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A perspective for reducing environmental impacts of mussel culture in Algeria

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Abstract

Purpose In Algeria, the Ministry of Fisheries and Halieutic Resources has designed a strategic plan for the development of marine aquaculture for the years 2015–2025, which aims at expanding the annual production of Mediterranean mussel from less than 150 metric tonnes year^{-1} in 2013 to 7600 metric tonnes year^{-1} in 2025. We used Life Cycle Assessment (LCA) for evaluating the environmental impact of suspended mussel culture in Algeria and suggest management practices which could reduce it.

Methods In order to estimate the current and perspective impact of this industry, we (1) applied LCA to one of the few farms currently operating in Algeria and (2) investigated two management scenarios for the farms to be established in the future in the same coastal area. The first scenario (Comp_S) represents the continuity with the current situation, in which each farm is competing with the other ones and is therefore managing the production cycle independently. In the second scenario (Coop_S), mussel farms are grouped in an aquaculture management area and shared the same facilities for post-processing harvested mussels before sending them to the market. The midpoint-based CML-IA method baseline 2000 V 3.01 was employed using SimaPro software. Furthermore, we carried out a Monte Carlo simulation, in order to assess the uncertainty in the results.

Results and discussion The analysis focused on impact categories related to acidification and global warming potential. We took into account the energy consumptions (electricity and vessel fuel), the rearing infrastructure, including longlines, and a building for stabling, grading, and packing the mussel. Electricity contributes with 38.1 and 31.8 % respectively to global warming potential (GWP) and acidification, while fuel consumption contributes with 19.5 % to GWP and 31.8 % to acidification. Results of this work are compared with other LCA studies recently carried out in France (Aubin and Fontaine 2014) and in Spain (Iribarren et al. 2010c).

Conclusions The LCA results show that important reductions in environmental impacts could be attained if the mussel farming activity would be operated according to the cooperative scenario here proposed. In this case, the environmental benefits will be a reduction of 3150 MJ and 156 kg CO_2 eq per metric tonne of mussel produced, compared with the alternative scenario. The results of this study suggest that LCA should be applied to the seafood production sector in Algeria, in order to identify best management practices.

Keywords LCA · Mussel · Algeria · Environmental performance · Uncertainty

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1 Introduction

In the last decades, the demand for seafood has been steadily increasing, thus stimulating the development of aquaculture worldwide (FAO 2014). In 2012, the global production of non-fed species from aquaculture was 13.4 million tonnes (FAO 2014). Sustainability is, however, a key issue for further expanding the aquaculture sector, which requires a comprehensive assessment of the environmental impacts of seafood production systems (Pelletier and Tyedmers 2007).

Life cycle assessment (LCA) is a widely accepted methodology to inform in the decision-making processes (Guinée et al. 2002; Fullana-i-Palmer et al. 2011). In the seafood sector, LCA can provide metrics for assessing sustainability indicators, in order to inform certification and eco-labeling criteria (Cao et al. 2013; Vázquez-Rowe et al. 2010; Vázquez-Rowe et al. 2016). According to Ayer et al. (2007), LCA of seafood production systems is a growing field of research, aimed at improving the efficiency and the environmental performances of fisheries and aquaculture systems and providing consumers with better information on the sustainability of seafood products.

There are already some examples in the literature concerning the application of LCA to non-fed aquaculture products and, in particular, to shellfish. Iribarren et al. (2010a, 2010b, 2010c) applied LCA to the mussel farming sector in Galicia (Spain). According to these authors, several improvements were identified in order to minimize the potential environmental impacts resulting from mussel farming and mussel processing in factories. They concluded that the results of their analysis were very useful for companies and governmental bodies in order to support decision-making.

Iribarren (2010) and Lozano et al. (2009, 2010) suggest the synergistic use of LCA and data envelopment analysis (DEA) as a methodological approach to link operational efficiency and environmental performance of mussel cultivation rafts in Galicia. Also, they claimed that this approach facilitates the interpretation of results and gives additional information in order to complement the LCA with the DEA: this is a well-known methodology, for assessing the relative efficiency of a set of comparable entities, known as decision-making units, with multiple inputs/outputs data by some specific mathematical programming models (Lozano et al. 2009; Samuel-Fitwi et al. 2012). Recently, Aubin and Fontaine (2014) used LCA to assess the environmental impacts of mussel farming in Mont-Saint-Michel Bay (France).

However, to our knowledge, there is no literature about LCA of seafood in Algeria and, in particular, on shellfish production. In this country, the Ministry of Fisheries and Halieutic Resources designed a strategic plan for the sustainable development of marine aquaculture (MPRH 2008), which is presently being implemented. This program aims at establishing 56 new Mediterranean mussel (*Mytilus galloprovincialis*) farms along the Algerian coast between 2015 and 2025: that would lead to an increase in production from less than 150 metric tonnes in 2013 to 7600 tonnes in 2025 (MPRH 2008).

