasing human population needs for healthy products and clean energy expand beyond land-based resources. Seaweed farming still faces constraints for its development and one of them is its economic profitability as in general the seaweed biomass has a rather low value with few exceptions of some species used for human consumption. Therefore, there is a need to increase production of seaweed biomass, but there is still a lack of realistic economic assessments that determine the economic potentiality of a seaweed farming project to attract investors. This article reports an economic model, fed with data of a pre-commercial *Macrocystis pyrifera* 21-ha pilot farm installed in southern Chile. The economic sensitivity analysis revealed that cultivation of *M. pyrifera* in southern Chile is profitable in a 10-ha cultivation system when the market price is at least US$ 87 wet t^{-1} and yields are kept at a minimum of 12.4 kg m^{-1}. We discuss the potential that seaweed cultivation has in Chile and we agree with previous studies that value, productivity and the farming model used are key factors for the economic success of seaweed farming.

1. Introduction

World aquaculture production reached 30.1 million tons (US$ 11.7 billion) on 2016, including *Spirulina* spp. and other aquatic plants, which contribute only with the 2% of the total production (FAO, 2018). The bulk of worldwide seaweed production comes from aquaculture, with China and Indonesia as the leading producers landing 86.6% of total biomass in 2016 (FAO, 2018). On the other hand, wild harvest seaweed only accounted for 4.2% of the total biomass landings in 2014, being in this case China and Chile the leading producers with 417.331 wet tons (WT) and 245.550 WT, respectively (Buschman et al., 2017). According to the FAO (2018), Chile is located in the 12th place of world aquaculture producers, but its contribution comes mainly from salmon and trout farming, and only a reduced proportion correspond to seaweeds (i.e. *Gracilaria chilensis* with 26.413 WT in 2016; Sernapesca, 2017). The high dependency of Chile from seaweeds obtained from wild stands seems to be progressively changing, as new policies for the incentive of cultivation and repopulation of seaweeds was approved in 2016 and started its implementation in 2017 (Law N°20.925, Republic of Chile). This new regulatory framework, together with the fact that the cultivation at open ocean of several species has being developed indicates that the basic technologies for a seaweed-based Chilean aquaculture development are available (Buschmann et al., 2008; Camus et al., 2018b). Regarding red seaweeds, commercial cultivation of *Gracilaria chilensis* started in the late 1980´s in Chile (Buschmann et al., 1995) and since then, hatchery cultivation and deployment of juvenile plants on seeded lines or nets has been demonstrated for different species of *Gelidium* (Santelices, 1987), *Gigartina skottsbergii* (Romo et al., 2006; Westermeier et al., 2012; Buschmann et al., 1999, 2001), *Sarcothalia crispata* (Ávila et al., 1999; Romo et al., 2001), *Callophyllis variegata* (Hernández-González et al., 2010; Ávila et al., 2014), and *Chondrachanthus chamissoi* (Bulboa et al., 2005; Bulboa and Macchiavello, 2006). This evidence demonstrates the technical feasibility of sea farming for several economically important red seaweeds in Chile. In the case of brown seaweeds, cultivation has been demonstrated for *Lessonia trabeculata* (Westermeier et al., 2006) and *Macrocystis pyrifera* (Westermeier et al., 2006, 2011; Gutiérrez et al., 2006; Macchiavello et al., 2010; Correa et al., 2016; Camus et al., 2018a). Also, a focus has been placed on restoration of kelps beds (*L. berteroana* and *Macrocystis pyrifera*) using holdfast fragmentation techniques (Westermeier et al., 2014, 2016), seeding substrata that can be installed in natural kelp stands (Vásquez et al., 2014) and inoculation of spores

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in the intertidal (Vásquez and Tala, 1995). Despite the existence of several cultivation studies, few have address real conditions at commercial scale, resulting in a limiting factor to consolidate solid strategies for commercial applications. Particularly, open-ocean cultivation of *M. pyrifera* in Chile started with experimental systems composed of a few 100 m lines, seeded either with free-floating plants or rope-seeded plants at the north and south of the country, reaching between 14 and 66 kg m^{-1} (Westermeier et al., 2011; Gutiérrez et al., 2006; Correa et al., 2016; Macchiavello et al., 2010). Nonetheless, some of the yield values have been obtained through extrapolation of individual sporophyte biomass, explaining the high variability of the yield reported. As the basis for this work, data from 3-year production cycles of a pre-commercial, 21-ha scale kelp farm installed in southern Chile was used as a bases for this work, yielding an average of 124 WMT ha^{-1} $year^{-1}$ (Camus et al., 2018a).

