Production and economic assessment of giant kelp Macrocystis pyrifera cultivation for abalone feed in the south of Chile

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Production and economic assessment of giant kelp *Macrocystis pyrifera* cultivation for abalone feed in the south of Chile

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Abstract

Kelp biomass availability for mass abalone cultivation remains a critical issue in Chile. The technical and economic feasibility of a commercial scale kelp farming activity has not been established. This study describes the production and economic results of a pilot scale unit installed in southern Chile. Our results show 25 kg m^{-1} of production over a 9-month spring-summer period, and 16.2 kg m^{-1} during the autumn-winter period. These values indicate that a total biomass production of 41.3 kg (wet) m^{-1} $year^{-1}$ can be obtained by placing the culture lines at 4 m intervals. High quality animal food-grade plants with a 9% protein content, over 5 m in length were harvested. Sensitivity analysis showed that by cultivating 30–50 ha with a market value of US\$ 78 ton^{-1}, a return on investment can be made after the first year.

Keywords: *Macrocystis* farming, abalone farming, biomass production, protein content, economic analysis

Introduction

Brown algal species were first cultivated commercially in Japan, China and Korea, mainly for human consumption (Tseng 1987; Hanisak 1998; Kaneko 1999; Sahoo & Yarish 2005). Kelp biomass is also in demand for alginate production (Bixler & Porse 2010) and biofuels (Wargacki, Leonard, Nyan Win, Regitsky, Santos, Kim, Cooper, Raisner, Herman, Sivitz, Lakshmanaswamy, Kashiyama, Baker & Yoshikuni 2012). Interestingly, demand for brown algae is also increasing due to the introduction of new uses, such as fertilizers, cultivation for bioremediation purposes, as well as abalone and sea urchin feed, among others (Chopin, Buschmann, Halling, Troell, Kautsky, Neori, Kraemer, Zertuche-González, Yarish & Neefus 2001; Ugarte & Sharp 2001; Buschmann, Riquelme, Hernández-González & Henríquez 2007; Craigie 2011).

Production of red abalone in Chile reached 794 tons in 2010 (Sernapesca 2011). The highest production levels are obtained in northern and southern Chile, reaching 339 tons (43%) and 279 tons (35%) respectively (Sernapesca 2011). In the southern zone (Los Lagos region), feed for abalone culture is based almost exclusively on *Macrocystis pyrifera* and, to a lesser degree, *Gracilaria chilensis* (Flores, Gutiérrez, Ellwanger & Searcy-Bernal 2007; Enríquez & Villagrán 2008). Nevertheless, due to the high water content and low protein level, abalone consumption of fresh algae can vary between 15% and 30% of daily weight in juvenile abalones (Hahn 1989; Greenier & Takekawa 1992; Uki & Watanabe 1992), requiring enormous quantities of fresh algae during the fattening stage. Recently, it has been established that a natural diet of fresh algae, whether using one species, or a combination of various brown algae, has produced better results than with animal feed (Naidoo, Maneveldt, Ruck & Bolton 2006). In experimental abalone cultures carried out in Baja California, Mexico, no significant differences were observed between the growth rate of abalones fed with *M. pyrifera* and those fed with

E. arborea (Zertuche-González, Sánchez-Barredo, Guzmán-Calderón & Altamirano-Gómez 2014). Furthermore, culture of abalones fed with algae has environmental advantages, given that artificial food produces greater quantities of nitrates and phosphates (Qian, Wu & Ni 2001). Artificial foods available also have a short useful life in water, making operational management difficult, especially in open-sea systems. Added to this, is the fact that abalone fed naturally have a greater value on the international markets.

Local environmental conditions in southern Chile have considerable consequences on *M. pyrifera* population dynamics (Buschmann 1992; Vásquez, Véliz & Pardo 2001; Buschmann, Vásquez, Osorio, Reyes, Filún, Hernández-González & Vega 2004). Populations in protected environments, such as the interior sea of Chiloé, where abalone cultures are located, present an annual life cycle and adult plants disappear in the autumn (Buschmann, Moreno, Vásquez & Hernández-González 2006). This produces a food scarcity for abalones and an increase in feed costs, given that food must be transported from further afield. This is an added incentive for the development of kelp culture in the south of Chile.

