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Blue mussel (*Mytilus edulis*) bouchot culture in Mont-St Michel Bay: potential mitigation effects on climate change and eutrophication

Joël Aubin¹, Caroline Fontaine¹, Myriam Callier², Emmanuelle Roque d'orbcastel³

Abstract

Purpose Bivalve production is an important aquaculture activity worldwide, but few environmental assessments have focused on it. In particular, bivalves' ability to extract nutrients from the environment by intensely filtering water and producing a shell must be considered in the environmental assessment.

Methods LCA of blue mussel bouchot culture (grown out on wood pilings) in Mont Saint-Michel Bay (France) was performed to identify its impact hotspots. The chemical composition of mussel flesh and shell was analyzed to accurately identify potential positive effects on eutrophication and climate change. The fate of mussel shells after consumption was also considered.

Results and discussion Its potential as a carbon-sink is influenced by assumptions made about the carbon sequestration in wooden bouchots and in the mussel shell. The fate of the shells which depends on management of discarded mussels and household waste plays also an important role. Its carbon-sink potential barely compensates the climate change impact induced by the use of fuel used for on-site transportation. The export of N and P in mussel flesh slightly decreases potential

eutrophication. Environmental impacts of blue mussel culture are determined by the location of production and mussel yields, which are influenced by marine currents and the distance to on-shore technical base.

Conclusions Bouchot mussel culture has low environmental impacts compared to livestock systems, but the overall environmental performances depend on farming practices and the amount of fuel used. Changes to the surrounding ecosystem induced by high mussel density must be considered in future LCA studies.

Keywords Carbon sink · Climate change · Eutrophication · LCA · Mussel

1 Introduction

Bivalve aquaculture is one of the fastest growing sectors in the food industry (FAO 2016). Understanding interactions between shellfish aquaculture and the ecosystem is necessary to develop a sustainable industry. Most concerns about bivalve culture include depletion of food organisms (e.g., plankton, sestons) in the water column caused by bivalve grazing, changes in nutrient and oxygen fluxes (Brigolin et al. 2009; Jansen 2012; Nizzoli et al. 2011; Richard et al. 2006), benthic impact from localized biodeposition (Chamberlain et al. 2000; Christenssen et al. 2003; Callier et al. 2006; Callier et al. 2007; Grant et al. 2012), and transfer of diseases and invasive species (Brenner et al. 2014). Introduction of non-native species is another concern. Pacific oyster *Crassostrea gigas* is often cited as an example; its deliberate introduction into Thau Lagoon (France) was associated with the introduction of 57 macroalgal taxa, demonstrating that mollusks are effective vectors of macroalgal introduction (Mineur et al. 2007, in Gosling 2015).

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In recent years, ecosystem-based studies were conducted to estimate carrying capacities of sites of bivalve culture. Production carrying capacity is the stocking density of bivalves at which harvests are maximized. While production carrying capacity focuses on the farmed bivalves and their food (nutrients and plankton), ecological carrying capacity includes other organisms and habitats in the ecosystem and is more complex to assess. Ecological carrying capacity is defined as the stocking density or farm density above which unacceptable ecological impacts become apparent (McKindsey et al. 2006).

Most studies focus on the outgrowing stage of bivalve culture because it is considered to have the most important interactions with the environment. Other activities related to bivalve culture may have potential environmental impacts: (1) seed (spat) collection (potential benthic disturbance induced by dredging, artificial collectors, hatcheries, or importation); (2) ongrowing (organic enrichment of the seafloor, providing reef-like structures, alteration of hydrodynamic regime, food web effects), with effects that differ according to the culture type; (3) harvesting (removal of biomass, nutrients, and non-target species; competition with predators); and (4) processing (transporting to auction houses, dumping bycatch, purifying, dumping shells, effluents from processing plants, spread of non-native species or diseases) (McKindsey 2012).

Broader approaches are required to better understand environmental consequences of mollusk culture. Besides social and economic benefits, providing food for human consumption (Lindahl 2011; Petersen et al. 2014) and fertilizer (Olrog and Christensson 2008), shellfish farming provides other ecosystem services such as providing reef-like habitats for other species (D'Amours et al. 2008; Wilding and Nickell 2013), nutrient extraction or water clarification (Nielsen et al. 2016), and decreased eutrophication (Filgueira et al. 2015). For example, a Danish mussel farm (18.8 ha) in a eutrophic fjord was estimated to remove 0.6–0.9 ton nitrogen (N) ha⁻¹ year⁻¹ and 0.03–0.05 ton phosphorus (P) ha⁻¹ year⁻¹ (Nielsen et al. 2016). Carbon (C) sequestration in shells can be considered an ecosystem service that mitigates climate change if it is included in an ecosystem-based approach (Filgueira et al. 2015).

Life Cycle Assessment (LCA) is increasingly used to assess environmental impacts of seafood production (Aubin 2013; Henriksson et al. 2012; Pelletier and Tyedmers 2008; Pelletier et al. 2007). Although several authors have recommended applying it to mollusk culture (Filgueira et al. 2015; Henriksson et al. 2012; Pelletier and Tyedmers 2008), few have done so. Thrane (2004) estimated energy consumption of mussel production in Denmark, and Fry (2012) estimated the C footprint of mussels and oysters in Scotland, while Iribarren et al. (2010a, b, c) performed LCA of the longline

mussel supply chain in Spain. More recently, Lourguioui et al. (2017) proposed an LCA of scenarios of longline Mediterranean mussel (*Mytilus galloprovincialis*) production in Algeria. Although the LCA framework is standardized (ISO 2006a, b), its standards do not define which models to use for material and energy flow calculations. Among these studies, the methods used to develop the inventory differed, as did consideration of effects of mussels on N, P, and C cycling in the marine environment.

