REVIEWS IN Aquaculture

Reviews in Aquaculture (2021) **13**, 91–118 doi: 10.1111/raq.12465

The decline of mussel aquaculture in the European Union: causes, economic impacts and opportunities

Lamprakis Avdelas[1], Edo Avdic-Mravlje[2], Ana Cristina Borges Marques[3], Suzana Cano[3], Jacob J. Capelle[4], Natacha Carvalho[5], Maria Cozzolino[6], John Dennis[7], Tim Ellis[8], José M. Fernández Polanco[9], Jordi Guillen[5], Tobias Lasner[10], Véronique Le Bihan[11], Ignacio Llorente[9], Arie Mol[12], Simona Nicheva[13], Rasmus Nielsen[14], Hans van Oostenbrugge[12], Sebastian Villasante[15,16], Svjetlana Visnic[17], Kolyo Zhelev[13] and Frank Asche[18,19]

1 Ministry of Environment and Energy, Athens, Greece
2 Fisheries Research Institute of Slovenia, Ljubljana, Slovenia
3 Direção-Geral de Recursos Naturais, Segurança e Serviços Marítimos (DGRM), Lisbon, Portugal
4 Wageningen Research, Yerseke, The Netherlands
5 European Commission, Joint Research Centre, Ispra, Italy
6 NISEA, Fisheries and Aquaculture Economic Research, Salerno, Italy
7 Bord Iascaigh Mhara (BIM), Cork, Ireland
8 CEFAS, Weymouth, UK
9 University of Cantabria, Santander, Spain
10 Thünen-Institute of Fisheries Ecology, Bremerhaven, Germany
11 University of Nantes, Nantes, France
12 Wageningen Economic Research, The Hague, The Netherlands
13 Executive Agency for Fisheries and Aquaculture, Burgas, Bulgaria
14 Department of Food and Resource Economics, University of Copenhagen, Copenhagen, Denmark
15 Department of Applied Economics, University of Santiago de Compostela, Santiago de Compostela, Spain
16 Campus Do Mar-International Campus of Excellence, Santiago de Compostela, Spain
17 Ministry of Agriculture, Zagreb, Croatia
18 Institute for Sustainable Food Systems and School of Forestry Resources and Conservation, University of Florida, Gainesville, FL, USA
19 Department of Industrial Economics, University of Stavanger, Stavanger, Norway

Correspondence
Jordi Guillen, European Commission, Joint Research Centre Ispra Sector, TP 051, Via Enrico Fermi 2749, Ispra (VA) 21027, Italy.
Email: jordi.guillen@ec.europa.eu

Received 17 March 2020; accepted 5 June 2020.

Abstract

In contrast to the increasing aquaculture production of mussels worldwide, production in the European Union (EU) has shown a decreasing trend over the last two decades. Aquaculture production of mussels in the EU peaked in the late 1990s at more than 600 000 tonnes; by 2016, production volume had dropped by 20% to 480 000 tonnes. As mussel production represents more than ⅓ of EU aquaculture production, this decrease is an important contributor to the stagnation of EU aquaculture. Previous studies have suggested diseases, lack of mussel seed (spat), and low profitability as the main causes of the EU mussel production decrease. In this study, we investigate how economic and environmental factors have contributed. Moreover, we examine if the different mussel production techniques (raft, longline, on-bottom, and 'bouchot') have been differently affected, by analysing the economic performance and cost structure evolution for the period 2010–2016. We complement these results with a SWOT (strengths, weaknesses, opportunities, and threats) analysis of the EU mussel sector based on expert knowledge.

Key words: access to space, atomization, economic performance, environmental factors, low impact, swot analysis.

Introduction

World mussel aquaculture production has been increasing steadily since the 1950s to reach 2 million tonnes in 2016, valued at 3.8 billion USD (€3.4 billion) (FAO 2019). Almost 94% of the world mussel production comes from aquaculture. The main mussel aquaculture producing countries in 2016 were China (43%), Chile 15%, Spain (11%), Thailand (6%), New Zealand (5%), Italy, France, Korea Rep. and the Netherlands (all four countries with about 3%), and with Europe contributing about 20% of total production. However, while European countries like Spain, Italy, France and the Netherlands are still significant producers, European mussel aquaculture production peaked at 600 000 tonnes in the late 1990s and has since decreased to 480 000 tonnes (valued at €420 million, or $465 million[1]) in 2016 (Fig. 1). Mussel production represents more than ⅓ of EU aquaculture production. Consequently, the mussel production decrease is key as it contributes to the stagnation of EU aquaculture and risk of failure to achieve the EU 2020 aquaculture production goals (Guillen *et al.* 2019a).

There is not a single cause to explain the mussel production decline in the EU. Mussel production is thought to have declined due to the spread of diseases, algal blooms, lack of spat, predation and low earnings. Such causes may have been exacerbated by local conditions such as the small size of mussel enterprises (Villasante *et al.* 2013; Theodorou & Tzovenis 2017), the lack of innovation in the mussel production processes (Labarta & Fernández-Reiriz 2019), the carrying capacity of the ecosystems to support the mussel production (Villasante 2009) and the impacts of climate change (Álvarez-Salgado *et al.* 2009; Rodrigues *et al.* 2015; Outeiro *et al.* 2018). The relative simple production technology also gives producers limited control of the production process, leading to fewer opportunities for innovation and productivity growth that are the main factors in the growth of aquaculture production in general (Asche 2008; Kumar & Engle 2016; Garlock *et al.* 2020), and makes production area-intensive.

In this study, we investigate economic and environmental factors that may have contributed to the decrease in EU mussel production, and whether the different mussel production techniques have been differently affected. The paper is structured with: a section on EU mussel aquaculture detailing the main farming techniques; a methods section where the main data sources and indicators are defined and presented; the results section that estimates the economic performance and cost structure evolution by production technique for the period 2010–2016; and a SWOT (strengths, weaknesses, opportunities and threats) analysis of the EU mussel sector based on expert-knowledge and summarized by country in the Appendix 1. The paper ends with a discussion and conclusions that build from the analyses of EU mussel aquaculture.

The EU mussel aquaculture sector

Mussels have been harvested from wild beds in most coastal European countries for food, fishing bait and as fertilizer for centuries (Voultsiadou, Koutsoubas, & Achparaki 2010). Mussel aquaculture based on gathering wild juveniles and moving them to on-grow in safer places had started by the Middle Ages. Nowadays, wild seed mussels are still gathered in several countries, although new spat collecting techniques (e.g. using ropes or shells as a substratum for the planktonic larvae to settle on) have been developed. Additionally, in some European countries, hatchery techniques have been implemented enabling spat (including polyploid) production (Piferrer *et al.* 2009; Kamermans *et al.* 2013). According to FAO data, four countries (Spain, Italy, France and The Netherlands) accounted for the bulk of EU mussel production (82% by weight and value) in 2016 (Fig. 2).

Four main mussel culture techniques are used in the EU, two being suspended and two being associated with the sea-bed as described as follows:

- *Raft culture*: A raft is a floating platform with suspended ropes of around 30 m which can be folded in the form of a matrix according to the depth where the platform is located. Seed mussels are attached to the rope and covered with a net that progressively disappears as the mussels attach to the rope in a natural way. Every row in the matrix corresponds to a particular harvest, which will be collected and replaced at an appropriate time to maintain a continual production throughout the year.
- *Longline culture*: A horizontal longline rope is suspended by a series of small anchored floats, and ropes or socks of mussels are hung from this rope back-bone. Longline culture is the most recent development for mussel culture and is often used as an alternative to raft culture in more exposed areas subject to higher wave energy.
- *Bottom culture*: This is based on the principle of transferring mussel seed (spat) from areas where they have settled naturally to areas where they can be placed at lower densities to increase growth rates, facilitate harvest and control predation. Bottom cultivation uses beds or poles fixed in the bottom where the mussels are deposited or attached.
- *'Bouchot' culture*: This technique uses vertical pilings or poles (known in French as '*bouchots*') implanted into the inter-tidal sea-bed. Ropes, on which the mussels grow, are tied in a spiral on the pilings with mesh preventing the mussels from falling and from predation.

The four farming techniques have different needs and efficiencies. Production efficiency (i.e. mussel production

[1]The exchange rate between the USD/EUR was 1.1069, according to the European Central Bank.

Reviews in Aquaculture (2021) 13, 91–118

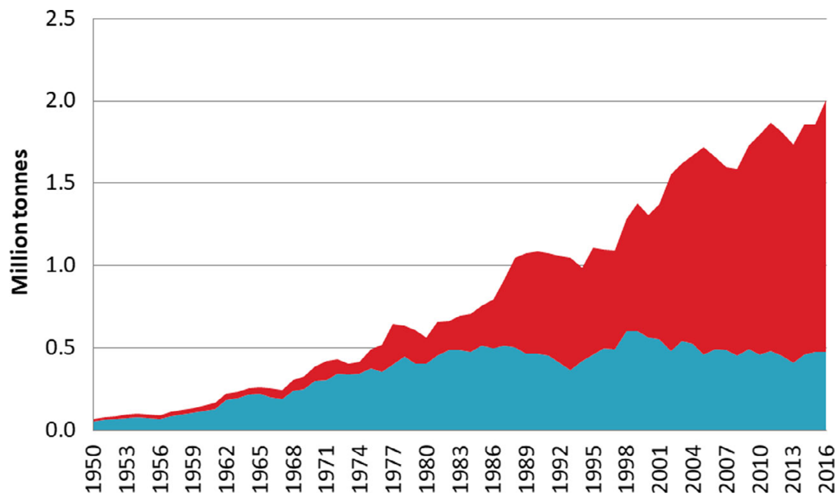

Figure 1 Evolution of mussel aquaculture production by weight (million tonnes) in the EU and the rest of the world (1950–2016). Source: own elaboration from FAO (2019) data. (■) Q rest of the World; (■) Q EU.

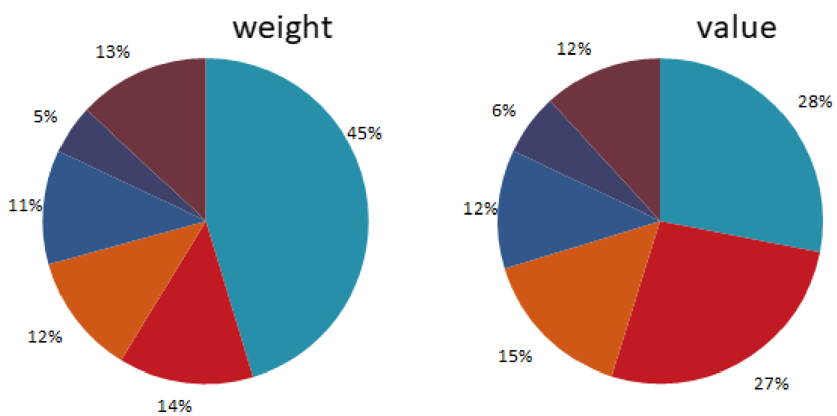

Figure 2 Mussel production by weight and value by EU Member State in 2016.
Source: own elaboration from FAO (2019) data. Weight: (■) Spain; (■) Italy; (■) France; (■) Netherlands; (■) Greece; (■) Others. Value: (■) Spain; (■) France; (■) Netherlands; (■) Italy; (■) Germany; (■) Others.

per volume of spat) is related to the differences in mortality and growth rate. It increases from bottom culture to 'bouchot' culture, to longline and raft culture (Kamermans & Capelle 2019). Growth rate of mussels is higher in off-bottom cultures, and higher when mussels are continually submerged than in inter-tidal zones (Kamermans & Capelle 2019). Rafts require a minimum depth of 8-10 m to be efficient (FIgueiras *et al.* 2002; Labarta & Fernández Reiriz 2019). Longlines require larger areas that are not always available due to competing water usages; however, it does enable mussel culture in shallow waters where rafts would not be suitable. While on-bottom techniques solve some of the problems with required surface space for longlines, they are not as efficient as rafts. 'Bouchots', however, do need an extensive inter-tidal zone.

Galicia (North-west of Spain) is the most important mussel producing area in the EU, with rafts as the dominant technique. Rafts are also used in Slovenia and the French Mediterranean. Bottom culture is mostly used in Northern European countries: the Netherlands, Germany and Ireland. Longlines are used in Italy, Greece, Denmark, Ireland, Bulgaria and Spain. The 'bouchot' technique is mostly used in France and is the predominant cultivation system for the English Channel and Atlantic areas (Fig. 3).

Materials and methods

The economic data for mussel aquaculture were collated from the Economic Performance of the EU Aquaculture Sector Report (STECF 2018) for those countries that reported data by segment for the period 2010–2016. In particular, the following variables were collated: number of enterprises, total value of assets, total employment, employment measured in full time equivalents (FTE), total sales volume, turnover, other income, personnel costs, imputed value of unpaid labour, energy costs, repair and maintenance costs, livestock costs, other operational costs and annual depreciation. This report provided data from eight EU mussel producing countries: Denmark, France, Germany, Ireland, Italy, the Netherlands, Slovenia and Spain. Data by country were aggregated at the segment (production method) level. Hence, the longline technique reflects the combined data from Denmark, Ireland and Italy; bottom technique the combined data from Germany, Ireland and the Netherlands; raft technique the combined data from Slovenia and Spain; and 'bouchot' data from France. According to FAO (2019), these eight countries represented 91% of the weight and 78% of the value of EU mussel aquaculture production in 2016.

The following economic performance indicators were then estimated based on STECF (2018):

$$\begin{aligned}\text{Gross value added (GVA)} &= \text{turnover} + \text{other income} - \\ &\text{energy costs} - \text{repair and maintenance costs} - \\ &\text{live stock costs} - \text{other operational costs}\end{aligned} \tag{1}$$

$$\begin{aligned}&\text{Earnings before interest and taxes (EBIT)} = \\ &\text{turnover} + \text{other income} - \text{wages and} \\ &\text{salaries} - \text{imputed value of unpaid labour} - \\ &\text{energy costs} - \text{repair and maintenance costs} - \\ &\text{livestock costs} - \text{other operational costs} - \\ &\text{annual depreciation}\end{aligned} \tag{2}$$

$$\text{GVA margin} = \text{GVA}/\text{turnover} \tag{3}$$

$$\text{EBIT margin} = \text{EBIT}/\text{turnover} \tag{4}$$

$$\begin{aligned}\text{Mean wage (gross)} = (&\text{wages and salaries} + \\ &\text{imputed value of unpaid labour})/\text{FTE}\end{aligned} \tag{5}$$

$$\text{Labour productivity} = \text{GVA}/\text{FTE} \tag{6}$$

$$\text{Employees per enterprise} = \begin{array}{l}\text{Total} \\ \text{employees}/ \\ \text{Number of enterprises}\end{array} \tag{7}$$

$$\text{Part} - \text{time share} = \text{FTE}/\text{Total employees} \tag{8}$$

$$\text{Unpaid share} = \begin{array}{l}\text{imputed value of unpaid labour}/ \\ (\text{wages and salaries} \\ +\text{imputed value of unpaid labour})\end{array} \tag{9}$$

STECF (2018) data and analyses were complemented with a SWOT analysis of the EU mussel sector

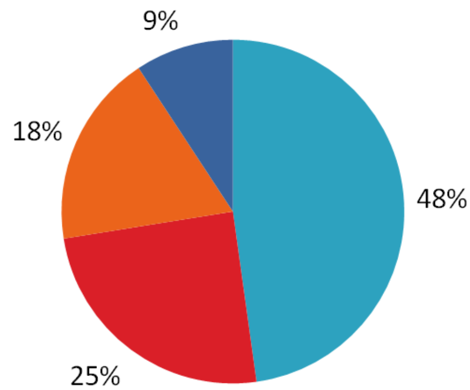

Figure 3 Mussel production in weight in the EU by technique in 2016. Source: own elaboration from STECF (2018) data. (■) Rafts; (■) Longline; (■) Bottom; (■) Bouchot.

summarizing the expert knowledge. This national expert knowledge was used to produce the country profiles in the Appendix 1, aiming to provide further insights for the main EU mussel producing countries, including those for which economic data were not reported here and also to provide qualitative explanation to the observed changes over time.

