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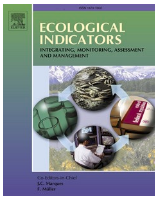

Sustainability of the seaweed *Hypnea pseudomusciformis* farming in the tropical Southwestern Atlantic

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ABSTRACT

Seaweed culture is generally referred to as a sustainable production system. Nevertheless, this concept is biased by an environmental approach only, neglecting the economic and social dimensions of sustainability. The objective of this study was to assess the sustainability of the seaweed *Hypnea pseudomusciformis* cultivation and its use as human food consumption. We developed a pilot farming with the Association of Algae Producers of Flecheiras and Guajiru, in the municipality of Trairi, Northeastern Brazil. We applied a set of indicators to access environmental, social, and economic dimensions of sustainability. The environmental indicators showed highly efficient use of energy, nitrogen and phosphorus, which increased in the algae biomass during culture by 383%, 894%, and 1860%, respectively. Besides, *H. pseudomusciformis* culture absorbs carbon, does not pollute, and shows low risk to the local biodiversity because of it is a native species. Social indicators revealed that 51% of all investment stays in the local community, and the income distribution is equal among workers. The farm presented a high labor demand, which is socially inclusive. The *H. pseudomusciformis* farm was highly profitable, with an internal rate of return of 119%, recovery of invested capital in 1.2 years and positive externalities, generating 262.00 US$.t^{-1} as additional income. The farm showed high performance in the environmental, economic, and social dimensions of sustainability. Thus, this activity may be a sustainable manner to produce high-quality human food and raw materials for industry. The results obtained in the present study provide secure information for farmers, investors, and policymakers, which may encourage small and medium farmers to start seaweed farming in tropical Atlantic Southwestern coast.

1. Introduction

United Nations (UN, 2019) data shows that the world population will reach 9 billion by the middle of the XXI century. As the population increases, the concern with food security arises. However, the issue is not only about food security but also with the sustainability of food production (FAO, 2018; Godfray et al., 2010). Glavi and Lukman (2007) stated that sustainable systems mean a form of an interconnected system linking environmental protection, economic performance, and societal welfare, guided by a political choice based on ethical and ecological imperatives. Therefore, sustainable production benefits the environment, the employees, the communities, and the organizations at the same time, leading to more economically feasible and productive enterprises (Lowell Center of Sustainable Production, 2019).

Food security is the central theme of the Sustainable Development Goals (SDGs) from the United Nations (UN) (UN, 2015), and aquaculture is highlighted among the solutions to produce food with sustainability (Boyd et al., 2020; Mustafa et al., 2018). Aquaculture may augment household and bring social benefits, as well. However, disorderly development of the activity may cause environmental damage and result in future social and economic losses (Saad et al., 2018). Therefore, it is necessary to ensure the conduct of aquaculture activities within the goals of sustainable production. In this context, it is essential to quantify the sustainability of the production systems. Sustainability is multidimensional and considers environmental, economic, and social features (UN, 1992, 2015; Glavi and Lukman, 2007; Singh et al., 2009). Some

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Fig. 1. A) Long-lines of *H. pseudomusciformis* farm in the sea with 30 days farming. B) *H. pseudomusciformis* harvested after 45 days farming.

methods have been used to evaluate aquaculture sustainability, such as emergy analysis, ecological footprint, life cycle analysis, and sets of indicators. However, some of these methodologies require data that are difficult to obtain, or access to a paid data set platform or do not evaluate all the three main sustainability dimensions. The indicators of sustainability to assess aquaculture developed by Valenti et al. (2018) are easy to calculate, need a simple data collection, and encompass the economic, environmental and social dimensions of sustainability, according to the SDGs defined in Agenda 2030 from UN, which makes it more applicable for users. In addition, they are easily understandable by society.

Seaweed farming has been considered a sustainable form of production. Nevertheless, this concept is biased by a single environmental approach, neglecting the two other dimensions of sustainability. To be sustainable, a production system should contemplate the economic, environmental, and social dimensions of sustainability, which must be achieved in a balanced and integrated manner (UN, 1992, 2015). Some authors have stated that seaweed farming is environmentally and socially friendly (Chopin, 2012; Edwards, 2015; FAO, 2013; Kim and Yarish, 2014; Marinho-Soriano et al., 2009; Msuya, 2014; Powell et al., 2014; Radulovich et al., 2015; Rebours et al., 2014; Visch et al., 2020; Wood et al., 2017; Yang et al., 2015). Seaweeds are photosynthetic organisms and, thus, sequester carbon (Duarte et al., 2017; Gouvêa et al., 2020; Mashoreng et al., 2019), and remove inorganic compounds from water (Chopin, 2014; Edwards, 2015). These characteristics indicate seaweed farms have a low environmental impact and provide ecosystem services (Chopin, 2014; Troell et al., 1999), suggesting a high potential to be environmentally sustainable. Regarding their environmental characteristics, seaweed farms are assumed to be sustainable (Duarte et al., 2017; Kim and Yarish, 2014; Powell et al., 2014; Radulovich et al., 2015; Rebours et al., 2014). However, the positive and negative environmental impacts of the seaweed farms and even environmental sustainability are still uncertain because of the absence of enough quantitative data (Burg et al., 2019; Kim et al., 2017; Taelman et al., 2015; Visch et al., 2020). Some studies indicated this activity needs low initial investment, shows a fast return of the invested capital (FAO, 2003; Valderrama et al., 2015), and promotes social improvement, mostly in developing countries (FAO, 2013; Msuya, 2014). However, no studies have quantified the social and economic sustainability aspects of any seaweed farm yet.