Blue mussel (*Mytilus edulis*) culture yielded 185,433 tons of shellfish worldwide in 2014 (FAO 2012). Mussels are produced using different techniques: on-bottom cultivation, bouchots (i.e., pilings), rafts, or longlines. Longlines and bouchots are used to produce blue mussels in France (74,138 tons of mussel per year, FranceAgimer 2016). The present study focuses on LCA of bouchot mussel culture, which is currently the only type of mussel culture in Mont Saint-Michel Bay. Mont Saint-Michel Bay is located between Brittany and Normandy (Fig. 1), two regions with high live-stock densities and where water quality is constantly challenged due to overloading of N and P caused by agricultural activities. Mont Saint-Michel Bay is a main mussel producing region in France (10,000 tons year⁻¹). Bouchot culture is the main cultural practice for mussels there, consisting of wooden pilings sunk into the foreshore as a support for the mussels.

We investigated the influence of location in the bay on environmental impacts. More specifically, we investigated mussel culture's potential ability to mitigate climate change by stocking C in mussel shells and decrease eutrophication by extracting N and P from the bay. We compared the environmental impacts of mussel with other animal protein production in the literature. We also make recommendations for performing LCA of mollusk culture, especially mussels.

2 Methods

2.1 General considerations

LCA is a standardized framework (ISO 2006a, b) designed to estimate potential impacts associated with producing a product by quantifying and estimating resources consumed and compounds emitted into the environment during all stages of its life cycle, from raw material extraction up to the end-of-life (Guinée et al. 2002). Each substance emitted or consumed is assigned to one or more impact categories based on its potential environmental impact and information from scientific literature. The LCA performed in this study followed the main guidelines in the ILCD handbook (Joint Research Centre 2010). In the inventory stage, a specific attention is paid on the fate of C, N, and P to better account their influence in climate change and eutrophication.

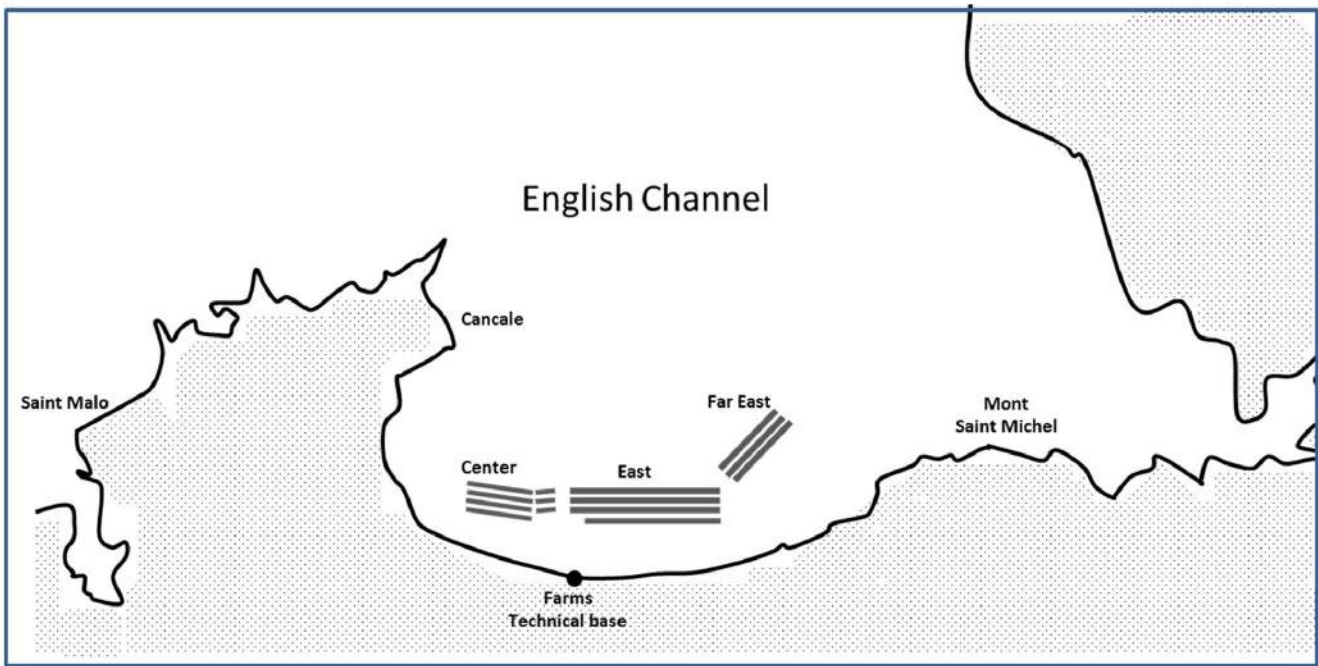


Fig. 1 Map of Mont Saint-Michel Bay showing the position of the mussel bouchots

2.2 Goal and scope

LCA was performed to estimate environmental impacts of Mont Saint-Michel mussels produced according to the “Appellation d’Origine Contrôlée” (AOC) label, with a second objective of highlighting potential impact hotspots. The functional unit was 1 ton of packed “ready-to-cook” mussels, the main way in which mussels are distributed, at the production plant. Boundaries of the production system included spat collection and transportation, the ongrowing stage (including equipment use, adult harvesting, and boats), and the processing and packaging stage at the production plant (Fig. 2). Distribution, marketing, and consumption stages were excluded from the study, but management of household waste was included to consider the fate of mussel shells after consumption.

