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Prospects and opportunities for mussel *Mytilus trossulus* farming in the southern Baltic Sea (the Gulf of Gdańsk)

by

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Abstract

In the Baltic Sea, where osmotic stress limits the growth of marine organisms, mariculture is driven primarily by the need to improve the status of the environment. To this end, several mussel farms have been attempted in selected areas, except the southern Baltic. The pilot culture of *Mytilus trossulus* was carried out with the use of a modified long-line system in the Gulf of Gdańsk in 2009–2012, providing the first evaluation of the mussel farming potential in this area. The growth rate of mussels (3.0–6.7 mm year^{-1}) in the gulf was in the low range, but the mean wet biomass gain (1.50 kg m^{-1} normalized culture rope) was among the highest in the Baltic. After a two-year growth period, one tonne of mussels fixed in their soft tissues from 93 to 98 kg N t^{-1} and 11 kg P t^{-1}. The cost-benefit analysis revealed a negative budget balance of production for human consumption, with a total income covering only 12.0% of the cumulative costs. Mussel farming in the gulf can therefore only be justified to improve the environmental quality if additional funding mechanisms are put in place to support farming activity.

Key words: pilot mussel farming; long-line system; biological and technological aspects; legislative framework; economy, southern Baltic Sea

online at www.oandhs.ug.edu.pl

1. Introduction

In many countries around the world, the economic use of bivalve mollusks involves the exploitation of natural resources and farming (mariculture) using specific technical infrastructure. Shellfish-related activities are primarily concentrated in the shallow water zone of supralittoral and sublittoral (permanently submerged zone), where abiotic conditions, such as high availability of suspended organic matter and reduced hydrodynamics, favor the development and rapid growth of bivalves. Harvested bivalves are mainly used for human and animal consumption as a valuable component of a high protein diet (FAO 2016). Potential applications of bivalve soft tissue and shells also include small-scale manufacturing of everyday objects (e.g. handicrafts, jewelry, furrier's tools, musical instruments, fabrics and even means of payment) as well as the production of antifouling agents (http://www.energiost.se). In addition, products derived from bivalve biomass are utilized in the production of agricultural fertilizers, feed additives for farmed domestic birds and fish, and as a source in the biogas production (Lindahl et al. 2005; Gröndahl et al. 2009; Nkemka & Murto 2013). In some coastal regions, bivalve polyculture supports also marine fish farming, where mollusks purify water from suspended particles, and thus reduce organic wastes and the environmental impact of aquaculture (Mazzola and Sara 2001; Sami Alias 2014). Due to the growing global demand for seafood, farming of marine organisms, including bivalves, for consumption has increased rapidly in recent decades. According to the report by the Food and Agriculture Organization of the United Nations (FAO 2020), the production of bivalve biomass from farming increased from 2010 to 2018 by approx. 3 447 000 t (25.5%) and currently accounts for as much as 21.0% of the global biomass production from mariculture. The main bivalve taxa in aquaculture include oysters (*Crassostrea* spp. and *Ostrea* spp.), scallops (family Pectinidae), mussels (family Mytilidae), clams (e.g. *Sinonovacula constricta*), cockles (e.g. *Anadara granosa*) and some species belonging to the Veneridae family (FAO 2020).

The growing interest in mussel farming has also been observed in the Baltic countries over recent years (Kotta et al. 2020 and references therein). In the Baltic Sea, owing to low salinity limiting the growth of many marine organisms (Sanders et al. 2018), bivalve farming for consumption by humans is not justified (https://www.mir.gdynia.pl). The development of aquaculture in the Baltic is mainly driven by the need to improve the state of the natural environment, which has deteriorated in many regions due to intensive agricultural and industrial human activity (HELCOM 2018a). Large terrigenous nutrient inflow has resulted in increased production of phytoplankton and increased deposition of suspended organic matter, followed by periodic oxygen deficiency in the benthic zone (Tamelander et al. 2017; HELCOM 2018a). Bivalves, through filter feeding, remove suspended organic matter from water and subsequently biogenic substances and many other contaminants (e.g. heavy and trace metals, persistent organic compounds, radionuclides), thus contributing to water quality improvement (Gallardi 2014). The cultivation of these organisms can therefore be used on a local scale as an effective tool to counteract the negative effects of eutrophication and pollution (Schultz-Zehden & Matczak 2013; Kotta et al. 2020; Wikström et al. 2020). Pilot studies along the eastern coast of Sweden indicate that mussel aquaculture in the Baltic Sea can offer measurable ecological and economic benefits. Areas in close proximity to mussel (genus *Mytilus*) farms have demonstrated an increase in water transparency, chlorophyll *a* depletion and ca. 20% reduction in the concentration of dissolved and suspended nitrogen (Kautsky 1982; Lindahl & Kollberg 2009; Lindahl 2011). Since the first Swedish studies, farms of mussels, including the zebra mussel (*Dreissena polymorpha*), have been developed on an experimental and industrial scale in Germany, Denmark, Sweden, Russia and Latvia, among others (Fig. 1), as part of research and development projects such as "Mussel-farming as an environmental measure in the Baltic" (Baltic 2020, 2009–2012), Aquabest (EU Baltic Sea Region Program 2011–2014), Baltic Ecomussel (EU Central Baltic Interreg Programme 2012–2014), Bucefalos (EU Life 2012–2015), Baltic Blue Growth (EU Interreg Baltic Sea Region 2014–2020) and LIFE IP Rich Waters (EU Life 2014–2020).

The objective of this study was to assess the potential of mussel farming in the Gulf of Gdańsk for the purpose of human consumption, nutrient uptake and improvement of the quality of the coastal environment. Preliminary technical conditions (e.g. selection of substrate for seeding, basic parameters of structural elements) and selected environmental aspects such as farm location, its optimal depth and production time were also determined. Combining the obtained biological and chemical data with economic estimates allowed a comprehensive evaluation of the production and economic performance of mussel farming in the southern Baltic Sea. In addition, regulatory and administrative aspects were identified to present the current legal framework and local requirements for Baltic mussel cultivation.

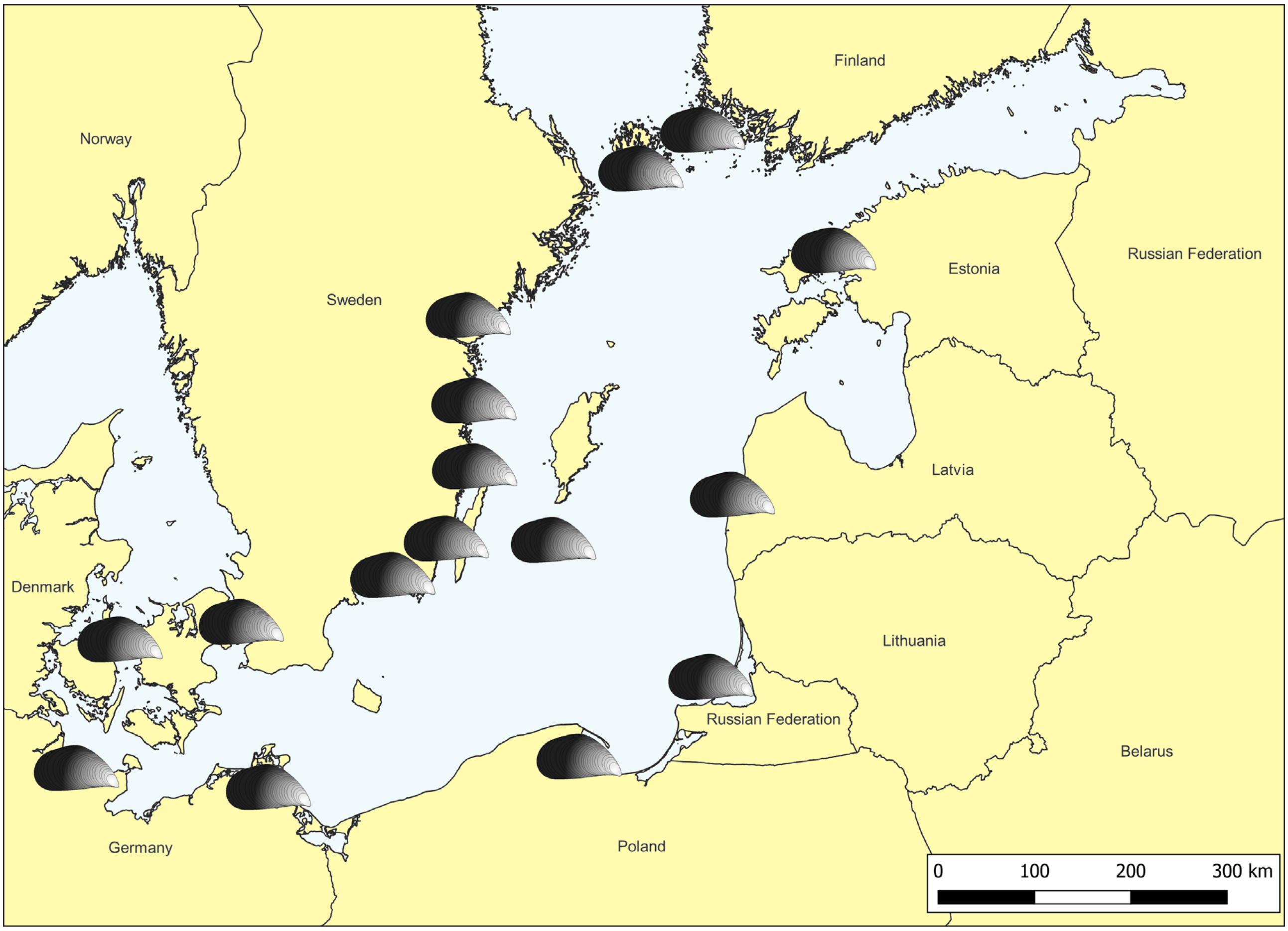

Figure 1

Location of the mussel farms in the Baltic Sea (based on the original map of de Grunt 2019, GIS data: © EuroGeographics for the administrative boundaries; Laboratory of GIS, University of Gdansk for the contour of the Baltic Sea).

