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Manila clam and Mediterranean mussel aquaculture is sustainable and a net carbon sink

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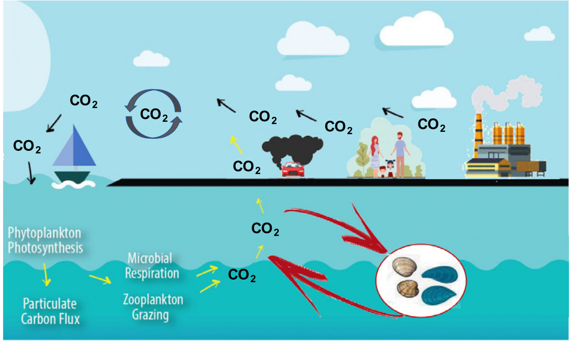
HIGHLIGHTS

- Clams and mussels have lower impact compared with intensive aquaculture production.
- The role of shells in the carbon balance must be considered in an ecosystem-based approach.
- In shells, bivalves sequester carbon dioxide into insoluble and indigestible calcium carbonate which acts as a carbon sink.
- Comparing production and captures in shells, mollusk aquaculture is a net carbon sink.

GRAPHICAL ABSTRACT



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ABSTRACT

Aquaculture is a globally expanding industry that contributes to feeding an increasing global population. Shellfish cultivation is one of the largest sectors of aquaculture and one of the few food productions that have the potential capacity of acting as carbon sink. In fact, >90 % of bivalve shells are calcium carbonate ($CaCO_3$), synthetized during biocalcification process, which incorporates a molecule of CO_2. Manila clam (*Venerupis philippinarum*, Adams & Reeves, 1850) and Mediterranean mussel (*Mytilus galloprovincialis*, Lamarck, 1819) are two of the major groups of cultivated shellfish. Our aim was to assess the potential role of those two bivalve species in the overall marine carbon balance using an ecosystem approach, and to evaluate if they can be definitely regarded as carbon sink. The contribution to CO_2 emissions (as CO_2 eq./kg of fresh products) due to mollusk farming has been also calculated as carbon-source term by means of Life Cycle Assessment (LCA). LCA is nowadays the most shared and accepted tool for evaluating the environmental impacts of aquaculture productions. As a case study, the Sacca di Goro coastal lagoon (Northern Adriatic Sea, Italy) has been considered, because it is the premier site in Europe for clam farming, and one of the most important for mussels. Our study has shown that for each kilogram of harvested and packaged clams and mussels, shell formation throughout the mollusk growth allows to permanently capture 254 and 146 g of CO_2, in the face of 22 and 55 g CO_2 eq. emitted for farming, respectively. As a result, clams and mussel aquaculture could be considered as a carbon sink, with a net carbon capture capacity of 233 and 91 g CO_2/kg of fresh product, respectively. In a wider context, bivalve aquaculture could be included in the carbon trading system and played a role towards the carbon-neutral economy.

1. Introduction

Climate change has been a much-debated issue for some years, but it is now widely accepted that well-established climate patterns are indeed

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changing (Gough, 2015). A multitude of climatic aberrations are occurring in aquatic and terrestrial environments and are linked to the accumulation of greenhouse gases, much arising from human activities (Horn and Bergthaller, 2019). In December 2015, the Conference of the Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC) adopted the "Paris Agreement" that stipulates a target of 1.5–2 °C above pre-industrial levels as maximum increase of the temperature to avoid abrupt and irreversible change in the global climate (Schleussner et al., 2016). This target, already internationally agreed as a very important common goal to achieve, corresponds to the Intergovernmental Panel for Climate Change (IPCC) recommendation (Forster et al., 2020) not only to mitigate the level of future change by reducing the anthropogenic greenhouse gases (GHGs) emissions, but also to develop plans to adapt our societies and economies to cope with the climate changes that will occur (Getahun et al., 2020).

The global food system is also a major source of GHGs emissions, emitting about 30 % of the global total (Clark et al., 2020). Taking into account its actual and foreseen emissions, in a perspective of continuously increasing population and food requirements, it is quite complicated to gain the IPCC targets by only reducing GHGs (Ganivet, 2020). In this regard, carbon capture and storage (CCS) is recently highlighted in several sectors as a promising "negative emission" approach, which allows us both to earn more carbon-neutral energy and reduce atmospheric CO_2 concentrations at the same time (Beuttler et al., 2019). Only a few of food sectors have the potential of serving as a carbon storage activity for diminishing anthropogenic emissions of CO_2 and shellfish aquaculture is potentially one of them (Alonso et al., 2021). Bivalves are mollusks whose soft bodies are enclosed by a shell consisting of two hinged valves (Onderz Form et al., 2020). The shell is an exoskeleton that acts as support for soft bodies of mollusks, while offering protection against predators and adverse environmental conditions.

Mollusk shells are principally composed of the mineral $CaCO_3$, synthesized during a biogenic calcification process, consisting in a reactions cascade mediated by the enzyme carbonic anhydrase, which involves aqueous CO_2 and its equilibrium ions in water (HCO_3^- and CO_3^{--}) in the presence of Ca^{++} ions (Lee et al., 2010a) (Table 1).