2.3 Life cycle inventory

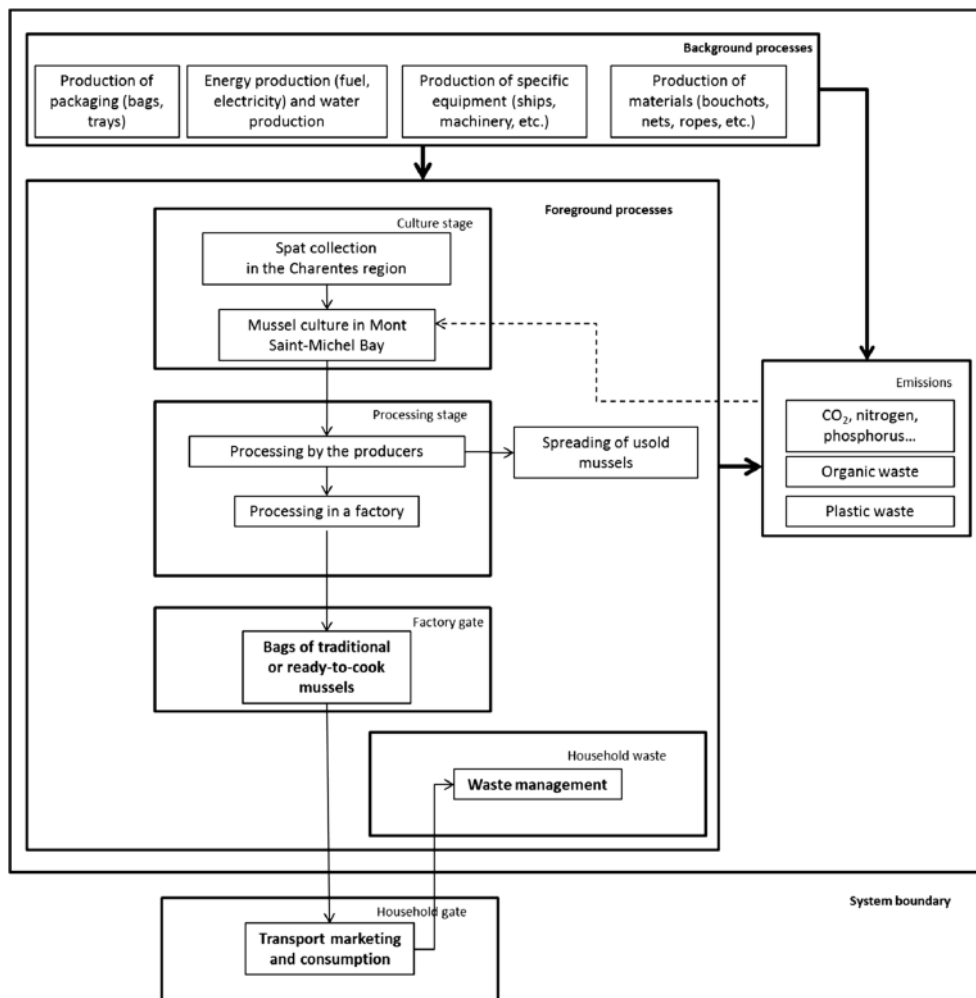
2.3.1 Production cycle inventory

Six of the main producers, operating in two or three subareas in the bay (Center, East, Far East) (Fig. 1) were interviewed in spring and summer 2012. They produced a total of 300–450 tons of mussels per year. Their practices are regulated according to AOC specifications, which restrict the percentage of bouchots in use at the same time (55–65%, depending on the subarea), and restrict the maximum mean annual yield to 60 kg of mussels per bouchot. These rules aim to preserve the productivity of the bay and consequently the mussel flesh filling rate. Some producers use only 50% of their bouchots at

the same time. Square bouchots, 5–6 m long and 10 cm wide, are sunk 1 m deep in the foreshore. Bouchots are constructed from exotic wood, usually *Lophira alata* and *Dinizia excelsa*, and are expected to last at least 15 years, when they will have lost half of their weight. They are then sold for landscape gardening or buried (their high salt content precludes burning). Bouchots are arranged in pairs of lines 100 m long and 25 m apart. The mussel life cycle on the bouchot lasts at least 8 months. Harvest begins once mussels reach 4 cm in length and meet criteria for condition and taste, usually in the first half of July. Mussels are harvested from amphibious boats using hydraulic arms that scrape off the all the mussels, leaving the bouchots bare.

Water conditions in Mont Saint-Michel Bay are not suitable for natural reproduction of the blue mussel. Therefore, spat collection starts in March in the Bay of Biscay, mainly in the Charentes region (300 km away). We described this stage using data provided by one producer, who produces 300 km of seeded ropes each year. Spat producers construct temporary wooden structures on the lowest parts of chosen beaches and then extend ropes made from hemp or coconut fibers on these structures. The ropes remain in place for about 2 months during the period of mussel spawning and larval attachment before they are transported to Mont Saint-Michel Bay by road. Upon arrival, the seeded ropes are coiled around free bouchots or laid out on temporary horizontal structures built on the foreshore until new bouchots are available. Once mussels start growing, producers stabilize the structure of the bouchot by progressively encasing each in three to seven polypropylene nets, depending on the wind

Fig. 2 Stages of the bouchot mussel production system included in and excluded from the LCA



and sea currents exposure of their sites. To reach the culture sites, producers use tractors, small aluminum boats, or amphibious boats. Specific data on amphibious boats were collected from the main shipbuilding company. The end of life of rope nets and material was not included in the study.

After harvest, mussels are placed in an oxygenated/aerated purification tank for at least 24 h, at the technical base. Water from the bay is pumped into a tank shared by all shellfish producers in the area. Afterwards, mussels go through a declumper, which separates the mussels and shreds the ropes and nets. Mussels are then cleaned in a brushing machine and calibrated, first mechanically, then by hand, to remove other waste (crabs, algae, broken mussels, etc.). Organic waste from cleaning and processing stages and all other types of waste are buried at the local landfill. Wastewater is returned to the sea without treatment. At this point, 20–30% of the mussels have been discarded, mainly due to undersized mussels. The discarded mussels are spread over the tractor roads in the bay. This practice serves two goals: stabilizing the

roads in the sand and keeping mussel predators away from the bouchots by giving them an easily available food source. Mussel spreading is currently under heavy debate and may soon be banned, due to potential visual and smell nuisances. Mussels are then placed in 5, 10, or 15 kg polypropylene bags of “traditional” mussels for sale. They may also pass through another machine that removes the byssus threads and be sold in 5, 10, or 15 kg polypropylene bags of “ready-to-cook” mussels or 1 kg polypropylene trays of “ready-to-cook” mussels. Although we performed LCA for each type of packaging, this article shows results for “ready-to-cook” bags of mussels only.