2. Experimental mussel aquaculture in the Polish sector of the southern Baltic Sea

2.1. Experimental set-up, harvesting and laboratory analyses

In the Polish sector of the southern Baltic Sea (Polish Exclusive Economic Zone, EEZ), mariculture of mussels has not been attempted so far. The first experimental mussel aquaculture of *Mytilus trossulus* was carried out in the Gulf of Gdańsk (southern Baltic Sea) as part of the research activity of the Institute of Oceanography of the University of Gdańsk. Parametrization for mussel farming and technical infrastructure were designed based on field and laboratory studies from other Baltic countries (e.g. Schultz-Zehden & Matczak 2013; Bonardelli et al. 2019). The biological and chemical results obtained allowed evaluation of the potential of mussel farming for the purpose of human consumption, nutrient uptake and overall improvement of the coastal environment quality. Preliminary technical conditions (e.g. choice of substrate for seeding, basic parameters of structural elements) and selected environmental aspects such as farm location, depth and production time were also determined. Due to increased eutrophication, small depth and limited water dynamics, the Gulf of Gdańsk (particularly its westernmost part – Puck Bay; the southern Baltic Sea) provides good conditions for mussel farming. The presence of research centers and the accumulation of industrial and agricultural activity in the nearby Tri-City agglomeration and the Pomeranian region create favorable opportunities for the utilization of the bivalve biomass produced. The gulf is the natural habitat of the mussel *M. trossulus*, which inhabits a variety of hard substrates (e.g.

boulders, pebbles, hydrotechnical objects, wrecks) and coarse-grained bottom sediments to a depth of up to 50 m (Wołowicz et al. 2006). In coastal regions, mussels form beds (usually in the shallow water zone) and clusters (in deeper waters) with a mosaic distribution. This type of spatial distribution favors an even occurrence of mussel larvae in the water column during the breeding season, i.e. from June to October. Larvae are carried horizontally with sea currents to various regions of the gulf (Dziubińska & Janas 2007; Dziubińska & Szaniawska 2010; Sokołowski et al. 2017a,b).

Pilot mussel farming in the Gulf of Gdańsk was carried as a field experiment at three coastal sites located in the sublittoral zone with a water depth of 11.8 to 12.0 m: 1) adjacent to the Głębinka Strait (site GLE), 2) close to the discharge of sewage from Grupowa Oczyszczalnia Ścieków (group wastewater treatment plant) "Dębogórze" (site MEC), and 3) near the city of Sopot (site SOP; Fig. 2). At each site, one experimental unit was deployed between April 2009 and April 2012. A single experimental unit consisted of five 7 m long polypropylene braided hawser ropes (32 mm diameter) submerged in a vertical position

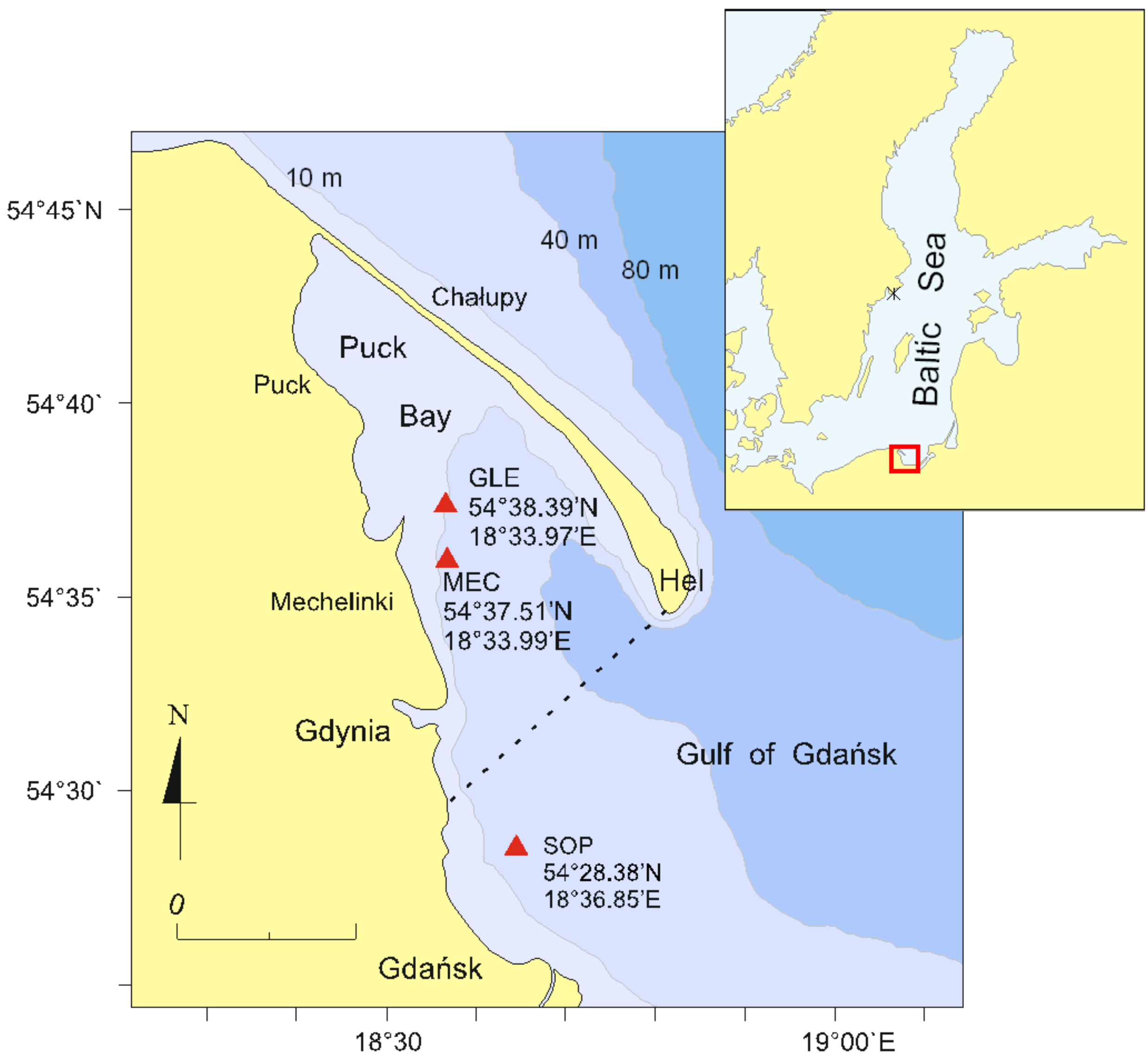

Figure 2

Location of the experimental mussel farming sites in the Gulf of Gdańsk (source: Sami Alias 2014, modified). Dashed line border of Puck Bay within the gulf.

about 5 m apart. Underwater buoys were attached to each rope to compensate for increasing mussel biomass (Figs 3 and 4). Each rope was equipped with a 40 kg concrete anchor and heavy sinking ropes between two neighboring anchors to mitigate the impact of waves. The design of the experimental units closely followed the commonly used submerged long-line system, where vertical culture ropes are connected by a horizontal carrying line. To prevent damage to the structure by random hydrological events (storm, ice cover) or destructive human activity (theft, devastation) and to constrain the growth of algae on the ropes, the farm structure was completely submerged 2.5 m below the water surface (Fig. 3; Sami Alias 2014). The ropes served as both collectors of spat and a substrate for the growth of sedentary mussel juveniles and adults.