Increased demand has already caused some deterioration of different kelp populations and, for this reason, new regulations are restricting kelp harvesting along the Chilean coast; extraction pressure on *Macrocystis* is also moving towards the south of Chile (Vásquez 2008). These biomass restrictions have encouraged the development of kelp farming studies in Chile (Gutiérrez, Correa, Muñoz, Santibáñez, Marcos, Cáceres & Buschmann 2006; Westermeier, Patiño, Piel, Maier & Müller 2006; Celis & Alveal 2012). However, in spite of considerable research efforts, production results are still variable. For example, same studies indicate biomass production values that range from 14.4 kg m^{-1} (Gutiérrez *et al.* 2006) to 80 kg m^{-1} (Westermeier *et al.* 2006). Those differences may be explained by culture methods, initial kelp size at the seeding stage and environmental conditions where the study was performed. However, most importantly, these values are largely the result of small-scale studies that are difficult to extrapolate.

Although considerable information on *Macrocystis* cultivation has been published in the past (e.g. North 1979), some basic knowledge, necessary to run a successful commercial activity, is still lacking. In particular, with regard to different environmental conditions and the complex morphological and reproductive variability between populations (Graham, Vásquez & Buschmann 2007), that can have important commercial consequences for kelp farming. Considering these new driving market forces, the potential impact of harvest on natural populations and the relatively reduced biological knowledge necessary to produce a high quality product, the aim of this article is to determine the biomass production potential of *M. pyrifera* on a pilot scale. Subsequently, and based on the installation and operating costs of a 2.4 ha farm in Chiloé Island, southern Chile, a profitability analysis was undertaken, through economic sensitivity analysis of two variables: production scale and market value.

Materials and methods

Study sites

Fertile sporophytes of *M. pyrifera* were collected in Calbuco, southern Chile (41°46′S; 73°08′W) in January 2005 and October 2006 (Fig. 1). The fertile tissues were brought to the kelp hatchery in Metri (41°35′S; 71°42′W) and the gametophytes and sporophyte germlings were produced over a 60 day period, strictly following the methodology described by Gutiérrez *et al.* (2006). During March, 2005 and December of 2006, 1 mm sporophytes were introduced into the sea at Puqueldón (42°26′S; 73°35′W), Chiloé Island in southern Chile (Fig. 2). The culture site is located in a semi-protected sector, with a low tide depth of 12 m and a stable sandy-pebbly substrate, which enabled the installation of reinforced concrete moorings as anchorage. The culture system was kept afloat by eight buoys (500 L), maintaining the horizontal culture ropes at a constant depth of 1 m (Fig. 3). The size of the pilot unit was 300 m long and 80 m wide, equivalent to 2.4 ha (Fig. 3a). This design enabled us to install 60 horizontal culture lines, each 80 m long and spaced at 4 m intervals. A total of 134 vertical ropes were installed along these horizontal lines (nursery phase) in the *M. pyrifera* suspended culture system in Puqueldón. Seeded ropes were installed surrounding a 6-m vertical rope (5 mm in diameter) (Fig. 3b). This initial culture design was installed in the field for 2 years and then extended to a 4 ha production unit that demonstrated their capability to resist winter conditions, while