All background data such as electricity, raw materials, infrastructure, and transport were extracted from the ecoinvent v3.1 database (Swiss Centre for Life Cycle Inventories 2013). For the bouchots, we assumed *L. alata* wood for durability. We used “process-specific burdens” to model household waste landfilling and incineration. Surveys of suppliers provided detailed inventories for materials (e.g., boats). Table 1 presents the average

Table 1 Main resources use recorded in the life cycle inventory of 1 ton of blue mussel at harvest stage and one ton of “ready to cook” mussel at farm gate. Averages of studied sites in Mont Saint Michel Bay

	For 1 ton of mussel at harvest	For 1 ton of “ready-to-cook” mussel at the farm gate	
Land occupation (m ² year)	564	Harvested mussel (ton)	1.3
Wodden stake (p)	29.5	Building use (m ² year)	1.7
Amphibious vehicle (kg)	1.4	Cold room use (m ² year)	0.1
Yawl (kg)	0.15	Equipment: stainless steel (kg)	1.9
Tractor (kg)	1.5	Equipment: polyethylene (kg)	1.1
Plastic net (km)	0.35	Polypropylene bags (kg)	4.6
Cotton net (km)	1.4	Sea water (m ³)	85.4
Polypropylene protection (kg)	0.87	Fresh water (m ³)	1.4
Rope for spat collection (m)	141	Electricity (kwh)	127
Diesel (kg)	51	Refrigerant R134a (kg)	0.003

values of the main items of the life cycle inventory of the studied production sites.

2.3.2 Carbon balance

We consider mussel culture an artificial ecosystem (especially in the sandy Mont Saint Michel Bay, where no mussels naturally grow), inducing a change in mineral and plankton dynamics. We hypothesize that growing a large amount of calcareous shells in this ecosystem may change the latter’s C balance, as proposed by Tang et al. (2011). Several factors influence the C balance of mussel production and consumption. The first is mussels’ ability to build shells composed of calcium carbonate (CaCO₃), whose C comes from two sources: mussel feed (Brigolin et al. 2009) and dissolved CO₂ in seawater (Chairattana et al. 2012). The amount of C fixed in the shell is presented in Table 2. At this stage, C storage in mussel flesh is ignored, since it is considered part of the short C cycle (Joint Research Center 2010), thus quickly reemitted by mussel metabolism, emissions of CO₂ due to respiration, or death of the mussel. We excluded CO₂ emissions due to respiration, since they are assumed to be reused by primary production (through photosynthesis) and to enter biological cycles. This approach is different from that of Murani et al. (2013) and Mistri and Munari (2013), who included respiration, thus concluded to a positive net CO₂ emission. The fate of shells will influence long-term C balance at two stages: processing and household waste management.

At the processing stage, some mussels are discarded (e.g., undersize, broken shells) and spread in the bay. The physical context of the bay (coastal seawater saturated with CaCO₃,

high pH, and shallow depths) implies C decomposition slow enough to be considered negligible, according to Fry (2012). Therefore, spread mussel shells can increase the CaCO₃ content of sediment and be considered a C sink. Nevertheless, this hypothesis ignores acidification of marine water, which can increase emission of CO₂ from marine organisms and sediment’s calcareous stocks (Zeebe and Wolf-Gladrow 2001). Since this approach can be considered controversial (Wolff and Beaumont, 2011), more research is needed to strengthen this hypothesis. At the household waste management stage, discarded mussel shells may contribute to C sequestration. We examined common waste-management practices in France. Since 44.4% of French household waste ends up in landfills (ADEME 2008), we assumed that the shells of 44.4% of all mussels sold in France would be buried. Since the shells are not composed of degradable organic C and are buried deep in the soil, they are assumed not to release C (IPCC 2006); thus, we considered their C content to be sequestered. The amounts of C considered in the stages of mussel production are presented in Table 3.

The wooden stakes are also considered when calculating C sequestration. They come from tropical forests where they fixed C through photosynthesis. During their 15 years (minimum) of use in the sea, they lose half of their weight due to erosion and biological breakdown. Because the C lost during this period feeds biological loops, it is excluded from the net C balance. After stakes are removed, their salt-laden wood is considered rot-proof and reused for landscape gardening (or buried). Since C decomposition is considered null, we thus considered 50% of stakes’ initial C content to be sequestered. In the CO₂ emissions associated with wooden stakes,

Table 2 Estimated C content in the shell and N and P contents in the flesh per ton of mussels included in the life cycle inventory

Element in shell or flesh	Per ton of harvested mussels
C in shell from ingested C (Brigolin et al. 2009)	198 kg C
C in shell from dissolved C (Chairattana et al. 2012)	18 kg C
N in flesh (Brigolin et al. 2009)	4.17 kg N
P in flesh (Brigolin et al. 2009)	0.38 kg P

Table 3 Fate of C in shell and N and P of flesh during blue mussel farming calculated on the basis of one ton of mussel harvested

	Mussel at harvest	Spread mussel	Sold mussel	Buried shell	Net export
Total weight (ton)	1	0.3	0.7	0.22	
C in shell (kg)	216	64.8	151.2	67.0	131.8
N in flesh (kg)	4.17	1.25	2.92		2.92
P in flesh (kg)	0.38	0.11	0.27		0.27

we included planting, harvest, loss of bark, processing, and transport according to ecoinvent V3 methodology. Emissions excluded, however, indirect and post-harvest effects on the forest (e.g., re-planting, further land-use change).