After thawing, all bivalves were gently scraped from the entire surface around the rope in three randomly selected subsections (subsamples), each 10 cm high (total surface area of 100.5 cm^2). The shell length (along the longest anterior-posterior axis) of each individual from each subsection was measured to the nearest 0.01 mm using a digital caliper. The organisms were then divided into groups of 5 mm length and counted. Next, the mussels were deshelled and the soft tissues were weighed to determine the individual soft tissue wet weight (shell-free wet weight, SFWW). The flesh and shell were air-dried for 72 h at 50°C to measure individual soft tissue dry weight (= shell-free dry weight, SFDW) and shell dry weight. Biomass of bivalves at each subsection was computed as a sum of individual weights of all mussels, which was then averaged for three subsections and recalculated per

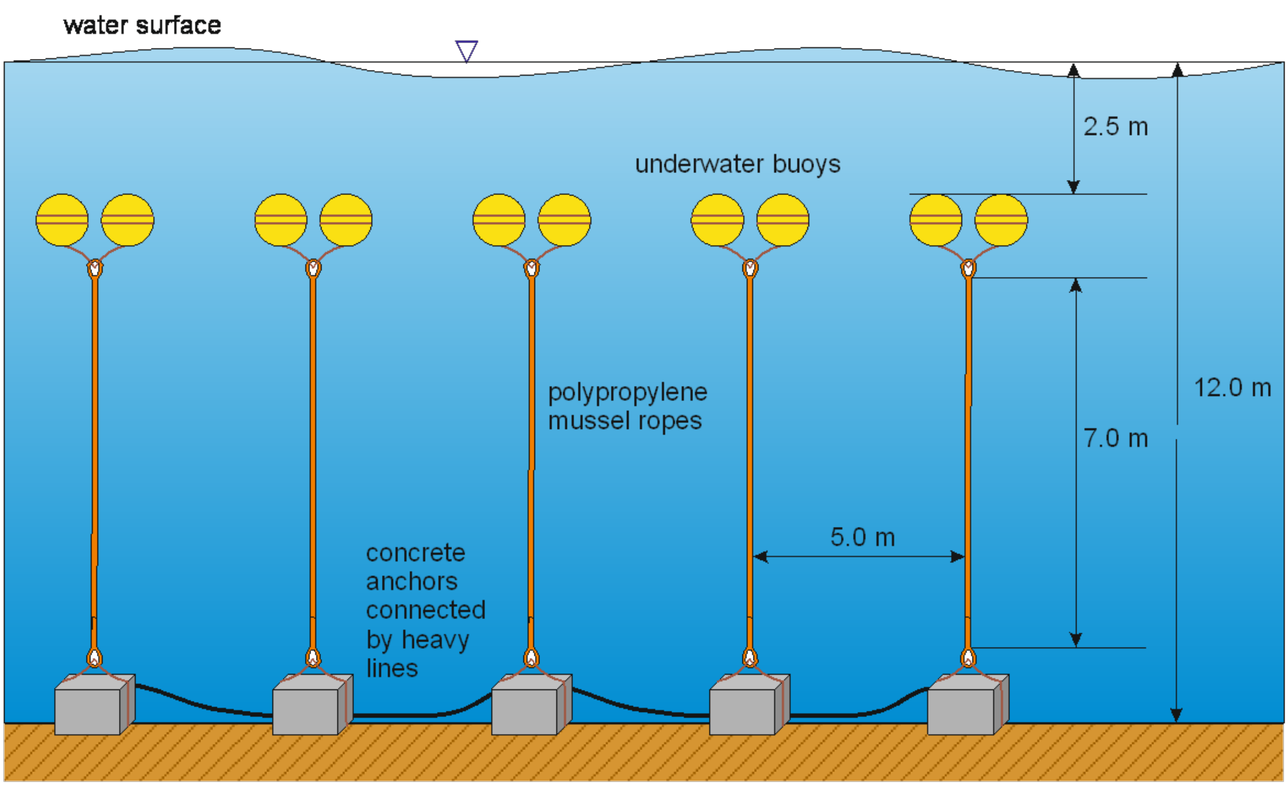

Figure 3

Diagram of the mussel farming structure in the Gulf of Gdańsk.

Mussels were collected by retrieving one culture rope at each site using the SCUBA diving technique every four months in the first year of farming and at the end of the following two years. The ropes were then divided into four sections: 0.0–1.0 m, 2.0–3.0 m, 4.0–5.0 m and 6.0–7.0 m corresponding to water depth zones: 3–4 m, 5–6 m, 7–8 m and 9–10 m, respectively, and each section was frozen at −20°C.

1 m long rope section (total surface area of 1005 cm^2). The annual growth rate of mussels was estimated as the mean shell increment for all individuals in each rope subsection per year. Filtration capacity of mussels (i.e. total volume of water filtered by mussels on one rope during a day and over a surface area of 2 ha) was calculated for the entire culture rope after two years of farming, assuming a filtration rate of 6.6

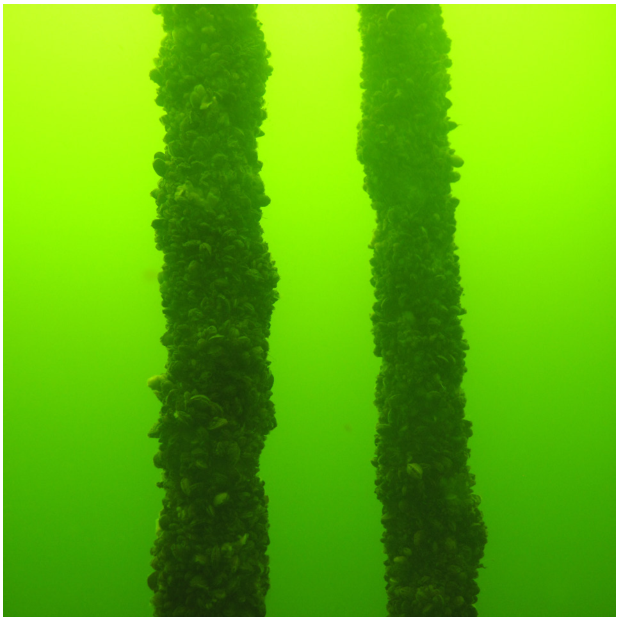

Figure 4

Culture ropes at the MEC site in Puck Bay after two years of exposure.

dm^3 h^{-1} g^{-1} SFDW, i.e. the value determined for the population of mussels inhabiting coastal waters of Askö (Sweden) in the central Baltic Sea (Kautsky et al. 1990), and uninterrupted filtration throughout a day. The choice of the source data was justified by the similar saline regime at both locations (7.0 and 6.5 in the Gulf of Gdańsk and Askö, respectively) and the same unit. Direct estimates of mussel filtration in the Baltic Sea are scarce, and measurements were usually made under different laboratory conditions and the obtained data were expressed in different units, e.g. dm^3 h^{-1} ind.$^{-1}$ (Clausen and Riisgård 1996; Riisgård et al. 2013) or dm^3 h^{-1} (Theede 1963). All these constraints may hinder direct geographical comparisons of physiological parameters of mussels across environmental variables and make it difficult to standardize the results. Elemental analyses of mussel soft tissue – Perkin Elmer Series II CHNS/O Analyzer for C and N, and wet high-pressure digestion followed by photometrical measurements (Grasshoff et al. 1999) for P – were carried out using individuals with a shell length within a range of 20.1–40.0 mm, which were randomly collected in triplicate at all sites after two years of farming. The content of C, N and P was expressed as % SFDW. In addition, basic environmental parameters (salinity, temperature, dissolved O_2) were measured in the overlying bottom water (ca. 20 cm above the seafloor) with a portable WTW Multiset 340i meter equipped with TetraCon 325 and CellOx 325 electrodes.

2.2. Environmental conditions

Seawater salinity varied from 5.8 (April 2009 at MEC) to 8.4 (April 2010 at GLE), temperature from 5.5°C (April 2010 at MEC) to 20.7°C (August 2009 at MEC), and dissolved oxygen concentration ranged from 2.0 mg dm^{-3} (August 2009 at SOP) to 15.4 mg dm^{-3} (April 2010 at SOP), indicating normoxic conditions. Environmental parameters at all farming sites were within the range typical for the near-bottom zone in the shallow areas of the Gulf of Gdańsk (Sokołowski 2009) and Puck Bay (Sokołowski et al. 2015).

2.3. Biological aspects of mussel culture

Despite the ice cover in the winter of 2009–2010 and a severe storm with extremely strong winds (gusts up to 130 km h^{-1}) from the east (generating large waves), the submerged farm units survived and did not move on the bottom. Mussels were found in large quantities on culture ropes in all seasons, with abundance varying with water depth and farming site (Table 1). Massive colonization of ropes by mussels indicates high availability of larvae throughout the year and thus the ease of obtaining spat for farming purposes in the studied regions of the Gulf of Gdańsk (Fig. 5). During the entire farming period, the largest density of the smallest organisms (< 2 mm in length) on the ropes was observed in December 2009, i.e. after 243 days (8 months) of farming (Table 1). Polypropylene ropes thus proved to be a durable and effective substrate for spat collection, which is an important element for planning mariculture on a larger scale. The number of juvenile forms on collectors was substantially higher in the vicinity of Sopot (SOP; nearly 150 000 ind. m^{-1} rope, i.e. 21 326 ind. m^{-2}) than at MEC (79 000 ind. m^{-1} rope, i.e. 11 232 ind. m^{-2}), which is likely due to the higher density of mussel beds on the sea floor close to Sopot (Kruk-Dowgiałło & Szaniawska 2008) and subsequently a larger number of larvae in the water column in the open part of the gulf (Bielecka et al. 2000).