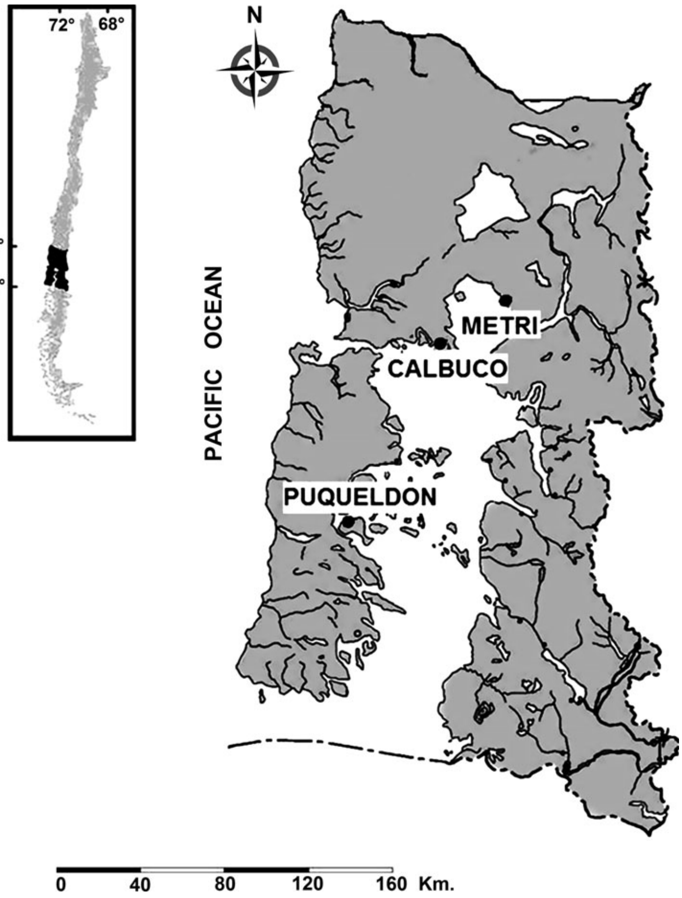

Figure 1 Map indicating the origin of the sporophyll (Calbuco); the hatchery location (Metri) and the culture site (Puqueldón) of *Macrocystis pyrifera* in the Los Lagos Region in southern Chile.

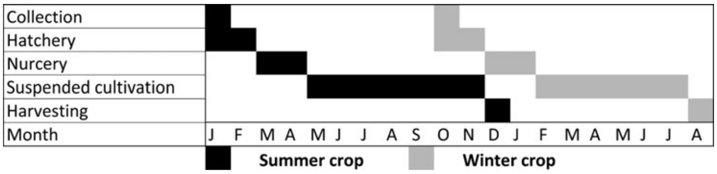

Figure 2 Production timetable of *Macrocystis pyrifera* in southern Chile, considering a summer crop and a winter crop.

maintaining investment costs as low as possible. A cost table was elaborated for this kelp culture unit and annual operational costs were estimated. This cost table considered fixed (human resources) and variable (licence of culture site, plants, support equipment, culture system, fuel, seeding and harvest).

Biomass production assessment

The *M. pyrifera* sporophytic germlings attached to the seeding ropes (see Gutiérrez *et al.* 2006; for methodology) were transferred in early March 2005 to Puqueldón (Fig. 2). In May, after 2 months of cultivation, 10 cm sporophytes were collected. Individual sporophytes were selected and attached with cable ties to 12 mm horizontal ropes (Fig. 4a). Three plants were installed per metre of horizontal culture line (Fig. 4b). The plants were cultivated from May to December (winter seeding trial). During this period, *M. pyrifera* individuals were measured monthly by randomly selecting seven independent culture ropes, and measuring the length of 10 random plants. To determine individual biomass using a non-destructive sampling method, a regression