The main hypotheses presented above are used all along the paper; nevertheless, different calculations of climate change were conducted with alternative hypotheses on C sequestration: without C sequestration in bouchots, without C sequestration in discarded spread mussel, without C sequestration in mussel shell, and without C sequestration in mussel shells and bouchots.

2.3.3 Nitrogen and phosphorus balances

We calculated N and P exports based on the amount of flesh contained in marketed mussels. Mussel flesh composition based on Brigolin et al. (2009) is given in Table 2. N and P are absorbed by the mussels during growth and then when mussels are harvested; N and P are permanently removed from the water body. Spread mussel flesh was excluded from our calculations since it belongs to a short cycle and did not influence overall nutrient balance of the bay. We did not account for the N and P release in water during the cleaning processes. Nevertheless, we assumed that the water released into the bay had a higher biochemical oxygen demand due to organic-matter processing, and bacterial decomposition of discarded spread mussels was accounted, to contribute to eutrophication potential.

Figure 3 shows the C, N, and P cycles included in this study, and Table 3 shows the fate of the nutrients accounted for the mass balance study.

2.4 Life cycle impact assessment

Impact categories were selected based on previous studies and guidelines in aquacultural LCA (Aubin et al. 2013, Pelletier et al. 2007). Climate change (kg CO₂-eq), acidification (kg SO₂-eq), and eutrophication (kg PO₄-eq) were calculated using characterization factors of CML2 baseline 2000 v2.03 (Guinée et al. 2002). Energy demand (MJ) was calculated using the Total Cumulative Energy Demand method, v1.03 (Frischknecht et al. 2004), excluding growth energy content in biotic resources. Water dependence (m³) was based on freshwater resource use, as developed by Aubin et al.

(2009). Calculations were performed with SimaPro® v8.0.5 software (PRé Consultants, Amersfoort, Netherlands).

2.5 Interpretation of results

Environmental impacts of mussels at each production subarea were calculated separately for each producer (13 subarea × producer observations) and then aggregated by subarea. We also identified the contribution of each production stage to impacts. We considered variability among the production subareas and performed uncertainty analysis using the procedure and matrix developed by Henriksson et al. (2014) applied to foreground data. We used lognormal distributions except for emission models, for which normal distributions were used. Monte Carlo analysis (1000 runs) was performed with SimaPro® v8.0.5.

Finally, we compared the environmental impact of mussel production to other sources of animal protein (terrestrial and aquatic). To compare impacts of different types of animal production, we considered 1 ton of edible protein as the functional unit. We assumed that 27% of mussel mass was meat, containing 11.9% protein (USDA 2012).

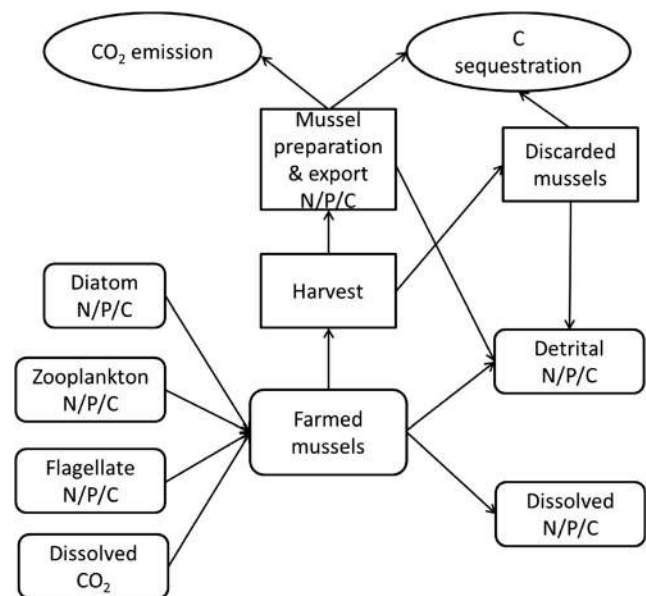


Fig. 3 Transfers of nitrogen (N), phosphorus (P) and carbon (C) in the mussel production system used to calculate mass balance in the LCA of bouchot mussel production

3 Results

3.1 Levels of impact

Table 4 presents mean impacts per ton of ready-to-cook mussels from Mont Saint-Michel Bay, while Fig. 4 presents a contribution analysis. Acidification impacts ranged from 1.5–2.7 kg SO₂-eq ton⁻¹, for which on-farm fuel use (54%), bouchots (16%), and infrastructure and equipment (15%) were the main contributors. Eutrophication impacts ranged from -1.7 to 0.6 kg PO₄-eq ton⁻¹, for which the on-farm growing stage (85%) was the main contributor. Energy demand ranged from 5674 to 8963 MJ ton⁻¹, for which on-farm fuel use (38%), cleaning and packing (30%), and infrastructure and material use (18%) were the main contributors. Water dependence ranged from 73.7–108.4 m³ ton⁻¹, for which cleaning and packing (99%) was the main contributor. According to the main hypotheses on C sequestration and shell fate, climate change impacts ranged from -50.0 to 86.0 kg CO₂-eq ton⁻¹ due to on-farm fuel use (53% of greenhouse gas emissions), infrastructure and material (12%), and spat collection and transport (8%), which increased impacts, but also due to C sequestration in bouchots (47% of mitigation effects), C sequestration in shells of marketable mussels (18%), and C sequestration in shells of unsold mussels spread in the bay (14%), which decreased impacts.

Table 5 presents the mean climate change of 1 ton of ready-to-cook mussels according to different hypotheses of C sequestration. The results range from 9.5 kg CO₂-eq ton⁻¹, while using the current hypotheses, to 325.2 kg CO₂-eq ton⁻¹ without C sequestration in shell and bouchot. Intermediate results are obtained without C sequestration in bouchots (212.9 kg CO₂-eq ton⁻¹), in spread mussel shells only (59.6 kg CO₂-eq ton⁻¹), and in all mussel shells (121.8 kg CO₂-eq ton⁻¹).