In the context of biomass production, *Macrocystis pyrifera* is the world's largest seaweed, with the fastest elongation rate record for any terrestrial or marine autotroph (Reed et al., 2008). Kelp chemical composition is variable in time and space, but in general a high amount of carbohydrates (e.g. alginate, mannitol, fucoidans), together with proteins and bioactive molecules (e.g. phloroglucinol, fucoxanthin) can be obtained from kelp biomass (Ortiz et al., 2009; Holdt and Kraan, 2011), making this resource attractive for the industry. Worldwide, kelp has an economic demand as human food, for alginate production, and recently for the introduction in new products of agrochemicals, feed, and cosmeceutical industries (Wells et al., 2017; Hafting et al., 2015). In Chile, beside the exploitation of kelp for alginate production, it is also used to feed abalones, an industry that produced 1.276 WT in 2016 (Sernapesca, 2017) and which per capita consumption rate of fresh algae can vary from 15% to 30% of daily weight (Uki and Watanabe, 1992). The demand of wild biomass of *M. pyrifera* and *Lessonia* spp. in Chile has already caused deterioration of kelp populations, and new regulations are restricting kelp harvesting along the Chilean coast (i.e. extractive ban, Subpesca, 2017).

Considering the particular scenario for Chilean seaweed aquaculture development, and the fact that there is not enough information published about economic models to run a seaweed farm in the western world, Correa et al. (2016) and Zuñiga-Jara et al. (2016) report studies of the economic feasibility of nearshore commercial cultivation of the giant kelp as feed for abalone production in southern and northern Chile. Correa et al. (2016) based their economic model assuming a biomass production of 41.3 kg (wet) m^{-1} $year^{-1}$ considering two harvests a year. Their sensitivity analysis revealed that with a market value of US$ 78 t^{-1}, cultivating 30–50 ha could make a return on investment after the first year. However, when reducing the cultivated area to 10 ha and maintaining the productivity, there is no return of investment in a 10-year term. This study concluded that, present kelp prices in Chile are not sufficient to support culture systems on a scale below 30 ha, suggesting that an optimization of the culture system is required, defining optimal environmental conditions of the selected sites of cultivation in order to maximize the yield of the farms.

On the other side, Zuñiga-Jara et al. (2016) reported that the cultivation of *M. pyrifera* in northern Chile is not profitable in the long term. Only in a scenario in which productivity is 211% higher than the base harvest and prices are 25% higher, cultivation becomes profitable (Zuñiga-Jara et al., 2016). These same economic restrictions, low value and productivity, have been found for other seaweed species (Valderrama et al., 2015; van den Burg et al., 2016; Domínguez-May et al., 2017). To improve economic profitability of kelp farming, Correa et al. (2016) suggest that 2 harvests per year could be achieved. However, this seems not to be a realistic scenario as summer seeding seems not to be productive enough at commercial scales (Camus et al., 2018a). In addition, sensitivity analysis confirmed that the recurring costs (see Table 3 of Zuñiga-Jara et al., 2016) are also a decisive factor responsible for the negative economic results in the long term (over 15 years of operation). This study argued that the main reasons of the low profitability of the cultivation are the limited harvest of biomass, low selling price, and high operating costs (mainly taxes associated to use of the sea area).