In this paper, we used LCA as a tool for assessing the environmental impact of suspended mussel culture in Algeria, based on current husbandry practices. Our analysis was applied to the oldest and most important farm in Algeria. Based on the results of the analysis, we provide some suggestions for allocating to-be-established farms in order to minimize their impact, in compliance with the current Algerian legislation.

2 Methods

2.1 Background of the case study

Suspended longlines is, by far, the most common mussel cultivation system in Algeria and worldwide. However, previous LCA studies have focused on raft (Iribarren et al. 2010c) and "bouchot" (Aubin and Fontaine 2014) cultures.

In general, the rearing cycle starts in May–June with the collection of wild seeds on hard infrastructure of farms, such as cables and buoys where early juveniles (seed) can attach by means of their strong byssal threads (Lin et al. 2016), and from natural banks of nearby farms. In the grow out phase of the rearing cycle, seed is removed, placed in tubular nets, and attached to suspended longlines, which are kept at a depth of about 3–5 m by buoys. Mussels are then harvested the following year, starting in April, when they reach the market size of 4 cm.

Longline farms are made up of a series of vertically oriented ropes attached to parallel cables suspended by buoys which are located at the sea surface. Cable longlines are usually oriented parallel to the dominating current directions (Rosland et al. 2011), although different spatial arrangements can be adopted to maximize the production in relation to the specific conditions of the cultivated area (Ferreira et al. 2007; Brigolin et al. 2008). The main components of this system are the ropes, the flotation system (buoys), and the anchoring system (concrete anchoring blocks). According to Algerian legislation (MAP 1997), harvested mussels should be treated in a purposely fitted building, in order to remove potential fecal bacterial contamination. This building is also used for the subsequent operations of mussel grading.

In this paper, LCA was applied to one of the few mussel farms currently operational in Algeria, located at Ain Chrob, about 50 km from Algiers, 1 km off the coast (decimal degrees latitude = 36.797276; longitude = 3.314366). This farm, which accounted for about 30 % of the national production in 2013 (150 tonnes), was selected as representative of the current scenario, being the one producing with highest continuity in the last 5 years. The farm was designed for producing approximately 50 tonnes year^{-1}, and this figure was taken as a reference for the current scenario, CS. Subsequently, two scenarios of expansion of mussel culture in the same area were compared (Table 1), in which the target production is achieved by distributing new farms in two different ways, as shown in Fig. 1. The target production in the area was estimated on the basis of the total production foreseen by the ministerial plan for developing mussel culture in Algeria. As mentioned above, the strategic plan for the sustainable development of marine aquaculture in Algeria (MPRH 2008) targets the establishment of 56 new mussel farms between 2015 and 2025, distributed over 14 coastal *Wilaya* (departments). Assuming that these farms would be equally distributed among all coastal *Wilayas*, four more farms could be established in the Ain Chrob area, beside the one which is currently operating. This would allow to increase the production to 250 tonnes year^{-1}, as the license procedure presently in place in Algeria puts a cap of 50 tonnes year^{-1} to the productivity of each single farm. This cap is expected to be removed after a few years of operation, thus allowing to reach the target total production of about 500 tonnes year^{-1} per *Wilaya* in 2025, consistently with the strategic plan.

Two scenarios were analyzed, namely a "competitive" and a "cooperative" one. In Comp_S, each farm is assumed to compete with the other ones and, therefore, to carry out its activity independently, which implies the need of having one building per farm. In this scenario, it was assumed that buildings will be located at a distance of at least 3 km from the port, as the Ain Chrob area is undergoing a strong coastal urbanization process.

As reported in Table 1, each farm in Comp_S and Coop_S will use five longlines of 200 m, in order to reach a target production of 50 tonnes year^{-1} of Mediterranean mussel *M. galloprovincialis*. It was assumed that longlines would have the same design in the three considered scenarios (CS, Comp_S, and Coop_S).

In Coop_S, in accordance with the Code of Conduct for Responsible Fisheries (FAO 2011) and the guidelines on allocated zones for aquaculture (GFCM 2013), it was assumed that the five farms cooperate in an aquaculture management area, as proposed by FAO and GFCM (GFCM 2013; FAO/World Bank 2015). In this case, we assumed that farmers would share the same building and would use two boats for husbandry practices and that the building would be located at a distance of 3 km from the port.

2.2 LCA methodology

LCA was performed according to the ISO 14040 (2006) standards including the description of the following steps: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation. Furthermore, an individual-based population dynamic model was used (Brigolin et al. 2009) for estimating the flows of N and P during mussel cultivation. This allowed us to take into account the potential of nutrient removal, which is increasingly perceived as an important ecosystem service provided by shellfish farming (Lindahl et al. 2005).