Considering that shell represents from 70 to 95 % of bivalve dry weight depending on the species and a high percentage between 90 and 99 % of their weight is $CaCO_3$, worldwide bivalve farming might provide a significant contribution in CO_2 sequestration (van der Schatte Olivier et al., 2020). Notwithstanding, the role of marine bivalves in CO_2 capture is still controversial, due to the lack of agreement on which processes contribute to the global carbon balance or how to include them, on the methods to calculate the various contributions, and on the most appropriate level at which the carbon balance should be considered, from the individual to the ecosystem scale (Dame and Kenneth, 2011). Some early literature supports the standpoint that bivalves are net generators of CO_2, because of the negative balance between the CO_2 trapped in the shell as $CaCO_3$ and the CO_2 released during biocalcification by a single mollusk (Beniash et al., 2010; Chauvaud et al., 2003a; Morris and Humphreys, 2019; Munari et al., 2013; Ray et al., 2018). On the contrary, more recently, the vast majority of scientific articles are markedly oriented towards considering shell formation not as an individual process but integrated within the entire marine ecosystem (Ahmed et al., 2015; Alonso et al., 2021; Bertolini et al., 2021; Dame and Kenneth, 2011; Filgueira et al., 2015a, 2015b; Jansen and van den Bogaart, 2020; Martini et al., 2022; Mitra et al., 2015; Tang et al., 2011; van der Schatte Olivier et al., 2020; Zhang et al., 2020).

Merely from an individual perspective, it makes sense that a bivalve is a net source of CO_2 (Filgueira et al., 2019). Han et al. (2017) have reported that the oyster *Crassostrea angulata* is a CO_2 generator in oyster-only culture mesocosms, while CO_2 concentration strongly decreases in all oyster-seaweed (*Gracilaria lemaneiformis*) co-culture systems, leading to a net uptake of carbon from seawater, according to an integrated ecosystem approach. Similarly, Jiang et al. (2014) have demonstrated that multi-trophic systems reduce the dissolved inorganic carbon, realizing an inter-species mutual benefit where seaweed actively take up and utilize the CO_2 released by bivalves, resulting in a net increase of sea CO_2-sink capacity. Moreover, the various ecosystem regulating services associated with bivalve culture can contribute to the distribution and performance of blue carbon habitats, such as seagrasses and macroalgal growth generating another potential source of indirect increasing of marine carbon sequestration (Jones et al., 2022).

More recently, the carbon sequestration capacity of bivalves has been included among the strategies for a sustainable and competitive aquaculture towards climate change mitigation (eur-lex.europa.eu).

Of about 8000 species of marine bivalves, only 79 are listed by FAO (United Nation Food and Agriculture Organization) as cultured, principally belonging to three major groups, oysters, clams, and mussels. From the last available data summarized in the FAO database (FAO, 2020), the global aquaculture production of marine bivalves represents >16.1 million metric tons per year: oysters and clams contribute almost 70 % to the total production, followed by mussels, which account for about 13 %. Italy is the first producer of clams and one of the main of mussels, in Europe, corresponding to 40 and 14 % of the total production, respectively (EUMOFA, 2021).

The aim of this research has been to assess the role of the main two species of bivalves, cultivated in Italy (clam and mussel) in the CO_2 balance, with particular attention on the specific function of the shells and their involvement as net carbon sink. The contribution to CO_2 emissions of mollusks farming has been also included, as a result of life cycle assessment (LCA) and considered as a net source term. As a case study, the Sacca di Goro coastal lagoon (Northern Adriatic Sea, Italy) has been considered, because it is the first site in Europe for Manila clams (*Venerupis philippinarum*, Adams & Reeves, 1850) production, the fourth after Spain, The Netherlands and France, for Mediterranean mussels (*Mytilus galloprovincialis*, Lamarck, 1819). Thus, the Sacca di Goro aquaculture industry, both for the quantitative importance and for the qualitative differentiation of the productions is an interesting testing ground to assess the role of marine bivalves in the overall carbon balance and model of study to understand the potential contribution of shellfish farming in the overall climate change mitigation.

1.1. Life cycle assessment (LCA) methodology applied to shellfish aquaculture

LCA has been extensively employed to evaluate the environmental impact of products, activities and processes considering the entire life cycle in terms of sustainability from cradle to grave. After several years of improvements, LCA is now become an international standard (ISO 14040 and ISO 14044) with consolidated procedures and methods. LCA can be, and indeed it has already been, applied to successfully detect environmental criticalities and explore opportunities for pollution prevention, environmental performances optimization, strategic planning and even policymaking. A collection of methods, approaches, applications, specific software packages, and insights regarding experiences and progress made in applying the LCA methodology coupled to optimization frameworks is by now provided by an extensive literature. Namely, in recent years, it becomes a common tool to assess the environmental impacts also for aquaculture systems. LCA methodology has been extensively applied to several seafood intensive production, as salmon, tilapia, trout (d'Orbcastel et al., 2009), sea bream and sea bass (Abdou et al., 2017), as well as to shellfish aquaculture, as oysters (Alvarenga et al., 2012; Tamburini et al., 2019), mussels (Iribarren et al., 2010; Lourguioui et al.,

Table 1
Main reactions involving Ca^{++} ions and CO_2 in seawater.

$2\ HCO_3^- + Ca^{++} \leftrightarrow CaCO_3 + CO_2 + H_2O$
$CO_2\ (g) \leftrightarrow CO_2\ (aq)$
$CO_2\ (aq) + H_2O \leftrightarrow H_2CO_3$
$H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow H^+ + CO_3^{--}$
$Ca^{++} + CO_3^{--} \leftrightarrow CaCO_3\downarrow$

2017; Tamburini et al., 2020), and clams (Turolla et al., 2020). Most of the studies have been carried out on mussels, *Mytilus galloprovincialis* and *Mytilus edulis*, whereas only few are focused on clams. Moreover, the studies are concentrated in Europe, mainly in Spain and Italy (Vélez-Henao et al., 2021).