Results

Economic performance

GVA and EBIT of mussel aquaculture in the EU show a decreasing trend since 2010, while sales volume and turnover indicate more variation and a less clear decreasing trend. The eight EU countries analysed accounted for more than 430 000 tonnes of mussel production in 2016 valued at €328 million. GVA for 2016 is estimated to be €214 million and EBIT €77 million (Fig. 4). The average price at farm gate was €0.82 per kg, with a minimum price of €0.72 per kg in 2015 (€0.76 per kg in 2016) and a maximum price of €0.96 per kg in 2013, when production reported its minimal level. The average price has decreased by 12% between 2010 and 2016, whilst the average production cost was €0.67 per kg, also decreasing 12% during the 2010–2016 period (see Table 1).

All mussel farming techniques are characterized by the absence of feed costs because mussels feed by filtering natural food from the seawater. Nevertheless, the differences between the four production techniques result in different cost structures. Costs relatively to total income increase over time for the bottom and raft techniques, leading to a decrease in the economic performance; while for 'bouchot' there was an economic recovery in 2015 and 2016, while for longlines profitability seems low for the whole period (see Fig. 5).

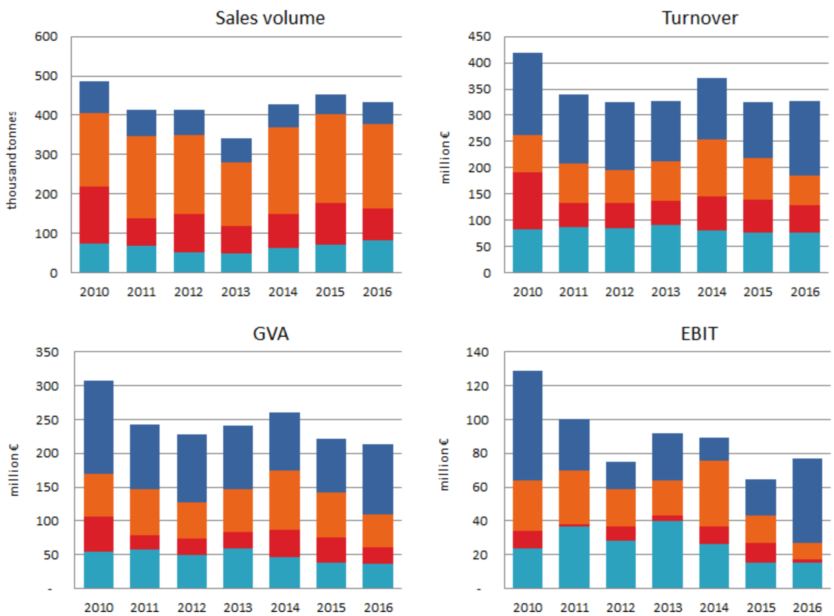

Figure 4 Sales volume, turnover, GVA and EBIT by farming technique for the period 2010-2016.
Source: own elaboration from STECF (2018) data. (■) Mussel Bouchot; (■) Mussel Raft; (■) Mussel Longline; (■) Mussel Bottom.

Labour is a main cost component for all the production techniques. Wages and salaries reflect the costs to remunerate the employees, while the imputed value of unpaid labour reflects the opportunity cost of labour for unpaid workers. Imputed value of unpaid labour is a cost category with significant differences between the production techniques. This is related to the legal form of the enterprise: raft and 'bouchot' techniques record most businesses as personal and family-owned, in which other members of the family randomly or periodically contribute to the activity without a formal contract or salary. In contrast, the longline and bottom segments are mainly composed of relatively large and professionalized companies where such informal labour is limited. This is also reflected in the importance of the unpaid share in the total employment in each technique, as shown in Table 1.

Energy and repair and maintenance costs are higher for bottom and longline techniques. In the bottom technique, most EU enterprises have at least one vessel (45 m average length), meaning that capital investment is high compared to other techniques such as rafts, as shown by the total value of assets per enterprise in Table 1.

The importance of livestock costs reflects the scarcity of spat, the different ways the mussel industry is trying to obtain them, and how they are accounted. The high livestock costs in the longline technique are because the Italian livestock costs include the salaries of the persons involved in seed collection by scraping rocks in rocky shores. In the bottom mussel industry, where boats must search harder and longer for seed mussel beds, they are often reflected in the energy costs. Other operational costs may include the mussel seed collector costs (if not directly reported under livestock costs) and the annual payment for licenses and concessions for the area where the mussels are farmed.

Hence, the average enterprise characteristics for each production technique vary significantly. Bottom enterprises have a high production, achieving a turnover close to €1M per year; while in the raft techniques, enterprises have an average annual turnover below €50 000 per year. Similar differences occur in labour productivity, where productivity in bottom culture enterprises is more than five times higher than in raft culture enterprises. These differences in labour productivity across techniques reflect the different labour and capital intensity across production techniques. In the bottom culture, production is based on a high input of capital; while in other techniques, the production is more labour intensive. Labour productivity shows high inter-annual variations as well over time. These variations are not explained by changes in the workforce, but reflect the natural variation in mussel production due to unstable seed abundance.

Despite this overall decrease in economic performance, all culture techniques remain profitable on average during the period analysed. Therefore, the reduction in profitability does not seem to be the origin of the decline in mussel production. Hence, it is necessary to investigate what are the potential factors behind this decline[2].

[2]Production of other types of shellfish such as oysters has also declined (Botta *et al.*, 2020).

Table 1 Performance indicators for the EU mussel aquaculture, average for 2010–2016

Variable	Unit	Raft	Longline	Bouchot	Bottom
Number of enterprises	#	2039	247	338	96
Turnover per enterprise	€	37 194	251 033	382 462	865 314
Total value of assets per enterprise	€	81 168	387 093	660 854	1 664 188
Employees per enterprise	#	5.2	6.2	5.8	2.3
FTE/employee (%)	%	25	78	65	75
Unpaid share (%)	%	68	7	50	2
Mean wage (gross)	€	15 037	18 110	30 335	45 810
Labour productivity	€	23 794	28 796	78 984	149 349
Average production cost per kg	€/kg	0.31	0.62	1.65	0.90
Average farm-gate price per kg	€/kg	0.37	0.66	2.04	1.25
GVA margin (%)	%	76	52	78	59
EBIT margin (%)	%	27	19	48	40

Abbreviations: FTE, full time equivalents.
Source: own elaboration from STECF (2018) data.

SWOT analysis

The EU aquaculture production of mussels has been decreasing over the last two decades and the sector overall seems far from reaching its potential, despite production increases in some countries. The overall farmed mussel production decrease is a result of several factors, often interrelated, that are discussed in this section.

Opportunities for the EU farmed mussel sector that could help to improve its economic performance were identified via literature review and brainstorming. This brainstorming was done based on expert knowledge, covering main EU mussel producing countries, as can be seen from the country profiles. The SWOT analysis (Table 2) of the EU mussel sector summarizes the country profiles within the Appendix 1. The relevance of the different factors (strengths, weaknesses, opportunities and threats) is weighted according to the grading[3] given by the experts.

Weaknesses

The main weaknesses identified that prevent growth in the EU mussel sector are the low price of mussels, the atomization of the producer sector, the lack of suitable space to enlarge or establish new farms and the difficulty to obtain permits.

Low prices. Ex-farm mussel prices in most EU countries are relatively low and have been stagnant for some years. In some countries, this is mainly due to the atomized primary producer sector (i.e. many small enterprises), who have little involvement in the secondary purification and marketing phases; this hands the market and bargaining power to the processing and depurating sector (see for instance, Girard & Mariojouls 2008).

Another important reason for the low price at the ex-farm level is the import of cheaper products from outside the EU (see for instance, Surathkal & Dey 2019). For example, depurating enterprises in Spain often import mussels from Chile (Labarta & Fernández Reiriz 2019). Chile has become the main mussel exporter into the EU, with Spain directly receiving 1/3 of the almost 40 000 tonnes imported in 2017 (Globefish 2018). The opportunity to import low price mussels enables the processing and depurating sector have the bargaining power to offer low prices to the local EU producers.

This could be solved via producer organizations (horizontal integration) that integrate vertically in the value chain (e.g. by acquiring depuration or processing factories). There are already some successful cases of integration 'production—marketing' and more recently 'production–processing–marketing' in the Galician (Spain) and Italian mussel sectors (see for instance, Friðriksson & Haraldsson 2018). Integration has also allowed the development of new business strategies and product diversification, e.g. basic product (without certifications), organic product and product with recognition of Protected Designation of Origin (PDO).

Access to space. Difficulties to access to space for expansions or new farms may prevent mussel production growth, in particular considering that mussel production is often extensive (i.e. demands more space) than other aquaculture production. Location desirability for a mussel farm depends on several factors, such as the distance to port, natural productivity and predation of mussel (Mongruel & Thébaud 2006). Coastal space is busy and under increasing demand. It is possible that the most suitable space may

[3]The grading of each factor is weighted by the estimated impact on production and the country's mussel production. The estimated impact is weighted as follows: without impact: 0; low impact: 1; medium impact: 2; high impact: 3; and very high impact: 4. While the mussel production is weighted according to the following criteria: more than 100 000 tonnes: 5; between 50 000 and 100 000 tonnes: 4; between 25 000 and 50 000 tonnes: 3; between 10 000 and 25 000 tonnes: 2; and less than 10 000 tonnes: 1. The total score of each factor is divided by the maximum score obtained, so that each factor is graded between 0 and 1.

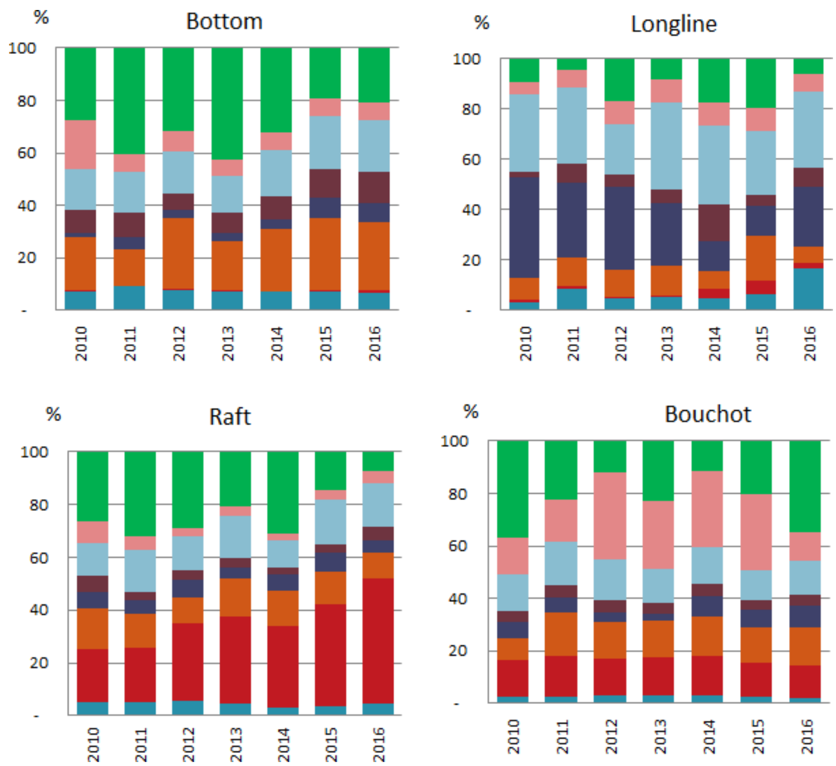

Figure 5 Costs evolution as a share of total income by mussel aquaculture segments for the period 2010–2016.
Source: own elaboration from STECF (2018) data. (■) Profits; (■) Depreciation of capital; (■) Wages and salaries; (■) Repair and maintenance; (■) Livestock costs ; (■) Other operrational costs; (■) Unpaid labour; (■) Energy costs.

Table 2 SWOT analysis for the EU mussel sector with grading (0–1)

Negative	Positive
Internal	
Weaknesses	**Strengths**
Access to space (0.9)	Existing markets (1.0)
Low price (0.8)	Low impact (0.8)
Availability of permits (0.8)	Clean water (0.6)
Atomization (0.7)	Incorporate added value (0.5)
External	
Threats	**Opportunities**
Harmful algal blooms (0.9)	Certification (0.9)
Climate change (0.9)	Subsidies (0.7)
Bad Weather (0.8)	Increase consumption (0.6)
Diseases (0.6)	Diversification (0.6)
Predators (0.5)	Maritime spatial planning (0.5)
Poor water quality (0.4)	Going offshore (0.4)
Lack of spat (0.4)	Multi-trophic aquaculture (0.3)

already be taken by aquaculture farms or other activities (Smaal 2002). For example, the production of mussels from rafts in Galicia reached a limit several years ago, due to the lack of additional available suitable space for new rafts[4].

[4]For example, the growth rate of mussels on raft in the mouth of the rias is higher than the ones from more inshore rafts (Navarro *et al.*, 1991).

Marine spatial planning, on-going offshore initiatives and multiple use management (Galparsoro *et al.* 2020) are three potential solutions (opportunities) to mitigate the lack of suitable space for aquaculture. Access to space is perceived as an important weakness in Spain, Italy, Germany, Portugal, Slovenia, the UK, and Ireland.

Availability of permits. The administrative burden, the long time this process often takes and the uncertainty of the outcome are significant drawbacks in the process of renewal or issuing of new permits, even if marine space is available for a mussel farm. The uncertainty and time are two factors posing great risk to producers and investors. Uncertainty is often caused by the limited licenses and strict production requirements, partly attributable to political will and conservation regulations[5].

The average time for license renewal varies by country; for example, in Italy it can take from 6 to 18 months, while in Ireland, it can take years. This variability is linked to the

[5]For example, in Wexford Harbour (Ireland), traditional bottom mussel producers are being threatened with having one third of their licensed ground removed to be used exclusively as feeding grounds for the local wading bird population. If this is endorsed, already struggling local mussel producers face the prospect of closure.

ability of a country or region to properly handle the bureaucratic, administrative and environmental impact aspects of the mussels sector. Hence, there is still the need to ease and harmonize the administrative burden for new permits. Availability of permits is perceived as an important weakness in Italy, Greece, Germany, the UK, Slovenia and Ireland (longline culture).

Atomization. The mussel aquaculture sector is characterized in many EU countries by the atomization of the industry into a large number of small producers. Most of EU mussel farmers are small or microenterprises. This atomization of the producer sector offers the processing and depurating sectors market/bargain power. This could be solved by horizontal integration of these producers into larger producer organizations. Atomization is perceived as an important weakness in Italy, Greece, Denmark, Spain, the UK, Bulgaria and Ireland (longline culture).

Strengths

The main strengths identified that sustain the EU mussel sector and may support its growth in the near future are the traditional consumption and markets, the increasing tendency to incorporate added value to the mussels produced, the low environmental impact of mussel production and their capacity to clean water and even sequestrate CO_2.

Existing markets. Traditionally, some EU countries (e.g. Spain, France, Italy and Belgium) have high levels of mussel consumption. The consumption of mussels in the EU varies by country, consumption varying from less than 200 g to nearly 4 kg per capita (Monfort 2014). In markets where high volumes of mussels are consumed, it is often easier for local producers to find buyers for their products. As a result of their limited shelf-life, live mussels can only be transported a few hundred kilometres from the coast, requiring a fast and efficient logistic network. The aquaculture sector is more efficient where there is an established and well-functioning seafood value chain (Gutiérrez et al. 2020). The existence of traditional consumption and markets is perceived as an important strength in Spain, France, Italy, Greece, Germany, Portugal, Bulgaria, Croatia and Slovenia.

Low impact (Eco-friendly). Hall *et al.* (2011) highlighted mussel farming as one of the least impactful methods to produce animal-source food, across a range of global/regional environmental indicators (eutrophication, acidification, climate change, space use, energy demand, biotic depletion). Furthermore, mussel aquaculture within the EU does not attract the local environmental and ethical criticisms directed at Pacific oyster *Crassostrea gigas* and finfish farming (e.g. Naylor & Burke 2005; Shepherd & Little 2014) as it:

- grows native species, typically sourced from the locality which therefore match the local genotype;
- can be categorized as extensive farming of species low in the food chain using natural in situ food resources. It does not require external feed inputs that use industrial fishery products (fishmeal/fish oil), and cause nutrification of the water column via excreted nitrogen and phosphorous wastes;
- does not involve use and discharge of medicinal or antifouling treatments;
- has not been associated with the amplification of pathogens that may then infect wild stocks;
- typically, does not require the control of higher vertebrate predators; and
- farms insentient invertebrates which do not merit animal welfare concern.

