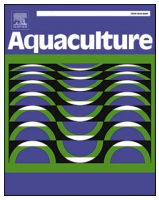
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Environmental sustainability assessment of offshore mussel farming: An LCA approach

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ABSTRACT

Shellfish aquaculture is typically located in sheltered nearshore environments, with offshore expansion offering potential to significantly increase production in less contested marine space. Life Cycle Assessment (LCA) analysis was conducted for blue mussel (*Mytilus edulis)* farming in Lyme Bay, UK, evaluating the environmental sustainability of this emerging aquaculture system. The main hotspots of the farming process, across all impact categories, are fuel use to access the farming area and use of plastic materials, and their subsequent disposal, in construction of the long-line system. Global Warming Potential (GWP) of the farming process (0.29 kg CO_2 eq. kg $^{-1}$ whole mussels) falls within the reported range for traditional mussel aquaculture, comparing very favourably to terrestrial meat production and fed aquaculture. GWP lowered (0.22 kg CO_2 eq. kg $^{-1}$ whole mussels) accounting for a proportion (40%) of carbon in mussel shells as sequestered. GWP of shucked meat was 0.45 and 0.89 kg CO_2 eq. kg^{-1} for 50% and 25% meat yields, respectively. Eutrophication Potential was low (0.23×10^{-3} Kg N eq. and 0.01×10^{-3} kg P eq. kg $^{-1}$ whole mussels), with net negative values (-9.71×10^{-3} Kg N eq. kg $^{-1}$ and -0.29×10^{-3} Kg P eq. kg^{-1} whole mussels) accounting for retention of nutrients in flesh and shell. Overall, the results demonstrate that offshore mussel farming is a highly sustainable food production system. As this form of aquaculture becomes more widespread, comparative LCA analysis could usefully be extended over a wider range of environmental and operational conditions.

1. Introduction

The interconnected challenges posed by population growth, climate change, food security, and human health underscore the urgent need to transform global food production systems (Poore and Nemecek, 2018; Costello et al., 2019; Krause et al., 2022). Current practices in food production are major drivers of environmental degradation, contributing 26% of global greenhouse gas (GHG) emissions, alongside extensive land and freshwater use, water pollution, and significant biodiversity loss (IPCC, 2019). Transitioning to sustainable food systems, including an increased focus on aquatic resources or "blue foods," is a critical objective of global initiatives such as the UN Decade of Ocean Science for Sustainable Development (2021−2030) and the UN Food Systems Summit (2021) (Gephart et al., 2021). Aquaculture has become the majority contributor to aquatic food systems, accounting for more than 50% of global aquatic food production. This sector's growth is predominantly driven by China, with freshwater species representing a large proportion of output (FAO Statistics, 2021). Marine-based systems, particularly those involving low trophic-level species such as filter-feeding bivalves, are notable for their potential to mitigate carbon emissions in food production, as they rely on naturally available resources and do not require external feed inputs (Van der Schatte Olivier et al., 2020). Among these, farmed mussels have the lowest GHG emissions of any animal-based food (Gephart et al., 2021; Yaghubi et al., 2021; Hilborn et al., 2018). However, global bivalve production remains modest at 17 million tons annually, compared to 340 million tons of terrestrial meat production (OECD/FAO, 2018; FAO Statistics, 2021).

Mussels can be farmed in both inshore and "offshore" locations, with this distinction defined by environmental and operational conditions as well as the characteristics of the farming system. Inshore farming takes

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place in sheltered waters close to the coast, often in rias and lochs, where tidal currents and nutrient-rich waters combine to provide ideal conditions and natural protection for mussel growth (Fairbanks, 2016). In contrast, "offshore" mussel farming uses suspended rope systems in exposed open water conditions, either distant from the coast or in exposed coastal settings. (Forster, 2013; Ögmundarson et al., 2011). Offshore mussel farming is a relatively new technology compared to the more established tradition of inshore farming, with opportunities to reduce conflict with coastal activities and potential access to improved water quality (Smaal, 2002; Langan, 2009; Ferreira et al., 2009; Cheney et al., 2010; Hassard et al., 2017; Lester et al., 2018; Avdelas et al., 2021; Webber et al., 2021; Pinn and Le Vay, 2023). These opportunities have spurred interest in offshore and exposed open water cultivation, which, despite its challenges, holds considerable potential for expansion (Buck and Langan, 2017; Krause et al., 2022). Evaluations of global ocean space availability for aquaculture, such as those by Gentry et al. (2017), highlight potential for offshore expansion but require realistic assessments of the implications of moving mussel farming offshore while retaining sustainability credentials.