The fact that shellfish are filter-feeders plays a key-role in their relatively low environmental impact calculated by LCA, since feed production is responsible for about 56 % of the total CO_2 emissions of other seafood production. Moreover, they do not require the use of antibiotics and consequently do not contribute to occurrence of antimicrobial resistance, that has been acknowledged as one of the biggest threats to global health and food security in future.

2. Materials and methods

2.1. Background

The study here presented has been carried out following the international standard method for LCA, considering all inbound and outbound flows related to the entire life cycle, from the raw material extraction to the end of life, of the two bivalve species, i.e., mussels (*Mytilus galloprovincialis*) and Manila clams (*Venerupis philippinarum*). In this study, the ILCD framework, consisting of four steps (goal and scope definition, life cycle inventory, impact assessment and results interpretation) has been pursued (Chomkhamsri et al., 2011).

2.2. Study area

The Sacca di Goro lagoon, a microtidal ecosystem approximately of triangular shape, has a surface area of 30 km^2 with an average depth of about 1.5 m. It is in the Po River delta region, in the northeastern coast of Italy. The Sacca di Goro is connected to the sea by a 1.5 km wide channel and several smaller channels recently opened along the sand banks, tidal amplitude is normally 50 cm. The lagoon is separated from the Adriatic Sea by a narrow sandy barrier with one mouth of about 3.6 km regulating saltwater exchanges, and it has four freshwater inlets. Despite its small dimensions, the Sacca di Goro lagoon supports the local economy and provides the main revenue of the resident population, which is about €60–70 million per year. Shellfish farming is socially relevant: it ensures about 1700 direct job positions in 60 cooperatives, corresponding to about 60 % of active population (aged 16–65), plus employment in seafood industries, commercial and side activities, e.g., shipbuilding and tourism. At present, local aquaculture is divided among clams, mussels and to a smaller extent oyster, collectively accomplishing about a half of the whole Italian farmed bivalve production. Notably, more than one third of the lagoon surface is cultivated with clams in delimited licensed areas called "*concessioni*", with an average production of 15,000 tons/year. Mussel farming is carried out 3-mile offshore in long-line plants, with a production of about 8000 tons/year, respectively. Detailed descriptions of production systems have been already reported elsewhere (Tamburini et al., 2019, 2020; Turolla et al., 2020) (Fig. 1).

2.3. LCA: goal and scope definition, functional unit, and system boundaries

LCA study was undertaken to calculate the environmental impacts of clam and mussel production in the Sacca di Goro area, with the purpose of complementing the amount of carbon dioxide emissions deriving from farming with the carbon dioxide captured during shellfish growth. The main goal of the analysis is to understand the effective contribution played by mollusks in the overall carbon balance and if bivalve cultivation could have a net marine CO_2-sequestration potential.

One kg of fresh bivalves harvested has been chosen as functional unit (FU), that is the mass reference over which all environmental impacts are calculated.

A cradle-to-gate analysis has been carried out, from wild seed procuring to harvesting, transporting to land, and packaging (Fig. 2). According to Italian regulations on food safety, clams farming includes the treatment in depuration plant. The system boundaries include inputs of energy, electricity, fuel and water, equipment, technical clothing (i.e., gloves, boots, diving vests), plastics and raw materials (i.e., stainless steel, glass fiber, wood) necessary for all the on-growing phases, as well as all outputs, as pollutant emissions to the air and sea, and waste. When possible, positive contribution of plastic recycling has been counted.

2.4. Life cycle inventory (LCI)

The overall LCI has been reported in Table 2. Primary data on all production phases were collected in the years 2019–2021 based on the personal expertise of the Authors and dedicated questionnaires submitted to about 200 local farmers.

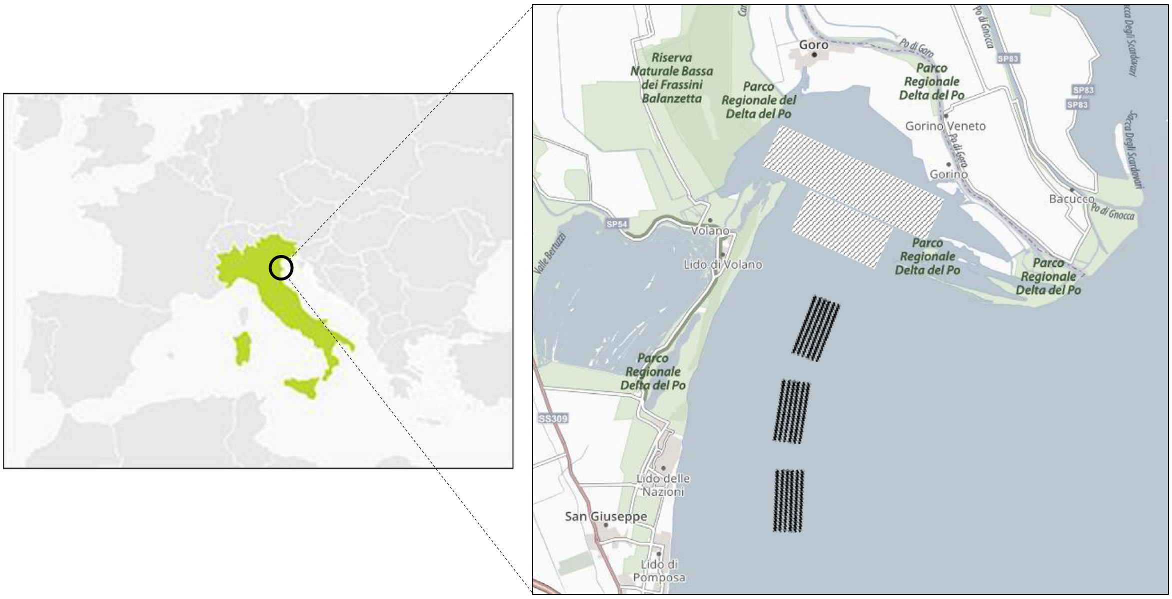

Fig. 1. The Sacca di Goro area, Adriatic Sea coastline, northeast of Italy (44.78–44.83° N and 12.25–12.33° E). The shadowed areas represent the portion of lagoon licensed for clams farming, whereas the paired bold lines stand for the offshore long line plants for mussel cultivation.