The issue of whether mussel farming does result in a net sequestration of carbon dioxide is subject of scientific debate (Bunting & Pretty 2007; Munari *et al.* 2013; Filgueira *et al.* 2015). In Italy, it has been awarded the first certificate of carbon credits for the CO_2 uptake in the shells of mussels during the production process. A pilot project has accounted for the CO_2 emissions in the mussel farming activities, showing that mussels absorb CO_2. This opens a new potential market, where mussel farmers can produce 'green' certificates for the volume of the CO_2 sequestrated and sell them to enterprises that are responsible of CO_2 emissions and need to buy such permits.

However, as with any food production, mussel farming cannot be considered completely benign and various local environmental impacts have been suggested or demonstrated (Kaiser *et al.* 1998; Beadman *et al.* 2004; McKindsey *et al.* 2011; Science for Environment Policy 2015). These include aspects such as culture systems adding physical structures to the environment which entrap wildlife and affect currents, sedimentation and light; removal of plankton; organic enrichment of the sea-bed via pseudo-faeces reducing biodiversity and abundance; movement of spat transferring indigenous and non-native pest species; spat collection (including dredging) removing wild individuals and affecting habitat and ecology. Nevertheless, judgement of such impacts needs to be balanced against potential local environmental benefits (Edebo et al. 2000; Jeffery et al. 2014; Suplicy 2020) which include structures providing shelter and habitat, and feeding reducing eutrophication. The low impact of mussel production is perceived as an important strength in Germany, UK, Croatia, Slovenia, Spain and Denmark.

Capacity to clean water. Shellfish aquaculture is the only human food production system that does not release pollutants from farming, but removes them from their production environment. Mussels and other filter feeders improve the water quality and clarity, making the marine ecosystem more suitable for organisms (Borthagaray & Carranza 2007). This gives the possibility of developing aquaculture for human consumption or for water purification (Lindahl *et al.* 2005; Lindahl & Kollberg 2008). When filter feeders are grown only for water purification, the product is normally reserved for use as agricultural fertilizer or animal feed. Otherwise, nitrogen and other pollutants, which remain in the shellfish meat, must be removed after harvest if they are to be suitable for human consumption. Their capacity to clean water is perceived as an important strength in Spain, Italy, Ireland, Bulgaria, Denmark, Croatia and Slovenia.

Incorporating added value. In a context of declining natural resources and increasing production costs, adding value to seafood products, and to lesser extent to aquaculture products, is a major concern for producers and public authorities. Traditionally, a large part of the national mussel production has been consumed fresh, while there has also been production of canned mussel (e.g. Spain). With the increase in frozen and canned mussel imports, in recent years, the canning industry has opted for more added value products through a greater degree of processing, especially ready-to-eat products such as boiled mussels (with and without shell) and even prepared dishes of fresh mussels in different sauces.

Initially, most of these processed products were not destined for the traditional local markets, but for export. However, their consumption increases year after year in the traditional market as well, due to changes in consumer behaviour. These new products have encouraged and strengthened alliances between producers and canners. In the case of mussels, it can also be important to enhance the traditional mussel offer with certified and organic mussels, as this has been successful approaches for other seafood products as well as food products more generally (Roheim *et al.* 2018).

Threats

The economic performance of the EU mussel sector may be challenged by some threats detected mainly at the production level. Harmful algal blooms, bad weather, diseases, predators, poor water quality and pollution may impact the mussel production.

Harmful algal blooms (HAB). Algal blooms, i.e. the rapid growth of algae populations, occur mostly due to the excessive amount of nutrients and organic matter in the water (Wells & Karlson 2018). The formation of these blooms often leads to changes in the pH and dissolved oxygen (eutrophication), as well as changes in the water colour due to the algae pigments (e.g. red tides). Harmful algal blooms are events that cause negative impacts to other organisms. Harmful algal blooms are often associated with large-scale marine mortality events and have been associated with various types of mussels and shellfish poisonings (Falconer *et al.* 1992; Amorim & Vasconcelos 1999; Álvarez-Salgado *et al.* 2008; Peperzak & Poelman 2008).

Thus, when harmful algal blooms occur, mussel producers are not allowed to sell their produce until the mussels are fit for human consumption. This can cause significant economic losses to the farmers (Hoagland & Scatasta 2006; Jin *et al.* 2008; Ahsan & Roth 2010; Rodríguez *et al.* 2011; Le Bihan et al. 2019; Theodorou *et al.* 2020), even if the exact impact is difficult to quantify (Rodríguez *et al.* 2011; Sanseverino et al. 2016; Theodorou *et al.* 2020). The number, intensity and consequences of harmful algal blooms episodes have been increasing (Glibert *et al.* 2005), which makes it more difficult to predict and effectively respond to these events. Harmful algal blooms affect mainly Spain, Portugal, Italy, France, Greece, Ireland (mostly longline culture), the UK, Bulgaria, Croatia and Slovenia.

Climate change and ocean acidification. Since the industrial revolution, human activities emitting greenhouse gases (CO_2 and others) have increasingly affected climate. Climate change has started affecting environmental parameters and more is to come: temperature increase in the ocean, sea level rise, ocean acidification, changes in rainfall and therefore salinity, and the concentration and quality of nutrients (Philippart *et al.* 2011). The economic damage caused by acidification alone to shellfish production in Europe is estimated to reach US$ 1 billion annually by 2100 (Narita & Rehdanz 2017).

An increase in the number and intensity of extreme weather and harmful algal bloom episodes is also expected. Indeed, the distribution and effects of harmful algal blooms are becoming more common, leading to more frequent and prolonged disruptions of product supply, which can easily result in a loss of market share for the affected production area. Seed mortalities are another indirect effect of climate change, more common in Southern Europe production areas, but also Northern Europe has recently being affected. Climate change is perceived as a major threat in Spain[6], Italy[7], France, Greece, Germany, Slovenia and Portugal.

[6]For example, Des *et al.* (2020) show that climate change will lead to less favourable conditions for mussel aquaculture in Spain.

[7]Temperature increases, as experienced in the Adriatic region, forces early harvesting of mussels. This implies harvesting mussels with lower meat content. This directly affects the mussel Scardovari, which is a recognized Protected Designation of Origin (PDO), since they have to be harvested earlier than required for the minimum quantity of edible meat. Thus, mussels are harvested but cannot be labelled as PDO because mussels do not have the minimum meat weight guaranteed in the rules of the Consortium. Hence, from an economic point of view, mussel producers suffer from an important direct damage (i.e., lack of product with a quantity of edible meat particularly appreciated by the market) and indirectly as the perception of the PDO mussels by consumers is damaged.

Bad weather or unfavourable weather conditions. Mussel farming tends to be carried out in more protected areas (e.g. bays or *rias*) than other marine aquaculture productions, and so it is generally less exposed to weather events. However, extreme weather events can do physical damage to stocks and supporting culture structures. The structures, holding suspended mussels, can be moved out of correct alignment and become strained or ruptured and can cause stock losses from structures to the bottom. Wave action from severe storm events can even dislodge bottom mussels in shallow waters, causing physical damage, which in turn allows secondary damage by opportunistic predator action later. Extreme weather events can also cause changes in the water column, e.g. sudden reductions in salinity due to freshwater input; resuspension of anoxic sediment deposited below mussel farms which can cause asphyxiation. Such storm events are becoming more frequent and extreme along the North west coast of Europe.

Some production techniques (e.g. longlines and rafts) can be more exposed to the weather effects, if they are not placed in areas protected enough. Likewise, offshore sites are more exposed to unfavourable weather conditions, which can lead to further costs (e.g. increased investment cost in more reinforced structures, higher repair and maintenance costs, due to more frequent storm damage occurring at greater distances from farm bases, exacerbated by having to wait out the duration of bad weather episodes, before taking action) (van den Burg *et al.* 2017). Bad weather conditions significantly affect France, Ireland (longline culture), Spain, Germany and Croatia.

Diseases and parasites. Mussels, as well as other marine bivalve molluscs, can be affected by a wide spectrum of parasites. Studies have mostly focused on agents causing mass mortalities, but they can also reduce the growth of mussels (Robledo *et al.* 1994). It often takes time to establish the causes (e.g. pathological, environmental or physiological) of mass mussel mortalities and sometimes can be difficult to establish (e.g. mass mortalities in France 2014) (Béchemin et al. 2015; Robert & Soletchnik 2016; Charles *et al.* 2020).

The presence of certain parasites can vary depending on the culture technique. Some studies show that the abundance of certain parasites can be higher in bottom techniques than in off-bottom ones, as well as in production at higher densities (Karagiannis *et al.* 2013). Disease and parasites significantly affect Italy, France and Slovenia (see for instance Bower *et al.* 1994; Karagiannis & Angelidis 2007; Karagiannis *et al.* 2013; Garrido-Maestu *et al.* 2016; Polsenaere *et al.* 2017).

Predators. Mussel farms are experiencing production losses caused by the predation from wild fish (e.g. *gilthead seabream*), sea-stars, comb jelly (*Mnemiopsis leidyi*)[8], among others. For example, in the Mediterranean (eastern Adriatic), mussel farms represent a highly attractive habitat for wild fish. Farm associated species belong mainly to the families Sparidae, Atherinidae and Mugilidae, with wild gilthead seabream as a major mussel seed predator (Šegvić-Bubić *et al.* 2011). A significant increase in wild gilthead seabream populations (both wild and farm escapees) documented in some coastline zones of the eastern Mediterranean has had a strong negative impact on mussel farms[9]. Fish predation has been reported to be a major cause of spat loss in commercial mussel farms in recent years (Šegvić-Bubić *et al.* 2011). A similar predation pattern was observed along the Galician coast (NW Spain), where mussel seed was strongly affected by predation of the black seabream *S. cantharus* (Peteiro et al. 2010).

According to Šegvić-Bubić *et al.* (2011), there were registered recruitment losses of 54% within just one month of monitoring. While Glamuzina et al. (2014) show that the socio-economic impact of the increase of the gilthead seabream population is evident, causing closure of many shellfish farms in the eastern Adriatic since production loss may reach over 90% of the production. Hence, predation has strong negative effects, especially on the loss of the production and the invested capital. Further plans on developing the shellfish industry should also take into account knowledge on occurrence, seasonal distribution and behaviour of potential predators in shellfish areas (their real-time impact) in order to achieve sustainable ecosystem-based management (Glamuzina et al. 2014). Predators have had a high impact (losses) in mussel productions in Greece, Germany, Ireland (mostly on the on-bottom segment), Denmark, Croatia and Slovenia.

Marine pollution. Pollutants and poor water quality can damage mussel. The filtering nature of mussels renders them vulnerable to two important but uncertain expositions: heavy metals and plastics. Mussels accumulate a wide range of heavy metals in their soft tissue (meat) by filtering the water (De Wolf 1975; Ritz *et al.* 1982; Bolognesi *et al.* 1999; Canesi *et al.* 1999; Pempkowiak *et al.* 1999; Štrok & Smodiš 2011; Stankovic *et al.* 2012; Chiesa *et al.* 2018). The transfer through the food web of heavy metals from mussels to other species has been

[8]Comb jelly preys on plankton, competing with mussels for feeding.

[9]The occurrence of large gilthead seabream schools could be potentially derived from restocking programs, accidental fish farm escapes or sea-cage spawners and also might be related to climate changes (Glamuzina et al., 2014). Moreover, according to Glamuzina et al. (2014), the gilthead seabream is facing very low competition from other local species which enhances its capacity to further populate the region.

Reviews in Aquaculture (2021) **13**, 91–118

demonstrated, and the consumption of heavy metals has a potential adverse effect on human health (see for example Stankovic *et al.* 2012).

A rising concern is plastics, and in particular micro-plastics, in the water. It has been estimated that 9 million tonnes of plastic end up as waste in the oceans and beaches every year, out of more than 300 million tonnes of plastics produced annually (UN Environment 2017). Plastics are currently affecting the Ria de Arousa in Galicia (NW Spain), where most of the Spanish mussel production is located, fishing vessels catch, on average, 12.7 ± 6.7 tonnes of marine litter by year (Villasante et al. 2020). The ingestion of micro-plastics has been reported in mussels (Browne *et al.* 2008; Von Moos *et al.* 2012; Farrell & Nelson 2013; De Witte, *et al.* 2014; Van Cauwenberghe & Janssen 2014; Van Cauwenberghe, *et al.* 2015; Li *et al.* 2016; Santana *et al.* 2016; Renzi *et al.* 2018). Moreover, the transfer of micro-plastics through the food web from mussels to other species has also been demonstrated (Farrell & Nelson 2013). The implications for the health of marine organisms, food chains and for human health still need to be determined.

Lack/unreliability of natural spat. There are three systems to obtain spat: wild harvest, use of suspended collectors and hatchery production. Spat availability influences which culture techniques are used. Mussels are characterized by high fecundity and a mobile living larval phase. Because of this generally abundant supply, mussel farming has always depended on the use of natural spat. However, obtaining natural supply of spat is often subject to large variations and cannot always match the increasing demand from the sector (Filgueira *et al.* 2007; Soria *et al.* 2014).

For wild harvest, spat is collected by dredges or beam trawlers and then are carried to areas where the growth conditions are better for the mussels (on-bottom culture). Spat can also be collected using suspended collectors (e.g. longlines and rafts), but this requires labour and the collection offshore implies higher costs. Hatchery production of mussels is possible, but it is not allowed in some EU countries (e.g. France). Moreover, hatcheries are the most expensive method to produce spat, with the price of mussels often being too low to make it economically viable (Kamermans *et al.* 2013; Carrasco *et al.* 2015; Figueroa & Dresdner 2016). The lack of spat affects mostly Northern EU countries: Germany, Ireland (mainly for the on-bottom segment), the UK, Denmark and Croatia.

Opportunities

The European mussel sector may benefit from different factors that would support its development: certification of mussel products, the availability of subsidies, increases in mussel consumption, product diversification, marine spatial planning, going offshore and integrated multi-trophic aquaculture.

Certification. EU consumers value the quality of seafood and have increasing exacting standards. Certification can guarantee the quality or origin of mussels. There is a tendency among consumers to appreciate the consumption of local mussels and to recognize their value if they have certificates of quality, organic or international recognition, such as PDO, which ensure the certainty of origin and the exclusivity of traditional production methods (Cozzolino 2014; Pirrone *et al.* 2017)[10]. For example, mussels produced with the 'bouchot' method have been designated with the French protected name status 'Moules de Bouchot' under the Traditional Speciality Guaranteed (TSG) since 2013. Also, in Galicia (Spain), the Designation of Protected Origin of mussels (DOP) included, in 2018, 55 enterprises and 2.090 mussel rafts with a production of 54 million kilos[11].

However, certification is not always an opportunity to achieve higher prices, but a business requirement. In that case, certification behaves as social licensing (Alfnes *et al.* 2018; Jenkins 2018; Amundsen *et al.* 2019). Some retailers insist on certification, such as the Marine Stewardship Council (MSC), to list a seafood product (Bonanomi *et al.* 2017). In consequence, only products with an appropriate label can enter the market.

At the beginning of the value chain, certifications are sometimes a conferring permission to act. For example, German mussel production takes place in the National Park Wadden Sea. In the authorization process for licenses, negotiations between the National Park, State Ministries and mussel producers take place. Mussel farmers certify their production system and products by MSC to verify their eco-friendliness and enhance their position in the political discussion. Fresh mussels can benefit from certifications in traditional markets. However, certification may prove even more useful for processed products or in non-traditional markets, where consumers may have more difficulty in appreciating quality.

Subsidies to promote environmental sustainability. In the European Maritime and Fisheries Fund (EMFF) from 2014 to 2020, there is an emphasis on environmental sustainability in fisheries and aquaculture. Support could be given to invest in aquaculture farms that reduce the negative environmental impacts of aquaculture (e.g. recirculating system) or contribute to a positive environmental impact (e.g.

[10]According to interviews carried out in the context of an Italian project on the certification of fish products, mussels' consumers would be willing to pay more if the product were certified. At present about 30% of the Italian mussel companies have some certification.

[11]https://www.mexillondegalicia.org/wp-content/uploads/2019/12/boletin-28.pdf

mussel production combats eutrophication)[12]. We expect that this emphasis on environmental sustainability in fisheries and aquaculture will continue under the EMFF beyond 2020.