Therefore, the knowledge of the environmental impacts and socioeconomic features in seaweed farming is still incomplete and fragmented. No one has estimated the seaweed farming sustainability until now, although this production is often considered a sustainable practice. Thus, in the present study, the environmental, social and economic sustainability of *Hypnea pseudomusciformis* (former "*musciformis*") farming is quantified, using a set of indicators, to test the hypothesis that this production is a sustainable activity in the Tropical Southwestern Atlantic coast. This study is the first that quantifies the three dimensions of sustainability for a seaweed farm.

2. Materials and methods

The macroalgae *H. pseudomusciformis* is a Rhodophyta epiphytic, widely distributed in the tropical Atlantic coast of South America, which have been largely studied in the past two decades (see Yokoya et al., 2020 for details). Recently, technology for its mass culture was developed (Pereira et al., 2020a) and patented on the Brazilian patent basis (#BR 10 2019 027,248 1; 19 December 2019). A market survey revealed a great acceptance as human food in Brazil, and a bioeconomic study showed that the culture of *H. pseudomusciformis* can be very profitable (Pereira et al., 2020b). Therefore, the sustainability assessment of this recent-developed technology is opportune.

We assessed the environmental, social and economic sustainability of the *H. pseudomusciformis* farming, using the set of indicators developed by Valenti et al. (2018). A total of 54 indicators were computed. The mathematical formulae relevant to the computation of each indicator are described and detailed explained in Valenti et al. (2018); thus, they were not repeated in the present article. Environmental sustainability indicators measured the use of natural resources (including energy, nitrogen and phosphorus), efficiency in using resources, release of pollutants to environment, the capacity to fixed carbon from greenhouse gases, and the risk to biodiversity. Social sustainability indicators measured the capacity of the production system generate social benefits to local communities (including creation of jobs, food security and health care), equitable income distribution, equality of opportunities (including gender, race, and age), and social inclusion. Economic sustainability indicators measured the efficiency in using financial resources, economic feasibility, externality incomes and costs, and resilience.

Data used for computing the indicators were obtained in a pilot culture conducted at facilities of "Associação de Produtores de Algas de Flecheiras e Guajiru" (APAFG) (Association of Algae Producers of

Flecheiras and Guajiru). This association includes a traditional coastal community enrolled with algae culture and ecotourism in northeastern Brazil. Farmer members of APAFG have about 20 years of experience in algae culture, and they collaborated in developing the technology to produce *H. pseudomusciformes* in the recent years.

2.1. Farm description

The seaweed farming was installed in Flecheiras beach, Trairi, Ceará State, Northeastern Brazil (3°13′10.73″S; 39°16′49.55″W) at APAFG facilities. This site is included in the marine province Tropical Southeast Atlantic, ecoregion Northeastern Brazil (Spalding et al., 2007). The beach region has a humid tropical climate, a near-shore open-sea area, and an extensive rocky shore with several species of seaweeds. Farm facilities includes a land-based 53 m^2 area with a shed for seaweed processing, drying, and storage, and a sea-based area placed ~1 km distant from the shoreline. In the sea-based area, water column is ~6 m deep and salinity is around 35–36.

We conducted a culture of the *H. pseudomusciformis*, using 30 m stretched modified-longlines, provided with two substrates for each meter (Fig. 1A). The production system and the management were defined according to the technology developed by Pereira et al. (2020a). Seedlings came from natural banks in Flecheiras beach. We cut the apical part of the thallus, using knives, leaving ~3 cm attached to the rocks to remain growing. Two seedlings with approximately 25 g each were tied in the substrates for each meter of longline. Management was performed by the farmers from APAFG, under our guidance. Production cycle was 45 days, from July to September 2017. Wet mass of each seedling were determined at planting and harvesting, using a 1 g precision scale (Tomate model SF-420). Seedlings grew from 25 ± 6 g to 319 ± 135 g (Fig. 1B). Productivity was calculated in wet and dry mass by dividing the total harvested biomass by the longline length and expressed in $kg.m^{-1}.cycle^{-1}$.

2.2. Procurement of data to assess environmental sustainability

The seaweeds, water, and sediment from the pilot farming were analyzed to obtain data for determining the sustainability indicators. Samples of the seaweeds, water and sediment were obtained at the seedling, middle of culture, and harvesting to determine the content of total nitrogen, phosphorus, carbon, and energy. Water and sediment were sampled under the long-lines and at a control spot, 100 m distant from the farm. Tripton samplers were used to collect sediment and evaluate sediment deposition below the longlines. Each sampler is comprised of six 1.876-L PVC tubes, 9.7 cm in diameter and 25.4 cm long, with a total area of 0.045 m^2 (David et al, 2017). Tripton samplers were installed at ~1 m under the long-line rope and in the control spot for 24 h.