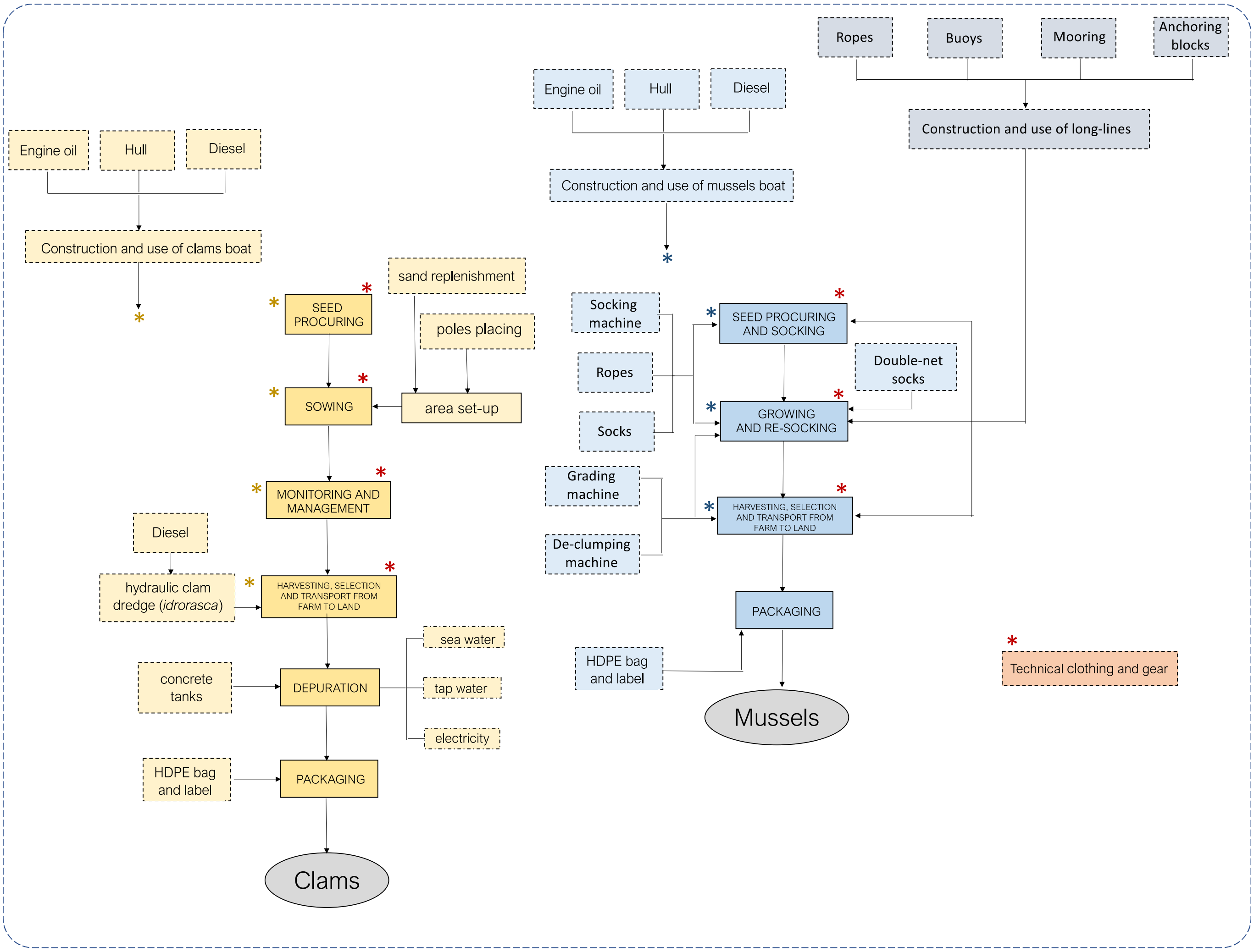

Fig. 2. System boundaries used in this study of clam and mussel production in Goro. The boxes represent processes (solid box = foreground process; dashed box = background process) and the grey circles represent products. Raw materials, electricity, tap water production and waste management have been considered as secondary processes from Ecoinvent™ data base and not reported. Asterisks correspond to all the process phases occurring with the use of the boat.

The impact of seed provisioning has not been accounted because it growths naturally on site, for both species.

For clams farming, area set-up has been included in the inventory. Sand replenishment and wood poles placing and/or replacement must be carried out every 5 years, because of sea storms or weather events. The total number of boat trips per growing season is 10 for sowing and 200 for management and harvesting, considering about 4 nautical miles per trip.

For clams and mussels farming, a depuration stage has been introduced in the supply chains. The purification station, consisting in 24-48 h resting in concrete tanks filled with filtered seawater, is shared at 80 % for clams and 20 % for mussels. The same percentage has been used in the LCI.

For mussels, the 3-miles off-shore long line plant construction and maintenance has been included in the analysis. About 205 boat trips per growing season have been included with mussels farming.