Increase consumption via new markets and consumers. Mussel meat is a low fat and low calorie food, marine animal protein. Moreover, it has highly competitive prices in food markets. In a global context of increasing population and increasing demand of food and protein (Godfray *et al.* 2010; Bene *et al.* 2015; Guillen *et al.* 2019b), we can expect an increase in the demand for mussels. The processing of mussels (e.g. frozen, canned, modified atmosphere, ready-to-eat products, prepared dishes of fresh mussels in different sauces) enables commercialization of mussels for new consumers and new markets, while extending their limited shelf-life mussel (Goulas *et al.* 2005; Bernárdez & Pastoriza 2011). For example, the pasteurization of fresh mussels allows them to be in excellent condition for human consumption for at least 60 days. This opportunity to expand to new markets and consumers is in line with the capacity of the sector to create new products with more added value and longer conservation time. In addition, on the global perspective, introducing mussels to human populations could be also advantageous in many ways. A substantial shift towards more sustainable diets worldwide is considered a key path towards sustainable food systems and healthy diets, and mussels could be an important addition to the array of plant-based food products available to humans (Willet et al. 2019).

Diversification and integration. Currently, the degree of diversification in the mussels sector is very low. This is partly explained by the atomization of the sector, being most of EU mussel farmers small or microenterprises. There are some cases of production diversification where, in addition to mussels, other species such as clams, oysters and in few cases finfish are produced[13]. The diversification of economic activities is more rare; there are only few cases related to tourism or direct processing. These few cases of vertical integration commonly imply incorporating depuration or processing factories, but this often requires some sort of an initial horizontal integration (e.g. creation of producer organizations).

[12]For example, because most of the nutrients in coastal waters come from agriculture, it would be reasonable that the EU agro-environmental aid program is extended to support mussel farmers. In practice, this could involve financial support for mussel farmers to reduce nutrients from the water by producing mussels, in a similar way as agricultural farmers are supported for operations that reduce nutrient leakage from their farms (Lindahl & Kollberg, 2009).

[13]This refers to the development of other productions, in parallel to the mussel production, and so it is not related to Integrated multi-trophic aquaculture (IMTA), which is considered in a different subsection.

Marine spatial planning. Marine spatial planning consists of delineating when and where to carry out human activities at sea in order to ensure their efficiency, safety and sustainability. Hence, marine spatial planning can help to allocate sea space to activities, in particular to the less traditional ones such as aquaculture. Thus, maritime spatial planning can help to mitigate the difficulty of access to space, i.e. ensure suitable spots to extend or establish new farms (Zanou *et al.* 2005; Gimpel *et al.* 2015; Theodorou *et al.* 2015; Stelzenmüller *et al.* 2017).

Moving offshore. Another solution for avoiding congestion in coastal areas is to move the mussel production systems offshore. However, going offshore is more costly and implies higher risks, especially those related to unfavourable weather conditions. Current technologies for mussel production offshore are less profitable than traditional farming, and new strategies are being investigated, such as multi-use platforms, where mussel farming can be combined with other activities such as offshore wind energy or even IMTA (Buck *et al.* 2004 2010; Ferreira *et al.* 2009; Troell *et al.* 2009; Brenner et al. 2007; Griffin *et al.* 2015; Jansen *et al.* 2016; van den Burg *et al.* 2017).

Integrated multi-trophic aquaculture (IMTA). Integrated multi-trophic aquaculture (IMTA) describes the arrangement whereby species are co-cultured for mutual benefit. IMTA allows the by-products, including waste, from one aquatic species to be the input (e.g. fertilizer, food) for another species (Whitmarsh *et al.* 2006). For example, seaweed and salmon or mussel farms together can co-exist in a mutually advantageous way (Ridler *et al.* 2007).

While IMTA helps to substantively reduce the environmental cost of aquaculture, integrating extractive species (e.g. mussels and/or seaweeds), with existing fed-monoculture operations, can potentially increase farm profits in the EU. The current positive public attitudes towards IMTA, as expressed by a willingness to pay a premium for its products, can further increase the profitability of adopting IMTA in the EU (Knowler *et al.* 2020; Carras *et al.* 2020). Moreover, their production in the contexts of mussels and IMTA would contribute to some of the Sustainable Development Goals (SDG), particularly SDGs number 2 and 14, and could become a new source of livelihoods for communities across the world (United Nations 2015).

Concluding remarks

The stagnation of the EU aquaculture sector is largely explained by a decrease in the EU aquaculture production of mussels. This production decrease is in contrast with the production increase in other farmed species (e.g. salmon, seabream and seabass) and with the EU aquaculture production goals for 2020 (Guillen *et al.* 2019a). However, mussel farming often does not receive attention despite representing more than ⅓ of EU aquaculture production. In 2016, EU aquaculture production of mussels was almost 480 000 tonnes, a 20% decrease compared to the annual production of more than 600 000 tonnes in the late 1990s, despite public and private efforts to increase production and profitability. This production decline (relative to a continued annual production of 600 000 tonnes) represents about €60 million and €20 million of foregone GVA and profits annually, respectively, just in the producer sector.

The four mussel culture techniques have different needs and efficiencies. Off-bottom culture tends to be more production efficient than on-bottom culture, but on-bottom culture often has less problems with competing marine space usages. While rafts require greater depths, longlines require more surface space. In general terms, longline, raft and 'bouchot' culture suffer more from access to space, atomization, difficulty to get permits, harmful algal blooms and bad weather; while on-bottom culture suffers more from predators and the lack of spat. Hence, no technique excels over the others, but each marine space has its most suitable mussel farming technique according to its characteristics as well as the availability and potential need to collect spat. The mussel sector differs between EU countries by technique and capital intensity. In all cases, it goes beyond the production and GVA figures, since it contributes to rural development, either by direct employment, linkages to other industries or by providing synergies to tourism and regional gastronomy.

The main causes for the overall decline of the EU mussel production are environmental factors rather than economic ones. The average mussel price decreased by 12% from 2010 to 2016, which may be partly or largely due to imports from Chile. However, a similar decrease in the production cost was experienced during the same period. Average profits for the EU mussel sector have decreased, but they have been positive during all the period analysed. Hence, it is mainly the decline in the EU mussel production that has resulted in a worsening of the economic performance of mussel producers. In particular, harmful algal blooms (red tides), the lack of spat, bad weather, predators, diseases and parasites, etc., have often led to a declining production (in quantity and quality) but also increases in the production costs per unit[14]. Producers have not been able to translate increased costs to increased ex-farm prices, largely due to their high atomization. The existence of a large number of small producers is typical in the raft, longline and 'bouchot' segments, in great part due to the small size and volumes of mussel farms. On the other hand, enterprises using bottom culture tend to be bigger and more capitalized, with a higher degree of vertical integration.

This atomization of the producers offers the processing and depurating sectors market/bargain power. The low ex-farm mussel prices also make the use of hatcheries to increase spat production and therefore mussel production economically unfeasible (Kamermans *et al.* 2013; Carrasco *et al.* 2015; Figueroa & Dresdner 2016). There is a need therefore to improve ex-farm prices, not only to increase profitability but also to enable an increase in production by mussel producers. There are initiatives in different EU countries to integrate mussel producers in producer organizations (e.g. the Regulatory Council of Mussel in Galicia and the Consortium of co-operatives in Italy). This horizontal integration of producers allows them to manage larger volumes of mussels, since it is hardly possible to enlarge or establish new farm sites. Thus, horizontal integration makes feasible the vertical integration by incorporating processing and marketing. This integration can also ease producers to obtain certifications such as organic and the Protected Designation of Origin (PDO). Even if certifications do not ensure a premium price in some countries, these accreditations (PDO, organic, environmental, social and fair trade) are in general here to stay and should be pursued by producers. According to the SUCCESS Project (Girard et al. 2019), labelling initiatives have created a dynamic within the sector and the value-chain that have improved economic and environmental sustainability, helping to meet current consumer expectations.

Marine spatial planning seems to be the main regulatory instrument to allow expansion or establishment of new aquaculture farms in the short term. With current low ex-farm mussel prices and available technologies, establishing mussel farms offshore is of limited profitability. However, there is still the need to ease the administrative burden for new permits. The political profile of nature conservation is reflected in limited licenses and strict production requirements, hampering the market's development in some EU countries.

Although mussel aquaculture production systems may have a (low) impact on the environment, the degree of impact should be discussed in a non-biased and case-specific way to find an optimum trade-off between food security, business activity and nature protection. Since mussels are filter feeders, they improve the water quality and clarity. This allows mussel aquaculture for human consumption or for water purification (Lindahl *et al.* 2005; Lindahl & Kollberg 2008). In addition, some studies show that mussels can sequestrate CO_2. Hence, the importance to support the sector and encourage further production and integration. This public support can be translated in specific actions under the environmental sustainability aspects in the EMFF

[14]Total mussel production costs are rather stable, since the variation of feed and energy costs does not affect the profitability as in finfish aquaculture and recirculation systems. In a context of increasing mortality and so declining in production, the cost per mussel produced tends to increase.

beyond 2020. Another important aspect is whether mussel farmers will be allowed to produce 'green' certificates for the volume of CO_2 sequestrated in their mussels, and be able to sell them to enterprises that are emitting CO_2. Both aspects may have an effect on how much, and in which direction the mussel aquaculture industry in the EU will develop.

Mussel production not only improves the quality of water and sequestrates carbon, but is also a cheap and healthy source of food. Mussels constitute a good source of animal protein and other nutrients, especially when considering the price, and also in the context of the need for a healthier human diet (Willet et al. 2019). Few products have a higher protein per euro spent. Therefore, we consider that the production of mussels should be further encouraged, on the one side for their capacity to clean the water and carbon sequestration, as well as in terms of food and nutrition security to feed an increasing population. However, for this to happen, mussels need to be healthy and edible. Hence, it is important to limit the presence of pollutants (e.g. heavy metals and plastics) in the water.

Climate change is increasingly affecting environmental parameters, such as increase in the sea temperature and sea level rise, ocean acidification, changes in rainfall and therefore salinity, and the concentration and quality of nutrients. Increases in the number and intensity of extreme weather events and harmful algal bloom episodes are expected. Thus, mussel farmers are exposed to increasing risks, affecting future aquaculture production and their economic results. Finally, the UK left the EU (Brexit) in early 2020, which may also have consequences at different levels of the market chain, from producers to consumers. However, these consequences are rather uncertain and will depend on the trade agreements established between the UK and the EU.

A coordinated effort to reverse the state of the EU mussel sector appears necessary. Apart from environmental factors, a lack of political planning seems to be a key factor explaining the current status of the EU mussel sector. The EU's Common Fisheries Policy (European Commission 2013a) set the objective of the sustainable development of EU aquaculture, and established a coordinated approach across the European Commission and EU Member States. Achievement of this objective was based on non-binding Commission Strategic Guidelines (European Commission 2013b) and Multi-annual National Strategic Plans (European Commission 2016) which translated those guidelines into objectives and actions specific to each Member State.

A stronger joint strategic approach for EU aquaculture has become even more relevant today. The review of the Commission Strategic Guidelines for the sustainable development of EU aquaculture aims to provide a common vision for the Commission, Member States and stakeholders to develop aquaculture as a sector that is both sustainable and competitive. Specific guidelines per subsector (marine fish, shellfish and freshwater fish) are also being developed.

These Commission Strategic Guidelines will need to develop strategic plans explicitly designed at national level, ideally with specific guidelines for the shellfish sector. These national strategic plans should capture the distinct aspects of the different aquaculture and mussel sectors across EU countries, and between regions within a country where necessary. They should aim to give the industry a stable and boosting framework to operate. They must define a clear vision of the future, and a strategy to realize it with goals and objectives for the environmental, social and economic aspects, in line with the ecosystem approach to aquaculture planning proposed by FAO (FAO 2010) and the European Green Deal's From Farm to Fork Strategy (European Commission 2019).

A good strategic plan should encompass the linkage and synergies with other economic sectors, such as tourism and regional gastronomy, to gain the support and political will needed (Brugère *et al.* 2010). A participatory approach is also essential to these initiatives as it gives legitimacy for the strategy and facilitates its implementation. The planning process also provides an opportunity to increase the sector's organization, add value to the production and discuss mechanisms to overcome problems caused by the sector atomization, such as improved producer's organization and representation, verticalization of the industry, and integration of depuration/processing industries and farmers. The development of GIS tools for planning and management of the marine space and aquaculture (e.g. MSP) are helpful to improve governance. The impact of diseases and red tides can be reduced with improved zoning and surveillance. Certification and traceability should also be set in the goals. Traceability is fundamental to increase consumers' trust in filter feeding seafood. Digitization, such as the establishment of block-chain technology along the supply chain, is expected to play a central role in ensuring traceability. Other actions that could be included in national strategic plans are the creation of an emergency fund to alleviate farmers' losses during extended harvest closure due to red tides or diseases.

References

Adamson E, Syvret M, Woolmer A (2018) Shellfish seed supply for aquaculture in the UK: report on views collected from the industry in 2017. [Cited 29 May 2019] Available from URL: http://www.shellfish.org.uk/files/Literature/Projects-Reports/Report-on-UK-shellfish-seed-Fishmongers-Company-June-2018.pdf.

Ahsan DA, Roth E (2010) Farmers' perceived risks and risk management strategies in an emerging mussel aquaculture industry in Denmark. *Marine Resource Economics* **25**: 309–323.

Alfnes F, Chen X, Rickertsen K (2018) Labeling farmed seafood: a review. *Aquaculture Economics & Management* **22**(1): 1–26.

Álvarez-Salgado XA, Labarta U, Fernández-Reiriz MJ, Figueiras FG, Rosón G, Piedracoba S *et al.* (2008) Renewal time and the impact of harmful algal blooms on the extensive mussel raft culture of the Iberian coastal upwelling system (SW Europe). *Harmful Algae* **7**: 849–855.

Álvarez-Salgado XM, Fernández-Reiriz MJ, Labarta U, Filguera R, Peteiro L, Figueiras FG *et al.* (2009) Influencia do cambio climático no cultivo de mexillón das rías galegas. In: Muñuzuri VP, FernándezCañamero M, GómezGesteira JL (coord.) *Evidencias do cambio climático en Galicia*. pp. 373–390. Xunta de Galicia, Consellería de Medio e Desenvolvemento Sostible, Spain.

Amorim Á, Vasconcelos V (1999) Dynamics of microcystins in the mussel *Mytilus galloprovincialis*. *Toxicon* **37**: 1041–1052.

Amundsen VS, Gauteplass AÅ, Bailey JL (2019) Level up or game over: the implications of levels of impact in certification schemes for salmon aquaculture. *Aquaculture Economics & Management* **23**(3): 237–253.

Anon. (2009) Shellfish production in the UK in 2008. *Shellfish News* **28**: 46–49.

Anon. (2012) UK shellfish imports and exports in 2011. *Shellfish News* **34**: 41–42,

Asche F (2008) Farming the sea. *Marine Resource Economics* **23**: 527–547.

Avdelas L, Papaharisis L, Galinou-Mitsoudi S (2015) Cost Structure and Profitability of Mussel Aquaculture in Greece. *2015 EAFE (European Association of Fisheries Economists) Conference Papers (No. 005)*. Nisea, Italy. Available from URL: https://ideas.repec.org/p/irf/wpaper/005.html

Beadman HA, Kaiser MJ, Galanidi M, Shucksmith R, Willows RI (2004) Changes in species richness with stocking density of marine bivalves. *Journal of Applied Ecology* **41**: 464–475.

Béchemin C, Soletchnik P, Polsenaere P, LeMoine O, Pernet F, Protat M *et al.* (2015) Episodes de mortalité massive de moules bleues observés en 2014 dans les Pertuis charentais. *Santé animale-alimentation*, 67. pp.6-9. Available from URL: https://www.anses.fr/en/system/files/BEP-mg-BE67.pdf#page=6

Bene C, Barange M, Subasinghe R, Pinstrup-Andersen P, Merino G, Hemre GI *et al.* (2015) Feeding 9 billion by 2050–Putting fish back on the menu. *Food Security* **7**: 261–274.

Bernárdez M, Pastoriza L (2011) Quality of live packaged mussels during storage as a function of size and oxygen concentration. *Food Control* **22**: 257–265.