2.2.1 Goal, scope definition, and functional unit

The goal of this research is to assess the environmental impacts of suspended mussel culture in Algeria in order to suggest management practices aimed at reducing its environmental impact. After performing an LCA on current practices, two alternative scenarios for the future development of mussel production described in Section 0 were investigated. The mussel production system in Algeria is schematically depicted in Fig. 2.

The function of the system is the production of mussels, *M. galloprovincialis*, using suspended longlines in seawater. Thus, the functional unit (FU) is 1 tonne (10^3 kg) of fresh Mediterranean mussels *M. galloprovincialis*, expressed as total wet weight (including shell).

A cradle-to-gate analysis was applied, taking into consideration the processes shown in Fig. 2, i.e., spat collection, mussel grow-out, harvesting, and treatment for commercialization. The latter treatment is limited to stabling mussels for controlled filtration in clean seawater, without using any chemical. Therefore, the construction of the building and the flows of energy and matter involved in mussel treatment after harvesting were included. Furthermore, in the grow-out phase, the flows of organic matter through the farm were taken into

Table 1 Different considered scenarios to produce suspended mussel

	Current scenario (CS)	Competing scenario (Comp_S)	Cooperating scenario (Coop_S)
Annual production (tonnes)	50	250	250
Number of farms	1	5	5
Total number of suspended lines	5	25	25
Length of each longline (m)	200	200	200
Number of buildings	1	5	1
Distance between buildings and the port	150 m	3 km	3 km
Distance between farms and port	1 km	2 km	2 km

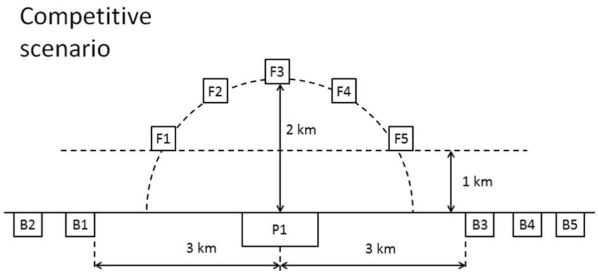

Fig. 1 Schematic figure of a hypothetical aquaculture management area (AMA) with five mussel farms (*F* mussel farms, *P* port, *B* building)

consideration, due to mussel filtration activity, using a dynamic simulation model (Brigolin et al. 2009). Waste treatment, boat, and farming equipment production, i.e., machinery production involved in mussel treatment after harvesting, were excluded from our analysis due to data unavailability.

2.2.2 Life cycle inventory (LCI)

The primary data for the current scenario, i.e., the production of 50 tonnes of Mediterranean mussel by the Ain Chrob farm, were estimated on the basis of interview with shellfish farmers, as summarized in Table 2. This information was used also for extrapolating the material and energy requirements concerning the two scenarios Comp_S and Coop_S, which were estimated by upscaling the number of suspended lines, the number of operating boats, and the number of buildings. Distances between farms and port were also taken into account, based on the hypothetical spatial arrangement shown in Fig. 1.

On-site operations are performed using an aluminum boat (14 m length), specifically designed for mussel culture. The longlines are made of polypropylene ropes. Polyethylene is the main component of floats. Concrete and steel are used both in the building construction and the anchoring block conception.

Life spans of materials specific to mussel culture were taken from the literature (Iribarren 2010): 10 years for textile materials and ropes, 20 years for floats and anchoring blocks, 25 years for the farming equipment, and 25 years for the building. Secondary data were taken from the ecoinvent database version 3 (Wernet et al. 2016).

Electricity consumption is due to the use of seawater pumps and different equipment inside the building. The yearly amount of fuel and electricity consumption was estimated on the basis of the data, concerning the year 2014,