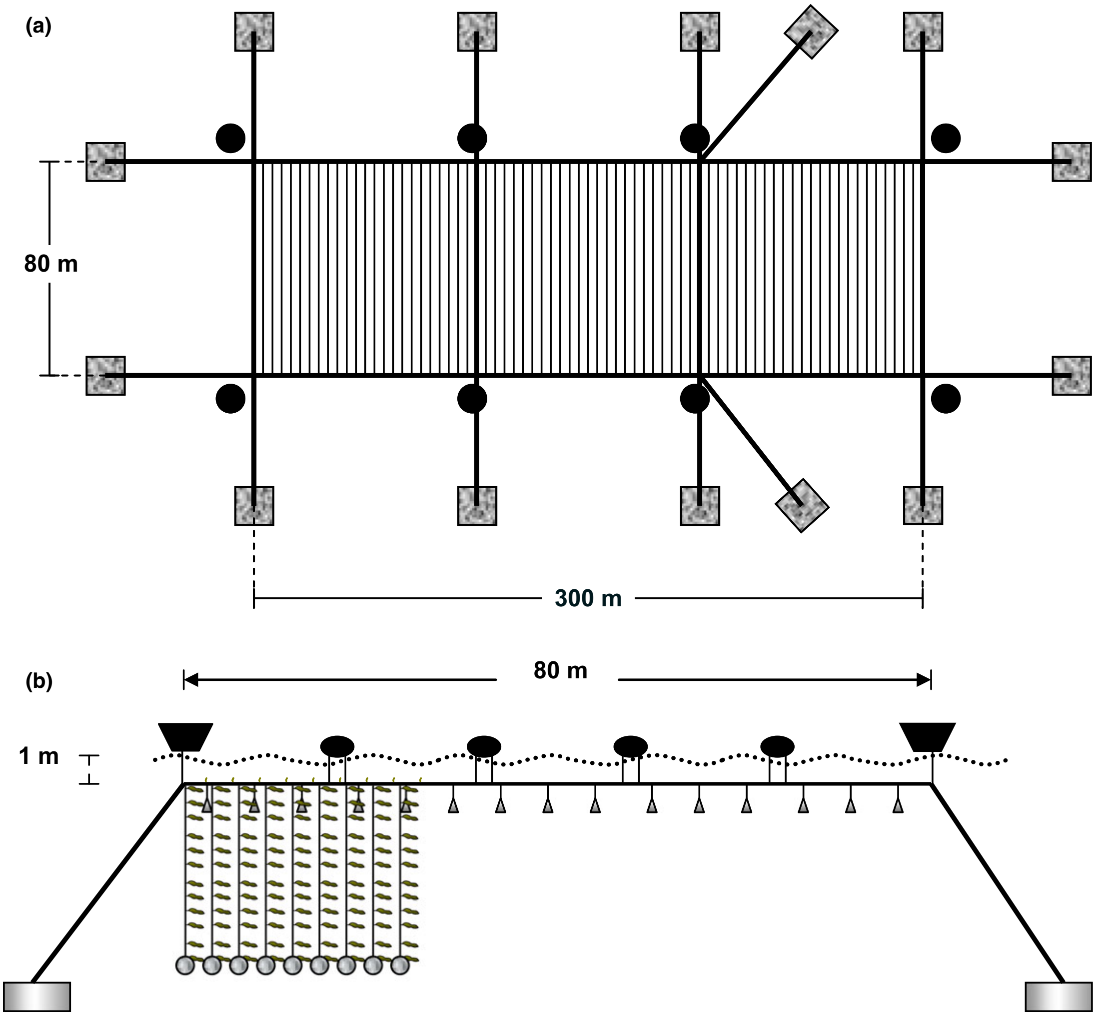

Figure 3 (a) Suspended culture system in Puqueldón, fourteen 3-ton concrete anchors, eight 500-l plastic buoys, main 12-mm polypropylene lines and 18-mm anchor ropes. (b) Lateral view of the long-line cultivation system, with vertical ropes for juvenile sporophytes.

equation between plant length and its fresh weight was obtained. Harvesting was undertaken by hand, moving a 5 × 5 m floating platform along the culture line; the latter was lifted onto the platform using a manual winch, where a knife was used to detach the plants at their base. Final fresh biomass, measured per metre of culture line, was determined, prior to delivering the seaweeds to an abalone farmer. A quality index of the kelp produced relevant to abalone farming was obtained by measuring the protein content of the plant tissue, according to the Kjedahl method (Bradstreet 1965). These values were compared, using a *t*-test, to another three samples of wild *M. pyrifera* collected in Puqueldón at the same time.

Using the same methodology, a second production trial was performed in December 2006 by installing *M. pyrifera* sporophytic germlings attached to the seeding ropes as described above (summer seeding trial). A total of 114 vertical ropes with sporophyte germlings were installed in Puqueldón. In February, after 2 months of cultivation, 10-cm sporophytes were collected and attached to horizontal ropes, applying the same technique used for winter seeding (Fig. 4a and b). The plants were cultivated from February to August 2007 (Fig. 2). During this period, *M. pyrifera* germlings were measured monthly by random sampling, following the winter seeding process. The final fresh biomass was measured in August.