After the first year of farming, the mussels reached an average length of 3.0 mm in the deepest section of the rope (SOP) to 6.7 mm in the shallowest section (MEC). After two years of exposure, the average shell length ranged from 7.2 mm to 14.2 mm in the depth zones of 7–8 m (SOP) and 5–6 m (GLE), respectively, while after three years, the average mussel shell length ranged from 7.2 mm to 13.1 mm in the deepest and shallowest zone (SOP), respectively. The youngest specimens demonstrated the largest growth dynamics (from 3.0 mm $year^{-1}$ to 6.7 mm $year^{-1}$) and the growth rate decreased with the age of bivalves, reaching only

Table 1

Average length (mm) and growth rate (mm year^{-1}) of mussels on ropes as a function of exposure time, depth zone and location of mussel farming site in the Gulf of Gdańsk in 2009–2012 (Sami Alias 2014, modified)

Exposure time (year)	Depth zone (m)	MEC		GLE		SOP	
		Mean shell length	Shell growth rate*	Mean shell length	Shell growth rate	Mean shell length	Shell growth rate
1	3–4	6.7	6.7	5.8	5.8	4.2	4.2
	5–6	6.2	6.2	5.4	5.4	3.7	3.7
	7–8	7.0	7.0	5.4	5.4	3.0	3.0
	9–10	4.7	4.7	4.4	4.4	3.2	3.2
2	3–4	9.0	4.4	11.3	5.5	10.0	4.9
	5–6	9.6	4.7	14.2	6.9	9.0	4.4
	7–8	9.2	4.5	11.1	5.4	7.2	3.5
	9–10	12.4	6.0	10.6	5.1	9.7	4.7
3	3–4	7.8	2.6			13.1	4.3
	5–6	11.8	3.9			8.5	2.8
	7–8	7.2	2.4			13.1	4.3
	9–10	9.8	3.2			7.3	2.4

*Due to the varying duration of the growing period in subsequent years of exposure (from 367 to 376 days), the shell growth rate was recalculated for a standardized period of 365 days across all sites

2.4 mm year^{-1} in the third year of farming (Fig. 6; Sami Alias 2014). The growth rate of mussels growing on polypropylene ropes in the Gulf of Gdańsk was similar to that of bivalves inhabiting the sea floor at a similar depth in the gulf (Cuena Barron & Wołowicz 1980). It exceeded the annual growth rate of bivalves cultured in the coastal waters of central-eastern Sweden (2.2–3.1 mm year^{-1}; Kautsky 1982) and western Finland (3.4–3.8 mm year^{-1}; Antsulevich et al. 1999), suggesting that mussels grew faster in the southern Baltic Sea. The elevated growth rate of mussels likely reflects the high eutrophication status of this area, which receives

a)

b)

Figure 5

Culture ropes after four (a) and 12 months of exposure (b).

considerable loads of nutrients from the Vistula River and agricultural runoff (HELCOM 2018b). In comparison to the sheltered areas of the western Baltic (30 mm year^{-1}; Loo & Rosenberg 1983) or the tidal zone in fully saline estuaries of western Europe (50 mm 18 months^{-1}; Bayne & Worral 1980), the growth of mussels in the gulf was, however, markedly slower, which inevitably results from the brackish nature of this water basin.

In order to determine the potential of mussel aquaculture for the purpose of human consumption, nutrient mitigation and improvement of marine environment quality, an increase in bivalve biomass was assumed to be of key importance as it indicates the potential of mussels to gain weight, purify water and remove biogenic compounds. At all study sites, the largest total mussel dry wet weight (i.e. soft tissue and shell, from 487 g m^{-1} rope at MEC to 1642 g m^{-1} rope at GLE) was recorded in the 3–6 m depth zone after 767 days of exposure. The highest efficiency of mussel production in the Gulf of Gdańsk was observed after two years of exposure. It is worth noting that prolonged mussel farming (up to three years) did not lead to a further increase in biomass and even caused a partial loss of the total mussel wet weight (Table 1), presumably as a result of the fact that large mussels were overgrown by small ones and the largest individuals fell off the culture ropes (Gagnon 2019). Bivalve biomass decreased gradually with water depth, reaching the lowest values in the near-bottom zone of 9–10 m depth (54 g m^{-1} rope after one year at SOP), where food availability is limited compared to the shallow zone (Wołowicz et al. 2006). Due to favorable thermal conditions and good light penetration, small planktonic algae develop most intensively in the shallow water layer throughout the growing season (March–October) providing mussels with high-energy and nutrient-rich food (Gosling 2004). The shallow euphotic zone down to ca. 6 m water depth should be therefore considered the most efficient for mussel biomass production in the gulf, despite potential impact of wave action and ice cover. Particularly good trophic conditions (i.e. high concentration of nutrients and increased primary production in the water column) occur in the western part of the gulf, where much greater growth of mussel biomass was observed (MEC and GLE). Since this part of the gulf is inhabited by numerous and diverse species of other hard-substrate fouling epifauna (e.g. barnacles *Amphibalanus improvisus*, sea mats *Einhornia crustulenta*), which promotes the deposition of mussel larvae on ropes (Sokolowski et al. 2017b), this region may be an effective location for mussel farming. It is noteworthy that the biomass of mussels (per unit of culture medium) in the experimental farming in the Gulf of Gdańsk can be classified among the highest in the Baltic Sea (Fig. 6), which proves favorable environmental conditions for aquaculture of this species.

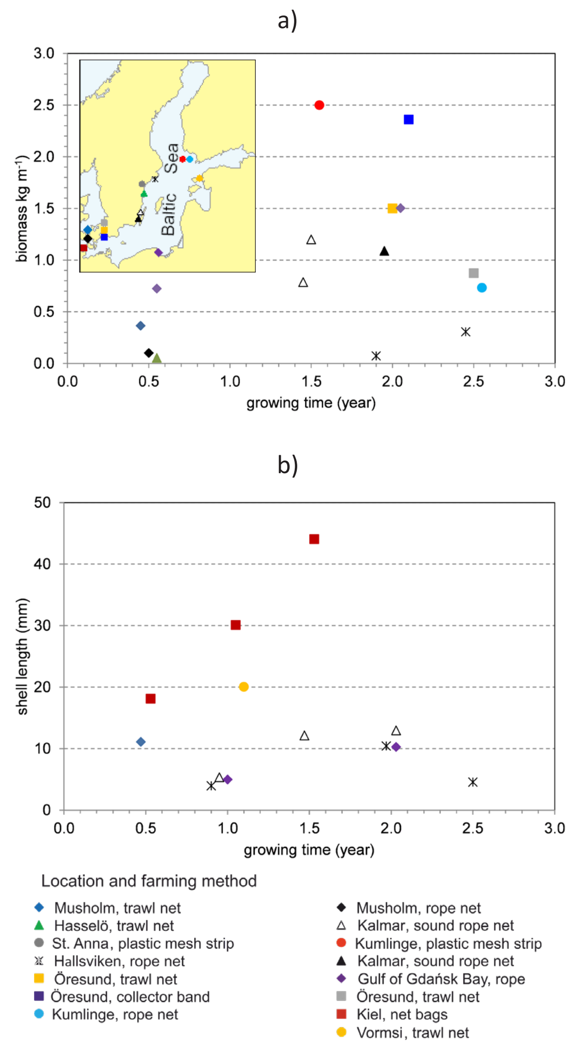

Figure 6

Wet biomass, i.e. soft tissue and shell (a) and mean shell length of cultured mussels (b) after different growing periods in the coastal zone of various regions of the Baltic Sea. For comparative purposes, biomass data were normalized to a common unit of kg m-1 of rope, belt or net. The insert map indicates the location of the farms; source of the graph: Minnhagen (2017) based on data from: Engman (2009); Wennström & Engman (2014); Lindahl (2012); Olofsson et al. (2014); Ek Hening & Åslund (2012); Sami Alias (2014); Schröder et al. (2014); Bucefalos project (2015); Moltke Lyngsgaard et al. (2017).

3. Technological solution tested in the pilot study

Harsh meteorological conditions in the southern Baltic Sea, including severe and extreme weather events such as increased storm frequency and severity in autumn and spring pose a threat to farming infrastructure and marine operations. Special focus on these risks and risk mitigation strategies is therefore a preliminary condition for mussel farm planning and management in this area (Ahsan & Roth 2010). Similarly to other coastal regions of the Baltic Sea, the formation and drift of sea ice and high-energy short waves (Lindahl 2012) can cause serious damage to farming infrastructure in the Gulf of Gdańsk. The optimal technological solution includes therefore farming modules that can be submerged (or optionally submerged) below the water surface permanently or over the wintertime. Based on our experience from the presented pilot study, the so-called "long-line" system, which supports submerged suspended cultures, can be recommended to reduce risk from damage and to ensure durability. Another technical solution with potential application is the commercial SmartFarm system (Smart Farm AS), which is widely and successfully used on different scales in mussel farms throughout Europe (e.g. Przedrzymirska et al. 2018; Hylén et al. 2021).