The seaweed samples were frozen and stored at −18 °C. In the laboratory, they were unfrozen, homogenized, and subjected to laboratorial analyses. For dry mass determination, the seaweed samples were weighed on an analytic scale (Shimadzu, 0.1 mg), dried in a forced circulation oven (Nova Etica, 400-6ND-200C) at 60 °C for 48 h, and weighted again. The proportion of dry mass was calculated and used to convert the production and productivity from wet mass to dry mass. For determination of nitrogen, phosphorus, carbon and energy content, seaweed samples were weighed on an analytical balance (Mettler Toledo AT21, precision 1 μg), oven dried at 95–100 °C, and weighted again (AOAC, 1995, method 934.01). The total nitrogen and total carbon contents were determined in an elemental analyzer (LECO CN 628) by high-temperature combustion as the Dumas principle method analysis. Total phosphorus was determined by the metavanadate colorimetry method, after samples were incinerated in a muffle furnace for 4 h at 550 °C (Michelsen, 1957). Energy content was determined by combustion the samples in an isoperibol calorimeter (IKA C2000 basic).

Total suspended solids (TSS) in water were measured according to APHA (2005, method 2540B). Total nitrogen and carbon in water were determined using a TOC-N elemental analyzer (Vario TOC Select analyzer Elementar®) after water samples were decanted for 3 h. This method uses the oxidation process in catalytic combustion. Total phosphorus was determined by using the persulfate digestion method (APHA, 2005, 4500-P.B5) to convert all phosphorus associated with organic matter in orthophosphates. Then, the orthophosphates was measured using the stannous chloride method (APHA, 2005, 4500-P D) and a digital spectrophotometer (Hach Model DR-2500, Hach Company).

Table 1
Characteristics of the *H. pseudomusciformis* farming simulated for the study of social and economic sustainability. Productivity is the real data obtained experimentally and reported as seaweed dry mass. All other values are projected.

Variable	Values
Total farm area (ha)	7.5
Cycle time (days)	45
Cycles/year	8
Long-lines/cycle	150
Seaweed productivity ($kg.m^{-1}$)	0.1
Annual production ($kg.year^{-1}$)	6000

The content of nitrogen, phosphorus, carbon and energy in the sediment were obtained by the same methods used for seaweed, described above. The accumulation of particulate material as a consequence of the culture was estimated by the difference between the sediment accumulated bellow the long line and the sediment accumulated in the control spot. The daily sediment rate was estimated by the mean of 3 samples obtained during the culture and used to compute the total material deposited during the 45 days of culture.

The total carbon content in the seaweed biomass at harvest minus the initial total carbon content in the seedlings was used as a proxy of the C stocked from the environment by the culture. The C stocked in the biomass was multiplied by 3.67 that is the molecular weight ratio of CO_2 to C to obtain the potential CO_2 absorption, according to Pendleton et al. (2012). This value was used to compute the indicator Potential of Global Warming (PGW) and the monetary value of the externality credit of carbon. In a similar manner, we estimated the quantity of nitrogen and phosphorus removed from the environment.

2.3. Procurement of data to assess social and economic sustainability

Socio-economic data were obtained from the APAFG members to assess social and economic sustainability of *H. pseudomusciformis* farming. The study was authorized by the ethics committee for research involving humans and traditional knowledge (CAAE: 91801118.0.0000.5466). A semi-structured questionnaire, developed by the authors (Appendix B), was answered by 6 producers. This information was complemented by local diary observations and a survey of the supply costs at the local and general market. In addition, data about the local population, such as gender, race, ethnicity, and mean income in 2017 were obtained from the official source of "Instituto Brasileiro de Geografia e Estatística" (Brazilian Institute of Geography and Statistics, IBGE).

These socio-economic data were combined with the production data obtained in the pilot trial to simulate farm to produce *H. pseudomusciformis,* considering a typical scale of an algae family-farm in the region. The planned farm occupied occupy 7.5 ha in ocean and 50 m^2 in land, comprised of 150 long-lines with 50 m each, performing eight production cycles per year (Table 1). Costs, revenues, labor and other parameters estimated for this simulated farm were used to calculate the economic and social indicators. All costs were acquired in the Brazilian market in the first semester of 2018, in Brazilian currency (Reals) and converted into US$ dollars. The exchange rate was US$ 1.00 = R$ 3.42 on 10 April 2018.

Table 2

Environmental indicator of *Hypnea pseudomusciformis* farming. Negative values indicate sequester of carbon and reduction on the organic carbon on effluent. Indicator values are showed in relation to the tonnes of algae produced or in percentage.