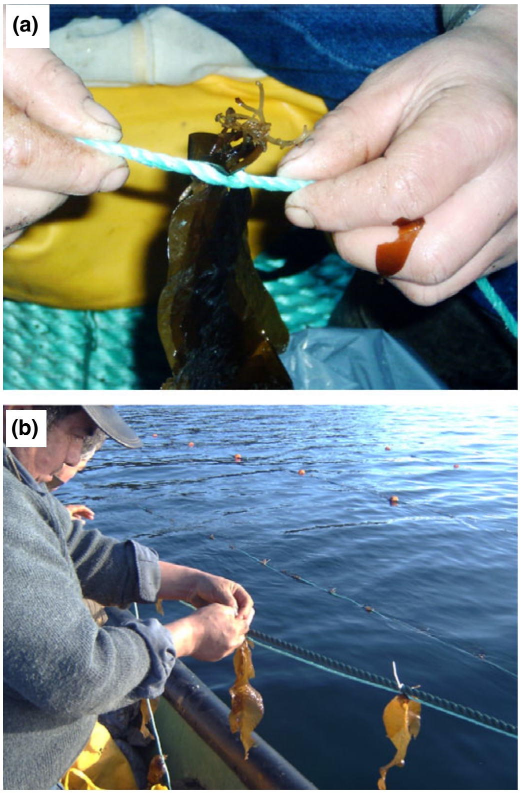

Figure 4 (a,b) Individual sporophytes cultivated in vertical lines until reaching 10 cm attached and then to horizontal ropes in suspended culture system in Puqueldón.

Before delivering the seaweeds to an abalone farmer, three culture lines were randomly selected, taking three samples of 1 m length; total plant biomass was measured and weighed. The biomass production values obtained for the summer and winter crops were compared using a *t*-test, after ensuring data normality and variance homogeneity.

Economic assessment

Based on present installation and material costs, the investment required for a kelp farm unit was estimated in US dollars (US$). Using this information, we constructed a 10-year cash flow chart that includes capital costs, amortization and the operational costs for a 10-hectare farm. Two harvests per year were considered. Internal rate of return, present net value and years for recovering the investment (YR) were determined, following the methodology described by Sapag (2007), applying a 12% discount rate suggested by MIDEPLAN (Ministerio de Planificación y Cooperación, currently the Ministerio de Desarrollo Social, Chile). Finally, we ran a sensitivity analysis for different farming scales (10, 30 and 50 ha) and market kelp prices (59, 78 and 98 US$ ton^{-1}).

Results

Starting the field culture in March (autumn) of 2005, with 0.1 cm *M. pyrifera* sporophyte germlings, we can obtain kelp sporophytes of 6 m length, equivalent to a plant biomass of 9–10 kg individual^{-1} (Figs 5–7). Attaching three individual plants per meter of culture line, culture biomass production obtained in summer was 25.1 kg m^{-1} (Fig. 8). The protein content of our cultivated *M. pyrifera* reached a value of 9%, which was significantly ($P < 0.05$) higher than that of wild populations close to the culture area (Fig. 7).

Initiating the field culture in December (summer) of 2006, with 0.1 cm *M. pyrifera* sporophyte germlings, we can obtain plants of 6 m, equivalent to a plant biomass of 10 kg individual^{-1} (Figs 6–7). By attaching three individual plants per metre of culture line, the culture biomass production obtained in winter was 16.2 kg m^{-1}. Thus, the summer crop was significantly ($P < 0.05$) higher than the winter crop (Fig. 8). These biomass production results allow us to indicate that an annual production of 41 kg m^{-1} year^{-1} can be obtained. Labour costs associated with seeding, projected over an area of one hectare represented a value of 184 man h^{-1}, while harvesting costs were calculated at 24 man h^{-1}.

Production cost projection for 10 ha of *M. pyrifera* culture, with two annual harvests, was determined at US$109.396. Fixed costs represent 13% and variables costs, 87% of the total cost (Table 1). Sensitivity analysis shows that, at a market price of US$78 ton^{-1}, and a culture area of 30 ha, profitability is achieved and recovery of capital invested occurs from year 1 of production (Table 2). According to price fluctuation during the year, best profitability would be obtained with a production scale of 50 ha.