To evaluate the economic feasibility of any seaweed farming system it is necessary to adjust the demand and values in the context of the actual global economic scenario, which is showing increasing demand of new sources of food, feed, chemicals and fuels. Also, a major point is that the economic assessment must be based on realistic production and cost value. By using the economic information gathered during the experience of cultivating 21-ha of *M. pyrifera* at southern Chile (published in Camus et al., 2018a), we aim to complement and test the validity of the information shown by other authors (e.g. Correa et al., 2016; Zuñiga-Jara et al., 2016). The objective of this study is to analyze the costs of production of the giant kelp *M. pyrifera* and evaluate the aquaculture production profitability in a model designed for biomass production at a commercial scale, incorporating new farming technologies (i.e. high density modular culture system according to Camus et al., 2018a).

2. Materials and methods

2.1. Techno-economic assessment (TEA)

As a basis for our macroalgae economic model, we used 124 t ha^{-1} $year^{-1}$ as mean yield, taken from the best production cycle from Camus et al., 2018a. As our culture system was composed of nearly 10,000 m of seeded rope per hectare, the biomass average used was 12.4 kg m^{-1}. A techno economic assessment of a 10-ha modular culture system was performed using several yields and selling prices scenarios to understand the economic feasibility of the culture. For this purpose, three main profitability measurements were utilized: Net Present Value (NPV), Internal Rate of Return (IRR), and Pay-Back time (PB). Net present value (NPV) represents the total value of future net cash flows during the life of the project, discounted to reflect the time value of money at the beginning of the project (i.e., at time zero). If an investment does not have a positive NPV, or if there are other opportunities with higher NPV, the investment should not be undertaken. The internal rate of return (IRR) represents the average intrinsic profitability of a project and it is a discounted rate that makes the NPV of all cash flows from a particular project equal to zero (discounted to reflect the value of money at the present year, using the weighted average cost of capital (WACC)) (Sapag Chain, 2011). The payback time (PB) represents the time needed for the total capital investment to be recovered by the cumulative net profits. The shorter is the payback time, more attractive the project appears to be, since the initial investment is more quickly recovered. TEA and income statement were analyzed considering a period of 10 years.

2.2. Economic modeling for macroalgal production

The model was based on the cultivation process commonly practiced for *M. pyrifera* in northern and southern Chile (Gutiérrez et al., 2006; Macchiavello et al., 2010; Correa et al., 2016; Camus et al., 2018a). The cultivation process of the giant kelp is divided in the production of juvenile sporophytes in a hatchery, and the sea farming of seaweed biomass in the open ocean. The hatchery phase lasts for 2 months, considering the preparation of supplies and 45 to 50 days of cultivation of plantlets until 2–4 mm long (Camus and Buschmann, 2017). The sea farming phase is considered to last between 7 to 8 months, usually from June to February in southern hemisphere, and the requirements in terms of personnel and equipment are detail in Table 1 for each stage (i.e. seeding, maintenance, harvesting, general operations and administration of the farm). For the purpose of this study, our first assumption is that there is local availability of seeding material from commercial hatcheries in the region of interest. Hatchery culture of *M. pyrifera* has been widely studied and optimized for

Table 1
Requirements for each stage of the sea farming phase.

Stage of sea farming phase	Requirements
Seeding	2 boats, one own, one rental. For plant shipping, 2 shipments are considered to seed one productive cycle. Extra hand labor is needed; 2 extra for 10 days.
Maintenance[a]	20 days a month for 8 months of cultivation.
Harvesting	Harvest machine yield 5 t h^{-1}, assuming 40 t daily. 4 temporary workers for 30 days = 1200 t Harvest boat is rental, with 100-t capacity for 30 days. Every 2 days, seaweed is delivered to abalone culture centers, which are located near the culture facility.
General operations	Farming team is composed of four persons - farm manager and 3 divers/operators
Administration	Farming activities are controlled from land, at a rented office/warehouse, located < 2 miles to the farm. Aquaculture license needs to be paid yearly. Accounting is outsourced.

[a] Maintenance is referred to a daily operation that involves divers inspecting and repairing infrastructure and following seaweed growth.

commercial conditions (Camus and Buschmann, 2017), and based on that experience, the cost of seeding material was estimated in US$ 0.13 linear m^{-1} of seeded rope.