Fig. 2 System boundary used in the LCA of suspended mussel production in Algeria

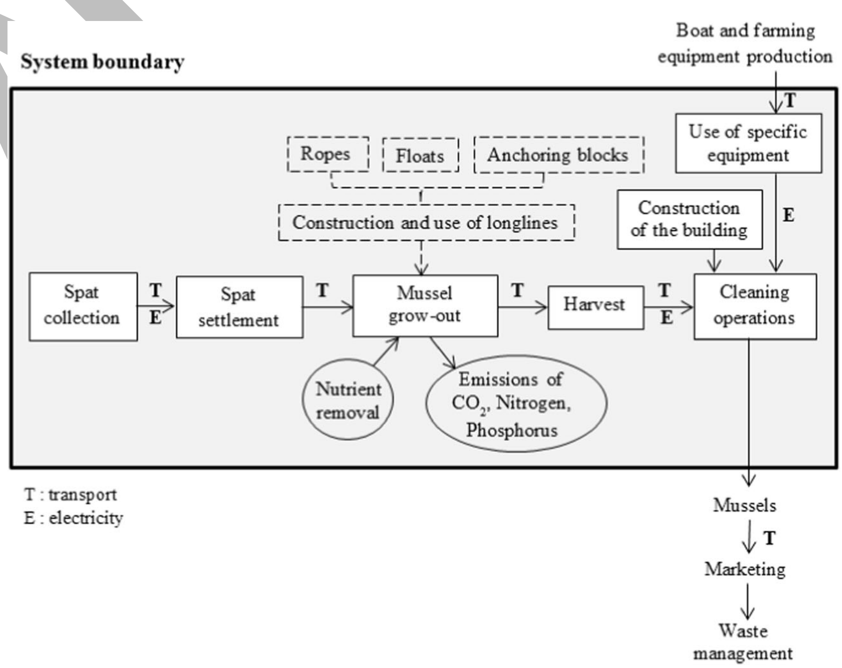

Table 2 Inventory of main data to produce 1 tonne of suspend mussel (expressed as total wet weight including shell) according to the different scenarios

Inputs	CS	Comp_S	Coop_S
Land use (m^2 a)	10	10	3.2
Seawater (m^3)	24,000	30,030	30,030
Materials and fuel			
Polypropylene (kg)	5.47	5.47	5.47
Polyethylene (kg)	3.8	3.8	3.8
PVC (kg)	5.09	5.09	5.01
Cotton (kg)	0.32	0.32	0.32
Steel (kg)	27.16	27.16	17.79
Concrete (kg)	246.64	246.64	94.12
Gasoline for boat (kg)	93.36	168.72	74.68
Energy			
Electric energy (kWh)	227.36	227.36	113.68
Outputs			
Product			
Mussel (tonne) (total wet weight including shell)	1	1	1
(+Emissions to water; −farm uptake)			
Carbon (kg)	−44.33	−44.33	−44.33
Nitrogen (kg)	−0.16	−0.16	−0.16
Phosphorus (kg)	+0.05	+0.05	+0.05

provided by the shellfish company. As reported by Bélaid and Abderrahmani (2013) in Algeria, the electricity market is held almost entirely by the national company SONELGAZ and the coverage of the country by the power grid is at 98 % with a capacity of 11,325 MW through 2009. This network has over 6.5 million customers. For the past few years, Algeria's electricity demand has been increasing fast, mainly due to expansion of economic activities and population growth (Bélaid and Abderrahmani 2013). Akbi et al. (2016) reported that the most part of electricity production in Algeria comes from gas power plants (gas turbine, steam turbine, combined cycle, and diesel). According to this authors, in 2013, the share of thermal power accounted for over 99 % of the electricity produced. In Algeria, despite the significant renewable energy potential (Stambouli et al. 2012), the Ministry of Energy (2016) reported that in 2015 wind and solar energies account for only 0.05 % of the electricity production.

2.2.3 Inventory of C, N, and P fluxes between cultivated mussels and the surrounding marine environment

Flows of N and P were quantified on the basis of the results of the individual-based population dynamic model by Brigolin et al. (2009). The model simulates the metabolic activity of *M. galloprovincialis* farmed population and the associated fluxes of C, N, and P. The daily amounts of C, N, and P excreted as feces and pseudofeces and in dissolved form and those ingested by mussels were quantified by the model. These quantities depend on mussel size and water temperature and, therefore, change during the mussel grow-out phase. Consequently, we integrated these flows along a typical farming cycle of 10 months, in order to draw a complete picture of the farm–environment interactions. Integral fluxes were computed in accordance with Brigolin et al. (2009). Figure 3 shows the flows of C, N, and P with reference to the functional unit.

2.2.4 Life cycle impact assessment

The life cycle impact assessment was carried out, entailing classification and characterization stages. The choice of appropriate impact categories is essential for achieving a comprehensive evaluation of the environmental impacts of aquaculture (Samuel-Fitwi et al. 2012). The impact categories presented in Table 3 were selected, which, according to Cao et al. (2013), were employed with the highest frequency in recent applications of LCA in aquaculture (Henriksson et al. 2012). The selected impact categories in this work were recognized by Parker (2012) to be used with a particular attention in LCA studies of seafood products. This author reports, in a review of