Technical clothes, as diving vests in polyvinylchloride (PVC), rubber gloves and boots, have been considered with a lifespan of 3 months to 5 years. Ropes are made of nylon, whereas HDPE (High Density Polyethylene) is the main plastic materials used in aquaculture, being the main component of net bags and buoys. Unfortunately, HDPE cannot be recycled and goes to incineration because of the accumulation of surface organic fouling.

2.5. Life cycle impact assessment (LCIA)

The mid-point CML baseline 2015, v 4.4 (Prè Consultants, Amersfoort, The Netherlands) method was used for impacts assessment calculations. All the LCA models have been operated by the open-source Open-LCA™ v1.10 software (GreenDelta, Berlin, Germany). Electricity, water, fuel, and materials productions, as well as infrastructure building and transportation have been taken from the database Ecoinvent™ v.3.7 as secondary data referred to European or global background.

All background data, as fuels, lubricant oils, electric energy were taken as dummy processes from Ecoinvent™ ("ecoinvent - Cerca con Google," n.d.). The Ecoinvent™ database actually lacks specific data concerning boats used in mollusk farming, so an average fishing boat of 1 ton of loading capacity from the Agribalise™ v.3.0 database has been considered as the best approximation of the reality.

Emissions to air and water were calculated by the software, and were mainly due to diesel combustion, boats and equipment production and materials manufacture. As mid-point impact categories, the Global Warming Potential at a time horizon of 100 years (GWP100, expressed as $kgCO_2eq/FU$), Eutrophication Potential (EP, expressed as $kgPO_4eq/FU$), Human Toxicity Potential (HTP, expressed as kg1,4-Dichlorobenzene eq (DCB)/FU) and Marine Aquatic Ecotoxicity Potential (MAETP, expressed as kg1,4-Dichlorobenzene eq(DCB)/FU), Acidification Potential (AP,

Table 2
Life cycle inventory (LCI) of clams and mussels farming in the Sacca di Goro lagoon. All inputs are referred to 1 kg of fresh whole mollusks harvested.

Inputs and outputs	Clams	Mussels
Natural resources		
Sea use (m^2/year)	0.06	1.54
Seawater (l)	30.76	17.20
Freshwater (l)	4.09	4.00
Materials		
High-density polyethylene (HDPE) (g)	1	3.94
Low-density polyethylene (LDPE) (g)	5	5.00
Polypropylene (PP) (g)	–	–
Polyvinyl chloride (PVC) (g)	0.15	0.83
Polisteel (g)*	–	1.97
Nylon (g)	–	14.97
Cotton (g)	–	0.21
Rubber (g)	<0.1	<0.1
Concrete (kg)	0.43	1.72
Steel (g)	<0.1	80
Wood (g)	188.00	–
Energy and fuels		
Diesel (l)	–	0.025
Gasoline (g)	30	–
Electricity (kW)	0.03	0.03
Emissions to air		
Carbon dioxide, fossil (kg)	0.00309	0.00143
Nitrogen oxide (kg)	2.63×10^{-6}	6.59×10^{-6}
Sulphur oxide (kg)	0.00342	6.59×10^{-6}
Methane, fossil (kg)	0.00040	5.87×10^{-7}
Non-methane volatile organic carbon (NMVOC) (kg)	2.29×10^{-5}	5.58×10^{-5}
Ammonia	3.43×10^{-6}	2.83×10^{-6}
Emissions to water		
Adsorbable organic halogen as Cl (AOX) (kg)	2.84×10^{-10}	2.29×10^{-9}
Biochemical oxygen demand (BOD) (kg)	0.00031	0.00014
Heat, waste (MJ)	0.00055	0.00011
Nitrate (kg)	3.44×10^{-8}	6.89×10^{-5}

expressed as $kgSO_2eq$), Abiotic Resources Depletion Potential (ARDP, expressed as and Photochemical Oxidation Potential (POP, expressed as kg ethylene eq.) have been calculated. Allocation was not necessary because we considered clams and mussels as unique process output.

A Monte Carlo simulation with 1000 runs has been performed, showing a right centered distribution for all the impact categories. Uncertainty of the results of each impact category was reported as a 95 % confidence interval of the distribution.

2.6. Carbon dioxide sequestration potential (CSP)

Wet mollusks whole weight and shells weight has been calculated as average of 50 commercial-sized mollusks collected in Goro, for each species. Shells and soft tissue moisture has been obtained by oven-drying at 105 °C overnight at atmospheric pressure. Shells $CaCO_3$ content have been estimated using literature data and are shown in Table 3 (Alvarenga et al., 2012; Mu et al., 2018). A relative molecular masses ratio between CO_2 and $CaCO_3$ of 0.44 has been considered (44.01 and 100.08, respectively). Finally, CO_2 sequestration capacity has been calculated for 1 kg of bivalves farmed and harvested, net of losses. CO_2 sequestration capacity indicates the part of the carbon dioxide from the environment (as hydrated HCO_3^-) permanently precipitated in shells.

Although an ample range of seasonal variability, the carbon content of soft tissues has been on average estimated using the values reported by Ishii et al. (Ishii et al., 2021), corresponding to 0.357 g C/g dry weight and 0.402 g C/g dry weight for *V. philippinarum* and *M. galloprovincialis*, respectively. These values are in accordance with the range 0.40–0.47 g C/g dry weight mentioned by Jansen et al. (2012a) as average C content in mollusks soft tissues.