2.3. Cultivation system

The culture system was designed as a 10-ha cross linked suspended system of horizontal lines placed at 4 m depth forming 10 1-ha quadrats. The whole system was anchored by 18 10-t concrete blocks and supported by 18 main buoys (12–1500 L floats and 6–3000 L floats). The rig was composed of a main external rope frame built with a 32 mm nylon rope, which was connected to the mooring lines and buoys by hardware. A conceptual view of the system is presented in Fig. 1. Each hectare (100 × 100 m) holds 99 culture lines (12 mm in diameter), with a line spacing of 1 m. Transversal lines every 20 m were secured to the culture lines to avoid entanglement.

2.4. Harvesting

Harvesting was done using an 80-t rent vessel with help of an operations boat. At one end of each hectare, a diver releases each culture line from the rig line, while at the other side, the rig is lifted with a power winch until it could be reached from the vessel. Once next to the vessel, each culture line was released from the other end and passed through the harvest ring pulled by a winch. Seaweeds were detached as the lines were pulled through and collected into 1-t bags by placing a funnel underneath the ring. Once the bags are full, they were moved onboard to a storage position with the use of a hydraulic crane. Harvesting rate was about 5 t hr^{-1}, giving approximately 40 t day^{-1}. Every 2 days, the vessel delivers harvested seaweed to commercial abalone culture farms in the vicinity (no further than 10 nautical miles). The whole harvest season was calculated to last 30 working days.

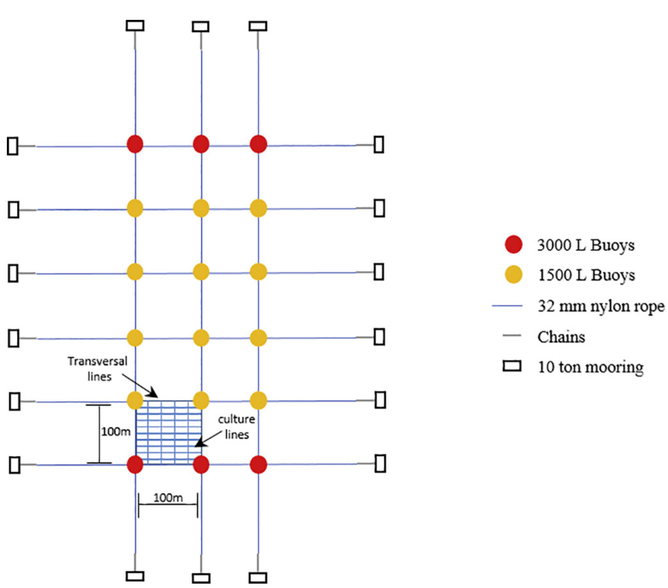

Fig. 1. Scheme of the 10-ha modular suspended culture system.

2.5. Market

In Chile, *Macrocystis* is sold mainly as dried biomass for the hydrocolloid industry, with market prices for the dried kelp fluctuating between US$ 1421 to 1612 t^{-1} in 2016–2017 (IFOP, 2018). Most of it is exported to Asia and Europe (Sernapesca, 2017) and a small portion is processed locally. The fishery is completely artisanal based on gathering casted seaweed on shore or actively harvesting from natural bed. Depending on the region in which the fishery takes place, wild-stock harvesting is regulated by bans. There is also a secondary market for *Macrocystis* in the country, using fresh biomass. The price of fresh seaweed used as abalone feed has been increasing steadily reaching US$ 264 t^{-1} during the past year in the north of the country (Zuñiga-Jara et al., 2016). In southern Chile, where the market for *Macrocystis* is mainly for abalone farming, the price of fresh biomass reached up to US $108 t^{-1} (Muñoz, 2015) due to no access quotas and biomass availability. Considering the price variation of the resource in Chile (southern Chile) we use for our evaluation a price range between US$ 90 and US$150 t^{-1}.