What makes bivalve mollusc farming economically and environmentally advantageous is the limited use of external inputs, with filter-feeding animals extracting nutrients naturally present in the water column (Suplicy, 2020). In addition to their minimal environmental impact, mussels are nutrient-dense, economically viable, and contribute valuable ecosystem services (Van der Schatte Olivier et al., 2021; Van der Schatte Olivier et al., 2020; Mascorda-Cabre et al., 2024a). For example, there is increasing evidence of the ability of offshore mussel farming to enhance marine biodiversity by providing habitat for other aquatic species (Shumway et al., 2003; Bridger et al., 2022; Mascorda-Cabre et al., 2024b).

Adequate financial investment is essential to support sufficient scale of development to achieve substantive food system change. A key role can be played by green finance, which is the sum of financial operations and investments aimed at investing in and promoting projects that are characterised by low carbon outputs with low environmental impact (Xiong and Dai, 2023; Berrou et al., 2019). Investment in sustainable food initiatives, such as offshore mussel farming, aligns well with the sectoral priorities and investment screening criteria identified in green taxonomies (eg www.greenfinanceinstitute.com/programmes/lnas-advisory-group/). An effective strategy for aquaculture producers to attract green investment is to evidence compliance with the investment criteria, promoting 'best practice' and reducing system vulnerabilities based on objective and comprehensive analysis provided by Life Cycle Assessment (LCA). This tool assesses the overall environmental impact of a product or process, from production to end-of-life, and provides key data to explore, improve or compare the environmental impact of the target item over time (Guinée et al., 2011).

Previous LCA analyses of nearshore coastal mussel aquaculture has demonstrated a relatively positive environmental footprint (Iribarren et al., 2010; Fry, 2012; Tamburini et al., 2020), including low greenhouse gas emissions. However, the moving of production to more distant offshore, sites introduces the potential for increased inputs and emissions arising from for example, vessel operations for management and harvesting. This study set out to consider a pioneering offshore mussel farming system in Lyme Bay, UK, as a case-study. A Life Cycle Assessment (LCA) was carried out using 1 kg of fresh live mussels, stored in plastic bags at the port gate at the end of the two-year production cycle, as the functional unit. The LCA was conducted across all impact categories. However, given the role of mussel biology in the cycling of carbon, nitrogen and phosphorus, the results for Global Warming Potential (GWP) and Eutrophication Potential (EP) were further combined with estimates of element sequestration to better reflect the biological contribution of mussel farming. Finally, the influence of key environmental factors and operational processes are modelled to give a more generalised perspective on the environmental credentials of offshore mussel farming.

2. Materials and methods

2.1. Study area and farming cycle

The offshore mussel farm site is located in Lyme Bay, on the south-west coast of England, which extends from Lyme Regis in Dorset to Torbay in Devon. The mussel farming site covers a total area of 12 km^2, divided into two main areas approximately 4–10 miles off the coast of South Devon (Fig. 1). With a maximum depth of 50 m, the bay features a diversity of seabed habitats, including sandy areas, muddy substrates, rocky outcrops, and cliffs (Mangi et al., 2011; Bridger et al., 2022). The area supports rich marine biodiversity, which led to Lyme Bay being designated as a Site of Community Interest in 2011 and subsequently as a Special Area of Conservation (SAC) in 2017 under the European Union's Habitats Directive (Sheehan et al., 2019; Huijbregts et al., 2016; Rees et al., 2016). The area is well-suited to mussel production, being well mixed with high tidal flow, peak spring tidal range of up 3.4–4.4 m, with an average salinity of about 35 ppt, influenced by the interaction between ocean currents and freshwater inputs from precipitation, and a seasonal seawater temperature range of 8–18 °C (Mascorda-Cabre et al., 2024a; Van der Schatte Olivier et al., 2021). However, the bay faces some challenges from anthropogenic activities, including significant nutrient inputs, leading to elevated levels of nitrates and phosphates (Brown et al., 2022).