Environmental indicators	Value	Unit
Use of space (S)	1.25	$ha.t^{-1}$
Dependence on water (W)	0.00	$m^3.t^{-1}$
Use of energy (E)	2.61	$MJ.t^{-1}$
Proportion of renewable energy (PRE)	100	%
Use of nitrogen (N)	2.86	$kg.t^{-1}$
Use of phosphorus (P)	0.13	$kg.t^{-1}$
Efficiency in the use of energy (EE)	383	%
Efficiency in the use of nitrogen (EN)	894	%
Efficiency in the use of phosphorus (EP)	1,860	%
Production actually used (PU)	100	%
Potential of eutrophication (PE)	1.01	$kg.t^{-1}$
Potential of organic pollution (POP)	−5.20	$kg.t^{-1}$
Potential of siltation (PS)	8.37	$kg.t^{-1}$
Potential of global warming (PGW)	−851.63	$kg.t^{-1}$
General Chemical Pollution (GCP)	0.00	$kg.t^{-1}$
Pollution by hormones (PH)	0.00	$kg.t^{-1}$
Pollution by heavy metals (PHM)	0.00	$kg.t^{-1}$
Accumulation of phosphorus (AP)	6.17	$kg.t^{-1}$
Accumulation of organic matter (AOM)	0.69	$kg.t^{-1}$
Accumulation of particulate material (APM)	3,189	$kg.t^{-1}$
Risk of farmed species (RFS)	1	

Initial investments were US$ 25,012.00, considering costs with longlines, installation, boat, vehicle, other minor expenses, and project cost. The production cost corresponded to US$ 43,537.00, which was the sum of fixed and variable costs. The fixed costs (FC) included vehicle property tax, maintenance, depreciation, and opportunity costs. We used the straight-line method to calculate depreciation (Engle, 2010). The variable costs (VC) included supplies for production, eventual labor, fuel, packing, taxes, and general expenses. The tables of the investment and total costs used to the economic analysis are in Appendix A.

The sustainability economic indicators were computed considering macroalgae will be sold to human consumption. Details of costs, revenues and market are showed in the neoclassical economic analyses provided by Pereira et al. (2020b). However, to compute the indicators of economic sustainability the project horizon should correspond to one human generation (20 years), positive and negative externality economic-values should be added to gross revenue, and expenses, respectively, and new indicators are added (Valenti et al., 2018).

Positive and negative externalities were assessed in the pilot farming. A list of possible externalities was developed based on the literature and our previous experience. The ecosystem services provided by the *H. pseudomusciformis* farming was counted as possible positive externalities. Ecosystem services were sorted into supporting, regulation, provisioning, and cultural functions (Groot et al., 2002). Reduction of extractive area, negative impacts on the environment and on the local community, and spatial conflicts were considered as possible negative externalities. Most of the positive externalities identified, were not monetized because of the lack of consistent data. In the present study, we monetized nitrogen, carbon, and phosphorous, considering the credit values provided by Chopin et al. (2010); the values were US$ 10 kg^{-1}, US$ 0.03 kg^{-1}, and US$ 4 kg^{-1}, respectively. Surprisingly, the price of carbon sequester shows an enormous variation in the international market, ranging from US$ 1 to US$ 127 t^{-1}, which add difficulties to choose the value for the analyses (World Bank Group, 2019).

3. Results

3.1. Environmental indicators

The environmental indicators of *H. pseudomusciformis* farming showed a minimum use of resources like space, energy, and phosphorus (Table 2). There was 383% of efficiency in the use of energy, and the proportion of renewable energy was 100%. The farming did not use inputs like fertilizers, chemistries, or fuel for a motorboat, so the energy considered to calculating these indicators were from seedlings and labor. The efficiency in the use of phosphorus was 3189%. The seaweed farming presented no pollution potential, and sequestered −851.63 kg of CO_2 by each tonne of algae dry-matter produced. Despite the low potential of siltation, the activity showed a 1857 $kg.t^{-1}$ accumulation of particulate material but only 0.69 $kg.t^{-1}$ corresponded to organic matter. The risk of farmed species was 1, the lowest level in the risk scale established in Valenti et al. (2018).

Table 3

Social indicators of *Hypnea pseudomusciformis* farming (US$1.00 = R$ 3.42). MH = Men-hours; MHY = Men-hours by year.

Social indicators	Value	Unit
Development of local economy (LE)	51	%
Use of local workers (LW)	100	%
Remuneration of work per unit of production (RLUP)	9.58	$US\$.kg^{-1}$
Investment to create direct employment (ICDE)	1471.31	$US\$.job^{-1}$
Investment to create total employment (ICTE)	1471.31	$US\$.job^{-1}$
Proportion of self-employments (SE)	100	%
Permanence in the activity (PA)	16	years
Required work per unit of occupied area (WA)	0.26	$MHY.m^2$
Required work per unit of production (WP)	3.26	$MH.kg^{-1}$
Safety at workplace (SW)	43	%
Local consumption of production (LC)	26	%
Pay equality (PE)	100	%
Proportion cost of work (PCW)	27	%
Income distribution (ID)	26.85	US$
Access to health-insurance programs (AHP)	0	%
Schooling (Sc)	100	%
Participation in outside community activities (PCA)	100	%
Gender inclusion (GI)	89	%
Racial inclusion (RI)	74	%
Age inclusion (AI)	72	%

3.2. Social indicators

Social indicators showed that 51% of the investment and operating expenditures is spent in local market. In addition, labor is totally recruited in the local community (Table 3). This farming requires 3.26 MH by each kilogram of dry seaweed produced and an investment of US $ 1471.00 for each job created. Safety at the working place is 43%, corresponding to the presence or absence of security practices and items. Only 26% of the consumption of the product is local. The income distribution is equal among workers, once the farm is organized as an association. However, there is no access to workers to social benefits, except for outside community activities. The activity is inclusive; indicators of gender, racial and age inclusion showed values higher than 70%, based on the proportion of the minority in the enterprise and the minority in the local community.