The traditional submerged long-line system consists of an anchoring system (anchors, anchor lines), lifting elements (buoys, floating lines and floaters), as well as single culture ropes (collectors) connected by a supporting line. Anchors are used to anchor the ends of the supporting line to the bottom. The harvesting of mussels requires raising the culture ropes on the vessel deck. The system is secured in the water column by stabilizing surface and submerged plastic buoys, whereas the collectors are attached to the horizontal supporting line and they are suspended in a vertical position parallel to each other (Fig. 7). The system does not include any rigid structure on the water surface or in the water column and presents minimal resistance to the effects of weather and sea. The much weaker movements of the structure under adverse hydrological conditions cause less wear on anchor lines and shackles (Johns & Hickman 1985). The system recommended in the Gulf of Gdańsk consists of single modules, each 200 m long, with a distance of 10 m between modules, which allows the installation of five modules over a surface area of 10 000 m^2 (1 ha). The length of culture polypropylene ropes is 7 m to cover the water depth optimal for mussel growth (3 to 6 m) and their diameter is 32 mm. The ropes are spaced 0.5 m apart, resulting in 400 ropes in each module. The modules are anchored with 3.0 t concrete anchors (or 2 x 1.5 t anchors) at each end parallel to the direction of the sea currents prevailing in the area of interest. Buoys of 35–40 dm^3 ensure the buoyancy of the system and are used as the main line floats and corner boys (3 buoys attached to anchor lines) following the recommendations of Bonardelli (2013) and Bonardelli et al. (2019). Basic technical information on the culture

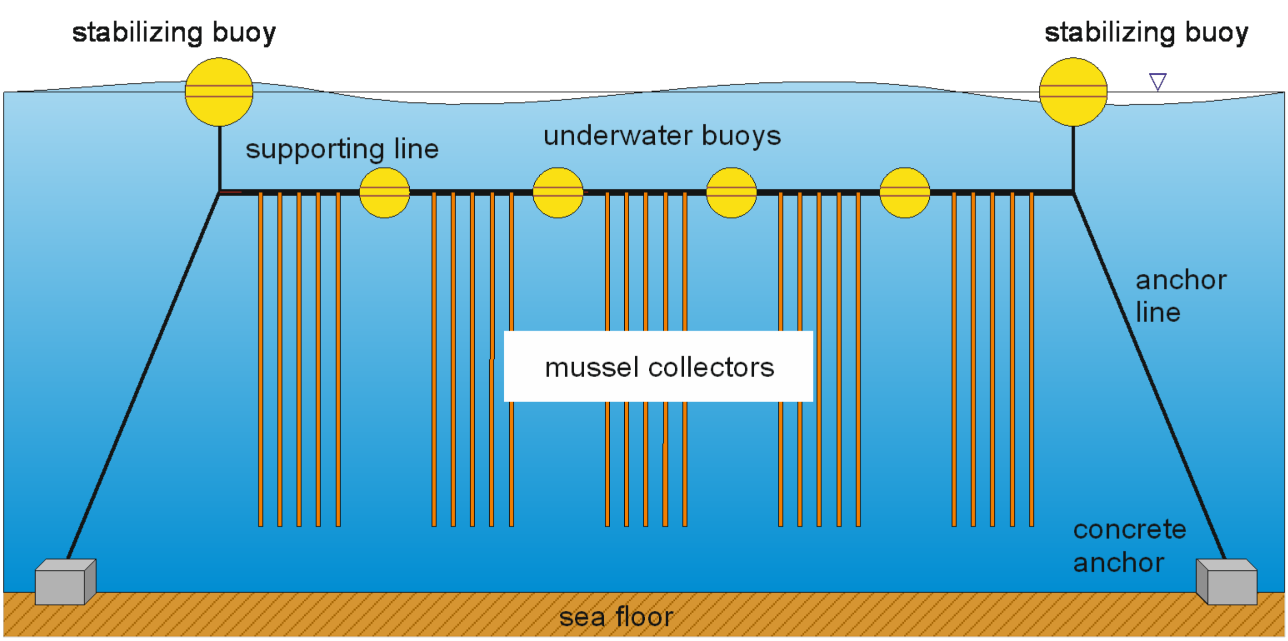

Figure 7

Long-line farm system (source: https://balticbluegrowth.eu, modified).

module in the long-line system is presented in Table 2. Assuming that the expected total biomass of mussels farmed is 4.5 t (this study) and that mussels lose 75% of their weight due to buoyancy in water (Bonardelli et al. 2019), 28–33 main line buoys should provide sufficient buoyancy for production of mussels over two years. When submerging the modules at more exposed sites, it is recommended to install also intermediate compensation floats with counterweights to stabilize and keep the supporting line horizontal at a proper depth during the entire farming period. It may also be advisable to increase the distance between the modules with increasing water depth (e.g. distance = 1.5 x water depth) and to increase the weight of an anchor to 5 t under open sea conditions as suggested by Bonardelli (2013) and Bonardelli et al. (2019).

Table 2

Selected technical parameters of the culture module in the long-line system

Parameter		
Length of supporting line/head rope	200	m
Length of growing rope (collector)	7	m
Diameter of head rope	32	mm
Diameter of growing rope	32	mm
Buoys buoyancy	35	dm^3
Number of buoys	30	
Total length of growing ropes	2800	m

4. Potential use of mussel farming

In many coastal and offshore areas around the world, mussels are mainly cultivated for human (and animal) consumption, contributing significantly to the nutritional quality of human diets (Chi et al. 2012; Suplicy 2020). Mussel meat is a cheap source of high-quality protein, including essential amino acids (EAA) in proper proportions, and is therefore considered to provide multiple dietary benefits (Astorga España et al. 2007). Due to salinity-induced osmotic stress, mussels in the Baltic Sea rarely reach marketable size (> 35 mm) within a reasonable farming time (Westerbom et al. 2002). In this study, only 1.0 to 1.7% of the mussels grown on the culture ropes reached shell length greater than 30 mm and only 0.2% of the mussels were > 35 mm long. Mussels from the southern Baltic have therefore limited potential for gastronomic use and direct human consumption (albeit still possible). Other ways of exploitation and end uses of mussels have been therefore developed in the Baltic countries with potential importance for animal nutrition and improvement of marine environment quality. These include the replacement of fishmeal by mussel flesh as poultry feed containing valuable amino acids, oils and proteins for meat and egg production, the use of mussel flour in the production of fish feed (Árnason et al. 2015; Kraufvelin & Díaz 2015; Suplicy 2020 and references therein), the use in animal feed production as high-quality calcium-rich food (Lindahl & Kollberg 2008; Jönsson 2009) and for plant cultivation as a good alternative for production of fertilizers (Spångberg et al. 2013). The production of mussels involves a large quantity of shells that need to be managed. It is worth noting that mussels can be processed along with their shells into feed for some animals (especially birds). The shells themselves can be used as a liming agent in acid soils, which also increases soil fertility. Other potential applications of shells include their use as biofiltration medium, water pH buffer, calcium supplements, bactericides, fillers, construction material, artificial bones, dehalogenating agents, adsorbents and catalysts (Jović et al. 2019 and references therein). As primary consumers, mussels occupy a low position in the marine trophic chain and their use in the production of fish feed is considered reasonable also in terms of sustainable management of marine resources (Muminović 2010; Lindahl 2013). This aspect may be of particular importance in the Baltic Sea, where stocks of many commercial fish species have been overexploited in recent years for fishmeal production (HELCOM 2018c).

The direct effect of mussel farming on the water column is primarily the improvement of water transparency through reduction of organic suspended particulate matter (phytoplankton and small detritus). Due to their natural filtration activity, mussels take up suspended particles from the ambient water and incorporate organic matter into their body. Bivalves thus reduce organic matter and the associated elements and chemical compounds, nutrients, silt, bacteria and viruses, and increase light transmission which, in turn, improves the condition of submerged vegetation (Shumway et al. 2003). In this study, the total volume of water filtered by bivalves on one culture rope during a day was estimated at 157 449.6 dm^3. When expanding the scale of long-line mussel culture up to a total surface area of 20 000 m^2 (i.e. comprising 4000 ropes, each 7 m long, grouped in 10 modules), mussels would filter ca. 18 893 952 m^3 of water in 30 days, which corresponds to 426 384 m^3 ha^{-1}. A high rate of water filtration by bivalves results in effective removal of suspension from the water column, which may be of particular importance during warm summer periods with intensive blooms of phytoplankton algae, including species producing toxic compounds (e.g. cyanobacteria such as *Nodularia* spp.; Mazur-Marzec et al. 2016). Given the possibility of relatively easy and cost-effective reallocation of mussel farms within the coastal zone, they could serve as effective biological filters in different regions. For example, such portable farms could be used in areas where the occurrence of toxic blooms in summer reduces tourist activity (e.g. beach resorts) and in areas of sewage discharge from wastewater treatment plants as a supplementary measure of water purification. Such an effect was observed in the Kiel Canal (western Baltic Sea), where water transparency, measured as the Secchi disc depth, increased by 30 cm in the vicinity of a mussel farm (mussel production efficiency of about 30 t year^{-1}; Schröder et al. 2014). In the heavily eutrophic Skive Fjord in Limfjorden in north-western Denmark, the concentration of chlorophyll *a* in the water column decreased by a maximum of 44% and the concentration of total suspended particulate matter by 15% as a result of mussel farming (Nielsen et al. 2016).