Discussion

The *M. pyrifera* biomass production values presented in this study were significantly higher than those recorded in a previous experiment (Gutiérrez

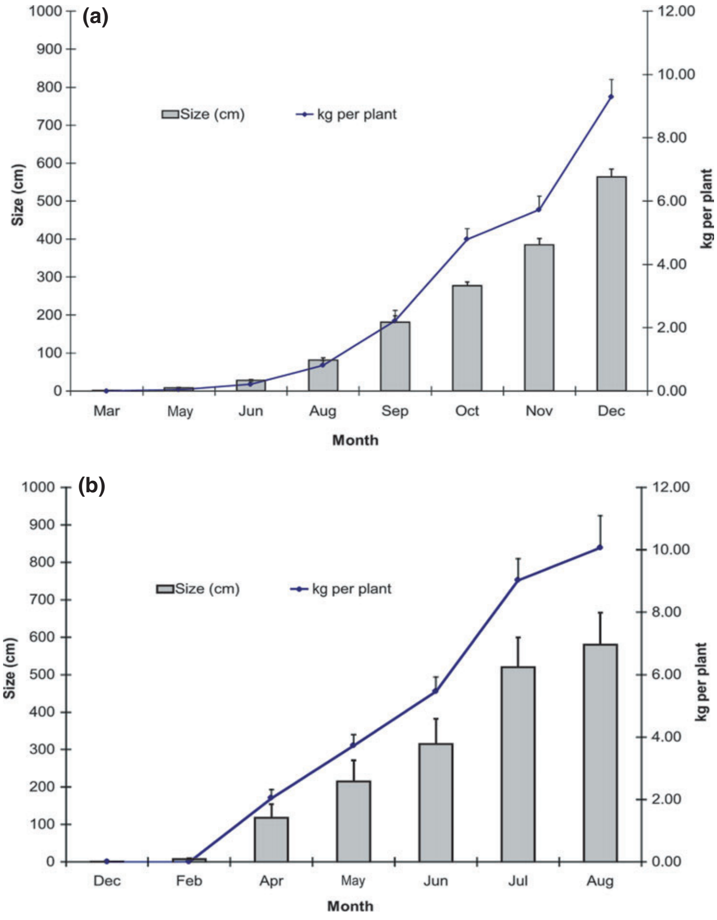

Figure 5 Growth in weight (line) and length (bars) of summer (a) and winter (b) crop of *Macrocystis pyrifera* in the south of Chile.

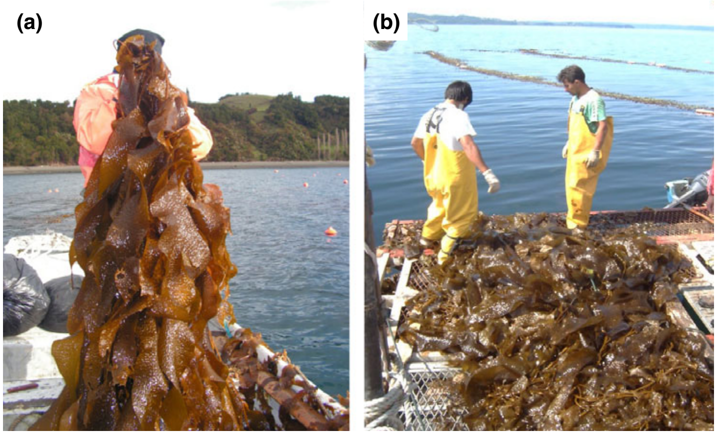

Figure 6 Crop of *Macrocystis pyrifera* in Puqueldón, August (a) and December (b).

et al. 2006). This would be due to changes in culture techniques associated with sea management; these included implementation of a 2-month 'nursery' and management of plant density, modifications that resulted in a 74% increase in biomass performance over the same seasonal period (summer harvest). Nevertheless, higher production values were obtained by Westermeier *et al.* (2006) based on individual plant seeding techniques obtained with the free-floating system. Twelve