3.3. Economic indicators

The farm impacts generated could be calculated as positive or negative externalities and added or subtracted from the income. No negative impacts as chemical, organic, and visual pollution were recognized, but sediment retention. However, it was not monetized. Also, there is no reduction of extractive area and negative impacts on the local community or spatial conflict. Therefore, the enterprise presented no negative externalities (En). On the other hand, we observed several ecosystem services provided by *H. pseudomusciformis* farming, such as the provision of protection and habitat for small invertebrates and fishes, production of high-quality food, regulation of eutrophication, and reduction of coastal acidification. In addition, the farm presented cultural services, such as recreation, contribution to science and education, cultural heritage, inspiration for the community and inclusion of

Table 4

Ecosystem services provided by the seaweed *Hypnea pseudomusciformis* farming studied.

Ecosystem service		Impact	Explanation of impact
Supporting	Primary production	+	Seaweeds are autotrophic organisms.
	Food web dynamics	+	As primary producers, they provide food for other organisms.
	Biodiversity	+	Presence of organisms as small invertebrates and fishes associated to farming.
	Habitat	+	Seaweed provides protection and habitat for organisms.
Regulating	Atmospheric regulation	+	Carbon uptake by seaweeds.
	Climate regulation	+	Reduction of coastal acidification.
	Sediment retention	–	Change on sedimentation rate in the cultivation area.
	Hydrodynamics modification	None	Change in the coastal ocean flow.
	Regulation of eutrophication	+	Uptake of P by seaweeds.
Provisioning	Food security	+	Production of high-quality food for the local community and workers.
	Raw material, chemical resources and energy	+	Increased biomass by cultivation.
	Genetic resources	+	Local strain conservation by farming.
	Chemical resources	+	Production by cultivation.
	Energy (from biomass only)	+	Production by cultivation.
	Space and waterways	None	Competition with other activities for space.
Cultural	Recreation	+	Aesthetic values and nuisance.
	Aesthetic values	None	Disturbance to viewer.
	Science and education	+	Contribution to science and education.
	Cultural heritage	+	Contribution to active coastal villages.
	Inspiration	+	Provision of inspiration to research, business ideas and sustainability solutions.
	Inclusion	+	Provision of work for women.
+	= positive impacts expected		
–	= negative impacts expected		
None	= no impact expected		

Table 5

Annual economic indicators of the *Hypnea pseudomusciformis* farming estimated (US\$1.00 = R\$ 3.42). *e*: indicates that the monetary values of the externalities were included in the computation. Externalities were computed as monetary value by tonnes of algae produced.

Economic indicators	Value	Unit
Ratio between net income and initial investment (RII)	210	%
Internal rate of return (IRR*e*)	119	% a.a.
Payback period (PP*e*)	1.2	years
Benefit-cost ratio (B/C*e*)	15.17	US\$
Net present value (NPV*e*)	352,075	US\$
Net profit (NP*e*)	45,756	US\$
Negative externalities (Em)	0	US\$.t^{-1}
Positive externalities (Ep)	262	US\$.t^{-1}
Annual income (AI)	52,547	US\$
Permanence of the farmer in the activity (PA)	16	years
Risk rate (RR)	18	%
Diversity of products (DP)	1	unit
Diversity of markets (DM)	5	unit

women in work. Ecosystem services observed in the present study were classified into four categories and listed in Table 4. The present study quantified nitrogen, carbon, and phosphorus retention and valued the credits. The absorptions of nitrogen were 137 kg.year^{-1}, carbon dioxide was 5126 kg.year^{-1} and phosphorus was 13 kg.year^{-1}. These nutrients absorption may generate positive externalities (Ep) that value 262 US\$.t^{-1}. This value was included as an income and was summed to the gross revenue from seaweed biomass sales.

The farm presented a high level of capital efficiency and profitability. The indicator ratio net income and initial investment (RII) was 210%, the internal rate of return (IRR) was 119%, the capital invested in the activity took 1.2 years to return (Table 5). The farm showed the capacity of continuity in the aquaculture sector with a positive annual income (AI) and 16 years of the permanence of the farmers in the activity (PA). The diversity of products (DP) was 1, which corresponds to dried seaweed. However, the product has a variety of markets (DM) of 5: human consumption, carrageenan extraction, animal food additive, fertilizer, and cosmetic industries. Therefore, the activity shows a high capacity for resilience to adversities.