Through filtering and taking up suspended particles, mussels assimilate and incorporate considerable amounts of carbon (C), nitrogen (N) and phosphorus (P) into their body structures (Jansen et al. 2011). These nutrients are stored in mussels and are removed from the marine environment when mussels are harvested (Petersen et al. 2016). Based on the results obtained at site MEC, which showed the largest increase in wet and dry biomass of mussels after two years of exposure, i.e. 11.2 kg of wet weight (soft tissue and shell) rope^{-1}, the maximum potential for using large-scale mussel farming for nutrient removal from water was assessed. The following initial culture conditions were assumed in the calculations: i) the mussel farm is constructed using the long-line system and consists of 10 modules, each 200 m long, over a total surface area of 20 000 m^2 (2 ha); ii) each module contains 400 vertical culture ropes, each 7 m long, spaced 0.5 m apart; iii) modules are located every 10 m in parallel; iv) the growth rate, biomass gain and filtration of mussels are the same on all culture ropes regardless of their position in the module, and v) the exposure period is two years. The estimated total wet mussel biomass (soft tissue and shell) reached 44.8 t (22.4 t ha^{-1}). The production efficiency of *M. trossulus* in the gulf could be further increased by submerging the farm in a shallow zone of up to 6 m water depth, i.e. where the largest production of mussel biomass was recorded. Elemental analyses of the mussel soft tissue after two years of exposure in the Gulf of Gdańsk revealed carbon content ranging from 48.6% to 49.2% SFDW, nitrogen from 9.3% to 9.8% SFDW and phosphorus content of 1.1% SFDW. One tonne of harvested mussels (wet weight of soft tissue and shell), corresponding to ca. 88.8 kg SFDW, yielded from 43.1 to 43.7 kg C, 8.3 to 8.7 kg N and 1.0 kg P, which is lower than the yield of 13.7 kg N t^{-1} and similar to 0.9 kg P t^{-1} obtained in a mitigation mussel culture in Limfjorden (Taylor et al. 2019). The maximum total amount of C, N and P fixed in mussel tissues on one 7 m long culture rope after two years of exposure was estimated at 483.1 g, 97.4 g and approx. 10.8 g, respectively, which corresponds to 2318 kg C, 468 kg N and 52 kg P for a mussel farm of a total surface area of 20 000 m^2 and 1159 kg C ha^{-1}, 234 kg N ha^{-1} and 26 kg P ha^{-1} (Table 3). The efficiency of nitrogen and phosphorus removal with harvested mussels (kg ha^{-1}) in the Gulf of Gdańsk

Table 3

Summary of biological parameters of mussels *Mytilus trossulus* harvested in the Gulf of Gdańsk and other selected Baltic areas. Technical details of the experimental set-up in the Gulf of Gdańsk are given in the text.

Parameter		(this study)	(Taylor et al. 2019)	(Kotta et al. 2020)		
		Puck Bay (Gulf of Gdańsk)	Limfjorden	Kumlinge (Åland archipelago)	Sankt Anna (Östergötland archipelago)	Kiel (Bay of Kiel)
farming period		2009–2011	2017–2018	2010–2012	2016–2018	2011–2012
farming technology		long-line	long-line	nets	spat catching ropes	ropes with collector bands
total wet biomass (soft tissue and shell) and SFDW (kg m^{-1})		1.60/0.142		0.72/–	3.40/–	2.5/–
total biomass production (wet soft tissue and shell; t ha^{-1})		22.4	41.0–90.4	16.0*	20.4*	16.7*
mean content of C/N/P in SFDW** (%)		48.6/9.8/1.1		–/3.2–3.8***/0.6***	–/ 4.4***/0.6***	–/5.6–7.5***/0.6***
content of elements in SFDW per 1 m rope (g m^{-1}):	C	80.5				
	N	16.2		3.7	23.3	22.3
	P	1.8		0.3	1.8	1.6
yield of elements in one t of harvested mussels (kg):	C	43.1–43.7				
	N	8.3–8.7	13.7			
	P	1.0	0.9			
maximum total removal of elements (kg ha^{-1}):	C	1159				
	N	234	600–1270	83	140	148
	P	26	40–100	6.4	10.8	10.8

*converted for a standard farm area of 1 ha; **shell free dry weight; ***source data (% soft tissue wet weight) were converted to % SFDW using an SFDW/SFWW conversion factor of 0.159% after Rumohr et al. (1987); – no data exceeds markedly the respective values in three farms in the outer (Bay of Kiel), central (Swedish Östergötland archipelago) and inner (Åland archipelago) parts of the Baltic Sea (Kotta et al. 2020), but were much lower than the elemental yields in Limfjorden (Taylor et al. 2019). The improved mitigation effect of the mussel farm in the latter likely results from higher nutrient storage capacity of bivalves under more saline conditions (Ritzenhofen et al. 2021). The rate of nutrient immobilization in soft tissue of cultured bivalves in the southern Baltic Sea is inevitably associated with their relatively large biomass production and elevated elemental content (Table 3). Mussel cultivation and harvesting in the Gulf of Gdańsk provides thus important extraction capacity and can be considered a viable and promising mitigation measure in this eutrophicated water basin. Remiszewska-Skwarek et al. (2016) provided data on annual discharge of N and P by the wastewater treatment plant "Dębogórze" (north of Gdynia) in 2015, so the comparison was possible to determine the potential of nitrogen removal by mussel culture. Deployment of a 20 000 m^2 mussel farm in the area receiving sewage from the wastewater treatment plant, which annually discharges ca. 148.5 t N and 12.8 t P to the gulf, could reduce nitrogen and phosphorus load by additional 0.16% and 0.20%, respectively, per year. The calculated efficiency of nitrogen and phosphorus removal with bivalve biomass is therefore low and of limited importance for nutrient reduction in the gulf. Mussel farming may, however, be a promising prospect for local nutrient mitigation, in addition to more traditional methods such as construction of large wastewater treatment plants, reduction of industrial emissions, changes in agricultural practices and restoration of wetlands (Lindahl et al. 2005).

Another potentially beneficial effect on the marine environment is the accumulation of mussel shells detached from culture ropes and other organic elements such as shells of other mollusks (e.g. snails), calcareous shells of crustaceans (e.g. barnacles) or fragments of plants underneath the mussel farm. Shell clusters on the sea floor offer a complex spatial structure and create new benthic microhabitats and trophic conditions that facilitate the development of mobile (e.g. snails, crustaceans, polychaetes, demersal fish) and sessile (e.g. mussels, sponges) benthic fauna (Wilding & Nickell 2013; Kotta et al. 2020). In consequence, there is a local increase in species diversity and abundance of macrobenthic communities, which in turn attract other animal species such as predatory fish and birds (Morrisey et al. 2006; Varennes et al. 2013). High mussel densities associated with aquaculture can thus increase the biodiversity of an area (Byron et al. 2011), and mussel farms can act as floating artificial reef systems for both pelagic and benthic fish species (Wang et al. 2015).

5. Potential negative environmental effects of mussel farms

The settlement and growth of a large number of bivalves on culture ropes, deployed on a relatively small area, can have adverse effects on the surrounding environment. By filtering water, mussels capture suspended particles, some of which are removed as rapidly depositing pellets of pseudofeces (before transport to the mouth) or feces (after passing through the digestive system). They form aggregates rich in organic matter and glued together by polysaccharide compounds (mucus), which sink to the bottom (Gosling 2004) and subsequently increase the organic matter pool in surface sediments in the immediate vicinity of the farm (Kaspar et al. 1985; Burkholder & Shumway 2011; Suplicy 2020; Wikström et al. 2020). As a result of increased sedimentation, organic matter accumulates in the sediments where it undergoes aerobic transformation, a process that enhances nutrient regeneration from the seabed and requires oxygen to oxidize soluble and refractory organic matter (McKindsey et al. 2011). Intensive decomposition of biodeposited organic matter can seasonally result in increased phosphate, silicate and ammonia fluxes, as well as oxygen depletion and hypoxia (oxygen concentration ≤ 2 cm^3 dm^{-3}) in the overlying bottom and interstitial water (Carlsson et al. 2009; Stadmark & Conley 2011). Mineralization of fresh biodeposists can thus lead to localized impacts on resident benthic organisms through reduction of oxygen concentration and alteration of geochemical conditions, e.g. accelerated release of ammonia and phosphate from sediments (Grant et al. 1995). For example, increased concentrations of ammonia and phosphates in the bottom zone impede the development of benthic vegetation (Vinther et al. 2008). Particularly susceptible to organic matter loading is the seagrass *Zostera marina*, which forms extensive submerged meadows in the shallow zone of the Gulf of Gdańsk (Vinther et al. 2008). In stagnant and poorly flushed areas with significant loads of organic matter, anaerobic conditions (anoxia, i.e. oxygen concentration of 0 cm^3 dm^{-3}) and even production of hydrogen sulfide (H_2S) may occasionally occur under dense mussel cultures (Stenton-Dozey et al. 1999; Hargrave et al. 2008), directly affecting the structure and density of benthic fauna (Vaquer-Sunyer & Duarte 2010). The extent of hypoxia and anoxia impacts depends largely on the rate of sedimentation, local geomorphological situation such as water depth and flow regimes, as well as season and climatic conditions (Newell 2004). If the surface layer of sediments remains well oxygenated (e.g. owing to high water circulation and large sediment grain sizes), detrimental impacts are minor and adverse effects on benthos may be negligible. In such areas, biodeposition under mussel farms can in turn contribute to increased biodiversity and abundance of the resident benthic infauna, which accelerates the rate of bioirrigation of surface sediments through bioturbation activity (Kraufvelin & Díaz 2015). During the pilot three-year mussel farming in the Gulf of Gdańsk, no deviation from the long-term seasonal cycle of basic hydrological parameters of the overlying bottom water was observed. For larger-scale farming, however, basic parameters of surface sediment and overlying bottom water should be monitored on a regular basis to avoid negative impacts of mussel farms on the benthic biocenosis. According to Hadberg et al. (2018), in small semi-enclosed Baltic waters (e.g. bays, reservoirs) with slow water exchange and low primary production, actively filtrating mussels can significantly reduce the concentration of phytoplankton in the water column, thereby reducing the availability of food resources for themselves and other filter-feeding animals. When this self-effect is combined with high water temperature during summertime, i.e. a period when mussel metabolic rate (including filtration, oxygen consumption, excretion, etc.) is elevated (Wołowicz et al. 2006), it can adversely affect the growth potential of mussels.