The farming cycle is continuous and lasts about two years, encompassing seed collection, socking, growth to commercial size, harvest and storage in plastic bags before transport to purification facilities. The cultivation area is divided into three sub-areas, each dedicated to a specific phase of the farming cycle of which 58% is allocated to each biennial farming cycle, while the remaining 42% are used for production from the previous or following year. The study is based on data collected during farming campaigns between 2022 and 2023, corresponding to an average annual production of 2200 tons. The seed settlement phase begins in April and ends in May, during which mussel larvae naturally settle on ropes specifically designed for this purpose. Once sufficient seed is collected, it is de-clumped and reseeded at a controlled density, using pure cotton socking onto continuous rope droppers, which are hung on the supporting headlines and left to grow until they reach commercial size. After harvesting, the mussels are packed in plastic bags with a capacity of 1 ton (1000 kg). The use of these containers for storage at the port is standardised according to the functional unit of 1 kg of product.

2.2. LCA framework

For the LCA analysis, as suggested by the ISO 14040 and 14,044 standards, the following stages were followed: (1) goal and scope definition, (2) life cycle inventory (LCI) construction, (3) life cycle impact assessment (LCIA) and (4) results interpretation. Goal and scope definition includes the choice of functional unit and system boundaries, that are useful to analyse the sustainability of the process being studied (Curran, 2000). One kg of fresh live mussel, stored in bulk at the port gate at the end of two-year production cycle, was the functional unit considered. In addition, results were also expressed per kg of edible meat, taking into account the range in meat yield (25–50%) that is characteristic of farmed mussels at the study site. The scope of the analysis was to assess the environmental impact of offshore mussel farming, focusing on emissions in various impact categories (Land use, GWP, IRP, ODP, FDP, MDP, WDP, ETP, HTP, FEP, MEP, PMFP, POFP, TAP; for more details see Table 3). A cradle-to-gate analysis was carried out for the mussel product, covering each step during the farming activity. However the production and end-of-life phases of infrastructures and materials were included. As the system boundaries extend from seed collection to landing at port, post-consumption processes, including the final fate and potential reuse or disposal of mussel shells, are not included in the assessment. Therefore, the long-term persistence of

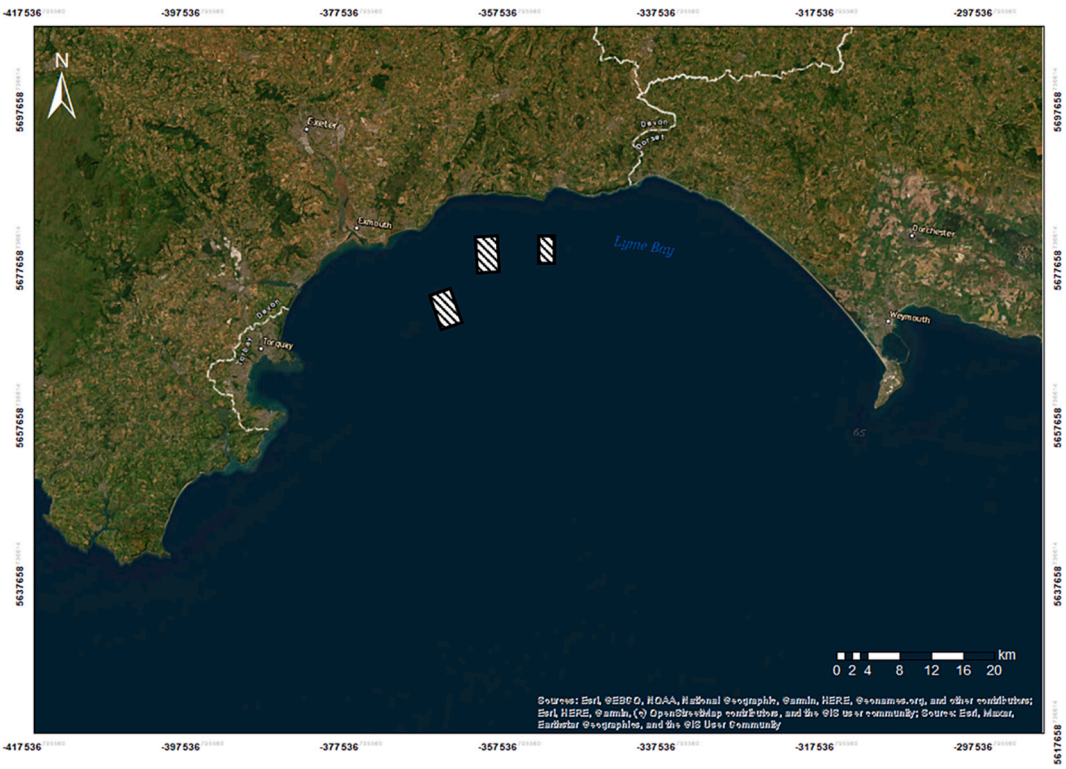


Fig. 1. Mussel farming area in the south of UK (modified from basemap of ArcMap, ArcGIS 10.2.2., ESRI, Redlands, California).