Carbon dioxide released through respiration of organic matter has been derived from Filgueira et al. (2019) and were quantified as 6.11 mol CO_2 kg^{-1} $year^{-1}$ for *M. galloprovincialis* and 19.74 mol CO_2 kg^{-1} $year^{-1}$ for *V. philippinarum.* Respiration and consequent CO_2 fluxes should be split towards shell and flesh as a function of their effective energy demand. It is widely accepted that most of the energy is devoted to maintenance, meat growth and reproduction rather than shell growth (Stevens and Gobler, 2018). Therefore, 10 % has been expected as a percentage of the total energy consumption for shell, whereas the remaining 90 % is allocated for soft tissue growth and maintenance (Hily et al., 2013; Lejart et al., 2012). These contributions are large enough to offset the CO_2 amount permanently immobilized in clams and mussels shell, as interpreted in some studies mostly focused on bivalves' physiology (Chauvaud et al., 2003b; Hily et al., 2013). However, more recent interpretations performed at the whole ecosystem scale (Filgueira et al., 2019), including this one, reconsider the role previously attributed to the respiratory contribution in the overall CO_2 balance in shellfish farming, as discussed further on in this manuscript.

3. Results and discussion

3.1. LCA results

The results of LCA are reported in Table 4 and are referred to 1 kg of packaged clam and mussels, respectively. For impact categories a cut-off of 10^{-5} has been applied.

The GWP assesses the impact of greenhouse gas emissions (principally CO_2, CH_4, and nitrous oxides) on the atmosphere's capacity of absorbing infrared radiation which contributes to the global greenhouse gas effect (Lashof and Ahuja, 1990). EP refers to the potential impacts of high levels of nutrients in the environment, in particular N and P (Smith et al., 1999). AP refers to the negative effects on soils, ground and surface water, and ecosystems of acidifying pollutants (Valente et al., 2019). The HTP and MAETP consider the impact on human health and aquatic ecosystems of the release of toxic substances derived from i.e. pesticides and persistent organic pollutants (Huijbregts et al., 2000).

For both clams and mussels, the main contributor to GWP100 is diesel and gasoline combustion in marine engine (36 %, 60 % of the total CO_2 eq emissions, respectively). In clams farming, another 25 % of emissions is due to LDPE-bags productions and about 20 % to the area set-up. For mussels, socks, ropes, and LDPE-bags contribute for about 25 % each to the total GWP100, followed by long-line plant construction and use, which accounts for about 14 % to CO_2 emissions. In all three cases, EP has low values, because no nutrients need to be added during mollusks growth.

The lower impact of clams farming originates from the fact that no plant or installation is needed, several operations are made by hand and the distance travelled by boat is minimal because the farming is completely carried out within the lagoon. In the case of mussels, the presence of off-shore long-line plants and the higher distances to be covered from inland play a significant role.

For the sake of comparison, intensive fed aquaculture of sea bass and sea bream (Kallitsis et al., 2020) have shown an EP of 0.189 and 0.142 $kgPO_4$ eq/kg, respectively. Pelletier et al. (2007) have reported a value of 0.049

Table 3
Shell and soft tissue characterization used in this study.

Species	Wet whole mollusk weight (g)	Wet shell weight (g)	Shell moisture content (%)	Soft tissue moisture content (%)	$CaCO_3$ in shell (%)
V. philippinarum	17.30	9.73 ± 0.20	1.32 ± 0.08	80.3 %	96.0
M. galloprovincialis	29.18	10.31 ± 0.76	2.14 ± 0.18	84.4 %	97.5

Table 4

Average environmental impacts from LCA for 1 kg of harvested and packaged bivalves in Goro. CV% have been calculated from Monte Carlo simulation uncertainties.

Impact category	Clams (*V. philippinarum*)		Mussels (*M. galloprovincialis*)		Unit
	Value	CV%	Value	CV%	
GWP100	0.022	10 %	0.055	21 %	$kgCO_2eq$
EP	0.0043	34 %	0.0002	27 %	$kgPO_4eq$
HTP	0.013	84 %	0.018	75 %	kg1,4-DCB eq
MAETP	1.46	57 %	34.58	61 %	kg1,4-DCB eq
AP	0.0003	35 %	0.0018	25 %	$kgSO_2eq$

$kgPO_4$ eq/kg for farmed salmon as an average of data collected in Norway, UK, Canada, and Chile (Pelletier et al., 2009). The total absence of drugs, antibiotics, pesticides, or disinfectants in mollusk farming leads to lower HTP and AETP values than those found in intensive aquaculture, that are at least several order of magnitude higher. For example, as reported by Kallitsis (Kallitsis et al., 2020) et al., HTP for sea bass and sea bream aquaculture are 2.59 and 2.82 kg 1,4-DCB eq/kg, and MAETP of $>10^6$ kg 1,4-DCB eq/kg. Note that MAETP has large absolute values for all options, because MAETP has a higher normalization reference value compared to the HTP category (Xu et al., 2013). Normalization is the procedure within the LCA methodology where the quantified impact of a certain process is compared to a reference value, for example, the average environmental impact of a European citizen in one year (Hélias et al., 2020). In the case of MAETP the reference value is higher probably because of the "proximity" between the emitting source and the marine organisms whereas the effects on human health can be considered like an endpoint target, which in some ways reduces the dose-response causality.

Even regarding GWP100, bivalve aquaculture has the lowest impact of all other intensive farmed fishes and crustaceans. Average GWP100 values reported in the literature for aquaculture production ranged from 0.76 to 2.45 $kgCO_2eq$/kg, depending on farming system for rainbow trout (Samuel-Fitwi et al., 2013); 1.87 $kgCO_2eq$/kg for sea bream and 2.00 $kgCO_2eq$/kg for sea bass, respectively (Kallitsis et al., 2020); 2.45 $kgCO_2eq$/kg for salmon at farmgate (Ellingsen and Aanondsen, 2006); 5.25 for Asian farmed shrimps (Cao et al., 2011); 0.96–6.12 $kgCO_2eq$/kg for farmed tilapia in intensive and semi-intensive systems, respectively (Yacout et al., 2016).