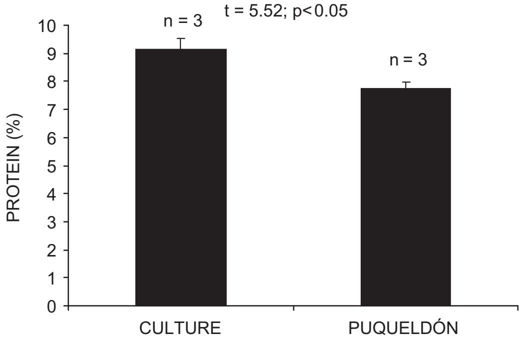

Figure 7 Average (+ SD) of protein content (% in dry base) of kelp produced by cultivation (culture) and collected from natural beds (Puqueldón).

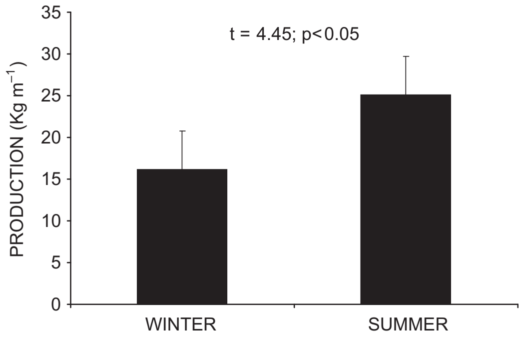

Figure 8 Average (+ SD) biomass yield of *Macrocystis pyrifera* culture in the south of Chile in winter and summer period.

Table 1 Annual costs of a 10 ha farm of *Macrocystis pyrifera* in Chile. Values in US$ and percentage of each cost item

Costs	US$	%
Human resources	14,118	12.9
Licence of culture site	1,295	1.2
Plants	8,627	7.9
Support equipment	26,667	24.4
Culture System	37,591	34.4
Fuel	3,529	3.2
Seeding	5,804	5.3
Harvest	11,765	10.8
Total	109,396	100

Table 2 Economic analysis using the net present value (NPV in US$), internal rate of return (IRR in %) and the years required to obtain economic profit (YR in years) of a long-line *Macrocystis pyrifera* cultivation in southern Chile. The analysis simulation was undertaken on three farming scales (10, 30 and 50 ha) and three at different kelp prices (59, 78 and 98 US$ ton^{-1})

Farming scale (ha)	Price (US$ ton^{-1})	IRR	NPV	YR
10	59	n.p	−657.741	n.p
	78	n.p	−544.183	n.p
	98	n.p	−430.991	n.p
30	59	n.p	−89.755	n.p
	78	153	291.101	1
	98	224	580.191	1
50	59	224	580.191	1
	78	339	1057.136	1
	98	452	1534.081	1

n.p, no profit.

months after the start of gametogenesis in the laboratory, they obtained productions of 80 kg fresh algae m^{-1} of culture line in the sea, and plants of 14 m length, during the summer. Sexual crosses of selected *M. pyrifera* gametophyte parents of different geographical origin along the coast of Chile, showed heterosis and produced sporophyte batches with superior growth performance, 66 kg m^{-1} of rope within 4–5 months (Westermeier, Patiño, Murúa & Müller 2011). On the other hand, recent small-scale studies in northern Chile, using the direct seeding technique (kelp individuals attached to ropes in the hatchery are transplanted and attached to the vertical ropes, without density management), have obtained plants with a maximum frond length of 1.75 m and a maximum harvest biomass of 22 kg m^{-1} of rope, after 120–150 days of culture in the sea, between May and September (Macchiavello, Araya & Bulboa 2010). Differences between the production results of the above cited authors and those of the present study reflect the different techniques used for the production of germlings and variations in the hatchery and sea culture protocols adopted. In particular, differences in the initial size of the transplanted kelp individuals are relevant and the scaling up of results permits more accurate prediction of a more realistic biomass production potential. Furthermore, the environmental differences between one site and another and between the different seasons of the year, also affect results. For this reason, our results suggest that our values are conservative and space for optimization still exists.