The uncertainty associated to the results depends on the impact categories. The highest level of uncertainty is obtained for climate change with a coefficient of variation (CV) equal to 165%. For water dependence, the CV is 48%. For acidification and energy demand, the uncertainty reaches,

respectively, 30 and 27%. The lowest level of uncertainty is obtained by eutrophication (CV = 9%).

3.2 Variability among production subareas

Standard deviations of impacts are high and vary greatly depending on the impact category (Table 4). One explanation is the high variability observed among production subareas (Table 6). We observed a negative correlation between subarea productivity and the distance to the technical base, where the facilities are located (Fig. 2). Mean productivity is lowest in the Center (12 ton ha⁻¹), closest to the technical base, and highest in the Far East (26 ton ha⁻¹), which benefits from the main current of the open sea but lies furthest from the technical base; fuel consumption for on-site transportation is a major contributor to energy demand and climate change. This negative correlation strongly influences climate change (Fig. 4). Negative climate change impacts were estimated for four farms in the Far East subarea with the highest yields, which induced the highest C sequestration in shells and overcompensates the CO₂ emissions of the amphibious boat use. Yield often influences environmental impacts of agriculture, and identifying sources of variability requires more accurate characterization of systems, practices, and locations (Nitschelm et al. 2016).

4 Discussion

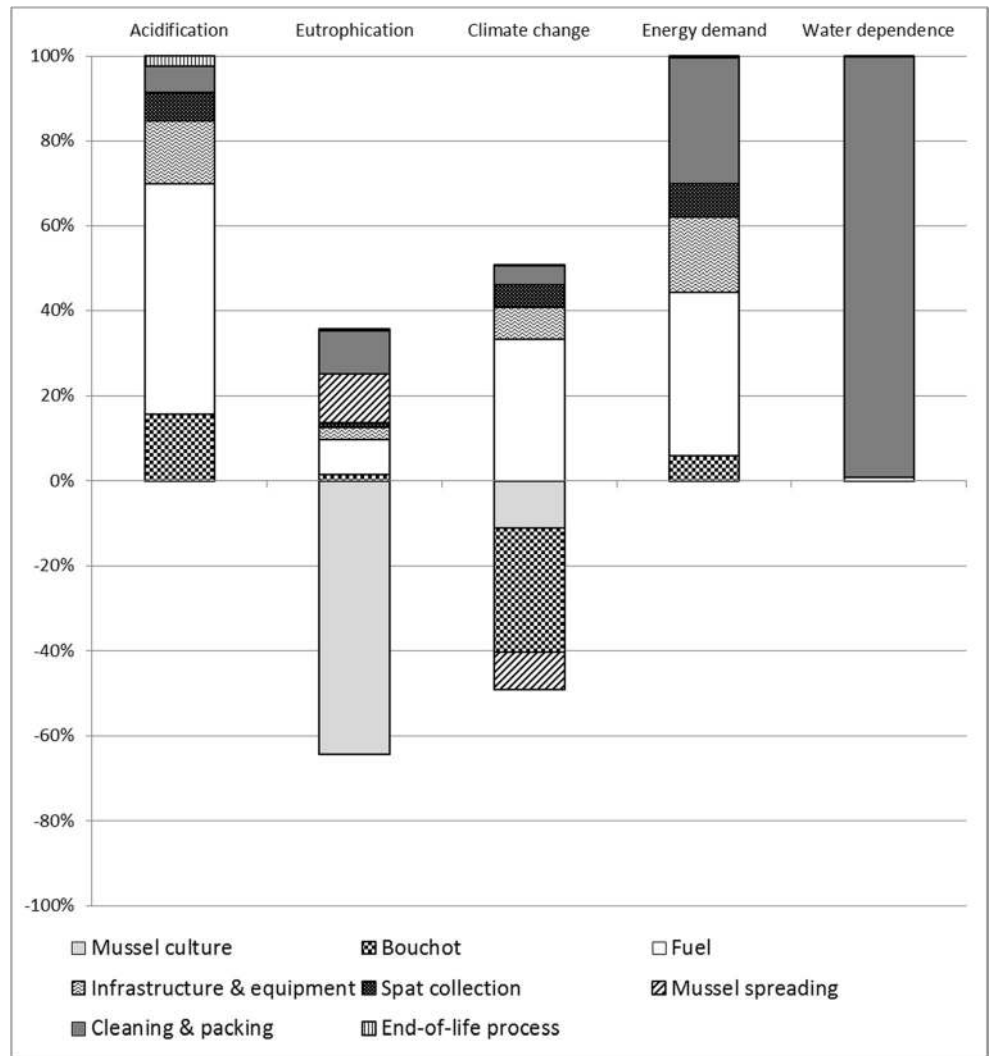
4.1 Comparison with previous studies

Acidification per ton of ready-to-cook mussel in our study is similar to that calculated by Lourguioui et al. (2017) (1.86 kg SO₂-eq ton⁻¹) and in the same order of magnitude as that of Iribarren et al. (2010a) (4.72 kg SO₂-eq ton⁻¹). Eutrophication in our study is similar to that calculated by Lourguioui et al. (2017) (0.24 kg PO₄-eq ton⁻¹) and in the same range as that of Iribarren et al. (2010a) (0.40 kg PO₄-eq ton⁻¹). Energy demand in our study is lower (33%) than that calculated by Lourguioui et al. (2017) (10,772 MJ ton⁻¹) and 20 times as high as that of Thrane (2004) (456 MJ ton⁻¹, limited to fuel consumption during harvest). With the main hypotheses on C sequestration, climate change in our study is 95% lower than those of Iribarren et al. (2010a) and Lourguioui et al. (2017) (472 and 404 kg CO₂-eq ton⁻¹, respectively), without C sequestration in shells and bouchots (Table 5), our result is only 20% lower. With the main hypotheses, climate change is 50% lower than the C footprint calculated by Fry (2012) (252 kg CO₂-eq ton⁻¹) which is near from our results without C sequestration in bouchots. Differences with results of previous studies can be explained by differences in the production practice studied or LCA characteristics (e.g., analysis, boundaries, databases, models).