3. Results

3.1. Techno-economic assessment

The investments costs for the capital goods were calculated for the whole 10 ha plot. In Table 2 the default values are summarized indicating that the main costs are the culture ropes and anchorage system. The deployment of the culture system at sea is not included in the costs. Instead, deployment is considered as a one-time service valuated at ~US$ 12,500. Besides the necessary goods for the farm itself, an operation boat with outboard engine, equipped with diving equipment for two was considered. Major investments for *Macrocystis pyrifera* sea farming in Southern Chile, under the assumptions used, account for 45% of total costs during the first year of operation. The depreciation schedule for the capital goods is shown in Table 3. It is based on a linear depreciation model, with different lifespans of items according to materials. Investment costs decrease constantly with time, as a function of depreciation. Once an asset is fully depreciated, a reinvestment is made.

Operational expenditures (Opex) include fixed and variable costs. Fixed cost includes salaries, land infrastructure rental, aquaculture license, accounting and communication costs (Table 4). Labor costs were calculated as the sum of permanent and temporary workers. Permanent

Table 2
Investments costs for the capital goods for a 10 ha modular culture system for *Macrocystis pyrifera*.

Capital goods	Quantity	Unit price (US$)	Total (US$)
Floats 3000 L	6	$ 520	$ 3120
Floats 1500 L	12	$ 380	$ 4560
Floats 200 L	30	$ 28	$ 840
Culture rope - Twisted 3 strands 12 mm × 220 m (Culture lines)	450	$ 37	$ 16,650
Culture rope - Twisted 3 strands 32 mm × 220 m (Reticulate)	13	$ 85	$ 3705
Culture rope - Twisted 3 strands 32 mm × 220 m (Anchoring)	9	$ 85	$ 2565
Long link chain 25 mm × 10 m	18	$ 45	$ 2610
Hardware - Connector plate	18	$ 54	$ 972
Hardware - Shackle 1 1/4 “	144	$ 5	$ 720
Hardware - Wire Thimble 1 ¼	126	$ 3	$ 378
Anchorage system (10 t blocks)	18	$ 600	$ 10,800
Outboard engine	1	$ 9000	$ 9000
Boat	1	$ 7700	$ 7700
Diving hookah	1	$ 2300	$ 2300
Diving Equipment	1	$ 1000	$ 1000
Harvest Machine	1	$ 15,000	$ 15,000
TOTAL			$ 81,920

Table 3
Depreciation schedule of capital goods.

Asset	Cost (US$)	Life	Depreciable base (US$)	Cumulative depreciation (US$)	Rescue value (US$)
Culture ropes	$ 16,650	5	$3300	$16,650	$ -
System ropes	$6270	10	$627	$3135	$ -
Anchors	$10,800	20	$540	$5400	$5400
Buoys	$8520	10	$852	$8520	$ -
Hardware	$2070	20	$104	$1035	$1035
Chains	$2610	20	$131	$1305	$1305
Outboard engine	$9000	10	$900	$9000	$ -
Boat	$7700	10	$770	$7700	$ -
Diving hookah	$2300	10	$230	$2300	$ -
Diving equipment	$1000	5	$200	$1000	$ -
Harvest machine	$15,000	10	$1500	$15,000	$ -
TOTAL	$81,920		$9183	$71,045	$ 7740

Table 4
Fixed and variable costs (US$) for a 10-ha modular culture system for *Macrocystis pyrifera*.

Fixed costs	
Labor	$ 37,800
Land Infrastructure Rental	$ 5544
Aquaculture license	$ 1420
Communications	$ 576
Accounting	$ 564
Total	$ 45,904
Variable costs	
Operation	$ 6162
Maintenance	$ 170
Support vessels[a]	$ 23,750
Seeding string	$ 12,474
Total	$ 42,556

[a] Support vessels includes harvest vessel and seeding rental vessels.

workers are composed of 1 culture manager and 3 operatives (2 divers). Divers are needed to inspect, maintain and repair the sea installations. Seeding and harvesting operations require extra labor, calculated as 20 and 50-person day, respectively (see Table 1).

Variable costs include all materials and fuels needed for operation and maintenance of capital goods, support vessels rental for seeding and harvesting, transportation of biomass, and the cost of seeding string (Table 4). In general, Opex are driven mainly by labor (fixed cost, Table 4) and support vessels (variable cost, Table 4), representing 43% and 27%, respectively.