6. Legislative framework

Mariculture in Poland is considered a developing sector and one of the nine maritime economic sectors with the greatest potential in many coastal areas in the future (Brodzicki et al. 2013). The overall main legal requirements for the establishment of mussel farms are derived from European legislation such as the Water Framework Directive (MFD), the Marine Strategic Framework Directive (MSFD), the Nature 2000 Framework and their individual national implementations, amended by special national laws (for instance fisheries law or special private regulations to use marine areas; https://projects.interreg-baltic.eu/projects/baltic-blue-growth). The Gulf of Gdańsk is located within the internal sea waters of Poland where human maritime activities related to fishery, exploitation, industry, research and tourism are currently regulated by the Act on the Maritime Areas of the Republic of Poland and Maritime Administration of 21 March 1991 (http://prawo.sejm.gov.pl). The act does not specify legal rules for aquaculture and indicates that detailed provisions regarding this type of activity can be specified in spatial management plans for internal sea waters, the territorial sea and the Polish Exclusive Economic Zone, which are drawn up by local maritime administrators competent for the area covered by the planning. Poland is at the beginning of the Maritime Spatial Planning implementation process, which is a public and strategic planning procedure consisting of analysis and spatial and temporal allocation of water areas for human activities (Turski 2017). The maritime spatial planning for the year 2020 for the gulf, including Puck Bay, is currently being developed and the documents under the working title "Pilot project of the maritime spatial planning covering the western part of the Gulf of Gdańsk" are of preliminary nature and thus do not form yet a formal framework for human maritime activities. They concern the area located west of the line connecting the tip of the Hel Peninsula with the border between the municipalities of Gdynia and Sopot (http://www.umgdy.gov.pl). The entire area has been divided into 30 smaller water areas for which the primary use (e.g. nature protection, fishery, transportation, etc.) and other possible uses have been defined. The draft plan allows mussel aquaculture in 12 such water areas (with the dominant nature protection use), which are mainly located in the Puck Lagoon (the inner part of Puck Bay) and in the western and north-western parts of the outer part of Puck Bay. The project does not introduce, however, any restrictions on the development of underwater temporary infrastructure for environmental protection, also in other areas, once the desirability of such investment is well justified. The construction of temporary structures would require: (a) an inventory of habitats in the area of planned farms; (b) the use of Best Available Techniques (BAT); and (c) compliance with the principle of efficient use of sea space (http://www.umgdy.gov.pl). More detailed legal regulations on the cultivation of marine organisms can be found in the Act on Marine Fisheries of 19 December 2014 (http://prawo.sejm.gov.pl). Pursuant to the provisions of Chapter 3 of this document (Articles 97–99), mariculture (including mussel farming) in marine areas of the Republic of Poland requires a permit, which is issued by the minister competent for fisheries, by way of decision. An application for a permit should describe farming details such as location, exposure period, culture system and target species, and should include a decision on environmental conditions, as referred to in the provisions of the Act of 3 October 2008 on the provision of information on the environment and its protection, public participation in environmental protection and environmental impact assessments.

Since a large part of the Gulf of Gdańsk lies within the Pan-European Natura 2000 protected areas network (Special Protection Area PLB220005 Zatoka Pucka and Special Area of Conversation PLH220032 Zatoka Pucka i Półwysep Helski) and the Coastal Landscape Park (Nadmorski Park Krajobrazowy), special regulations for the development of mussel farming should also be considered when planning to locate mussel farms. In the case of establishing submerged culture structures within Natura 2000 areas, the implementation of the so-called good environmental practices for effective integration with areas of the greatest natural value plays an important role. These include adapting aquaculture to the requirements of the European directives on the protection of biodiversity, ensuring the development of sustainable and environmentally friendly aquaculture or supporting production systems that promote diversification of economic activities and lead to their "environmentally friendly" status (Gil 2009). In addition, pursuant to the Act of 18 July 2001 Water Law, the entire Gulf of Gdańsk was classified as coastal waters, which in accordance with Directive 2000/60/EC imposes an obligation that any activities carried out in this area do not deteriorate the ecological status of its waters.

7. Economic aspects

The economic performance of mussel farming was assessed using the experimental results of this study and the market retail prices of materials and services available for the individual consumer in 2020. Prices in PLN were converted to EUR at the average exchange rate published by the Polish National Bank for January–February 2020 (https://www.nbp.pl/). The calculations were performed for the long-line system, which can be regarded as the most economical option and can be easily made in-house from commercially available components. To be consistent with the technological solutions tested in the Gulf of Gdańsk and to allow realistic scenario simulations, the following basic parameters were assumed for computing basic investments costs: i) farming time is two years and ii) the farm consists of 10 modules with a total length of culture ropes of 28 000 m, which are submerged over a total surface area of 20 000 m^2 (2 ha). The dimensions of the farm are similar to those of the three largest full-scale mussel farms in the Baltic Sea with a total length of all culture ropes ranging from 22 000 to 49 000 m (https://www.submariner-network.eu). To conform with other studies on economic aspects of coastal and off-shore mussel aquaculture in the Baltic Sea (e.g. Schernewski et al. 2012; Gren 2019; Schultz-Zehden et al. 2019) and other European basins (e.g. Buck et al. 2010), all costs of items that need to be considered by potential mussel investors were divided into two main categories: investment costs and operational/maintenance costs. Investment costs are the fixed costs to be incurred for materials (e.g. ropes, mooring constructions), ready-to-use components (floats) and the equipment required to build a complete and operational long-line system when starting a project. Operational costs include labor to deploy modules at sea, regular maintenance and monitoring of a farm during its operation, and boat/vessel rental costs (preferably existing spare capacity of local fishermen, which require adaptation for coastal aquaculture). In long-line mussel farms, the modules are deployed in the first year of farming and do not need to be retrieved after mussel harvesting. The farming infrastructure requires, however, periodic cleaning off algae, and repairs (at least once a year), as well as regular inspection (once every month or two). Mussels should be harvested just before the breeding season when they store high-energy biochemical compounds and develop gonads, i.e. gain the highest soft tissue mass (Wołowicz et al. 2006). The selection of an appropriate harvesting period should therefore be preceded by a test sampling of mussels (e.g. every two weeks) and analysis of their gonad development stage in spring and early summer, when rising temperature and increased availability of phytoplankton in the water column stimulate the maturation of gonads. The income from mussel farming in the Gulf of Gdańsk was estimated for different potential uses of mussels harvested after two years of culture, i.e. for human consumption, feed production and removal of nutrients from the ecosystem (so-called ecosystem service of farming; Schultz-Zehden et al. 2019). The economic valuation assumed stable mussel production efficiency (i.e. similar spat supply, mussel growth and biomass increase, predation rate, fouling dynamics, etc. throughout the production period as previously described for the pilot study).

Due to the lack of a market for mussels and trade from Baltic farms in Poland, the price of raw material remains difficult to estimate. The available market prices of mussels offered in Polish shops for human consumption, which come from the North Sea and the Atlantic, range from EUR 7 to over EUR 9 kg^{-1} (this study). Based on an extensive interview with experts, Ozolina & Kokaine (2019) estimated the market price of Baltic mussels to be on average EUR 4.0–5.0 kg^{-1} for frozen mussels and EUR 6.0–10.0 kg^{-1} for fresh mussels. In Denmark, small mussels are sold for EUR 100 t^{-1}, i.e. EUR 0.1 kg^{-1}. In this study, EUR 5.0 kg^{-1} and EUR

0.1 kg^{-1} were therefore assumed for fresh mussel for human consumption and for animal feed production, respectively.