Table 4 Mean impacts from LCA of one ton of Mont Saint-Michel “ready-to-cook” mussels. Standard deviations (SD) are based on Monte Carlo uncertainty analysis of weighted production at the bay scale

Impact category	Mean	SD
Acidification (kg SO ₂ -eq)	2.04	0.61
Eutrophication (kg PO ₄ -eq)	-0.89	0.08
Climate change (kg CO ₂ -eq)	9.52	15.75
Total cumulative energy demand (MJ)	7231	1971
Water dependence (m ³)	87.48	42.20

Fig. 4 Contribution to environmental impacts of production stages for ready-to-cook mussels in Mont Saint-Michel Bay



4.2 Differences in mussel production practices

The present study assessed bouchot culture characterized by intensive use of amphibious boats which consume large amounts of fuel (38% of energy demand), which differs from longline culture. This can explain the differences in energy demand calculated by Iribarren et al. (2010a) and Thrane (2004). These authors also excluded cleaning and packing, which represented 30% of energy demand in our study. Our

study does not confirm the high energy demand caused by electricity consumption calculated by Lourguioui et al. (2017).

4.3 Differences in modeling

For eutrophication, the present study modeled mass balance of N and P more accurately than Iribarren et al. (2010a). The N and P removed with the mussel flesh during harvest indirectly

Table 5 Sensitivity of climate change (kg CO₂-eq) of one ton of Mont Saint-Michel “ready-to-cook” mussels to hypothesis of C sequestration in mussel shell and bouchot

	Mussel culture	Mussel spreading	Bouchot	Fuel	Other processes	Total
Full hypothesis	-62.2	-50.1	-165.0	187.6	99.2	9.5
Without C in wooden stake	-62.2	-50.1	38.4	187.6	99.2	212.9
Without C spread mussel shell	-62.2	0.0	-165.0	187.6	99.2	59.6
Without C in shell	0.0	0.0	-165.0	187.6	99.2	121.8
Without C in shell and wooden stake	0.0	0.0	38.4	187.6	99.2	325.2

Table 6 Means and standard deviations (SD) of impacts calculated for one ton of “ready-to-cook” mussels according to their location (subarea) in Mont Saint-Michel Bay

Impact	Center		East		Far East	
	Mean	SD	Mean	SD	Mean	SD
Acidification (kg SO ₂ -eq)	2.27	0.23	2.32	0.24	1.62	0.12
Eutrophication (kg PO ₄ -eq)	-0.74	0.46	-0.64	0.72	-1.24	0.27
Climate change (kg CO ₂ -eq)	10.46	66.91	29.28	38.90	-10.79	29.94
Total cumulative energy demand (MJ)	7801	972	8006	795	6115	567
Water dependence (m ³)	82.57	7.80	89.09	12.50	88.81	12.49

decreases dissolved N and P concentrations in the water, decreasing eutrophication by approximately 1 kg PO₄-eq per ton of “ready-to-cook” mussels. The organic matter released by mussels, approximately 2.4 tons of sludge (i.e., feces and pseudofeces) per ton of mussel produced, may contribute to a decrease in oxygen availability in the bay (Dabrowski et al. 2013). The eutrophication impact category in the CML method includes the oxygen demand associated with organic matter degradation. We excluded this factor, however, because it requires calculating chemical oxygen demand of the organic matter in mussel food (sestons), which was not available and is highly uncertain (Fréchette et al. 2016). In addition, the hydrology of Mont Saint-Michel Bay (strong currents and high tides) prevents deposition of organic matter, rapidly transferring it to the open sea, where the high dilution renders the bay less sensitive to eutrophication. In other practices such as longline culture, for which organic matter deposition may be high in non-dispersive environments, a specific impact category associated with changes in the benthic ecosystem is required to consider changes in the ecosystem (Callier et al. 2008). Since Lourguioui et al. (2017) modeled total N and P balances, our results for eutrophication are similar to theirs.

Climate change differed more between our study and previous studies because we included C sequestration in mussel shells and bouchot wood, which are also sources of uncertainty in calculations of climate change impact (Fig. 4, Table 5). The C sequestration in shells was not accounted in the studies of Iribarren et al. (2010a) and Lourguioui et al. (2017), but was in Fry (2012) which explain huge differences in results. Estimates of C sequestration in bouchots are sensitive to the C sequestration model used, the tree species from which the wood comes, the lifespan of the bouchots, and their final fate. Inventories from the ecoinvent database used to model exotic wood production were standard ones, and estimates of a wood’s C sink effect are debatable. In the ecoinvent database, C sequestration by *L. alata* wood is based on its C content (49.4% C by mass). This is consistent with ILCD recommendations (Joint Research Center 2010); however, other approaches can be used, such as dynamic LCA (Levasseur et al. 2013). Therefore, the C balance associated to wooden stake could evolve considering the methodology and the system boundaries. The inclusion of deforestation effects,

planting, and post-harvest effects to forest may change the climate change levels associated to bouchots. Farmers recently have tested new materials that may have greater durability and resistance to shipworms (*Teredo navalis*). Investigating new materials, such as other exotic wood from Paraguay or Brazil and recycled plastic, would improve our analysis. The percentage of household waste sent to landfills can vary greatly depending on the region and time period. Spreading of discarded mussels may soon be banned in Mont Saint-Michel Bay. These factors influence the amount of C sequestered and consequently the climate change impact (Table 5).