The project was calculated with a capital structure of 70% loan and 30% own capital to get the benefits of the tax shield produced by the amortization of the loan. A 7-year loan with an interest rate (IR) = 12% was used, based on actual market conditions (simulation from Banco Santander Chile, April 2018). To build the model, the income for each period was obtained by multiplying the production (seaweed t ha^{-1}) by the number of hectares, times selling price. Selling price was considered to increase at a 3% per year base, and initial selling price was set at US $90 taken from Muñoz (2015). For the NPV, the Federal tax in Chile is 25%, loan interest rate of 12%, and the expected profitability from the investor was 21%. Discount rate, WACC, was estimated in 12.6%. Under the initial assumptions of the model, NPV was US$ 15,448, IRR = 15%, Payback time (PB) was 7.4 years and a total annual income of US$ 111,600.

The sensitivity analysis was performed using productivities from 9 to 15 kg m^{-1} and selling prices from US$ 80 to 150 t. For the actual scenario, with a productivity of 12.4 kg m^{-1}, a price value of US$ 87 t^{-1} takes the NPV to zero, and a price value of US$ 150 t^{-1} gives an NPV of US$ 358,433, an IRR = 101% and PB 1.1 years. In Fig. 2, the NPV sensitivity to price and yield is shown within the parameters established before. In Table 5, NPV, IRR, PB are shown for selected productivities and prices where a price value above US$ 120 t^{-1} gives a reasonable economic output, with a recovery time of 2.3 years, under the 12.4 kg m^{-1}. Any increase in price or productivity would led to a better business.

4. Discussion

The present economic sensitivity analysis revealed that *Macrocystis pyrifera* cultivation in southern Chile, is currently profitable in a 10-year evaluation period when the price over US$ 87 wet t^{-1}, keeping the yield at 12.4 kg m^{-1} in a 10-ha cultivation system. Our results were calculated based on the costs involved in a 3-year production cycle on a 21-ha farm located in Chiloe, south of Chile (see Camus et al., 2018a). Bioeconomic analysis of *M. pyrifera* cultivation in Chile has been previously reported for the north (Zuñiga-Jara et al., 2016) and south of the country (Correa et al., 2016) showing different outcomes. Zuñiga-Jara et al. (2016) conclude that in the north of Chile, cultivation is not profitable in the long-term (over 15 years farming period) considering selling price and harvest yield. While in southern Chile it is economically feasible cultivating *M. pyrifera*, if the farm size exceeds 30 ha (Correa et al., 2016). The kelp cultivation systems evaluated in Chile present several differences in materials (investments), personnel and most important, the operation and design of the culture (continuous production and seeding of spore-inoculated ropes in Zuñiga-Jara et al., 2016 and free-floating plants in Correa et al., 2016) which has implication on the use of farming space. In our experience, 9900 lineal m were seeded per ha (i.e. 99 lines of 100-m long per ha) vs 800 lineal m per ha (8200-m culture rope in 2 ha) and 2000 lineal m per ha (60 lines of 80 m each in 2,4 ha) in Zuñiga-Jara et al., 2016 and Correa et al., 2016, respectively, indicating that the associated costs of hatchery production, seeding and harvesting operations are reduced when maximizing the used area. It is true that the yield per m is lower in this study, 12.4 (wet) kg m^{-1} in the year (vs 43.33 (wet) kg m^{-1} year and 41.3 (wet) kg m^{-1} year for Zuñiga-Jara et al., 2016 and Correa et al., 2016, respectively), but the net value of biomass per ha obtained with our configuration of the culture system is significantly higher (1.5× Correa et al., 2016 and 3.5× Zuñiga-Jara et al., 2016) due to the increased number of culture lines per hectare. This farming configuration have impact on the cost analysis and due to its scale in space and time, it provides a more realistic scenario for the economic assessment.