carbon stored in shells depends on downstream pathways that fall outside the scope of this LCA. As a second step, a sensitivity analysis was performed to assess the influence of key environmental and technical parameters on the environmental impacts of the farming process.

2.3. Life cycle inventory (LCI)

2.3.1. Farming plant

The life cycle inventory was developed using primary data collected from a commercial offshore mussel farm in Lyme Bay, covering three farming areas within the site and representing overall farm operations. The farming plant consists of two parts: the permanent longline installation and the temporary farming units. The longline installation consists of a series of subsurface ropes (header lines), which are parallel to the seabed. Each line, spaced 50 m apart, is 150 m long, anchored to the seabed and kept suspended by floats. Suspended from each header line are farming units (1850 m), which are spat collection ropes, for collecting seed, and grow-out ropes/cotton socks, used during the growth phase until the mussels reach commercial size (Fig. 2). In the longline installation there are 2 types of floats/buoys: navigational aids and pencil floats that support the lines. The navigational aids are multi-component "special mark" buoys, with a radar reflector on the top, used to mark the site and indicate the presence of the aquaculture farm to other maritime users. In 12 km^2 there are 12 navigational aids, 6 for each farming area. Their life span is established 50 years, with yearly maintenance and, if necessary, some small components are changed. The maintenance of navigational aids was not considered as it cannot be standardised, and the impact of part replacement was considered

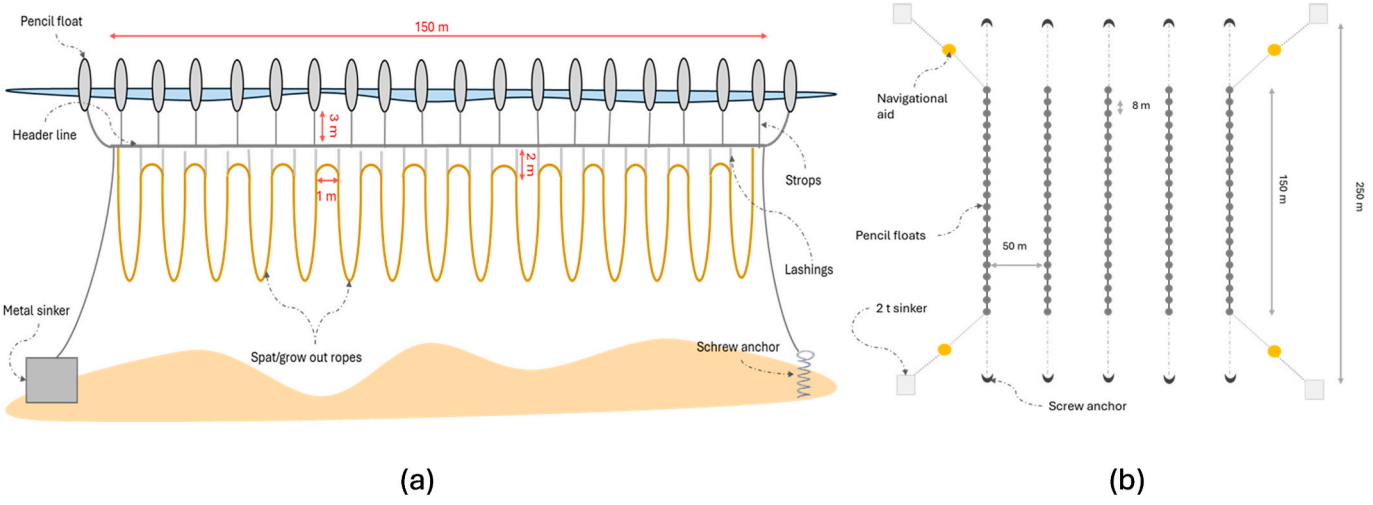


Fig. 2. Illustration of offshore continuous rope mussel farming equipment, as installed, from a) lateral view and (b) plan view.

negligible. Navigational aids are moored to the bottom by a concrete / steel mooring sinker of 2 tons (for a total of 12 sinkers). The supplier is local and a life span of 50 years was considered. Each navigational aid and the correspondent concrete/steel sinker are connected by 20–30 m of self-coloured steel chain. It is purchased from a local supplier and changed every 5 years.