The system boundary is thus essential when considering the fate of C sequestered in shells and considering shells a potential C sink. In our study, using the main hypotheses, C sequestration generally compensates the greenhouse gas emissions caused by on-site transportation. At best, blue mussel bouchot culture in Mont Saint-Michel Bay seems to induce little to no climate change, but it cannot be considered a C sink. In contrast, other studies predict substantial mitigation of climate change Fry (2012) estimated 180 kg CO₂-eq due to C sequestration per ton of mussels). A close attention on the hypotheses and system boundaries has to be paid before using such results. The C cycle in marine water is particularly complex and depends on the ecosystem characteristics (Lerman and Mackenzie 2005). The pathway of C with or without mussel culture may differ greatly depending on the biophysical context and the level of mussel production. Therefore, several assumptions used in our study (e.g., on the storage of carbon from discarded mussels) have to be considered with caution. More research is needed to propose a realistic scheme of long-term C storage in marine systems, natural and associated to aquaculture.

4.4 Comparison with other types of animal production

Per ton of edible protein, bouchot mussel production had the lowest eutrophication and climate change impacts, the third-highest acidification impacts, and the highest energy demand (Table 7). Mussel production does not incur the large contribution of feed to impacts, like most other types of animal production, and its extraction of C, N, and P benefits the environment. Unlike other types of animal production,

Table 7 Comparison of potential environmental impacts of agricultural animal products per ton of edible protein (NS, not studied, UK, United Kingdom)

Product	Source	Acidification (kg SO ₂ eq)	Eutrophication (kg PO ₄ ³⁻ eq)	Climate change (kg CO ₂ eq)	Energy demand (MJ)
Ready-to-cook bouchot mussel	This study	69.5	-27.7	296	225,270
Longline mussel	Iribarren et al. (2010a)	180	20	18,000	NS
Longline mussel	Lourguioui et al. (2017)	57.9	7.5	12,574	335,263
Cow milk (New Zealand)	Basset-Mens et al. (2009)	523	203	34,238	81,395
Chicken (France)	Katajajuuri (2008)	329	197	19,539	150,376
Pork (France)	Basset-Mens and Van der Werf (2005)	437	209	22,840	158,888
Egg (UK)	Williams et al. (2006)	2029	511	36,671	93,501
Beef (UK)	Williams et al. (2006)	2468	826	83,158	146,316
Fish from aquaculture	Aubin et al. (2006, 2009); Ayer and Tyedmers (2009); Papatryphon et al. (2004); Roque d'orbcastel et al. (2009); Boissy et al. (2011)	50–860	110–590	11,000–103,000	146,000–1,584,000

bivalves aquaculture benefit the environment by lowering eutrophication and provide significant ecosystem services (Newell and Koch 2004). However, specific hydrodynamic conditions are necessary to decrease sludge accumulation and risks of eutrophication.

The relatively small amount of edible protein harvested per unit of energy demand is questionable and represents a hotspot for the sustainability of the practice. Following this study, the local mussel producers' organization intends to change their transportation strategy and technical base location.

5 Conclusions

Currently, eutrophication of coastal water induces significant environmental and societal issues and is a challenge for the European Union according to the Water Framework Directive published in 2000. Therefore, a better understanding of interactions of coastal activities and natural environment is a key issue for sustainable development. Using LCA, this study estimated global and local environmental impacts of bouchot mussel production with an emphasis on its potential positive effect on climate change and eutrophication. This study has proved once again that LCA can be a valuable management tool for aquaculture development. At the local scale, it helps prioritize potential improvements to the production system to assess the cost-benefit ratio of each modification.

This study demonstrates that bouchot mussel production has low eutrophication and climate change impacts in comparison with other food productions. Including the chemical composition of mussel flesh and shells to more accurately describe their extractive capacity in the environment

influenced estimates of these impacts. Cultivating filter feeders such as mussels may help to reduce eutrophication, which generates food, while improving coastal water quality.

Whereas bouchot mussel culture is a low-impact aquaculture activity considering eutrophication and climate change impacts, improvement can be proposed on energy demand of this industry; decreasing fuel consumption to transport workers and mussels is a key factor to decrease energy demand. Choice of lower-impact materials, such as the wood for the bouchots, is also essential to decrease the culture's environmental impacts.

More studies have to be conducted on mussel farm waste, especially shell fragments, empty shells, and sludge; amazingly those data are still scarce in literature and have to be provided. Mussel production is often considered as a low impact activity, but the growing awareness of existing waste is necessary to improve farm, productivity, and health management and decrease local impacts of farms; LCA could help in dealing with that.

System boundaries, especially those that include post-production processes such as shell cleaning and waste treatment, have a large impact on estimated acidification, energy demand, and eutrophication impacts. Producers must document these stages more accurately to choose the most sustainable method to produce and process their products and to treat and optimize their waste.

The different environmental impacts of each location suggest that including ecosystem heterogeneity and variability in practices is necessary to render LCA increasingly spatially explicit. Results indicate that bouchot mussel culture potentially improves water quality by modification of the water column nutrient and plankton compositions. We developed a

method to include the composition and fate of shells during production and after consumption; however, it did not confirm that mussel shell represents a carbon sink. Similar approaches are required for other production systems, with or without quality certification, other mollusks, and other regions. Future studies could also analyze the impact of sea area use and compare cultural practices, and give recommendations for aquaculture spatial planning.

LCA can be used at the regional scale to identify the most appropriate strategy for sustainable aquaculture production. In 2009, the French government implemented national and regional development plans to encourage development of sustainable aquaculture (Tanguy et al. 2008). The objective was to identify geographic areas targeted toward aquaculture and their related operational conditions. Combined with economic and social analyses, LCA could be used within the framework of these plans to identify the most suitable strategy to ensure sustainable production.

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