4. Discussion

The indicators of sustainability calculated in the present study demonstrate that the *H. pseudomusciformis* farm may be not only environmentally, but also socially and economically sustainable. The present farming assimilates energy, nitrogen, phosphorus and carbon from the environment, sequester carbon from the atmosphere, does not generate any pollution and the amount of sediment accumulated is low. In addition, this species is native from South Atlantic West coast (Yokoya et al., 2020), which avoids the risk of liberating exotic genes in the environment. Besides, *H. pseudomusciformis* culture generates work positions and income for local communities, promotes gender, racial and age inclusion and contributes to improve the local economy and food security. The activity is economically feasible, profitable, resilient, and generates positive externalities. Although seaweed culture is generally referred to as sustainable production systems, just one study in the world has obtained and analyzed data on the sustainability of the macroalgae farm. Taelman et al. (2015) assessed the Life Cycle Assessment of Saccharina latissima farm, however, this study not include social and economic aspects. Therefore, the current work is the first that quantified different features to assess the sustainability of a seaweed culture, considering the three dimensions.

H. pseudomusciformis farming demands large space to produce a tonne of algae: 1.25 ha for 8 cycles of 45 days, which means ~6 t.year^{-1} of dry biomass, considering an interval between cultures of 15 days. This area is larger than those used in other inland aquaculture systems to produce food. For instance, 0.001 ha are necessary to produce a tonne of Nile tilapia during 150 days in net-cages placed into a reservoir located in the same region that the present study was performed (Moura et al., 2016); this means ~0.006 ha to produce 6 t/yr, considering 30 days between culture cycles. However, farming *H. pseudomusciformis* requires marine area, which does not compete with the space used for other kinds of food production, does not use fresh water, which generally occurs in the culture of tilapia or other inland aquaculture systems used to produce food. Taelman et al. (2015) showed that seaweed production in Europe requires less land resources when compared with microalgae and some terrestrial vegetable crops with similar moisture content, which seems that marine biomass can reduce pressure on land.

H. pseudomusciformis farming extracts a large amount of nitrogen, phosphorus, and carbon (22.69 kg.t^{-1}, 2.23 kg.t^{-1}, and ~232 kg.t^{-1}, respectively) from the environment. The only input of these nutrients in the culture was the content in the initial biomass of seedling. Chopin et al. (2010) showed monetary values to pay for ecosystem services for nitrogen, phosphorus and carbon absorption, which corresponded to 10 US\$.kg^{-1}, 4 US\$.kg^{-1}, and 0.03 US\$.kg^{-1}, respectively. Considering these values, the present study accounted for a credit of US\$ 262.00 by each tonne of algae produced as credit for ecosystem services, which represents ~2% of the gross revenue. In addition, the study demonstrated that at least ten other ecosystem services might be monetized and increase the gross revenue if paid by government or private sector. On the contrary, seedlings collection in natural banks may be a negative externality. However, *H. pseudomusciformis* (former "*musciformis*") shows great callus formation and stem regeneration potential (Bravin et al., 2006). These characteristics are essential morphogenetic processes for the success of micropropagation (Bravin et al., 2006). Therefore, obtaining seedlings by vegetative propagation, which was previously demonstrated by the authors (unpublished data), should be considered. That practice avoids natural seaweed banks depletion and may even protect them from the illegal catches.

In *H. pseudomusciformis* farming, all biomass-produced is used, and thus, no waste is produced. Seaweeds are nutritious and functional human food, rich in soluble dietary fibers, proteins, minerals, vitamins, antioxidants, phytochemicals, and low caloric polyunsaturated fatty acids (Ganesan et al., 2020; Macartain et al., 2007; Mohamed et al., 2012). The large-scale production of seaweeds for human food consumption may transform the global scenario of food security (World Bank Group, 2016). Algae also supply the vegan market, which is increasing all over the world (Jones-Evans, 2018).

Farming a native and local seaweed species contributes to the protection of biodiversity and genetic conservation. For example, Visch et al. (2020) observed an increase in diversity and abundance of benthic infauna at *Saccharina latissima* farming site in Swedish west coast. Conversely, the culture of alien species may cause environmental damage, such as have been observed with the introduction of *Kappaphycus alvarezzi* outside its natural geographic distribution (Chandrasekaran et al., 2008). *H. pseudomusciformis* is native from tropical South-Atlantic West coast (Yokoya et al., 2020), and therefore its culture may be beneficial for the marine environment, as they are a food source for some herbivorous species and provides habitat for small invertebrates like amphipods, juveniles of crustaceans, mollusks, and fishes (Berchez et al., 1989). The farming technique does not use nets, avoiding the risk of accidental capture of local fauna.

The longlines may impair the regular water movement and increase sedimentation in the farm area. We estimated that 3189 kg of particulate matter (mostly inorganic) accumulated in the bottom by each tonne of algae produced. This sediment retention could affect sediment deposition in the beach area, once the particle stays in the farm area. Therefore, it was assumed as a negative impact, i.e., an ecosystem disservice. More studies are necessary to understand the consequences of this sediment retention in the coastal zone. We suggest the rotation of farm structures in the area to minimize this impact. Zehua et al. (2016) observed that large-scale culture of *Laminaria japonica* reduced in average ~50% of currents flow velocity and changed sedimentation patterns in Heini Bay, China. In the present study, we noted that sedimentation did not display a considerable impact on the environment. Changing coastal currents dynamics and sedimentation may be more relevant in large-scale farms (Zehua et al. 2016). The *H. pseudomusciformis* farming may not affect the ocean hydrodynamic as *L. japonica* farming because of its production system is different: the latter uses vertical ropes and the former, horizontal ones. The present study did not observe hydrodynamics modification, and thus, it was assumed that this variable did not impact the environment. Studies should investigate the benthic community below the long-lines to confirm these assumptions.