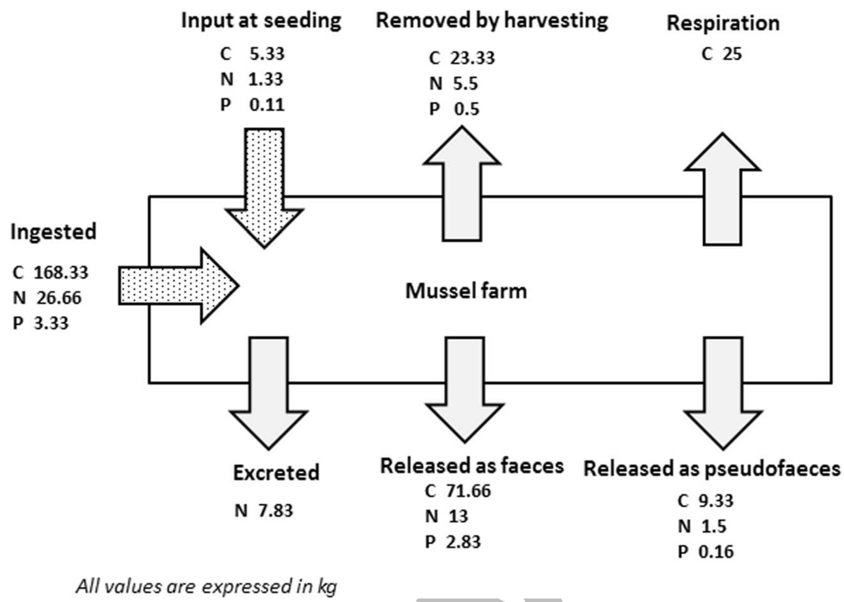

Fig. 3 Organic carbon (C), nitrogen (N), and phosphorus (P) budgets per tonne of mussel produced—according to the estimation made by Brigolin et al. (2009)

LCA research on products derived from fisheries and aquaculture, that the global warming potential, acidification potential, eutrophication potential, and energy use have been applied by numerous studies (Pelletier et al. 2007; Aubin et al. 2009; Cao et al. 2011). In order to be useful to decision-making, Aubin (2013) remarked that the selected impact categories must represent the environmental issues relevant to the system under study.

The analysis was carried out using the software package SimaPro® v 8.0.3.14 (PRé 2014), a software package widely used by practitioners of seafood LCAs, as reported in different reviews (Parker 2012; Avadí and Fréon 2013; Avadí and Fréon 2015).

In order to assess the uncertainty of the results, a Monte Carlo simulation was performed for the three considered scenarios: CS, Comp_S, and Coop_S. Using SimaPro® software v 8.0.3.14. One thousand iterations were performed, assuming a lognormal distribution using a pedigree matrix (Weidema and Wesnæs 1996) considering a confidence interval of 95 %.

3 Results and discussion

3.1 Current scenario

The results of the LCIA are presented in Fig. 4, which shows the relative contribution of energy consumptions (electricity and vessel fuel), the rearing infrastructure (longlines), and the building. The impact categories related to acidification and global warming potential show a similar pattern, which demonstrates the importance of energy contribution (59.7 % to AP and 57.6 % to GWP). As expected, electricity contributes with 38.1 and 31.8 % respectively to GWP and acidification while fuel contributes with 19.5 % to GWP and 31.8 % to

Table 3 Impact categories considered in this study

Impact category	Parameter	Unit	Method
Acidification	Acidification potential (AP)	kg $SO_{2\ eq}$	CML method baseline 2000 V 3.03 (Guinée et al. 2002)
Eutrophication	Eutrophication potential (EP)	kg PO_4^{3-} eq	CML method baseline 2000 V 3.03 (Guinée et al. 2002)
Global warming	Global warming potential (GWP)	kg CO2 eq	CML method baseline 2000 V 3.03 (Guinée et al. 2002)
Energy use	Total cumulative energy demand (TCED)	MJ	CED V 1.08 (Frischknecht et al. 2003)

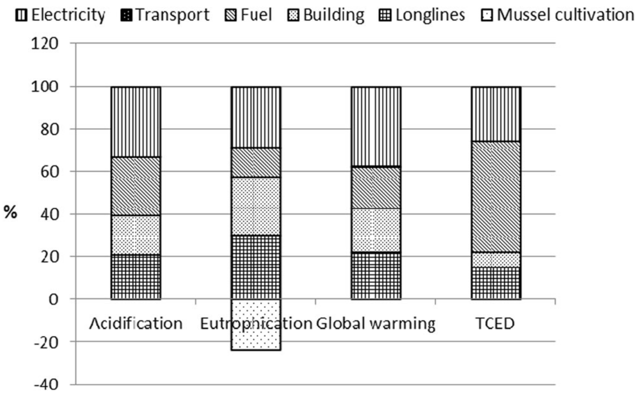

Fig. 4 Contribution to environmental impacts of the production of suspended mussel (current scenario)

acidification. Electricity is used for pumping water and by the farming equipment for conditioning, washing, cleaning, and grading. The longlines present almost the same contribution to AP and GWP (21.3 and 22.4 %, respectively) and are responsible for 32.9 % of the EP. Also, the contributions of the building to the AP and GWP show a similar pattern (18.8 and 20 %, respectively) and contribute with 30 % to the EP. Figure 4 also shows negative values (−0.083 kg PO_4^{3-} eq per tonne of produced mussel) of eutrophication, due to nutrient removal by mussel. Fuel is the major contributor to total cumulative energy demand (TCED), with 51.9 %, while electricity and longlines contribute respectively with 25.9 and 14.8 %.