Pencil floats, are 250 L cylindrical floats made of HDPE, spaced about 8 m apart, with a total of 20 floats per header line. These floats are not routinely replaced during the lifetime of the farm. Instead, they are subject to periodic maintenance and repaired when necessary following unpredictable damage events. As a result, no standard replacement interval can be defined, and for LCA modelling purposes, a conventional long-term lifespan of 99 years was assumed to reflect their continuous use rather than actual material persistence. The pencil floats suspend a 150 m long header line, which support mussel-growing ropes. Header line is a 40 mm diameter, Duradan rope, made from 75% of PP and 25% HDPE, with a specific weight of 0.741 kg m^{-1}. The same materials are used to produced strops, which are short ropes that attach the pencil floats to the header line, with diameter 24 mm/m and specific weight 0.273 kg m^{-1}. The strops are changed every year, and the header lines every 30 years. To stabilize the header lines at both ends, they are anchored to the seabed using screw anchors, which are designed to minimize their impact to the benthic ecosystem. Screw anchors are made of 80 kg of marine grade steel. All ropes and screw anchors were manufactured in, and imported from, New Zealand, while the manufacturer of navigational aids and pencil floats is located in Chesterfield (UK), therefore the transport of this equipment was included in the analysis. For all materials, end-of-life management was included in the analysis. The fate of plastic components this was assumed to be municipal incineration, as presence of fouling precludes recycling. For metal components, potential sorting and recycling was assumed. In addition, the occupation of sea area is included, considering 12 km^2 per 2 years, relating to the location of the entire production equipment.

Farming units are connected to the header lines by Duradan lashings, (diameter 7 mm, length 2 m), with 150 lashings per header line, and a total of 72,000 m for the entire farm area. Spat collection ropes have a rock core, the weight of which is specific to customer requirements, loops are made of PP yarn. Based on manufacturer suggestions, spat collection ropes should be changed after 10 uses; therefore a life span of 20 years (10 x two-year cycles) was considered. End-of-life municipal incineration, as a mix of plastics, was assumed. Grow-out ropes and cotton socks are used to grow mussels to commercial size. The grow-out ropes are the same as spat ropes and socks are made of 100% cotton and are completely biodegradable after one cycle. Farming units and lashing were manufactured and imported from New Zealand (Table 1).

Table 1
Life cycle inventory (LCI) of the mussel farming infrastructure (longline system and associated components) in the study area, based on primary data provided by farm operators.

Input name	Amount	Unit	Unit process @ OpenLCA
Longline installation - 240 lines			
Navigational aid (offshore)	12	items	Navigational aid production
Navigational aid transport	5.6 * 480	t * Km	Transport, lorry 16-32 t, EURO5
Navigational aid mooring chain	360	m	Navigational aid mooring chain production
Concrete sinker	6	items	Concrete sinker production
Metal mooring sinker	6		Metal sinker production
Pencil floats 250 L	4800	items	Pencil floats 250 L production
Pencil floats transport	168 * 734Km	t * Km	transport, lorry 16-32 t, EURO5
Strops	19,200	m	Strops production
Strops transport	3.921 * 20,000 km	t * Km	Transport, transoceanic freight ship
Screw anchor	480	items	Screw anchor production
Screw anchor transport	38.4 * 20,000	t * Km	Transport, transoceanic freight ship
Duradan ropes (d 40 mm)	72,000	m	Duradan ropes (d 40 mm) production
Header line transport,	53.352	t * Km	Transport, lorry 16-32 t, EURO5
Lashing 3 strand d 7 mm	72,000	m	PP Lashing d 7 mm production
Lashing transport	1.584 * 20,000	t * Km	transport, transoceanic freight ship
Occupation, sea and ocean	125 * 2 years	ha*a	
Farming unit			
Spat collecting rope	3700	m	Spat collecting ropes production
Spat collecting rope transport	10.36 * 20,000	t * Km	transport, transoceanic freight ship
Grow out rope	9250	m	Grow out rope production
Grow out rope transport	10.36 * 20,000	t * Km	transport, transoceanic freight ship
Cotton socks	185,00	m	Cotton sock production
Cotton socks transport	1.543 * 20,000	t * Km	transport, transoceanic freight ship