The *H. pseudomusciformis* farm analyzed used only renewable energy corresponding to 2.61 MJ by each tonne of product. This value is the sum of seedlings and labor. Approximately four-fold of this high-quality energy consumed in the process were recovered in the algae biomass by conversion of solar low-complexity energy to high-quality energy (Odum, 1973 *sensus*). Thus, the efficiency is almost 400%. However, fossil energy will be necessary as fuel for boats and probably energy to dry the algae in large cultures. The high human-labor energy used in the culture indicates high demand for human work and consequently the creation of work positions, which is very positive for the social dimension of sustainability (Valenti et al., 2018).

Social indicators showed that the farm contributes positively to create job positions and develop the local economy. Most of expenditures are spent in the local market and all workers are local residents. The labor demand by occupied area was low, but labor demanded by the production unit was high. These are a consequence of the low productivity of the seaweeds. The profit is shared equally between workers. However, worker health may be negatively affected by intense manual labor with physical efforts and exposures to the sun and sea dangers (Fröcklin et al., 2012). Once seaweed farming is highly time-consuming and sometimes cannot conciliate with other economic activities, some communities are not interested in this activity when the income is low (Cooke, 2004). The present study showed that *H. pseudomusciformis* has a high market value, which allows farmers obtain higher income than the average household income in the same municipality. Perhaps, this scenario allows the satisfaction of the farmers with their work. Half of the expenses to maintain the *Hypnea* farm are spent in local commerce, and thus, move and develop the local economy. However, the local consumption was less than 50%, which is low for the food security. Local consumption of *H. pseudomusciformis* is low because the resident people do not have the culture to consume seaweed; the major consumers are tourists. Despite this, the algae culture increases the household income and consequently the buying power and food security of the farmers.

H. pseudomusciformis farming promotes other social benefits beyond income. This business is inclusive, especially concerning gender. Seaweed farming may be participated in by women and men, however, exist a gender consideration for physical strength for the distribution of responsibilities in seaweed farming were the women do less physically straining as seedling preparation and men do farm construction and management (Suyo et al., 2020). In the farm studied, both men and women work in the seaweed farm and this gender work distribution were recognized. In some regions, the farming stays away from the houses and the woman's work can depart the mother from homes that may dislocate kids from the school (Kronen et al., 2010). The present study did not evaluate the school access of sons and daughters of workers but assessed the schooling of workers. All of them receive training and other non-formal education by non-governmental organizations and universities, which increases their skill and, consequently the sustainability of the system. Spatial conflicts were not observed in the studied farm, although it is common in coastal maricultures (Alleway et al., 2019). Local people do not perceive any negative aesthetic view and the seaweed culture attracts tourists, actions of non-governmental organizations and research institutions, increasing interactions of the local population and social development. The time of permanence in the activity is high, and middle-aged adults are the most representative workers. Farming is installed in a tourist area, and tourism-linked jobs could be more attractive for young adults than seaweed cultivation (Namudu and Pickering, 2006), which may be a future problem for farming activity permanence. However, the seaweed farm fascinates the tourists, and it is a huge opportunity to explore the farm as a tourist attraction, with boat visits and environmental education activities.

H. pseudomusciformis farming showed a list of positive ecosystem services generated in supporting, regulation, provisioning, and cultural aspects. Our results showed more positive impacts than obtained by Hasselström et al. (2018) to seaweed cultivation in the west coast of Sweden. Different from Hasselström et al. (2018), we obtained a negative impact of sediment retention and positive impacts of cultural services, which were negative in their study. In addition, the present study quantified the nitrogen, carbon, and phosphorus credits that turns in receiving a monetary return for positive externalities, which resulted in increased revenue. *H. pseudomusciformis* shows the potential to generate more positive externalities values in addition to the three services calculated. Externalities are an essential value in neoclassical economics

(Gómez-Baggethun et al., 2010), so further studies in this area should be done. Rewards obtained for environmental and social services is an economic incentive to encourage farmers to develop and implement sustainable practices (Chopin et al., 2010). Porras et al. (2015) showed that the payment for ecosystem services in smallholder agriculture, specifically carbon financing, may increase sustainability. The environmental compensation may be attractive to the community according to the kind of the product, and thus, adjustments in the monetary values should be made for each production sector (Yang et al., 2018). Another challenge is the lack of governmental payment for ecosystem services in some countries (Schomers and Matzdorf, 2013). This situation may be compensated by the establishment of private in-country exchange trading, in which large companies pay for environmental compensation of their activities or give to the farms access to an international platform for environmental services trading.