3.2 Environmental benefits of the cooperative scenario

The impacts concerning the CS with the two scenarios of development of mussel farming activities (Comp_S and Coop_S) are summarized in Table 4, which also compares our findings with those obtained in similar studies, i.e., Iribarren et al. (2010c) and Aubin and Fontaine (2014). As one can see, the cooperating scenario is less impacting than the competitive one, leading to a marked decrease in all impact categories, namely the acidification potential, by 49.15 %, the eutrophication, by 58.62 %, the global warming potential, by 48.12 %, and the total cumulative energy demand, by 53.47 %.

The use of LCA for suspended mussel culture in Algeria not only gives data about contribution of each impact category but it also allows the different stakeholders to prioritize opportunities to reduce the environmental impacts during the culture system. In this case, efforts should focus on adoption of the concept of aquaculture management area (AMA). As reported by Sanchez-Jerez et al. (2016), development of aquaculture spatial plans as a framework for the establishment of allocated zone for aquaculture (AZAs) and AMAs will help avoid environmental degradation and provide business opportunities for aquaculture development. Our assumption in the Coop_S is that five mussel farms are grouped in the same AMA and shared the same building for inland operations, using two boats for sea operations. Table 4 shows that, in fact, mussel production in the cooperation scenario would lead to a decrease, per functional unit, of 29.24 % of TCED and 38.61 % of the GWP with respect to the current situation: as a consequence, the environmental benefits will be 3150 MJ/FU and 156 kg CO_2 eq/FU, respectively. According to the government plan 2015–2025 to develop fisheries and aquaculture in Algeria, the new planned production for this period will be 5600 tonnes of mussels. LCA results show that the environmental benefits can be 17,640 GJ and 873.6 tonnes of kg CO_2 eq, if one adopts Coop_S, instead of CS.

3.3 Uncertainty analysis

Among the several methods to quantifying uncertainty in LCA, the most used and commonly available propagation method is the Monte Carlo simulation (Lloyd and Ries 2007; Henriksson et al. 2015). Table 5 shows the results of the uncertainty analysis conducted by the Monte Carlo simulation for the three considered scenarios: CS, Comp_S, and

Table 4 Comparison between environmental impacts of mussel culture (related to 1 tonnes of mussel)

Impact category	Unit	Raft (Spain)[a]	Bouchot (France)[b]	CS	Comp_S	Coop_S
Acidification	kg SO_2 eq	4.72	1.59, 2.24	1.86 ± 0.44	2.36 ± 0.71	1.2 ± 0.31
Eutrophication	kg PO_4^{3-} eq	0.4	−1.24, −0.98	0.24 ± 0.09	0.29 ± 0.11	0.12 ± 0.07
Global warming (GWP)	kg CO_2 eq	471.8	−6.56, 77.4	404 ± 55.4	478 ± 73.6	248 ± 34.5
TCED	MJ		1069, 11,360	10,772 ± 2490	16,382 ± 5250	7622 ± 2120

a Iribarren et al. (2010c))

[b] Aubin and Fontaine (2014)

Table 5 Results of the uncertainty analysis obtained from the Monte Carlo simulation (1000 iterations)

Impact category	Unit	Mean	Median	SD	CV	2.5th percentile	97.5th percentile
Acidification (AP)	kg SO_2 eq	1.84	1.77	0.44	30.1 %	1. 53	4.18
CS		2.4	2.22	1.31	54.6 %	1.49	4.51
Comp_S		1.19	1.13	0.31	26 %	0.79	2
Coop_S							
Eutrophication (EP)	kg P-O_4^{3-} eq	0.236	0.226	0.09	39.3 %	0.084	0.428
CS		0.288	0.278	0.11	38.6 %	0.106	0.542
Comp_S		0.116	0.109	0.07	61.5 %	−0.003	0.281
Coop_S							
Global warming (GWP)	kg CO_2 eq	404	400	55.4	13.7 %	314	531
CS		483	474	81.2	16.8 %	354	665
Comp_S		248	245	34.5	13.9 %	191	329
Coop_S							
Total cumulative energy demand (TCED)	MJ	10,700	10,300	2490	23.2 %	7090	16,700
		16,500	15,300	5250	31.9 %	9280	29,100
CS		7630	7300	2120	27.8 %	4720	12,700
Comp_S							
Coop_S							

Coop_S. As one can see, the cooperative scenario allows one to obtain the lowest mean and median values for each impact category. Furthermore, the comparison between the mean and median values obtained for the competitive scenarios and the 95 percentiles of the cooperative scenarios shows that the latter are lower for all impact categories: this indicates that the results given in Table 4 are very robust and suggests that Coop_S is less impacting, even in the presence of uncertainty in the input data.