3.2. CO_2 sequestration potential

The CO_2 sequestration potential during bivalves growth due to biocalcification process and soft tissues formation is reported in Table 5, calculated for 1 kg of mollusks. Calculations were based on data reported in Section 2.3.

CO_2 captured in soft tissues by clams and mussels, respectively, has not been included in the overall carbon sequestration capacity because it represents an apparent sequestration. In fact, once harvested and used as food, it becomes part of the short-term carbon cycle due to human digestion process, returning back to the atmosphere as CO_2 released by catabolism.

Mussels showed a lower CO_2 capture capacity in form of $CaCO_3$ because of their lower shell:flesh ratio (about 35 % vs. about 60 % of clams). Clams show a significant capacity to sequester CO_2 as biocalcificated $CaCO_3$, corresponding to about one fourth of their whole fresh weight.

Table 5

CO_2 captured from surrounding marine environment by 1 kg of harvested bivalves in Goro.

Species	CO_2 captured in shell (kg)	C captured in soft tissue as CO_2 (kg)
Clams (*V. philippinarum*)	0.254	0.115
Mussels (*M. galloprovincialis*)	0.146	0.152

When bivalves are harvested, a relevant consideration is that the shells, being part of the mollusks, are physically extracted from the water and ended up on land for consumption, so the amount of CO_2 entrapped in them is effectively and permanently removed from the sea, and represent a long-term carbon sink (Lee et al., 2010b).

In the case of cultivated shellfish an explicit differentiation between the flesh, that is the food product of aquaculture, and the shell, usually considered a waste without a market value should be done. In that situation shell formation becomes a side-process which permits to valorize a waste as a permanent carbon sequestration system. Moreover, the end of life of shells, as undifferentiated waste usually sent to thermo-valorization or controlled landfill (Bernstad Saraiva Schott and Andersson, 2015), as end-point destination (Vélez-Henao et al., 2021).

Otherwise, the critical point is what is the fate of the different CO_2 contributions during mollusks growth and their relative effects on the overall balance. The offset between the net amount of CO_2 sequestered as carbonate and the one released in respiration is the key issue to understand the role of bivalves as net carbon source or sink.

Besides respiration and biocalcification, the other processes that should be considered within the carbon cycle, involved in bivalve metabolism are the food ingestion, feces production and the egestion of undigested food (pseudofaeces). Focusing on a single specimen, all these contributions affect the overall carbon/carbon dioxide balance and should be accounted as additive or subtractive terms. As reviewed by Jansen and van den Bogaart (2020), several authors have concluded that, at individual scale, bivalves are net generators of CO_2 because the amount of carbon sequestered during biocalcification is not enough for counterbalancing the amount released. However, such an approach is merely partial and improper at the ecosystem scale since it neglects considering bivalve metabolism together with phytoplankton dynamics and benthic – pelagic coupling within the whole marine ecosystem budget of carbon. As reported by Filgueira et al. (2015a), the contribution of bivalves on carbon biogeochemical cycles cannot be limited to the singular scale, merely calculating the chemical balance between shell formation and CO_2 release during biogenic calcification and organisms respiration. Therefore, an ecosystem approach that accounts for the trophic interactions, including dissolved and particulate organic and inorganic carbon forms and relative transformation processes, is needed to provide a correct assessment of the role of bivalves in the CO_2 cycle.

Detailed estimates have been made to account single metabolic processes and relative contributions to carbon budget. For example, it has been estimated that during the growth process a mussel produces about 12.9–13.7 g of feces as dry weight, which contains an average of 6.4–7.0 g of CO_2 (Jansen et al., 2012b). Feces contain a labile fraction of organic matter that are rapidly metabolized in oxygenated water on a timescale of about 2 days (Carlsson et al., 2010). In bivalves, respiration and consequent CO_2 fluxes was split into the relative demand for shell and flesh anabolism (Stevens and Gobler, 2018): 10 % has been expected as a percentage of the total energy consumption for shell, whereas the remaining 90 % is allocated for soft tissue growth and maintenance (Hily et al., 2013; Lejart et al., 2012). According to this proportion, in the present study, the contributions to CO_2 balance of respiration due to shell formation correspond to 86.5 g and 26.9 g CO_2 kg^{-1} $year^{-1}$ for clams and mussels, respectively. As discussed here after, these terms do not affect the function of carbon sink driven by biocalcification process, but their quantitative importance is undeniable and underlines the high contribution of bivalves' farming to the overall ecosystem carbon metabolism, allowing comparisons with other blue carbon coastal ecosystems, in a carbon trading system and carbon-neutral economy perspective (Mcleod et al., 2011).