Economic indicators showed high efficiency in the use of investments, fast return on capital, and profitability. The *H. pseudomusciformis* farming was an attractive enterprise, because it showed a high ratio between net income and initial investment (210%) and internal rate of return (190%). The first variable is suitable to assess the attractivity to small farmers, whereas the second one is useful for investors. The farm allows the permanence of people in the aquaculture sector and shows resilience to changes in scenarios. The APAFG has 16 years of existence, which is high for aquaculture enterprises, showing that farming seaweeds is a stable activity in the community. The farmers can explore market diversity, such as human food, carrageenan extraction, animal food additive, fertilizer, and cosmetic industry. These market opportunities allow farmers to explore more than one market, enhancing the resilience of the activity. However, the activity is still risky because of the lack of a well-established market for native seaweed and consistent planning for the algae culture in Brazil. The farmer association may establish regular activities of ecological or educative tourism to attract youngsters and secure the permanence of members of the community in the activity, increase revenues, and improve socio-economic sustainability. Another farm risk is the grazing by herbivore animals like turtles and marine gastropods, as the system does not use protection nets. The *H. pseudomusciformis* grazing intensity will vary according to the natural food available to herbivorous animals and their presence in the farming area (Berchez et al., 1989). In the present study, we observe that turtles prefer to eat *Gracilaria birdiae* than *H. pseudomusciformis*. No negative impact of grazing in productivity was observed during the study and the farmers reported rare cases of herbivory.

In the present study, the quantification of several features of the *H. pseudomusciformis* culture allows the computation of sustainability indicators. They confirmed the hypothesis that *H. pseudomusciformis* culture may have environmental, social, and economic sustainability. Therefore, this activity can be a sustainable way to produce high-quality human food and raw materials for the cosmetic and agricultural industries. Similar results might be obtained for the culture of other seaweed species. Further studies should be performed to confirm this hypothesis. The results obtained in the present study provide secure information for farmers, investors and policymakers, which may encourage small and medium farmers to start seaweed farming in tropical Atlantic West coast. This activity may contribute to socioeconomic development, producing food and raw material, with low impact on the marine environments.

Ethical statements

This article was authorized by the ethics committee for research involving traditional knowledge (CAAE: 91801118.0.0000.5466). This article does not contain any studies with animals performed by any of the authors.

Table A1

The initial investments to set up a farm comprised of a 50 m^2 land-based shed and 7.5 ha sea-based area with long-lines. (US\$1.00 = R\$ 3.42).

Items	Unit	Quantity	Price Unit (US $)	Total Cost (US $)	%
Long-line 50 m*	un	150	77.02	11,552.63	46.2
Braided rope*	kg	37.5	20.47	767.54	3.1
Anchor*	un	300	20.47	6140.35	24.5
Buoy*	un	300	1.46	438.60	1.8
Waterbox**	un	2	43.86	87.72	0.4
PET bottle	un	4050	0.00	0.00	0.0
Commercial Scale*	un	1	58.48	58.48	0.2
Knife*	un	1	7.31	7.31	0.0
Boat**	un	1	877.19	877.19	3.5
Life Jacket**	un	2	26.32	52.63	0.2
Shed***	un	1	584.80	584.80	2.3
Handling table*	un	1	397.66	397.66	1.6
Drying table**	un	4	146.20	584.80	2.3
Vehicle**	un	1	2046.78	2046.78	8.2
Project cost	%	6		1415.79	5.7
Total				**25,012.00**	**100**
Total (US$/ha)				**3331**	

* Useful life estimated at 5 years.

** Useful life estimated at 10 years.

*** Useful life estimated at 15 years.

Table A2

Annual production costs (US\$) and the percentage (%) of total cost (US\$1.00 = R\$3.42).

Items description	Unit	Price/ Unit (US $)	Quantity	Total Cost (US$)	%
Variable cost				**31,973.45**	**73.4**
Ribbon	kg	3.51	120	421.05	1.0
Cotton yarn	kg	5.70	24	136.84	0.3
Eventual labor	person-day	14.62	800	11,695.91	26.9
Fuel	L	1.23	32	39.20	0.1
Kraft paper bag	unit	0.01	60,000	350.88	0.8
Rural Social Security Special Contribution[a]				2017.54	4.6
Tax on the sale of the product[b]				15,789.47	36.3
General costs[c]				1522.55	3.5
Fixed cost				**11,563.46**	**26.6**
Vehicle property tax*				81.87	0.2
Maintenance**				471.93	1.1
Annual depreciation				4218.66	9.7
Interest on working capital[d]				1789.00	4.1
Remuneration on fixed capital[e]				1375.68	3.2
Remunerations of the entrepreneur				3626.32	8.3
Total Cost				**43,536.90**	**100**

*4% of vehicle value. **2% of investments; a 2.3% of gross revenue; b 18% of gross revenue; c 5% of variable cost; d 8.75% a.a. on half of the effective operational cost; e 12% on half fixed investments.

CRediT authorship contribution statement

Stefany A. Pereira: Conceptualization, Methodology, Investigation, Writing - original draft. **Janaina M. Kimpara:** Conceptualization, Methodology, Investigation, Visualization, Investigation, Writing - review & editing. **Wagner C. Valenti:** Conceptualization, Methodology, Project administration, Funding acquisition, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

See Tables A1 and A2.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2020.107101.

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