A winter harvest, initiated with germlings cultivated in a controlled environment and seeded in the sea in summer, constitutes a new production scenario for the culture of *M. pyrifera* in protected environments in southern Chile, given that the biomass of natural populations in protected environments tends to disappear in the winter, showing an annual life cycle (Buschmann *et al.* 2006). In these wave-protected environments, the high mortality of populations in summer would appear to be related to the high temperature and low nutrient concentration. For this reason, a significant loss of biomass is produced during the autumn-winter period. The perennial populations can lose part of their canopy, but still maintain a sporophyll stock and reproduce all year round (Buschmann *et al.* 2006; Buschmann, Pereda, Varela, Rodríguez-Maulén, López, González-Carvajal, Schilling, Henríquez-Tejo & Hernández-González 2014a). As a consequence, the productive scenario that permits winter harvests ensures the food supply required by the abalone industry at a critical period of the year, when natural population biomass in protected environments tends to disappear. This also provokes an increase in the production costs, as food supplies must be obtained from further afield, where populations are perennial.

In this study, cultivated plants obtained a significantly higher percentage of protein than the plants in natural beds. According to the present state of culture development of this alga, if we compare the *M. pyrifera* suspended culture system with the traditional form of harvesting by diving, it is feasible to suggest that biomass production under culture is more efficient, given that production can be programmed and managed. Furthermore, a better quality (higher protein levels) of algae could be obtained, with increased availability (summer and winter) as food for the abalone, thus supplementing decreasing abundances of natural populations. Recent research has shown that nitrogen produced by a fish farming system can increase the productivity of macroalgae which, at the same time, remove the dissolved nutrients (Buschmann, Troell & Kautsky 2001). It has also been determined that brown (Petrell & Alie 1995; Ahn, Petrell & Harrison 1998) and red (Buschmann, Troell, Kautsky & Kautsky 1996) algae display a high capacity for removal of dissolved nitrogen present in fish effluents and that algae production in areas surrounded by floating salmon culture cages is greater than in isolated cultures (Troell, Halling, Nilsson, Buschmann, Kautsky & Kautsky 1997). From this point of view, *M. pyrifera* culture systems located close to salmon floating cages in southern Chile, with a greater nitrogen content availability, can increase the protein content up to 13–15% of dry weight (Buschmann, Varela, Hernández-González & Huovinen 2008). This situation would also enable seaweed cultivation units to recycle waste products (inorganic nitrogen, carbon and phosphores) produced by salmon culture and, as a result, improve water quality (Neori, Shpigel & Ben-Ezra 2000).

The production cost structure is mainly determined by variable costs, which results in a low operating leverage; thus, possible negative sale scenarios can be managed more effectively, whether they be related to supply or product price. At present, from an economic point of view, kelp prices are not sufficient to support culture systems on a scale below 30 ha. However in this study, we only introduced one culture line every four metres. It seems feasible to duplicate this amount of culture lines (placed at 2 m; Buschmann, Prescott, Potin, Faugeron, Vázquez, Camus, Infante, Hernández-González, Gutiérrez & Varela 2014b). This may reduce the production size of a farm by half, but this needs to be demonstrated technically and financially. Although the specific characteristics of the culture site have not been analysed in this study, aspects such as culture depth, current speed and nutrient availability, require further analysis when selecting a site. Additional research initiatives are also important for restoring or increasing production in the future, such as procuring a selected strain and the ability to manage epibionts, grazers and pathogenes (Buschmann *et al.* 2014b).

Nevertheless, the increased demand as a result of higher abalone production levels and new uses (Buschmann *et al.* 2007) currently being developed, project an increase in prices. In view of the particular environmental characteristics of the interior sea of the southern zone, the development of culture engineering on a larger scale must aim towards optimizing seeding processes and mechanization of harvest procedures, as well as improving the design and operation of the floating culture system. On the other hand, under the administration of artisanal fishermen's organizations in management areas, the economic results could be improved, especially if actual mussel facilities already in operation can be adjusted for the production of algae and molluscs. This study concludes that *M. pyrifera* culture is both technically and economically feasible, in the present context in southern Chile. It also provides an initial technical and economical base for the development of giant kelp aquaculture in Chile. Nevertheless, several issues still require clarification, such as disease management and the development of higher productive strains, as discussed by Buschmann *et al.* (2014b).

Acknowledgments

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