Given their nature as primary consumers, bivalves release CO_2, but when scaling individual fluxes to the multi-trophic surrounding environment, shells can be considered net sinks of CO_2, for the following reasons, and consequently provide additional ecosystem services besides the food provided by as flesh (Filgueira et al., 2019). All terms of bivalve metabolism are part of a short-term recycling of carbon which also includes the mineralization of uningested phytoplankton and labile detritus. Accordingly, at the ecosystem level, it's better to refer all this terms to short-term carbon transformations or "CO_2 recycling" rather than considering them as terms of new production (Waldbusser et al., 2013). In detail, the CO_2 release due to the metabolic contribution in bivalve shell biodeposition doesn't alter the overall carbon budget, since ingested food, i.e. phytoplankton and labile detritus, oxidized to CO_2 by mollusks, would be anyway mineralized by microbes in the open marine environment. Mineralization time ranges from site to site, according to local conditions and mostly temperature, from a few days to a few weeks (Enríquez et al., 1993; Rodger Harvey et al., 1995). Thus, bivalve respiration can't be accounted as net CO_2 production in the carbon budget. As a matter of fact, phytoplankton and detritus digested by clams and mussels are made of labile carbon which, if not ingested by bivalves would anyway follow another oxidative pathway, no matter if driven by microbial, protozoan or metazoan activities. The fate of phytoplanktonic carbon is established incontrovertibly by its biodegradable nature and involved organisms play a minor role in establishing its mineralization rate (Rodger Harvey et al., 1995; Dafner et al., 2002).

Additional contributions deriving from bivalves' filtration activity may be quantitatively important (Zhang et al., 2020), highlighted that a large amount of particulate and dissolved organic carbon can be released in seawater by mixed mariculture systems. Both in water column and sediments, this organic carbon supply may enter the microbial food loop and food chain or be accumulated as recalcitrant, dissolved and particulate, carbon. The relative importance of these pathways is still under debate and likely very much site dependent.

In the Sacca di Goro lagoon, feces and pseudo-feces release and sedimentation is quantitatively relevant and a large portion of this particulate organic carbon is subjected to mineralization in the seafloor and sediments. Both in clams and mussels farming area the release of this particulate carbon corresponds to a steep increase of benthic metabolism, proof of the dominant biodegradable nature of these materials (Bartoli et al., 2016; Nizzoli et al., 2006; Nizzoli et al., 2005; Politi et al., 2019). Clam farming sites are in areas at high hydrodynamics, where hypoxic and anoxic conditions are very unlikely to occur at the sediment-water interface, even temporarily. In these conditions, of good, constant oxygen availability, organic carbon oxidation mostly proceeds via aerobic respiration, at rates comparable with those measured in sites without bivalves farming. Thus, in the case of feces and pseudo-feces release, clams and mussels metabolic activity spatially concentrate particulate materials but without changing their fate.

Biocalcification stoichiometry implies the release of one molecule of CO2 for each atom of carbon calcified in the shell (Mistri et al., 2012; Munari et al., 2013). Although pertinent in the analysis of bivalves' physiology, the application of the same ratio to the scale of whole ecosystem may result misleading. In an ecosystem perspective, of the two molecules of bicarbonate involved in the calcification reaction, one is permanently stocked in the shell, and one is returned as CO2 to the carbon dioxide-bicarbonate-carbonate equilibrium of seawater, where it had been taken up by the phytoplankton, digested by the bivalve. When processes are considered at the ecosystem scale, it appears clearly that bivalves' filtering activity and metabolism do not alter overall carbon budget, except for the term permanently stocked as carbonate in shell.

A comparison between the terms of emissions due to the production operations (data from LCA), which act as net source, and the terms of sequestration due to shell formation during mollusk growth, which, on the contrary act as net sink, is reported (Table 6).

Table 6

CO_2 net balance for 1 kg of harvested and packaged bivalves in Goro.

Species	CO_2 emitted (Net source) (g)	CO_2 captured (Net sink) (g)	CO_2 balance (g)
Clams (*V. philippinarum*)	22.0 ± 2.5	254.0	−233.0
Mussels (*M. galloprovincialis*)	55.0 ± 11.5	146.0	−91.0

Clam aquaculture permits a net sequestration in shell of 233 g of CO_2 per kg of harvested and packaged product. Mussel aquaculture contributes for about 91 g of CO_2 per kg of harvested and packaged product. In economic terms, the impact of this result could be significant for farmers, depending on the local policies on carbon emission trading application and on which value will be assigned to a ton of CO_2. Assuming a production of about 15,000 tons of clams and 8000 tons of mussels per year from the local industry, it corresponds to a value of about 3500 tons and 730 tons of CO_2 effectively sequestered in bivalve shells and subtracted from the environment. In the next Common Agricultural Policy (CAP) the EU Commission already included carbon farming in its recommendations towards a carbon-neutral economy for the Member States' Common Agricultural Policy (CAP) Strategic Plan. At an actual value of 80.84€/ton of CO_2 quote, it corresponds to >365,000 € for the entire industry per year.

4. Conclusions

Globally increasing bivalve aquaculture production has triggered the interest of current challenges around environmental sustainability and carbon credits market. In this study, LCA has been performed on clam and mussel farming in the Sacca di Goro, Italy, as one of the most important aquaculture industries in Europe. Clam and mussel production guarantees the lowest environmental impact, especially in terms of GWP100 category, of all the other intensive farmed fishes or crustaceans (22 g and 55 g CO_2 eq./kg of fresh product, respectively). Moreover, bivalve aquaculture can provide a significant effect on the overall carbon cycle in coastal marine ecosystems. Moving upward from the individual scale and using an ecosystem approach, both clams and mussels have shown a considerable carbon capture capacity, allowed to sequester 233 g and 91 g of CO_2 /kg of fresh product, respectively. This suggests that clam and mussel shells can be considered as a net carbon sink and that bivalve aquaculture could potentially play a significant role in the carbon trading system.

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CRediT authorship contribution statement

Elena Tamburini: data curation, formal analysis, methodology, writing original draft, review and editing.

Edoardo Turolla: data curation, methodology, validation, writing - review and editing.

Mattia Lanzoni: methodology and data curation.

David Moore: review and editing.

Giuseppe Castaldelli: conceptualization, writing – original draft.

Declaration of competing interest

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

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