3.4 Comparison with previous studies

As pointed out by Parker (2012), the comparison among LCA studies is difficult due to the use of different functional units and different methods (Henriksson et al. 2012). For these reasons, we compared our findings with those obtained in two studies, in which the same methodology, i.e., CML midpoint, was used, but different processes were considered in the inventory, as summarized in Table 6. As said in Section 0, our analysis did not consider the boat and machinery productions and the waste treatment. It is worth remarking also that the SimaPro software and the ecoinvent database were used (with different versions) in the three considered works.

As one can see from Table 4, the application of LCA generated different values of potential impacts. Overall, the orders of magnitude are the same for two out of three impact categories, namely AP and EP. As far as AP is concerned, our estimate for the current scenario is within the range given in Aubin and Fontaine (2014) and about 40 % lower than that provided by Iribarren et al. (2010a, 2010b, 2010c), who presented the first complete LCA study for the mussel sector in Spain. As regards eutrophication, Aubin and Fontaine (2014) found negative values (between −1.24 and −0.98 kg PO_4^{3-} eq per tonne of “bouchot” mussel) due to an uptake of N and P by mussel during the grow-out phase: this indicates a potential mitigating effect on water quality. In our study, in accordance with Iribarren et al. (2010c), we found instead slightly positive impacts. It appears that the longline structures used in the current study contribute for approximately 33 % to the eutrophication potential. This is due essentially (almost 70 %) to the anchoring blocks (made entirely with concrete and steel). Production and use of electricity also contribute (22 %) to eutrophication potential effects.

The highest discrepancy among these studies concerns GWP: in this case, our findings are comparable with those of Iribarren et al. (2010c), and both estimates are markedly higher than the range provided by Aubin and Fontaine (2014). This difference can be explained by the peculiarity of the “bouchot” culture system which takes place in the foreshore and, therefore, farmers need to cover only a short distance, using tractors or small aluminum boats, to reach the culture sites. Differently, farmers using suspended longlines need to use boats to approach their sites and cover longer distances to reach farming areas. In our specific case, we assumed that farms are located at an average distance of 2 km from the harbor, since, as said, the Algerian ministry recommendations do not allow to install new farms within 1 km from the coast. It is worth remarking, however, that the “bouchot” culture system can be applied only to limited areas, while longlines are, by far, the most common mussel farming system in the Mediterranean area.

Table 6 Comparison between the different stages considered in the reviewed LCAs of cultured mussels

Criteria	Raft culture (Spain) (Iribarren et al. 2010c)	Bouchot culture (France) (Aubin and Fontaine 2014)	Present work (Algeria)
Considered processes	- Seed collection and rope thinning - Construction and maintenance of the raft - Mussel culture and harvest - Emission to water - Energy production - Packaging (stabling and dispatching are not included) - Construction and maintenance of the boats for husbandry	- Spat collection - Production of small tools (wooden stakes, nets, ropes) - Mussel culture and harvest - Emission to water + organic and plastic wastes - Energy production - Processing (at farm and factory) and packaging - Boat and equipment production	- Spat collection and settlement - Conception and use of longlines - Mussel culture and harvest - Emission to water - Energy use - Cleaning operations (in the building) - Use of farm equipment and boat - Construction of a building for stabling and grading
Calculation methods	- CML midpoint method (2001)	- CML2 midpoint method (Baseline 2000 version 2.03) - Total cumulative energy demand (TCED) method	- CML2 midpoint method (Baseline 2000 version 3.01) - Total cumulative energy demand (TCED) method
Software	SimaPro® 7.0	SimaPro® 7.0	SimaPro® 8.0.3.14
Database	Ecoinvent version 2.0	Ecoinvent version 2.2	Ecoinvent version 3

3.5 Limitations

In this section, we discuss the expected influence on the results of the assumptions stated in the current study. As pointed out by Heijungs and Lenzen (2014), all sources of uncertainty associated to input data and assumptions should be taken into consideration in LCA studies. The fact that our calculation did not consider the boat and machinery production, which took place in European factories, could generate uncertainties in the results. Also, in our calculations, we did not consider the waste treatment. This was based on two main reasons: first, seawater used for cleaning and washing mussels is returned to sea without any treatment, and then mussels are sold at the farm gate without processing in factories: farmers sell mussel directly to restaurant or hotels in reusable plastic boxes. In Europe, as an example, the marketing process is different. Mussels cultured in Mont Saint-Michel Bay (France) are processed and sold in different packaging: polypropylene bags of "traditional" mussels or polypropylene trays of "ready-to-cook" mussels (Aubin and Fontaine 2014). Iribarren et al. (2010c) considered the mussel by-product (shell and mussel organic remains) management and examined the option of mussel shell valorization (production of calcium carbonate). They reported that most of the cultured mussels in Galicia (75 %) are performed in dispatch centers and canning factories, in order to produce fresh and canned mussels and the rest is processed in cooking plants. This generates considerable part of mussel by-product. In our study, we assumed that, after mussel consumption, shells are disposed in public dumps. Guermoud et al. (2009) note that 96.8 % of Algerian municipal solid waste is dumped openly and only 2 % of waste is recycled. With respect to the role of bivalve shells as part of the C trading system, we agree with the vision by Filgueira et al. (2015), and we highlight that further work would be required to assess quantitatively the influence of mussel biodeposit mineralization on benthic biogeochemistry and benthic–pelagic coupling in this area (see, e.g., Rampazzo et al. 2013).