2.3.2. Farming cycle

One production cycle lasts about 2 years. Production is continuous; therefore some assumptions are considered; in each year 100 lines (occupying an area of 1.25 km^2) are used for growth of mussel that will be harvested in the following year and 100 lines are used for mussel that are harvested in the current year. The remaining 40 lines are used in a discontinuous way for spat settlement. The annual production is 22 tons per header line, means 2200 tons per 1.25 km^2. Meat yield, expressed as a percentage of total live mussel weight, ranged from 25% to 50%. These values were derived from primary data provided by the producer and represent seasonal variability observed over two production years. The inventory for 2-year's mussel farming are reported in Table 2 and includes: seed collected from seed settlement phase, mussel socked from socking phase, raised mussels from grow out phase, boats and their maintenance, diesel consumed to power boats and for socking, plastic bags for storing mussels during transport to the depuration facility (but excluding transport impacts).

To reach the farming area and to manage farming activities, two boats are used. Both are made of marine grade aluminium ($AlMg_3$). The harvesting boat is 24 m and 64 t weight, with 45ton load capacity, the service boat is 15.5 m and 18.5 t weight with 10 t of load capacity. Production from virgin aluminium was considered, even if the boats technically could be built using recycled raw material. As in LCA databases (Ecoinvent, Agribalyse, Agri-footprint) there is no process listed for the production of an aluminium boat, the category "barge production" process in the Ecoinvent database was adapted, with substitution of steel with aluminium and avoiding the use of painting and coating that an aluminium boat does not require. The life span of the boats was assumed to be 50 years, and end-of-life-management was excluded. Each boat has 2 engines, each of 500 hp., and an auxiliar engine of 325 hp. The maintenance of boats consists in the beaching and scrubbing once per month. This type of maintenance is manual, and the use of energy or materials are avoided, therefore it is not included in the analysis. The maintenance of engines involves the consumption of lubricating oil that

Table 2
LCI for the production of 2200 t of commercial size mussels.

Input flow name	Amount	Unit process @ OpenLCA
Seed settled	**137 t**	**Seed settlement process**
Header lines	40 items	–
Spat collecting ropes	3700 m	–
Socked musse l	**137 t**	**Mussel socking process**
Socking machine	1 items	mussel socking machine production
Raised musse l	**2200 t**	**Mussel grow out process**
Header lines	100 items	–
Grow out ropes	**9250 m**	–
Cotton socks	185,000 m	–
PPE		
Gloves	240 items	Gloves production
Safety Ha t	10 items	Safety Hat production
Bib and Brace	20 items	Bib and Brace production
Waterproof jacket	20 items	Waterproof jacket production
Boots (pair)	40 items	Rubber Boots production
Life Jacket	10 items	Life Jacket production
Boat	**2 items**	**Aluminium boat production | barge | APOS, U**
Maintenance of boat	**2 items**	**Maintenance of boat**
Diesel consumption	**148,680 kg**	**Diesel burned in a marine engine (fishing ship for example)**
Bag for storage and transport	**2200 items**	**Bag for storage and transport production**

is changed every 6 months. Every year, for two engines of two boats, a total of 140 L is consumed, plus 100 L for two auxiliary engines. Lubricating oil waste is collected in the port communal waste oil tank, where it is taken for re-refining and further use. However, due to lack of refining process data, the end-of-life of this waste was excluded from the analysis. The fuel consumed is diesel, which is used to power the boat and the machinery on board. In one year, 148,680 kg are consumed. Part of this is consumed in transit to the farming area and management activities associated with spat collection, socking and monitoring of mussel that will be harvested in subsequent years, and a part is consumed in monitoring and harvesting mussels that are harvested in the current year. Therefore, the consumption of diesel in one year is representative of the fuel necessary for farming mussels over a 2-years cycle. The activities are carried out by a crew of five people per boat. Personal Protective Equipment (PPE) includes the use of 1 pair of gloves per month for each crew member, rubber boots, a bib and brace, a safety hat, a safety jacket and a waterproof jacket. The safety hat and jacket are replaced every 5 years, while other PPE are replaced every 1 year. The end of life of the clothing was assumed to be recycling for plastic materials and incineration for organic materials. Once harvested, mussels are transported to the port and stored in bags. Bags are made by PP textile which single capacity is about 1 t. Bags are single use, and their recycling was included.