Bolognesi C, Landini E, Roggieri P, Fabbri R, Viarengo A (1999) Genotoxicity biomarkers in the assessment of heavy metal effects in mussels: experimental studies. *Environmental and molecular mutagenesis* **33**: 287–292.

Bonanomi S, Colombelli A, Malvarosa L, Cozzolino M, Sala A (2017) Towards the Introduction of Sustainable Fishery Products: The Bid of a Major Italian Retailer. *Sustainability* **9** (3): 1–8.

Borthagaray AI, Carranza A (2007) Mussels as ecosystem engineers: their contribution to species richness in a rocky littoral community. *Acta oecologica* **31**: 243–250.

Botta R, Asche F, Borsum JS, Camp E (2020) A review of global oyster aquaculture production and consumption. *Marine Policy* **117**: 103952.

Bower SM, McGladdery SE, Price IM (1994) Synopsis of infectious diseases and parasites of commercially exploited shellfish. *Annual Review of Fish Diseases* **4**: 1–199.

Brenner M, Buck BH, Köhler A (2007) New concept combines offshore wind farms, mussel cultivation. *Global Aquaculture Advocate* **10**: 79–81.

Browne MA, Dissanayake A, Galloway TS, Lowe DM, Thompson RC (2008) Ingested microscopic plastic translocates to the circulatory system of the mussel, *Mytilus edulis* (L.). *Environmental Science & Technology* **42**: 5026–5031.

Brugère C, Ridler N, Haylor G, Macfadyen G, Hishamunda N (2010) Aquaculture planning: policy formulation and implementation for sustainable development. FAO Fisheries and Aquaculture Technical Paper, No. 542. Rome, FAO. 70 pp. Available from URL: http://www.fao.org/3/i1601e/i1601e00.pdf

Buck BH, Krause G, Rosenthal H (2004) Multifunctional use, environmental regulations and the prospect of offshore co-management: potential for and constraints to extensive open ocean aquaculture development within wind farms in Germany. *Ocean and Coastal Management* **47**: 95–122.

Buck BH, Ebeling MW, Michler-Cieluch T (2010) Mussel cultivation as a co-use in offshore wind farms: potential and economic feasibility. *Aquaculture Economics & Management* **14** (4): 255–281.

Bunting SW, Pretty J (2007) Aquaculture Development and Global Carbon Budgets: Emissions, Sequestration and Management Options. Centre for Environment and Society Occasional Paper 2007-1. Colchester, UK, University of Essex. Available from URL: http://library.enaca.org/mangrove/publications/centre_for_environment_op2007-1.pdf

Canesi L, Viarengo A, Leonzio C, Filippelli M, Gallo G (1999) Heavy metals and glutathione metabolism in mussel tissues. *Aquatic Toxicology* **46**: 67–76.

Carras MA, Knowler D, Pearce CM, Hamer A, Chopin T, Weaire T (2020) A discounted cash-flow analysis of salmon monoculture and Integrated Multi-Trophic Aquaculture in eastern Canada. *Aquaculture Economics & Management* **24**(1): 43–63.

Carrasco AV, Astorga M, Cisterna A, Farías A, Espinoza V, Uriarte I (2015) Pre-feasibility study for the installation of a Chilean Mussel Mytilus chilensis (Hupé, 1854) seed hatchery in the lakes region. *Chiles. Fisheries and Aquaculture Journal* **5** (3): 1.

Castelo O, Perez-Dorca A (1997) *El sector productor mejillonero: su crisis. Feuga*. Consellería de Pesca, Santiago de Compostela, Spain.

Charles M, Bernard I, Villalba A, Oden E, Burioli EA, Allain G *et al*. (2020) High mortality of mussels in northern Brittany-Evaluation of the involvement of pathogens, pathological conditions and pollutants. *Journal of Invertebrate Pathology* **170**: 107308.

Chiesa LM, Ceriani F, Caligara M, Di Candia D, Malandra R, Panseri S *et al*. (2018) Mussels and clams from the Italian fish market. Is there a human exposition risk to metals and arsenic? *Chemosphere* **194**: 644–649.

Cozzolino M. (2014) Artisanal fisheries can benefit from certification. *Eurofish magazine* **6**: 37–38. https://www.eurofishmagazine.com/.

Cush P, Varley T (2013) Cooperation as a survival strategy among west of Ireland small-scale mussel farmers. *Maritime Studies* **12**: 11.

Dare PJ (1980) *Mussel cultivation in England and Wales*. Laboratory Leaflet 50. Ministry of Agriculture, Fisheries and Food, Directorate of Fisheries Research, UK. Available from URL: https://www.cabdirect.org/cabdirect/abstract/19811419862

De Witte B, Devriese L, Bekaert K, Hoffman S, Vandermeersch G, Cooreman K *et al*. (2014) Quality assessment of the blue mussel (*Mytilus edulis*): comparison between commercial and wild types. *Marine Pollution Bulletin* **85**: 146–155.

De Wolf P (1975) Mercury content of mussels from West European coasts. *Marine Pollution Bulletin* **6**: 61–63.

Des M, Gómez-Gesteira M, de Castro M, Gómez-Gesteira L, Sousa MC (2020) How can ocean warming at the NW Iberian Peninsula affect mussel aquaculture? *Science of the Total Environment* **709**: 136117.

Dias PJ, Dordor A, Tulett D, Piertney S, Davies IM, Snow M (2009) Survey of mussel (Mytilus) species at Scottish shellfish farms. *Aquaculture Research* **40**: 1715–1722.

Edebo L, Haamer J, Lindahl O, Loo LO, Piriz L (2000) Recycling of macronutrients from sea to land using mussel cultivation. *International Journal of Environment and Pollution* **13**: 190–207.

European Commission (2013a) No 1380/2013 of the European Parliament and of the Council of 11 December 2013 on the Common Fisheries Policy, amending Council Regulations (EC) No 1954/2003 and (EC) No 1224/2009 and repealing Council Regulations (EC) No 2371/2002 and (EC) No 639/2004 and Council Decision 2004/585/EC. Publications office of the European Union. Luxembourg. Available from URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32013R1380

European Commission (2013b) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Strategic Guidelines for the sustainable development of EU aquaculture. COM/2013/0229 final. Publications office of the European Union. Luxembourg. Available from URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52013DC0229

European Commision (2016) *Multiannual national aquaculture plans summaries by country*. [Cited 1 Feb 2019] Available from URL: http://ec.europa.eu/fisheries/cfp/aquaculture/multiannualnational-plans_en.

European Commission (2019) Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal. COM/2019/640 final. Publications office of the European Union. Luxembourg. Available from URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588580774040&uri=CELEX:52019DC0640.

Eurostat (2019) Production from aquaculture excluding hatcheries and nurseries (from 2008 onwards). Online data code: fish_aq2a [Cited 9 Apr 2019].

Falconer IR, Choice A, Hosja W (1992) Toxicity of edible mussels (Mytilus edulis) growing naturally in an estuary during a water bloom of the blue-green alga Nodularia spumigena. *Environmental toxicology and water quality* **7**: 119–123.

FAO (Food and Agriculture Organization) (2010) Aquaculture development. 4. Ecosystem approach to aquaculture. FAO Technical Guidelines for Responsible Fisheries. No. 5, Suppl. 4.Rome, FAO. 2010. 53 p.

FAO (Food and Agriculture Organization) (2019) Aquaculture production 1950–2016. In Fisheries and aquaculture software: FishStatJ - Software for Fishery and Aquaculture Statistical Time Series. FAO Fisheries and Aquaculture Department. Rome.

Farrell P, Nelson K (2013) Trophic level transfer of microplastic: Mytilus edulis (L.) to Carcinus maenas (L.). *Environmental pollution* **177**: 1–3.

Ferreira J, Sequeira A, Hawkins A, Newton A, Nickell T, Pastres R *et al*. (2009) Analysis of coastal and offshore aquaculture: application of the FARM model to multiple systems and shellfish species. *Aquaculture* **289**: 32–41.

Figueiras FG, Labarta U, Fernández Reiriz MJ (2002) Coastal upwelling, primary production and mussel growth in the Rías Baixas of Galicia. *Hydrobiologia* **484**: 121–131.

Figueroa Y, Dresdner J (2016) Are mussel seed producers responsive to economic incentives? Empirical evidence from the Benthic Resource Management Areas in Chile. *Aquaculture Economics & Management* **20**(3): 283–311.

Filgueira R, Peteiro LG, Labarta U, Fernández-Reiriz MJ (2007) Assessment of spat collector ropes in Galician mussel farming. *Aquacultural Engineering* **37**: 195–201.

Filgueira R, Byron CJ, Comeau LA, Costa-Pierce B, Cranford PJ, Ferreira JG *et al*. (2015) An integrated ecosystem approach for assessing the potential role of cultivated bivalve shells as part of the carbon trading system. *Marine Ecology Progress Series* **518**: 281–287.

Friðriksson KS, Haraldsson G (2018) Impact assessment of technological and regulatory innovations. Deliverable 5.1 of the Horizon 2020 project SUCCESS (GA number 635188), Available from URL: https://www.umr-amure.fr/wp-content/uploads/2019/06/D5.1_success.pdf.

Galparsoro I, Murillas A, Pinarbasi K, Sequeira A, Stelzenmüller V, Borja A *et al*. (2020) Global stakeholder vision for ecosystem-based marine aquaculture expansion from coastal to offshore areas. *Reviews in Aquaculture* 1–19. https://doi.org/10.1111/raq.12422

Gardner JPF, Skibinski DOF, Bajdik CD (1993) Shell growth and viability differences between the marine mussels *Mytilus edulis* (L.), Mytilus galloprovincialis (Lmk.), and their hybrids from two sympatric populations in S.W. England. *The Biological Bulletin* **185**: 405–416.

Garlock T, Asche F, Anderson JL, Bjørndal T, Kumar G, Lorenzen K *et al.* (2020) A Global Blue Revolution: aquaculture growth across regions, species, and countries. *Reviews in Fisheries Science and Aquaculture* **28**: 107–116.

Garrido-Maestu A, Lozano-León A, Rodríguez-Souto RR, Vieites-Maneiro R, Chapela MJ, Cabado AG (2016) Presence of pathogenic Vibrio species in fresh mussels harvested in the southern Rias of Galicia (NW Spain). *Food Control* **59**: 759–765.

Gimpel A, Stelzenmüller V, Grote B, Buck BH, Floeter J, Núñez-Riboni I *et al.* (2015) A GIS modelling framework to evaluate marine spatial planning scenarios: Co-location of offshore wind farms and aquaculture in the German EEZ. *Marine Policy* **55**: 102–115.

Girard S, Mariojouls C (2008) French consumption of oysters and mussels analysed within the European market. *Aquaculture Economics & Management* **7**(5–6): 319–333.

Girard S, Cozzolino M, Avdelas L, Galinou-Mitsoudi S, Turenhout M, LLorente IBaraibarDiez E (2019) Mussel case study. In: Daures F, Girard S, Dieudonne E, Mardle S (eds) *Comparative Analysis of Production Systems in Fisheries and Aquaculture*. Deliverable 3.6 of the Horizon 2020 project SUCCESS (GA number 635188). Available from URL: https://www.umr-amure.fr/wp-content/uploads/2019/02/D3.6-Final-report.pdf.

Glamuzina B, Pešić A, Joksimović A, Glamuzina L, Matić-Skoko S, Conides A, *et al.* (2014) Observations on the increase of wild gilthead seabream, Sparus aurata abundance, in the eastern Adriatic Sea: problems and opportunities. *International Aquatic Research* **6**(3): 127–134.

Glibert PM, Anderson DM, Gentien P, Granéli E, Sellner KG (2005) The global, complex phenomena of harmful algal blooms. *Oceanography* **18**: 137–47.

Globefish (2018) Monthly Trade Statistics. Statistics update: December 2017. Food and Agriculture Organization. January 2018 issue. 109 pp.

Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF *et al.* (2010) Food security: the challenge of feeding 9 billion people. *Science* **327**: 812–818.

Gonzalez-Poblete E, Rojo C, Norambuena R (2018) Blue mussel aquaculture in Chile: Small or large scale industry? *Aquaculture* **493**: 113–122.

Goulas AE, Chouliara I, Nessi E, Kontominas MG, Savvaidis IN (2005) Microbiological, biochemical and sensory assessment of mussels (Mytilus galloprovincialis) stored under modified atmosphere packaging. *Journal of Applied Microbiology* **98**: 752–760.

Griffin R, Buck B, Krause G (2015) Private incentives for the emergence of co-production of offshore wind energy and mussel aquaculture. *Aquaculture* **436**: 80–89.

Guillen J, Asche F, Carvalho N, Fernandez Polanco JM, Llorente I, Nielsen R *et al.* (2019a) Aquaculture subsidies in the European Union: Evolution, impact and future potential for growth. *Marine Policy* **104**: 19–28.

Guillen J, Natale F, Carvalho N, Casey J, Hofherr J, Druon JN *et al.* (2019b) Global seafood consumption footprint. *Ambio* **48**: 111–122.

Gutiérrez E, Lozano S, Guillen J (2020) Efficiency data analysis in EU aquaculture production. *Aquaculture* **520**: 734962.

Hall SJ, Delaporte A, Phillips MJ, Beveridge M, O'Keefe M (2011) *Blue Frontiers: Managing the Environmental Costs of Aquaculture*. The WorldFish Center, Penang, Malaysia. [Cited 12 Dec 2019] Available from URL: http://aquaticcommons.org/5758/1/Blue_Frontiers_Report.pdf

Hambrey J, Evans S (2016) SR694 Aquaculture in England, Wales and Northern Ireland: an analysis of the economic contribution and value of the major sub-sectors and the most important farmed species. 162 pp. [Cited 29 May 2019] Available from URL: https://www.seafish.org/media/publications/FINALISED_Aquaculture_in_EWNI_FINALISED__-_Sept_2016.pdf

Hoagland P, Scatasta S. (2006) The economic effects of harmful algal blooms. In: Graneli E, Turner J (eds) *Ecology of harmful algae*. Ecology Studies Series. pp. 391–402. Springer-Verlag. Dordrecht, The Netherlands.

Howard AE (1998) Shellfish production in the UK in 1997: Shellfish production and disease control in England and Wales. *Shellfish News* **6**: 32–33.

Jansen HM, Van Den Burg S, Bolman B, Jak RG, Kamermans P, Poelman M *et al.* (2016) The feasibility of offshore aquaculture and its potential for multi-use in the North Sea. *Aquaculture international* **24**: 735–756.

Jeffery KR, Vivian CMG, Painting SJ, Hyder K, Verner-Jeffreys DW, Walker RJ*et al.*(2014) Background information for sustainable aquaculture development, addressing environmental protection in particular. [Cited 12 Dec 2019] http://www.aquacircle.org/images/pdfdokumenter/efterret14/Draft%20SUSAQ%20Report%20C6078A%20for%2018%20September_for%20release.pdf.

Jenkins K (2018) Can I see your Social Licence please? *Policy Quarterly* **14**(4): 27–35.

Jin D, Thunberg E, Hoagland P (2008) Economic impact of the 2005 red tide event on commercial shellfish fisheries in New England. *Ocean and Coastal Management* **51**: 420–9.

Kaiser MJ, Laing I, Utting SD, Burnell GM (1998) Environmental impacts of bivalve mariculture. *Journal of Shellfish Research* **17**: 59–66.

Kamermans P, Capelle JJ (2019) Provisioning of mussel seed and its efficient use in culture. In: Smaal A, Ferreira J, Grant J, Petersen J, Strand Ø (eds) *Goods and Services of Marine Bivalves*. Springer, Cham.

Kamermans P, Galley T, Boudry P, Fuentes J, McCombie H, Batista F *et al.* (2013) Blue mussel hatchery technology in Europe. In: Allan, G, Burnell, G (eds) *Advances in aquaculture hatchery technology*, pp. 339–373. Elsevier, New York, NY.

Karagiannis D, Angelidis P (2007) Infection of cultured mussels *Mytilus galloprovincialis* by the protozoan Marteilia sp. in the Thermaikos Gulf (N Greece). *Bulletin of European Association of Fish Pathologists* **27**: 131–141.

Karagiannis D, Vatsos IN, Theodoridis A, Angelidis P (2013) Effect of culture system on the prevalence of parasites of the Mediterranean mussel *Mytilus galloprovincialis* (Lamark, 1819). *Journal of Hellenic Veterinary Medicine Society* **64**: 113–122.