Mussel culture can be considered as a recent activity in Algeria comparing to European countries. Thus, the life spans of materials specific to mussel culture were taken from the literature (Iribarren 2010) where estimations are made according to questionnaires filled out by experiment Galician shellfish farmers. Although several authors (Yacout et al. 2016; Jerbi et al. 2012; Ewoukem et al. 2012) used European database (ecoinvent) to characterize the aquaculture activities in Africa, we consider that the use of ecoinvent, which is a database of European countries, can give uncertainties to our results. The future inclusion of Algerian site-specific data for the material life span and the development of an African database can considerably reduce uncertainties.

Mussel cultivation in Galicia (Spain) dates back to the 1940s (Rodríguez et al. 2011): at present, this region is the largest mussel producer worldwide, accounting for a 15–25 % of the world annual mussel production (Garrido-Maestu et al. 2016). As reported by Iribarren et al. (2010c), the Galician mussel sector does not focus only on cultivation. It also comprises other activities such as those performed by dispatch centers, mussel cooking plants, and canning factories. The authors consider that all these activities generate several waste materials that have to be managed, and they elaborate an LCA of mussels from a sectorial perspective. In a review of LCA research on products derived from fisheries and aquaculture, Parker (2012) report that processing, packaging, transport, sale, consumption, and waste management are not commonly included life cycle stages in seafood LCAs. This may be particularly important for products processed into value-added ingredients or cooked for consumption. In Algeria, the mussel sector, which is considered as a promising economic activity, is focused on cultivation. Algerian mussel production is, at present, still small. Mussels are sold fresh directly to consumers, after stabling. Based on these differences and, in particular, on the absence of dispatch centers and canning factories, the present study was focused on the mussel value chain to the farm gate.

The actual implementation of the governmental plan to develop aquaculture in Algeria will increase considerably the mussel production, and dispatch centers will be needed to sell mussels. Using LCA, Iribarren et al. (2010c) found that dispatching activities presented the largest contributions to the potential environmental impacts, clearly ahead of farming operations. They concluded that the processing in dispatch centers showed an unsustainable operation linked to the excessive consumption of electricity and recommended the use of new electrical systems with frequency inventers.

In Algeria, electricity is produced with conventional thermal sources (Stambouli 2011), of which natural gas accounts for more than 96 % (Akbi et al. 2016). Aubin et al. (2009) quantified the influence of the energy context on the environmental impacts resulting from different finfish production systems. They stated that fossil fuels used in power plants contribute to the production of greenhouse gases and acidifying substances, thus increasing the GWP and the AP. These authors reported that impact of climate change and acidification of a recirculating system located in Greece, where 95 % of electricity is produced by fossil fuel combustion, would be four times higher than a recirculating system located in France, where 82 % of electric energy is provided by nuclear plants, which produce less greenhouse gases (Aubin et al. 2009).

We support the idea that for Algeria the use of renewable energy (RE) could represent a mean to reduce the GWP and the AP. Stambouli et al. (2012) reported that Algeria presents an enormous potential of RE. Bélaid and Abderrahmani (2013) reported that solar energy potential of Algeria represented over 60 times the current electrical consumption of the European Union. Also, according to Himri et al. (2009), Algeria has introduced laws and regulations aimed at promoting RE. Recently, Akbi et al. (2016) studied the opportunity of reduction of GHG emissions in Algeria through RE. They remarked that the use of RE can significantly reduce carbon dioxide or equivalent (CO_2 eq) emissions compared to their fossil equivalents. However, they consider that the relatively high generation cost of RE is one of the main barriers to their development and large-scale deployment.

4 Conclusions

The work successfully applied LCA to study the environmental impacts of different scenarios of future development of mussel aquaculture in Algeria. In particular, our results showed that the application of aquaculture management area, AMA, can represent a viable solution, bringing to lower environmental impacts. LCA pointed out that, with respect to current situation, a reduction of 3150 MJ and 156 kg CO_2 eq per functional unit could be obtained if mussel farming activities will be operated in cooperation, thus reaching higher levels of efficiency.

The results of this study, and of former LCA-mussel studies reviewed in this work, strengthen the idea that LCA should be applied to the seafood production sector in Algeria. We advocate for further studies in this area, which can foster the development of sustainable aquaculture production in this country. However, the development in the future of a database more adapted for the African aquaculture sector will be more convenient and can considerably reduce uncertainties.

Finally, we highlight that future research will have to take into closer consideration specific environmental features of the sea areas allocated to aquaculture.

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