7.1. Basic investment costs

The cost of a single farming module in the long-line system was EUR 8555 and the costs of individual components of the system and equipment used to harvest and sort mussels are listed in Table 4. The minimum total investment costs amounted to EUR 107 924 and included EUR 85 550 for modules and EUR 22 374 for equipment (i.e. stripping and declumping/sorting machines). As suggested by Schernewski et al. (2012), the expected lifetime of the equipment used to support growth and harvesting of mussels under the Baltic conditions (depreciation period) is 15 years. When assuming that modules will therefore be used for mussel farming in the Gulf of Gdańsk for eight two-year production cycles to reach the highest mussel production efficiency, and the equipment for 16 cycles (with harvesting every two years), the basic investment cost for one cycle was ca. EUR 12 092. To be able to harvest mussels every year, two independent farms should be operated simultaneously, one being established one year after the other, i.e. two farms are started within two consecutive years.

7.2. Operational/maintenance costs

Based on the experience of suspended culture aquaculturists from other Baltic coastal areas and pilot assessments conducted in this study, the annual labor effort for the deployment was assumed to be 150 man-hours (three men, 50 h each). Maintenance and monitoring of the farm during the two-year production cycle amounted to 130 man-hours (for one or two men depending on the tasks) and the workload for mussel harvesting was 1260 h (three men working simultaneously). After including an hourly rate of PLN 50 (including all elements of tax-deductible costs) into calculation, the cost of labor for one production cycle totaled EUR 18 054. The working time of a boat/vessel for all marine operations, such as deployment of the farms, their maintenance, inspection, as well as mussel harvesting and initial processing during the two-year production cycle was estimated at ca. 600 h, which resulted in renting cost of EUR 45 000 at a unit rate of EUR 900 for 12-hour vessel rental.

7.3. Summary costs

The total investment and operational/maintenance costs for a mussel farm in the Gulf of Gdańsk over a two-year production cycle amounted to EUR 69 670 (EUR 6258 in deployment costs, paid at the start of the farm establishment, was spread evenly over 8 production cycles) but the actual costs should be considered higher. Additional costs account for onshore labor (preparing the long-line system, sorting of mussels, etc.) and other items that are variable over time and difficult to estimate. They include interest on fixed capital and miscellaneous costs such as insurance premium, accounting services and administrative costs, road transport of structural elements and harvested bivalves, an onshore facility to store equipment and to perform onshore activities such as tying and repairing modules and other equipment, as well as office and licensing costs. Additional costs

Table 4

Estimated costs (EUR) of materials (including shipping) required for one 200 m long long-line module and equipment used for mussel harvesting in the long-line system

Component	quantity	price
Polypropylene twisted rope (32 mm diameter) used as the main and anchoring lines (including provision for ties and loops)	260 m	491
Polypropylene braided hawser rope (32 mm diameter) used as a growing line (including provision for securing ends)	2860 m	6111
Polypropylene twisted rope (18 mm diameter) for tying up growing lines and buoys	440 m	265
Polypropylene twisted rope (6 mm diameter) to prepare loop cords for setting attachment points on the mainline	220 m	15
Submersible buoys with a buoyancy of 35 dm^3	38 items	970
Self-made concrete blocks (anchors) of 1.5 t (including the cost of purchasing concrete, materials to build wooden molds, reinforcing bars, stainless steel rods for line attachment loops)	4 items	703
TOTAL		8555
Basic harvesting equipment (stripping and declumping/sorting machines)		22374

will also arise during farm decommissioning, and in addition to the costs of removing farm modules from the water, they may also include costs for disposal of the materials used. Depending on the size of the farm, the duration of farming and the method of financing (purchase, lease, rent, etc.), these additional costs can constitute up to 19% of the total costs (Buck et al. 2010). It is worth noting that the calculation did not include either potential costs of cleaning the mussels in filtered seawater pools or their storage in refrigerators prior to sale for human consumption, i.e. the procedures which are commonly employed for cultured mussels in many European countries (Lees et al. 2010). In addition, if mussels are not acceptable for human consumption or for use in animal feed production due to bacterial and/or chemical contamination, disposing of mussel biomass will be necessary. The disposal of bivalve waste will then generate additional costs, which vary from ca. EUR 25 to ca. EUR 100 per 1 t depending on the rendering plant and the classification of waste based on its composition and hazard. The largest part of the operating costs is the vessel rental, so for vessel owners, e.g. local fishermen who use boats for fishery and/or aquaculture, production costs may be substantially lower.

7.4. Revenue

Given that only 1.0 to 1.7% of the mussels cultured in the pilot experimental study reached a shell length greater than 30 mm and 0.2% above 35 mm, the economic model assumes that 1.7% (ca. 0.76 t) of the total mussel biomass (44.8 t) is sold for direct human consumption and the remaining 98.3% (ca. 44.04 t) for animal feed production. The total revenue was then EUR 8204, i.e. EUR 3800 and EUR 4404 from sales for consumption and feed production, respectively. The total income from mussel farming in the gulf can therefore cover only ca. 12.0% of its total costs (cumulative investment and operational/maintenance costs), indicating negative budget balance (deficit) for such an investment. Even when assuming that local fishermen use their own boats for all marine operations, aquaculture is not profitable. For this reason, development of mussel farms in this basin can be justified only for the purpose of improving the quality of the marine environment. Extensive mussel farming for nutrient mitigation and reduction of primary production in the water column (so-called "mitigation culture"; Taylor et al. 2019) has recently received increasing attention in many Baltic countries and has been suggested as a promising abatement option (Gren 2019). This is particularly so as activities aimed at combating eutrophication and ameliorating the environmental status in coastal areas of special importance for local marine spatial planning (e.g. ecotourism) can be supported by additional funding programs such as the European Maritime and Fisheries Fund (EMFF) and the Natural Capital Financing Facility (NCFF; Schultz-Zehden et al. 2019). Another source of funding is in line with the polluter pays principle that requires polluters to take measures to reduce pollution, to measure pollution, and in some cases to pay taxes or charges for pollution and compensate for pollution impacts (ten Brink et al. 2009; Schultz-Zehden et al. 2019). As suggested by Lindahl & Kollberg (2009), significant financial support for mussel farming can also come from additional taxation of fertilizers that are used in agriculture or diversion of some agricultural subsidies. The estimated cost of removing 1 kg of nitrogen with mussels harvested in the Gulf of Gdańsk was ca. EUR 130, i.e. nearly eleven times more than the corresponding cost incurred by a conventional wastewater treatment plant in the water treatment process. For example, in the wastewater treatment plant "Dębogórze" north of Gdynia, where the average cost of treating 1 m^3 of water is EUR 1.17 and the nitrogen removal efficiency reaches 90%, the cost of removing 1 kg of nitrogen was estimated at EUR 11.84. This contradicts the findings of Petersen et al. (2016) that mitigation mussel production could be a cost-effective measure for nutrient removal relative to much more expensive onshore measures. According to Schultz-Zehden et al. (2019), another alternative for funding mussel farming includes companies and persons that benefit directly or indirectly from the improved environmental quality, such as private foundations, individuals through crowdfunding, companies from profitable economic sectors or public authorities. The income from mussel farming can also be generated from selling carbon credits to industry, i.e. emission certificates for CO_2 that is imbedded in shells of harvested mussels, thus contributing to the reduction of greenhouse gas concentrations in the atmosphere. For example, using verified Certified Emission Reductions (CERs), Schernewski et al. (2012) estimated a price of carbon dioxide capture in mussel shells at EUR 12 t^{-1}, which can bring additional economic incentive.

8. Conclusions

Recognizing high potential of the Gulf of Gdańsk for bivalve aquaculture due to the presence of a natural mussel population on the one hand and the necessity to improve the state of the marine environment on the other hand, the pilot farming of *Mytilus trossulus* was conducted to evaluate the efficiency, technical solutions, potential biomass use and economic profitability in the southern Baltic Sea. The growth rate (3.0–6.7 mm $year^{1}$) and the mean wet biomass gain (1.50 kg m^{-1} normalized culture rope) of mussels in the gulf were among the highest in the Baltic Sea. After two years of culture, the total amount of N and P fixed in the soft tissues of bivalves varied from 93 to 98 kg t^{-1} harvest and 11 kg t^{-1} harvest, respectively. This provides a promising additional prospect for local nutrient mitigation, next to or instead of more common methods that can be used, such as construction of large wastewater treatment plants, reduction of industrial emissions, changes in agricultural practices and restoration of wetlands (Lindahl et al. 2005). Although these more common methods may enable easier and more effective reduction of nutrients, with smaller impact on the environment, they are often insufficient and/or economically or logistically difficult to implement. When mussel production for human consumption and animal feed production was considered, the cost-benefit analysis revealed a negative budget balance with a total income covering only 12.0% of the cumulative costs (investment and operational/maintenance costs) for a two-year farming cycle. The development of mussel farms in the southern Baltic Sea can therefore only be justified for the purpose of improving the coastal environment quality (as a complementary measure to onshore measures such as wastewater treatment or reduction of agriculture fertilizers to control eutrophication), but requires support from additional funding programs and mechanisms.

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