Knowler D, Chopin T, Martínez-Espiñeira R, Neori A, Nobre A, Noce A *et al.* (2020) The economics of Integrated Multi-Trophic Aquaculture: where are we now and where do we need to go? *Reviews in Aquaculture* **1–16**: https://doi.org/10.1111/raq.12399.

Kumar G, Engle CR (2016) Technological advances that led to the growth of shrimp, salmon, and tilapia industries. *Reviews in Fisheries Science* **24**: 136–152.

Labarta U, Fernández Reiriz MJ (2019) The Galician mussel industry: Innovation and changes in the last forty years. *Ocean and Coastal Management* **167**: 208–218.

Laing I, Spencer BE. (2006) Bivalve cultivation: criteria for selecting a site. Science Series Technical Report, Cefas Lowestoft, 136: 34 pp. [Cited 29 May 2019] Available from URL: https://webarchive.nationalarchives.gov.uk/20150204144706/http://www.cefas.defra.gov.uk/publications-and-data/scientific-series/technical-reports.aspx.

LeBihan V, Guillotreau B, Morineau B, Pardo S. (2019) The impact of shellfish trade bans caused by Harmful Algal Blooms (HABs) on a french regional economy: an input-output approach. Oceanext - Interdisciplinary Conference, Nantes, France, July 3–5 2019. Available from URL: https://oceanext-2019.sciencesconf.org/

Li J, Qu X, Su L, Zhang W, Yang D, Kolandhasamy P *et al.* (2016) Microplastics in mussels along the coastal waters of China. *Environmental Pollution* **214**: 177–184.

Lindahl O, Kollberg S (2008) How mussels can improve coastal water quality. *Bioscience Explained* **5**: 1–14.

Lindahl O, Kollberg S (2009) Can the EU agri-environmental aid program be extended into the coastal zone to combat eutrophication? *Hydrobiologia* **629**: 59–64.

Lindahl O, Hart R, Hernroth B, Kollberg S, Loo LO, Olrog L *et al.* (2005) Improving marine water quality by mussel farming: a profitable solution for Swedish society. *Ambio* **34**: 131–138.

Malvarosa L, Cozzolino M, Gambino M (2017) Co-management for sedentary species. The case of the "fasolari" fishery in Northern Adriatic. Slow Fish biannual event, May. Genova. Italia.

McKindsey CW, Archambault P, Callier MD, Olivier F (2011) Influence of suspended and off-bottom mussel culture on the sea bottom and benthic habitats: a review. *Canadian Journal of Zoology* **89**: 622–646.

Monfort MC. (2014) The European market for mussels. *Globefish Research Programme* 115. FAO, Rome, Italy.

Mongruel R, Thébaud O (2006) Externalities, institutions and the location choices of shellfish producers: the case of blue mussel farming in the Mont-Saint-Michel bay (France). *Aquaculture Economics & Management* **10**(3): 163–181.

Munari C, Rossetti E, Mistri M (2013) Shell formation in cultivated bivalves cannot be part of carbon trading systems: a study case with Mytilus galloprovincialis. *Marine Environmental Research* **92**: 264–267.

Munro LA, Wallace IS, Mayes AS (2013) *Scottish shellfish farm production survey 2012*. Marine Scotland Science, Edinburgh, UK. Available from URL:https://www.gov.scot/publications/scottish-shellfish-farm-production-survey-2012-report/

Narita D, Rehdanz K (2017) Economic impact of ocean acidification on shellfish production in Europe. *Journal of Environmental Planning and Management* **60**: 500–518.

Navarro E, Iglesias JIP, Perez Camacho A, Labarta U, Beiras R (1991) The physiological energetics of mussels from different cultivation rafts in the Ria de Arosa. *Aquaculture* **94**: 197–212.

Naylor R, Burke M (2005) Aquaculture and ocean resources: raising tigers of the sea. *Annual Review of Environment and Resources* **30**: 185–218.

O'Sullivan G (1998) Present situation and future prospects for cultivation, commercialisation and industrialisation of mussels in Ireland. *Globefish* **55**: 55–60.

OESA - Fundación Biodiversidad (2017) *Cultivo del mejillón (Mytilus galloprovincialis), Cuadernos de Acuicultura 8*. Fundación Biodiversidad, Madrid, España. Available from URL: https://www.observatorio-acuicultura.es/sites/default/files/images/adjuntos/libros/cuaderno_mejillon.pdf

Outeiro L, Villasante S, Sumaila RU (2018) Estimating fishers' net income in small-scale fisheries: Minimum wage or average wage? *Ocean and Coastal Management* **165**: 307–318.

Pempkowiak J, Sikora A, Biernacka E (1999) Speciation of heavy metals in marine sediments vs their bioaccumulation by mussels. *Chemosphere* **39**: 313–321.

Peperzak L, Poelman M (2008) Mass mussel mortality in The Netherlands after a bloom of *Phaeocystis globosa* (prymnesiophyceae). *Journal of Sea Research* **60**: 220–222.

Peteiro LG, Filgueira R, Labarta U, Fernández-Reiriz MJ (2010) The role of fish predation on recruitment of Mytilus galloprovincialis on different artificial mussel collectors. *Aquacultural Engineering* **42**: 25–30.

Philippart CJ, Anadón R, Danovaro R, Dippner JW, Drinkwater KF, Hawkins SJ *et al.* (2011) Impacts of climate change on European marine ecosystems: observations, expectations and indicators. *Journal of Experimental Marine Biology and Ecology* **400**: 52–69.

Piferrer F, Beaumont A, Falguière JC, Flajšhans M, Haffray P, Colombo L (2009) Polyploid fish and shellfish: production, biology and applications to aquaculture for performance improvement and genetic containment. *Aquaculture* **293**: 125–156.

Pirrone C, Paolucci C, Malvarosa L, Masson E, Mariojouls C, Daurès F*et al.* (2017) Consumer perceptions about coastal fishery and its products What Focus Groups from Italy and France tell us. Slow Fish biannual Event. Genova, Italia.

Polsenaere P, Soletchnik P, LeMoine O, Gohin F, Robert S, Pépin JF *et al*. (2017) Potential Environmental Drivers of a Regional Blue Mussel Mass Mortality Event (Winter of 2014, Breton Sound, France). *Journal of Sea Research* **123**: 39–50.

Renzi M, Guerranti C, Blašković A (2018) Microplastic contents from maricultured and natural mussels. *Marine Pollution Bulletin* **131**: 248–251.

Ridler N, Wowchuk M, Robinson B, Barrington K, Chopin T, Robinson S *et al*. (2007) Integrated multi− trophic aquaculture (IMTA): a potential strategic choice for farmers. *Aquaculture Economics & Management* **11**(1): 99–110.

Ritz DA, Swain R, Elliott NG (1982) Use of the mussel Mytilus edulis planulatus (Lamarck) in monitoring heavy metal levels in seawater. *Marine and Freshwater Research* **33**: 491–506.

Robert S, Soletchnik P. (2016) Réseau national d'observation de la moule bleue Mytilus edulis, MYTILOBS / Campagne 2015. Convention DPMA 2015/ n°14/1211577/F. . Available from URL: https://archimer.ifremer.fr/doc/00334/44494/

Robledo JAF, Santarém MM, Figueras A (1994) Parasite loads of rafted blue mussels (Mytilus galloprovincialis) in Spain with special reference to the copepod, *Mytilicola intestinalis*. *Aquaculture* **127**: 287–302.

Rodrigues LC, van den Bergh JCJM, Massa F, Theodorou JA, Ziveri P, Gazeau F (2015) Sensitivity of Mediterranean bivalve mollusc aquaculture to climate change and ocean acidification: results from a producers' survey. *Journal Shellfish Research* **34**: 1161–1176.

Rodríguez GR, Villasante S, do García-Negro MC (2011) Are red tides affecting economically the commercialization of the Galician (NW Spain) mussel farming? *Marine Policy* **35**: 252–257.

Roheim CA, Bush SB, Asche F, Sanchirico J, Uchida H (2018) Evolution and future of the sustainable seafood market. *Nature Sustainability* **1**: 392–398.

Sanseverino I, Conduto D, Pozzoli L, Dobricic S, Lettieri T. (2016) Algal bloom and its economic impact. JRC Technical Reports: 1–52. Publications Office of the European Union. Italy. Available from URL: https://ec.europa.eu/jrc/en/publication/algal-bloom-and-its-economic-impact

Santana MFM, Ascer LG, Custódio MR, Moreira FT, Turra A (2016) Microplastic contamination in natural mussel beds from a Brazilian urbanized coastal region: Rapid evaluation through bioassessment. *Marine Pollution Bulletin* **106**: 183–189.

Schlauch J (1999) Entwicklung und Struktur der deutschen Molluskenfisherei und -kultur im trilateralen Vergleich mit Danemark und den Niederlanden. Bamberger Wirtschaftsgeografischen Arbeiten, heft 10 (in German).

Science for Environment Policy (2015). Sustainable Aquaculture. Future Brief 11. Brief produced for the European Commission DG Environment by the Science Communication Unit, UWE, Bristol. [Cited 12 Dec 2019] Available from URL: http://ec.europa.eu/science-environment-policy.

Seafish (2019) Aquaculture profile: mussels *Mytilus edulis*. [Cited 29 May 2019] Available from URL: https://www.seafish.org/aquaculture/profile/15/mussels.

Šegvić-Bubić T, Grubišić L, Karaman N, Tičina V, Jelavić KM, Katavić I (2011) Damages on mussel farms potentially caused by fish predation-self service on the ropes? *Aquaculture* **319**: 497–504.

Shepherd CJ, Little DC (2014) Aquaculture: Are the criticisms justified? II—Aquaculture's environmental impact and use of resources, with special reference to farming Atlantic salmon. *World Agriculture* **4**: 37–52.

Smaal AC (2002) European mussel cultivation along the Atlantic coast: production status, problems and perspectives. *Hydrobiologia* **484**: 89–98.

Soria G, Lavín MF, Cudney-Bueno R (2014) Spat availability of commercial bivalve species recruited on artificial collectors from the northern Gulf of California. Seasonal changes in species composition. *Aquaculture Research* **46**: 2829–2840.

Stankovic S, Jovic M, Stankovic AR, Katsikas L (2012) Heavy metals in seafood mussels. Risks for human health. In: Lichtfouse, E, Schwarzbauer, J, Robert, D (eds) *Environmental Chemistry for a Sustainable World*, pp. 311–373. Springer, Dordrecht. The Netherlands.

STECF (Scientific, Technical and Economic Committee for Fisheries) (2018) The economic performance of the EU aquaculture sector. JRC scientific and policy reports. Publications Office of the European Union. Luxembourg.

Stelzenmüller V, Gimpel A, Gopnik M, Gee K (2017) Aquaculture site-selection and marine spatial planning: the roles of GIS-based tools and models. In: *Aquaculture Perspective of Multi-Use Sites in the Open Ocean*, pp. 131–148. Springer, Cham.

Štrok M, Smodiš B (2011) Levels of 210Po and 210Pb in fish and molluscs in Slovenia and the related dose assessment to the population. *Chemosphere* **82**: 970–976.

SUCCESS H2020 (2017) Finding a formula for Success – Coastal fisheries. The first workshop on mussel farming hosted by the SUCCESS H2020 project in Cattolica, Italy, 27 May 2017. *EurofishMagazine* **4**: 56–58

Suplicy FM. (2018) A review of the multiple benefits of mussel farming. *Reviews in Aquaculture* **12**(1): 204–223.

Surathkal P, Dey MM (2019) Import penetration and price relationships: An empirical analysis of the US catfish market. *Aquaculture Economics & Management* **1–18**: https://doi.org/10.1080/13657305.2019.1699199.

Theodoridis A, Batzios C, Ragkos A, Angelidis P (2017) Technical efficiency measurement of mussel aquaculture in Greece. *Aquaculture International* **25**: 1025–1037.

Theodorou JA, Tzovenis I (2017) Managing the risks of the Greek Crisis in Aquaculture: a SWOT Analysis of the Mediterranean Mussel Farming in Greece. *Agricultural Economics Review* **18**: 18–26.

Theodorou JA, Tzovenis I, Adams CM, Sorgeloos P, Viaene J (2014) Risk factors affecting the profitability of the Mediterranean mussel Mytilus galloprovincialis Lamarck 1819, farming in Greece. *Journal of Shellfish Research* **33**: 695–708.

Theodorou JA, Perdikaris C, Filippopoulos NG (2015) Evolution through innovation in aquaculture: the case of the

hellenic mariculture industry (Greece). *Journal of Applied Aquaculture* **27**: 160–181.
Theodorou JA, Moutopoulos DK, Tzovenis I (2020) Semi-quantitative risk assessment of Mediterranean mussel (*Mytilus galloprovincialis* L.) harvesting bans due to harmful algal bloom (HAB) incidents in Greece. *Aquaculture Economics & Management* 1–21. https://doi.org/10.1080/13657305.2019.1708994
Theodorou JA, Viaene J, Sorgeloos P, Tzovenis I (2011) Production and Marketing Trends of the cultured Mediterranean mussel *Mytilus galloprovincialis* L. 1819, in Greece. *Journal of Shellfish Research* **30**(3): 1–16.
Troell M, Joyce A, Chopin T, Neori A, Buschmann AH, Fang JG (2009) Ecological engineering in aquaculture—potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. *Aquaculture* **297**: 1–9.
Turner AD, Stubbs B, Coates L, Dhanji-Rapkova M, Hatfield RG, Lewis AM *et al*. (2014) Variability of paralytic shellfish toxin occurrence and profiles in bivalve molluscs from Great Britain from official control monitoring as determined by pre-column oxidation liquid chromatography and implications for applying immunochemical tests. *Harmful Algae* **31**: 87–99.
United Nations (2015) Transforming our world: the 2030 Agenda for Sustainable Development. Available from URL: https://sustainabledevelopment.un.org/post2015/transformingourworld
UN Environment (2017) Marine Litter Socio Economic Study, United Nations Environment Programme, Nairobi. Kenya.
van den Burg S, Kamermans P, Blanch M, Pletsas D, Poelman M, Soma K *et al.* (2017) Business case for mussel aquaculture in offshore wind farms in the North Sea. *Marine Policy* **85**: 1–7.
Van Cauwenberghe L, Janssen CR (2014) Microplastics in bivalves cultured for human consumption. *Environmental Pollution* **193**: 65–70.
Van Cauwenberghe L, Claessens M, Vandegehuchte MB, Janssen CR (2015) Microplastics are taken up by mussels (*Mytilus edulis*) and lugworms (*Arenicola marina*) living in natural habitats. *Environmental Pollution* **199**: 10–17.
Villasante S (2009) Magnitud e implicaciones de la Política Pesquera Comunitaria: aplicación de indicadores de sostenibilidad sobre el metabolismo de los ecosistemas marinos. PhD Thesis, University of Santiago de Compostela, Spain, 645 pp.
Villasante S, Pita P,Rodrigues JCastelao D,Pita C. (2020) Economic costs of marine litter for fisheries in NW Portugal and Galicia, Report N° 3 - NetTag - "Tagging fishing gears and enhancing on board best-practices to promote waste free fisheries" project, 25 pp. Available from URL: http://net-tag.eu/
Villasante S, Rodríguez-González D, Antelo A, Rivero-Rodríguez S, Lebrancón-Nieto J (2013) Why are prices in wild catch and aquaculture industries so different? *Ambio* **42**: 937–950.
Von Moos N, Burkhardt-Holm P, Köhler A (2012) Uptake and effects of microplastics on cells and tissue of the blue mussel Mytilus edulis L. after an experimental exposure. *Environmental Science & Technology* **46**: 11327–11335.
Voultsiadou E, Koutsoubas D, Achparaki M (2010) Bivalve mollusc exploitation in Mediterranean coastal communities: an historical approach. *Journal of Biological Research* **13**: 35.
Wells ML, Karlson B. (2018) Harmful algal blooms in a changing Ocean BT - global ecology and oceanography of harmful algal blooms. In: Glibert P, Berdalet E, Burford M, Pitcher G, Zhou M (Eds.) *Global Ecology and Oceanography of Harmful Algal Blooms. Ecological Studies (Analysis and Synthesis)*, Vol **232**. pp. 77–90. Springer, Cham.
Whitmarsh DJ, Cook EJ, Black KD (2006) Searching for sustainability in aquaculture: an investigation into the economic prospects for an integrated salmon–mussel production system. *Marine Policy* **30**: 293–298.
Willet W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S *et al.* (2019) Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. *The Lancet* **393**(10170): 447–492.
Zanou B, Anagnostou Ch, Papathanassiou E (2005) Seeking the factors to stimulate the users in the coastal zones planning. Case study: Open discussions with mussel farmers in the Axios river (GR). *Mediterranean Marine Science* **6**: 107–115.