From an economic point of view, the search to optimize the use of

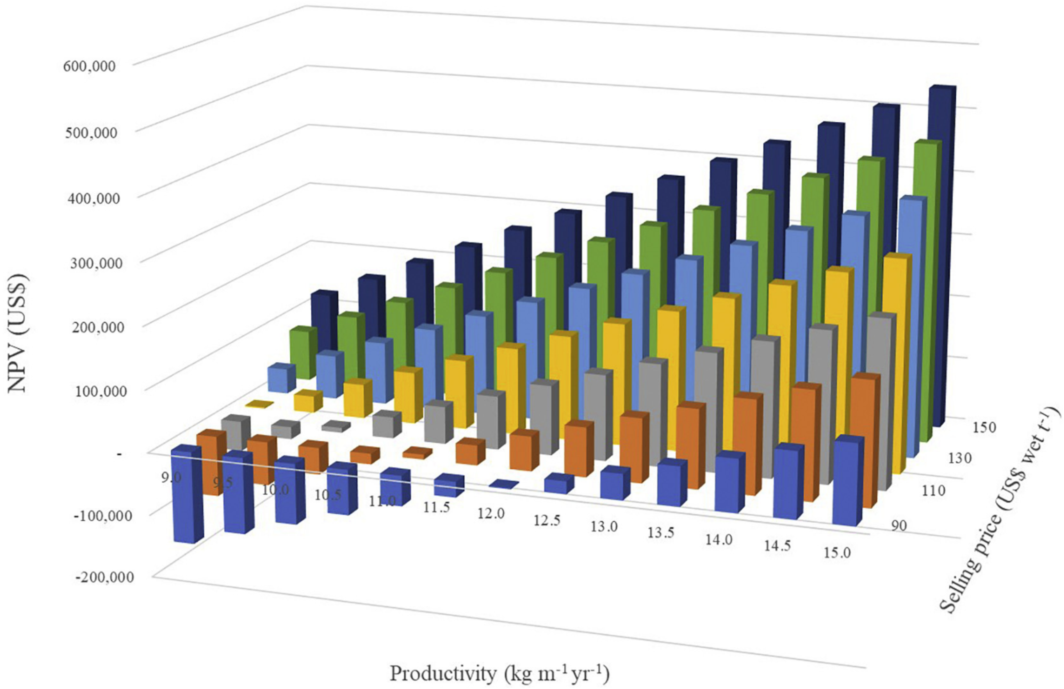

Fig. 2. Net Present Value (NPV) sensitivity analysis to different price (US$) and yield (Kg m^{-1} year^{-1}) scenarios.

Table 5
Price and yield sensitivity scenarios assuming different yields. NPV: Net Present Value, IRR: Internal Rate of Return, PB: Payback time.

Yield (kg m^{-1} $year^{-1}$)	Price (US$ WMT^{-1})	Net Present Value (NPV)	Internal Rate of Return (IRR)	Payback time (PB)
12	$ 100	$ 54,313	23%	5.3
	$ 120	$ 164,902	48%	2.3
	$ 140	$ 275,491	78%	1.4
13	$ 100	$ 100,392	33%	3.6
	$ 120	$ 220,197	63%	1.9
	$ 140	$ 340,001	96%	1.1
14	$ 100	$ 146,471	44%	2.7
	$ 120	$ 275,491	78%	1.4
	$ 140	$ 404,511	115%	< 1
15	$ 100	$ 192,549	55%	2
	$ 120	$ 330,785	93%	1.2
	$ 140	$ 469,021	133%	< 1