Appendix

Country profiles

This appendix presents country profiles of the EU mussel producer countries, including information on the economic performance evolution, production specificities and main threats to the mussel production.

Spain

Mussel rafts
The mussel industry in Spain, most of it concentrated in Galician *rias*, represented the 73% of the total Spanish aquaculture production in terms of quantities in 2016. The evolution during 2015 and 2016 illustrates how dependent is the mussel production to the environmental conditions in the Galician *rias,* where red tides can close the production areas for long periods of time. Annual mussel production reflects high fluctuations over time; in 2016 suffered a decrease of 4.3% respect to 2015 until 215 thousand tonnes. Mussel production in Galicia has been severely affected in 2010, 2013 and 2014 by red ties. The number and intensity of these events have been multiplied by 4 during the decade (from 2000 days of closed polygons of mussel rafts in 2007 to 8000 days in 2016), making the mussel industry more vulnerable to climate change impacts and putting at risk the capacity of the sector to supply the seafood markets (OESA 2017).

The production value of this segment was €118 million in 2016, the highest production value during whole period analysed; which represents an increase of 2.4% compared to 2015. This increase is mainly explained due to the growth of prices in 2016 (€0.55/kg), the highest observed price since 2008.

This is the biggest segment in terms of employment, with 2610 FTE in 2016, which was 1.5% higher than in 2015; and it also the highest number of people employed in the segment during the period analysed (2010–16). Traditionally, it is a sector where there are a high number of people working a part of the year; most of them are self-employed workers due to the familiar characteristics of these small units.

The mussel is cultivated mostly in Galicia, where it is a traditional and consolidated sector with a significant impact on the economy (Labarta & Fernández-Reiriz 2019). Most of the people working in the sector are from the local areas. Mussel farming is a family-owned business. OESA (2017) estimated that around 3669 rafts were held by around 2300 families in Galicia. The number of rafts in Galicia has reached a limit several, due to the lack of additional available suitable space for new rafts.

Traditionally, mussels in Spain have been marketed fresh or canned. It is important to highlight that the sector is closely related to the canning industry, also situated in the same areas, and in which most of the inputs are from Galicia. In recent years, there have been some initiatives in order to produce new product presentations which more added value through its transformation. Furthermore, there are no external investments in the Spanish mussel sector, but Spanish companies are investing in the mussel industry abroad, such as in Chile (Gonzalez-Poblete *et al.* 2018). These investments have contributed to the substantial increase in the production (e.g. Chile production of mussels have gone from less than 24 000 tonnes in 2000 to more than 300 000 tonnes in 2016 according to FAO). This has resulted in Chile becoming the main mussel exporter into the EU, with almost 40 000 tonnes in 2017, and Spain directly receiving 1/3 of these imports (Globefish 2018).

The establishment of the Regulatory Council of Mussel in Galicia in 1995 led to a significant positive impact on the process of aggregation of producers into producer organizations (2092 rafts being part of about 20 producers organizations in 2018) and promoted the recognition of Protected Designation of Origin (PDO). This has also resulted in some level of vertical integration in the sector (Castelo & Pérez-Dorca 1997).

The fresh mussel markets in Galicia (Spain), in which the producer organizations themselves own marketing facilities, combined with the high volumes exported (especially to France and Italy) have transformed the marketing channels in Spain. This led to the increasing incidence of the major retailer chains, mainly Mercadona—who may have sold around 25 000 tonnes of fresh mussels from the Galician Rias—as well as others, such as Carrefour, Eroski and Gadis whose supplier strategy is one of agreements with processing companies, all of which helped to consolidate the fresh mussel market in Spain (Labarta & Fernández Reiriz 2019).

Italy

Mussel longline

The mussel sector, as reported in the National Strategic Plan for Aquaculture[15], is considered very important both in terms of volumes produced and employees. It represents the most important aquaculture segment at national level, in terms of production volume with 47% of sales in 2016 and a turnover of 35% of the entire Italian aquaculture. But mussel farming in Italy is not attractive for future investments, mainly caused to low ex-farm prices and the scarce introduction of best practices that may increase the consumers' willingness to pay (STECF 2018).

Domestic production is not always able to meet the demand, also in relation to the seasonality of the supply that characterizes the national product. Mussel segment, during the 2016, indeed, has a reduction in volume of sales around 30% due to low abundance of commercial product in size. High temperatures caused the product to be caught ahead of time. It has been offered on the market in advance and therefore cuts to smaller and with less quantity of edible meat. Furthermore, high amounts of product were offered concentrated in a short time, so producers were forced to further reduce ex-farm prices, and the turnover, during 2016, decrease more than 25% compared to 2015.

Production companies, based on the modest market value of the mussels and the expansion of farming into new areas, must meet the objective of maximizing production efficiency, focusing on the areas in which they deem the conditions most suitable from the point of view of the productivity parameters. The creation of 'protected' marine areas for mussels is a goal that is expected to be reached by 2019, in line with the forecasts and actions reported in the national Strategic Plan for Aquaculture. The sector suffers from the inability of the operators to increase the ex-farm price, which is related to the absence of a centralized supply distribution channel. The greatest weakness is the lack of aggregation of supply: the producers are not involved in the purification/depuration and relaying stages of mussels, which compromises the ability to control the price.

Only recently, also with the support of the EMFF funds, in some Adriatic regions, companies, mostly producer cooperatives, are starting investments to buy boats equipped with mussel purification plants. The boats are

[15]Piano Strategico per l'acquacoltura in Italia 2014-2020 according to Art. 34 'Promozione dell'acquacoltura sostenibile', Reg. 1380/2013/EU on CFP.

more than 18 m long and have the double function of being at the service of the installations and also of bagging the product intended for commercialization. In the last three years, important innovations are taking place in the sector, especially as regards the vertical integration of the production chain. Further interest has been that of being able to sell pre-growth product to other installations both in Italy and abroad.

From 2002 to 2016, in Italy the productive dynamics of the shellfish sector show a clear signs of territorial specialization. This has determined the consolidation of an already strong activity since 2002 in some Italian regions, as is the case of the Emilia Romagna region, which passed from an annual production of molluscs (mussels, oysters and clams) of 22 000 tonnes in 2002 to about 52 000 tonnes in 2016 (personal communication of the National President of Mussel Producers). Specifically, for mussels, the Emilia Romagna Region registered the equivalent increase recorded in the broader shellfish segment.

The analysis of ex-farm prices of mussels has shown that prices remained almost the same during the last 5 years, though both consumption and consumer prices have gradually increased. In 2016–2017, mussel prices reached more than EUR 2.50 per kg were recorded for mussels with organic certification and for mussels carrying PDO (Cozza di Scardovari DOP) labels.

The H2020 Success[16] project investigated the bottlenecks and the opportunities for the Italian mussel sector. It concluded that the Italian mussels sector consists of relatively small companies that have limited negotiation power towards the supermarkets. Producers should produce and merge in consortia and then have one professional seller of their produce which could strengthen the ability to negotiate higher prices. Organic produced mussels do not always fetch higher prices and that makes investments in organic certification more uncertain.

Costs for certification in general are not awarded by higher prices in supermarkets. It is a demand for market access today. The bureaucracy should be reduced and speedier. Another limit is the banks—it is hard to get loans for fish farmers. They would like to have the same conditions for approving loans as the agriculture sector in Italy. In case a producer loses his production because of weather conditions or similar, there is not the same compensation between regional authorities as it can vary from 0 to 90%. The authority's compensations to farmers should be coordinated between regions to be fairer. The feature of the segment, in terms of profitability, or poor capacity to generate revenue, is due to the highly based, low-capitalized structure. The human resources employed are on average below the average number that would be appropriate to make work more efficient (Malvarosa *et al.* 2017; Success 2017).

[16]Strategic Use of Competitiveness towards Consolidating the Economic Sustainability of the European Seafood sector, project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 635188.

France

Blue mussel (*Mytilus edulis*) and Mediterranean mussel (Mytilus galloprovincialis), the two cultivated species, represent around 33% in weight, 20% in value of the whole French aquaculture production. Output has varied widely from 60 000 to 94 000 tonnes, valued at between €117 and 172 million over the period. French mussel production is not adequate to meet the national demand. The imports of mussels mainly from Chile, Netherlands and Spain exceed widely the exports revealing a structural trade deficit.

Blue mussel represents around 96% of total volume and value of French mussel production. From 2010 to 2016, the price blue mussel varied from €1.83 to €2.02 per kg, with an average price of €1.90 per kg. The most important operational cost items are wages and salaries and the imputed value of unpaid labour, which are higher than the operating costs. The spat supply is exclusively on wild source, so the livestock costs are very limited (9%) and concern only the mussel farmers rearing in the areas where no mussel recruitment exists due to low temperature of water or salinity to much important. Investments are important for this activity. The depreciation of capital item attains 33% of the total costs.

Mussel 'bouchot'

Since 2010, the production of mussel is decreasing. In 2016, mussel production volume is 69 thousand tonnes with a value of €139 million. This decline was due to unfavourable weather causing a deficit of production and poor quality of mussels (2011, 2012). The deficit comes also from the resurgence of predators (sea-star) in some areas of production (Channel and Atlantic coasts).

Since 2014, a high mortality of mussels has been located in production areas located in the West of France (Pertuis Breton and bay of Bourgneuf). The mortalities have reached up to 100% on the longline for some professionals and 50-80% of the 'bouchot' cultivation system. The causes of these mortalities are difficult to establish (pathological, environmental and physiological) (Béchemin et al. 2015; Robert & Soletchnik 2016; Charles *et al.* 2020). Given the short cycle of the mussel, producers cannot replenish their stocks and mussel production in hatcheries is not allowed in France. As with a lot of environmental hazard causing shellfish mortalities, the prevention methods or the tools for reducing the economic consequence are limited. Financial difficulties are important (drop in sales, net loss of turnover), while cleaning of leaseholds (remove the mussels) causes significant costs. These mortalities are forced certain mussel farmers to dismiss employees or remove the seasonal contracts in order to reduce the costs of wage. That is why the mean wage decrease by 44% between 2014 and 2015. If older companies have cash to cover fixed costs, young companies, much more indebted, have significant difficulties. Measure 56.1.f of EMFF was mobilized in order to compensate the mussel farmers impacted.

Since 2015, in Mediterranean, shellfish producers deal with two sale bans due to harmful algal blooms's (*Alexandrium catenella*) or norovirus during autumn. The duration of bans can reach 5 weeks among years.

Shellfish farmers dread climate change increasing risk of epizootic, the emergence of diseases in the marine environment and the increase of shellfish trade ban due to harmful algal blooms (*Dinophysis*, *Alexandrium*, *Lepidodenium*, etc.). This climate change will affect the environmental parameters: temperature change on ocean acidification, on rainfall and therefore the salinity and the concentration and nutrient quality. This will have consequences on future aquaculture output and on the economic results as in 2011 or 2014 where the EBIT margin decreased sharply. As mussel farming is capital intensive, the fixed costs are high. These costs structure exposes financially the businesses in case of natural hazard impacts. The most important challenge of the mussel farmers is the capacity to cover fixed cost when market bans or production losses occur. The fluctuations of the prices do not always allow to compensate the natural hazard impacts on the level of production. Mussel producers are afraid of the multiplication of natural events occurring either mortalities or market trade bans which over time would question the profitability of their activity.

Netherlands

Mussel on-bottom

Sales volume has oscillated between 36 thousand and 56 thousand tonnes between 2008 and 2016, but sales value has decreased since 2013 due to a decrease in the blue mussel price. Most production is sold in Belgium. This has led to a decrease on the economic performance during the last years. The oscillations in the production volumes are influenced by the collection of mussel seed in the 2–3 years before production sales.

Most important costs items include other operational costs (41%), wages and salaries (27%), and repair and maintenance (12%). Within other operational costs, rental costs for the area where the mussels are farmed are important, as well as the costs that relate to the mussel seed collectors. There are competing claims for the most suitable areas (i.e. good growing locations) and operating in Nature 2000 areas, In an agreement with the Dutch Ministry and environmental NGOs, the mussel sector started a transition from wild seed fisheries to sustainable alternatives (mussel seed collectors) in 2020. Although the collectors work quite well and guarantee a quite stable mussel seed production, the work requires a lot of labour.

Mussel losses from waves and currents are the major risk factor for farmers. Environmental conditions are becoming more variable and less predictable creating large fluctuations in growth. In addition, recent events of mass mortality in Oosterschelde seem to be due to a disease, even if reasons are not known yet,

There is some vertical integration in the supply chain and diversification in larger companies. There will be some pilot projects of offshore mussel aquaculture in the Dutch waters, but no for IMTA.

Greece

Mussel aquaculture, being the most important shellfish aquaculture in Greece (circa 15% of the annual aquaculture production volume), produces annually 16 thousand to 23 thousand tonnes of mussels valued between €6 million and €8.5 million (Eurostat 2019)[17]. There exist two main on-growing techniques: the pole system with small farms (500 m^2) in shallow (3–5 m) coastal sheltered areas and the longline system in areas with depths greater than 10 m. Mussel spat for aquaculture use is collected from natural populations. According to Avdelas *et al.* (2015), labour cost (42% including sprat collection), repair and maintenance (19%), energy (17%) and depreciation of capital (11%) are the main cost components of mussel aquaculture. The average mussel price has been relatively stable at a less than €0.4 per kg since 2011, being between the lowest among the EU mussel producing countries (Eurostat 2019). While producers are able to cover the operational costs, profit estimation depends mostly on the assumptions used for the estimation of the opportunity cost for unpaid labour (Avdelas *et al.* 2015; Theodoridis *et al.* 2017). Theodoridis *et al.* (2017) collected data in 2013 and 2014 from three regions (Chalastra, Kymina, and Makrygialos) in the Thermaikos Gulf through a survey of 66 mussel farms. According to Theodoridis *et al.* (2017), labour cost represented 31%, variable costs including sprat collection (38%) and fixed costs (28%). Theodorou *et al.* (2014) collected data from eight farms in 2008 and modelled the costs by farm size. According to Theodorou *et al.* (2014), labour cost represented 25%, variable costs (22%), fixed costs (14%) and

[17]However, there are many elements that render these production estimations too uncertain. Uncertainty comes from environmental conditions including harmful algae blooms, temperature, etc., as well as the existence of unlicensed farms. Theodorou et al. (2011, 2014) estimate a total production of 36 thousand tonnes of mussels in 2008.

depreciation (39%) in an average farm of 2 hectare. Although the small size of the farms has been identified as a financial risk (Theodorou *et al.* 2014), producers seem to take into account mainly the environmental risks and regular supply by producing at multiple small farms in various locations. Approximately 50% to 70% of the annual production is exported mainly to Italy and other EU countries. Mussels are sold live or fresh, and the most common diversification activity is basic processing (de-shelling of mussel bodies). There are no voluntary certified products.

The race for nutrients among licensed and unlicensed farms, predators (such as the blue crab in the main production areas) and uncertainty arising both from the current environmental conditions (periods of banned sales mainly due to bio-toxins or presence of toxic algae) and the changing environmental conditions (sea temperature rise) are the main threats faced by the mussel aquaculture in Greece nowadays. Due to the licensing scheme operating in Greece, mussel aquaculture is mainly comprised of small and poorly mechanized farms with low bargaining power and no means to cover the regular supply needs of the modern retail chains. To this end, economies of scale and gains in bargaining power can be achieved both by mergers and acquisitions and by the establishment of producer organizations (Avdelas *et al.* 2015; Theodorou & Tzovenis 2017). The importance of the internal country market that could match the seasonal production to seasonal demand during the summer in touristic areas is overlooked by the producers who are mostly export oriented. No significant rise of the production is expected in the near future. Research for the identification of suitable farming areas would be needed in order to further develop mussel aquaculture in Greece.

Germany

Mussel on-bottom

The German blue mussel aquaculture takes place at the world heritage and National Park of the Wadden Sea. Therein strict restrictions limit the total number of licenses for harvesting mussel seeds and culture areas (Schlauch 1999). In consequence, the number of enterprises, which are organised in two producer associations, is stable at 11 to ten companies since the 1990s. Nonetheless, the production volume and value have varied a lot in the past. In 2009, there was a unique low of about 4000 tonnes (and a value of around €5 million). A peak of about 22 200 tonnes harvested (and a value of around €25.3 million) happened in 2016. The average landings between 2008 and 2016 have been about 9860 tonnes and €13.20 million. As the overwhelming majority of landings are sold via auction at Yeserke in the Netherlands, German mussel fishers are price takers due to price transmission effects from Netherland harvests. From 2008 to 2016, the price of blue mussel has varied from €0.84 to €2.17 per kg, with an average price of €1.38 per kg.

Most important cost items have been repairing and maintenance (23%), other operational costs (22%; including the costs for licenses and the rents for seed collectors from the Netherlands), and wages and salaries (21%) in 2016. Regarding the profitability on micro-level, an income of around one million euro per enterprise or €800 000 per vessel is needed as an average to cover the operating costs[18]. The high variance and unpredictable fall of wild mussel seed, the loss of catching areas through the invasion of the alien pacific oyster (*Crassostrea gigas*), strict conservation regulations and ocean dumping are identified as the most challenging factors by the mussel farmers. The increased ocean dumping in the recent years is assumed to influence negatively the blue mussels' growth rate at Lower Saxony's Wadden Sea. There is no ocean dumping in the parts of the Schleswig Holstein Wadden Sea, where the growth rates of blue mussel cultures are significantly higher. Nonetheless, blue mussel farming can be considered as a profitable business in Germany.

The overall economic trend of the German blue mussel segment is—against all listed restrictions—positive. In outstanding good years (e.g. 2016), the gross profit margin can be higher than 35%, which is key to compensate bad years, where the gross profit margin can be negative (e.g. −7% in 2009). Anyway, the decisive question for German mussel cultures has a more political nature: Will future trade-offs between nature protection objectives and mussel producers enable mussel cultures in the National Park of the Wadden Sea in the next decades or not? The difficult and long negotiations for the so-called 'mussel peace' in 2015 infer that the existence of mussel production in Germany is first of all the result of a political compromise. Now, until 2030 mussel production licenses are ensured at least for the Northern part of the National Park of the Wadden Sea.

Ireland

Traditionally, the main production areas for bottom culture are in the southeast and the southwest, and in the southwest for rope culture (O'Sullivan 1998). Rope mussel output has remained within a gentle oscillation, while bottom culture output has undergone a large and overall downward trend over the observed period.

Shared limits to economic expansion of both the rope and bottom cultures in Ireland are: i) distance to market and competition with the large domestic production of the countries exported to. ii) Regulation; license applications and

[18]Personal communication, Suitbert Schmüdderich (CEO COFAD—Consulting Agency for Fisheries, Aquaculture and regional Development, Weilheim) on costs of mussel culture operations.

renewals are lengthy procedures due to most aquaculture sites being within or adjacent to Natura sites. Producers are subsequently denied access to government grant aid and new grounds. iii) Harsh, unpredictable Irish weather conditions complicate management and can lead to poor growth, poor meat content, stress and mortality, resulting in poor prices. Disease, thus far, is not an issue for Irish mussels.

Mussel on-bottom

Output has varied widely from 3000 to 17 000 tonnes, valued at between €800 and 1200 per tonne, over the period. Businesses and vessels are mainly local, family owned, providing mainly full-time employment, with significant partnership investment by Dutch companies. The segment is fragmented but groupings will collectively lobby over seed fishing access and resource management in general. Sales are entirely export, predominantly to the Netherlands and France, with some exports to the UK and Italy.

The main threat to the segments' viability is the almost complete reliance on the appearance of wild seed beds for stock input, and these appear to be diminishing over the period as a whole. The already high costs of maintaining, running and crewing sea-going vessels in Ireland are exacerbated by the greater effort required to find wild seed. The limited use of alternative seed sources or collection systems such as those used by the rope culture are probably due to issues of licensing conditions as much as technical difficulty. On the other hand, there are conflicting reports of the negative effects of one bivalve stock presence upon another, with the mussel producers of Castlemaine harbour regarding the neighbouring Gigas oyster producer stock of killing their stock and the opposite accusation made by the oyster producers of Loughs Foyle and Swilly upon their mussel producing neighbours. However, there is no scientific study to back either claim.

The future evolution of this segment is as uncertain as the fate of the wild seed beds upon which it continues to depend, the management of which is complicated by the 1965 Vosinage agreement between the UK and Ireland and the unfolding nature of Brexit. Sales price, despite vigorous marketing campaigns to distinguish Irish mussels, struggles to compete with that of its competitors.

Mussel longline

This segment reliably produces between 8500 and 10 500 tonnes annually of mainly fresh but also processed products exported to France, the Netherlands Italy and elsewhere in Europe, and some half-grown product is occasionally sold to the Bottom mussel segment. This is a fragmented segment, almost entirely family and locally owned, offering mainly part-time or seasonal employment alternatives to agriculture, tourism and fisheries in remote areas, with a significant degree of unpaid labour sustained by the owners themselves. The segment is becoming gradually more capital intensive, overall employment and the number of individual businesses is declining. As the age profile of license holders advances, more and more sites are being leased or transferred to better-equipped and more professional entities.

The sector has struggled to remain profitable, despite minimal costs compared to other segments, successful investment in technical innovation and efficiencies, as well as in quality product certifications. There are particular factors limiting Rope mussel production: (i) health and safety: red tide bay closures can be lengthy and can occur at the height of harvest season, disrupting supply, reducing sales value and increasing losses of stock from the lines, (ii) low market price relative to competitors continues, as does the higher costs of getting the exported product to market compared to mainland European competitors and (iii) increasing labour costs.

The amount of licensed production ground will not increase significantly, if at all, due to increased competition for limited space and a very successful anti-fish farm lobby. Volume output is expected to remain within the current observed pattern. Continuing efforts to increase the profile and value of Irish mussels abroad and to develop the home market close to production sites is expected to gradually improve sales price. Business amalgamation and declining seasonal employment trends are expected to continue (Cush & Varley 2013). The red tide issue and the resulting tight margins, brought on by relatively high costs and low product unit values, are being combatted by larger companies by acquiring sites in different bays, thereby increasing their capability of maintaining continuity of product supply and unit value even if one or two of their sites are closed by red tide, thereby spreading the risk.

UK[19]

In 2016, the UK accounted for 3% of EU aquaculture production of mussels. Mussel farming dominates shellfish aquaculture across all four regions of the UK (Scotland, England, Northern Ireland and Wales), with both on-bottom, raft and longline techniques being used (Laing & Spencer 2006; Seafish 2019). The main species farmed is the blue mussel (*Mytilus edulis*) (Laing & Spencer 2006), although the Mediterranean mussel (*M. galloprovincialis*) and hybrids also occur (Gardner *et al.* 1993; Dias *et al.* 2009; Seafish 2019). Much UK production is sold live to northern mainland European countries (Anon 2012), where large-scale facilities exist for depuration. UK

[19]In this study, the United Kingdom is analysed together with other EU Member State because the UK was a member of the EU until 31 January 2020.

cultivated mussel production is supplemented by additional landings from fisheries (Dare 1980; Anon. 2009).

UK aquaculture production of mussels decreased by 61% between 2008 and 2016, from 37 460 to 14 685 tonnes. The year-on-year decline over this period is highly significant ($r = -0.986$, $P < 0.001$) and steeper than in other EU countries. However, there are regional differences with Scotland showing an opposite production trend ($r = +0.780$, $P < 0.01$) to the other three UK regions. DCF economic data for mussel to support an assessment are limited and only available for the period 2012-2016; over this period estimated income, GVA and net profit all decreased.

Challenges for UK mussel aquaculture are considered to include: microbiological water quality; a lack of depuration plants to purify large volumes of mussels; a highly variable (and relatively low) mussel price; imports of frozen mussels from the Southern hemisphere; harmful algal blooms; and the non-native *M. trossulus* which has thin, fragile shells that are damaged during harvesting/grading (Dias *et al.* 2009; Anon. 2012; Turner *et al.* 2014; Hambrey & Evans 2016; Seafish 2019). Wild seed availability is not generally considered to be a problem, although variability in supply has been raised as an issue for some areas (Howard 1998; Munro *et al.* 2013; Adamson *et al.* 2018).

Although per capita mussel consumption in the UK is lower than elsewhere in Europe, domestic demand for both live and convenience products is increasing (Hambrey & Evans 2016). There is considered to be considerable potential to expand UK mussel aquaculture, but further development would be constrained by site availability and the regulatory bureaucracy associated with fishing, navigation, environmental and microbiological concerns (Laing & Spencer 2006; Hambrey & Evans 2016). Significant new offshore longline production has recently started in England, and there is some interest in developing mussel hatcheries and/or specialist seed collectors to even out variations in supply (Hambrey & Evans 2016). As economies of scale are important, some smaller enterprises are organizing into groups or co-operatives for operation and marketing (Hambrey & Evans 2016).

Bulgaria

Mussel longline

The production of mussels in the country is presented only by Mediterranean mussel (*Mytilus galloprovincialis*), and this segment of Bulgarian aquaculture is the only one representative of the marine aquaculture with 33 enterprises which increased by 10% compared to 2015 and by 43% compared to 2014.

The value of the total income in 2016 was €1.2 million, 99% of the income came from the sales, 1% is from other income. The amount of total sales volume was 1.6 thousand tonnes in 2016, which was 10% more than in 2015, and 98% more than the average value for 2008–2015. The average price of Mediterranean mussel was €0.89/kg in 2015 and decreased by 17%, so in 2016 it was €0.74/kg.

In terms of economic indicators, the amount of Gross value added generated by the mussels' production in 2016 was €1.1 million and has decreased by 13% compared to 2015 and increased by 19% over the period 2008–2015. The amount of Operation cash flow in 2016 was €1 million and decreased by 22% compared to 2015, while the amount of Earning before interest and tax in 2016 was €-0.02 million and increased by 98% compared to 2015. The amount of net profit in 2016 was €-0.02 million increased by 98% compared to 2015 but decreased by 105% compared over the period 2008–2015.

The largest cost item of mussel longline production in 2016 was the consumption of fixed capital with 73% of the total costs. Wages and salaries represented 18% of all operational costs and other operational costs were 4%.

In last years, there are no major problems in front of Bulgarian producers of Mediterranean mussel and cultivation for these species is quite stable. Demand is not only for the domestic market but also for export which could be explained by the low price and good quality. All these aspects and preliminary result of production for 2018 could support the stable production or its increase as an outlook.

Denmark

Mussel longline

The aquaculture of blue mussel on longlines is a relatively new and small sector in Denmark. The production volume has fluctuated between 800 to 2500 tonnes corresponding to a sales value between €0.5 and €1.8 million. In the last three years, the production has been more stable and growing, which is also reflects in a stable gross value added just below €1 million and a positive net profit. The single most important cost item is wages and salaries covering one third of the total cost. One of the major challenges for the Danish sector is the small scale of operation, which make the enterprises vulnerable to natural fluctuation in seeds settlement and growth of the mussels. Furthermore, the access to the central European market is limited due to weak bargaining power compared to producers in France, Belgium and the Netherlands.

Croatia

Mussel longline

Between 2013 and 2016, total mussel production in Croatia remained stable with small variations, between 700 and 750 tonnes per year. Most of the mussel production comes from companies mainly using longlines to produce mussels, but some minor production comes from aquaculture companies mainly producing oysters, and sea bream and seabass.

The majority of these 112 mussel longline companies are small family companies with <5 employees and long tradition in aquaculture, concentrated at few locations suitable for shellfish farms and some of them protected as special reserve, which ensures the stability of farming conditions but also affects the vulnerability of farms to biotoxins and diseases. The production is based on the collecting of shellfish in early stages from nature, but some of the producers are buying additional juvenile individuals from other farms to increase production.

In most cases, the production of mussels is combined with the production of oysters. Since the demand for local European flat oysters is growing, many farmers are focusing on the production of oysters. Oysters' longline is expected to move towards protected designations of origin and the possibility of organic production to encourage growth towards export to the EU market. Diversification has been increasing in recent years, starting the production of finfish, which caused the increase of income from other activities and the appearance of livestock and feed costs

Shellfish farms are experiencing severe damages caused by wild fish, especially gilthead seabream. According to Šegvić-Bubić *et al.* (2011), gilthead seabream in only one month caused recruitment losses of 54%, which indicates a strong negative impact on farm management stability.

Mussel production grow in most recent years, which is probably connected with the EU funds invested in the sector, but also with an improved data collection and reporting system. Production volume and value is expected to continue increasing. Although a stronger growth was expected after joining the EU, the mussel sector has faced some obstacles, both at operational and market levels. Only 1–2% of the total mussel production was exported, while the rest was sold to local restaurants and fish markets.

Slovenia

Mussel rafts

Sales volume and value of Slovenian mussel rafts sector increased in the period 2008–2016 for 165% and 460%, respectively. The economic performance of the sector has decreased in recent years, despite a production increase. The gross value added is positive in the period from 2008 to 2016, while net profit is negative in the last two years. This is due to decrease in the Mediterranean mussel prices from 2013, the decrease in other income and the increase on the depreciation costs.

The largest cost item of Mussel rafts sector in 2016 was the depreciation of the capital, accounted for 49% of the total operational costs. Other operation costs made up 34% of all operational costs. In 2016, depreciation of the capital increases by 12% regarding 2015 and by 1690% regarding 2008. The Slovenian mussel raft sector has over the past few years, with the help of EU funds, invested significantly in new equipment and production facilities. Therefore, these new investments are the main reason for the increased depreciation costs. In 2011, also with the help of EMFF funds, Slovenian mussel sector diversified by starting the production of Warty Venus.

In the past years, especially in 2010, considerable difficulties occurred in the production of shellfish due to the frequent closures of sales because of the occurrence of biotoxins, which prevents shellfish farms to be used to their full production capacity. Damage on shellfish farms caused by wild fish, especially by sea bream, also presents major problems in the last few years. Recently, one of the threats is also Comb Jelly (*Mnemiopsis Leidyi*) which probably came in to the Adriatic with ballast waters and represents one of the main food competitors.

Future development of Slovenian mariculture is strongly conditioned by the small size of the Slovenian Sea. In 2007, three larger areas were designated for marine aquaculture in Slovenian territorial waters that were subsequently separated into 22 plots, for which concessions were granted for the use of marine water in 2009. It is expected that these plots will not be able to expand, due to the use of Slovenian territorial waters for other purposes. All Slovenian maritime fish and shellfish farms are currently operating at about 60% of their capacity. In the future, it can be expected increasing production to maximum capacity and then stagnation of Slovenian marine aquaculture.

Portugal

The sales volume of mussel's production has fluctuated between 2008 and 2016, but tended to increase, reaching a maximum of almost 1000 tonnes in 2016. The value of sales followed the pattern of sales volume, reaching €1.75 million in 2016. There are only 17 mussel production units in Portugal, although concentrated in a much more limited number of companies. Besides that, more than 80% of production and sales value came from four establishments.

GVA has fluctuated greatly between periods of growth and decline, however, with a growing trend. Net income, however, has been falling sharply due to the increase in financial costs due to investments made in recent years. Wages and salaries represent 40% of production costs and repairs are responsible for 25% of costs. It should be noted that while the former have been increasing, the latter have decreased. Overall, costs have been rising during the period of analysis.

If natural resources are available in quantity, mussel seeds may be collected manually in a controlled manner, for restocking of aquaculture establishments, but also the placement of collectors is promoted.

Some Portuguese companies are currently conducting their business to produce sustainability-certified mussel in organic production. These companies aim to use the certifications in pates, canned or frozen mussel, with which they want to compete in high demanding markets such as Northern Europe and North America, making this activity profitable.

Portugal has been making an effort towards maritime spatial planning, namely with the creation of aquaculture production areas, giving national aquaculture a strong growth potential in the coming years, especially with regard to the exploration of new areas in the open sea. The expected increase in the productive capacity of the mussel culture is thus based on the creation of new offshore aquaculture production areas, to be allocated under concession.