space will impact cost significantly as discussed above, so increasing the density of seeded ropes per ha or the number of plants per meter, must be evaluated considering the biology of the organism, as self-thinning will take place at certain threshold. But, there is a second factor influencing the use of space, which is the cost of sea space. When calculating the cost of sea area (e.g. marine concessions) use to produce 1 t of seaweed, in our study the cost is equivalent to US$ 1.20 t^{-1}, whereas US$ 4.3 t^{-1} and US$ 1.81 t^{-1} in Zuñiga-Jara et al., 2016 and Correa et al., 2016, respectively. In Zuñiga-Jara et al., 2016 it is reported that the 28% of the total yearly cost corresponded to lease of the sea area (18.7% for government fees and 9.3% for market premium fees) meanwhile Correa et al., 2016 reported a 1.2% which is in line with our estimation of 1.61%. Chilean law establishes that there is a yearly payment (i.e. fee) for aquaculture concession that is equivalent to 2UTM (Unidad Tributaria Mensual or Monthly Tax Unit, equivalent to US$73) per ha per year (paid on a yearly basis) (Article 84, Law N°18.892 Ley General de Pesca y Acuicultura). Apparently, Zuñiga-Jara et al. (2016) misinterpreted this and calculated it on a monthly basis increasing 12× the price for the concession. It is worth mention that in countries like Chile, the cost of aquaculture licenses is fixed, independent of the resource under cultivation (i.e. fish, mussels, seaweed, among others). We believe that this should be review in order to considered the differential impact that different types of aquaculture produce on the environment and translate into proper policies that promote more sustainable industry like offshore seaweed cultivation. The societal benefits of seaweed cultivation (i.e. bioremediation of contaminated waters, ecosystem services) should be converted in financial benefits.

In aquaculture, a number of factors (sources of uncertainty) that may affect the final production represent daily concerns for the producer. The main sources of uncertainty can be divided into biological, environmental and operational–technological factors (Domínguez-May et al., 2017). Most of the data and assumptions used in this work were derived from a previous experience (Camus et al., 2018a), where we had the opportunity of making several production cycles in different seasons, depths, densities, and harvest times. This allowed us to understand the system and reduce some of the uncertainty by narrowing down the best seeding, growing and harvesting strategies. The productivity value of 12.4 kg m^{-1} is the average of the last production cycle of Camus et al. (2018a), which reflects an optimized but conservative result.

In the actual context, where the global demand for seaweed biomass is expanding rapidly due to high growth of the hydrocolloid industry (2–3% per year, Porse and Rudolph, 2017), together with consumer demands for new protein sources and healthy food supplements, the relevance of economic feasibility of seaweed production in various countries is of most importance. At present, the demand is being satisfy mostly by Asian countries, with the Philippines and Indonesia in the recent years, increasing their participation in the market (FAO, 2018). On the other side, in European and American countries the extraction from natural beds still dominates the local industries (Rebours et al., 2014), with several initiatives for cultivation in open ocean and land tanks being developed (e.i. Norway (Seaweed Energy Solution AS), France (Algolesko), Portugal (AlgaPlus) and United States (GreenWave)). However, unlike Europe, which envisioned seaweed as a feedstock for a bio based economy (van Hal et al., 2014), Chile produces dry raw biomass mainly for hydrocolloid extraction traded at lower prices (Buschmann et al., 2008; Camus et al. accepted), and when the demand increases, instead of increasing the price, there is an increase in the amount of harvest biomass from natural beds. In light of the reported results, the cultivation of *M. pyrifera* is technically and economically feasible, which is a starting point to promote the cultivation in a moment where Chile is subsiding farmers (Law N°20.925, Republic of Chile) to increase the sustainable production of the resource. Still there is a need for a constant demand of biomass and with an increased present value to encourage the initial investment of kelp aquaculture in Chile. The traditional view of focusing on a single product (such as alginate, agar, or feed for abalone) needs to evolve to the development of different products through the cascading biorefinery approach that might be key to the development of a feasible seaweed industry. Finally, this study demonstrates that it is highly relevant to perform an economic assessment based on reliable technical and economic information that can be extrapolated into a commercial scale. For example, the economic feasibility of seaweed production in the North Sea was evaluated by van den Burg et al. (2016) in combination with offshore wind farm energy generation. These authors concluded that is not economically feasible, however recognized that is too early to draw final conclusions on the economic viability of developing a North Sea seaweed value chain because there still are uncertainties about exact costs of production and the potential revenues. From this point of view, it is highly relevant that any new seaweed farming activity is based on well-established productivity and technical information that allow the determination of realistic economic performance.

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Declaration of interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aquaculture.2018.12.030.

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