During seed settlement, 1 m spat collecting rope can provide enough seed for 16 m of socked mussels, at the right density. To produce enough seed for 2200 tons of commercial size mussels, about 40 lines are used in this activity. The contribution of this phase of production to equipment deterioration, was quantified as dividing the time of use by the material lifespan. The same approach was applied to PPE use.

When mussel seeds are settled on spat collecting rope, they are harvested, de-clumped and socked. De-clumping and socking are managed by the same machine, which is bought from a local supplier, and fabricated in New Zealand. To include socking machinery in the inventory, one commonly used in rope farming of mussels was considered as reference. Based on the farm manager's experience, the durability of this machine is assumed to be 30 years, if it is used every year, 60 years considering two-years cycle. For end-of-life, the transport and sorting of steel from this machinery for recycling was included, but maintenance was excluded as a negligible contribution, which could not be standardised. Energy consumed by the socking machine was included in diesel consumption. Use of seawater for moving and washing mussels during socking was not considered, as it is discharged back to the sea without consumption of resources or waste production. Mussels are socked onto grow-out ropes and suspended from header lines until mussels reach commercial size (in about 1.2–1.75 years), when they are harvested.

2.3.3. Life cycle impact assessment and uncertainty analysis

The software used to carry out the analysis was OpenLCA ® 1.10.3, an open-source software package developed by GreenDelta (Berlin, Germany). Primary data were collected from farm operators and the farm manager across the different farming areas within the commercial site. These data include operational parameters such as production volumes, fuel consumption, material use, and the lifespan of infrastructure and equipment, and were used to construct the life cycle inventory. Secondary data, which are relative to primary material production and end-of-life processes were collected from the Ecoinvent ® v.3.7 database (APOS system model). To convert input and output of all processes involved in mussel farming into environmental impacts, the ReCiPe Midpoint (H) v. 1.10 was used and all impact categories were considered without applying any threshold for exclusion (Table 3). Although all impact categories were considered, particular emphasis was placed on Global Warming Potential (GWP) and Eutrophication Potential (EP), in order to integrate them with the biological processes specific to mussel farming, such as the cycling and sequestration of carbon, nitrogen and phosphorus.

The uncertainty analysis was calculated using a Monte Carlo (MC) simulation. This analysis allows calculation of data dispersion simulating a number of possible results. In this analysis, 1000 iterations and a 95% significance level were considered. The MC analysis followed a semi-quantitative pedigree matrix, with each flow given a value between 1 (best) and 5 (worst) related to reliability, completeness, geographical, temporal and technological correlation (Fig. 3).

For primary data, pedigree-matrix values were assigned to each category of information collected. For secondary data, uncertainty values provide by the Ecoinvent database were applied. All qualitative values were used to calculate a geometrical standard deviation (SD), assuming a lognormal distribution. The uncertainty grade of results was expressed as MC standard deviation and coefficient of variation (CV), which is calculated as percentage of data dispersion around the LCA mean.

2.4. Modelling farming parameters

Modelling of farming parameters for offshore mussel aquaculture was undertaken to assess the potential influence of variability in environmental and operational factors on the sustainability and productivity of this method of shellfish farming. The Lyme Bay system was used as a baseline for this modelling. We simulated different scenarios by varying key parameters such as the distance of the farm from the coast, the duration of the mussel growth cycle and the productivity rate per unit area. These scenario simulations were carried out using deterministic variations applied to the baseline values, representing hypothetical adjustments of the model rather than empirical observations. Indeed the use of farming equipment and materials was assumed to remain constant. For this reason, the sensitivity datapoints are not associated with statistical dispersion. In order to determine how increased distance from the coast, compared to inshore systems, could affect fuel consumption and associated emissions, different scenarios were modelled by

Table 3
Description of impact categories considered by ReCiPe Midpoint (Huijbregts et al., 2016).

Impact category	Acronym	Description	Scale
Agricultural land occupation potential Natural land transformation potential Urban land occupation potential	Land use	Measures the impact of land use for agricultural, industrial, urban and marine area occupation, directly and indirectly related to the case study, resulting in biodiversity loss and ecosystem degradation.	Local/ Regional
Global warming potential	GWP	Describe the potential risks of ionising radiation, greenhouse gases and ozone-depleting substances to human health, the ecosystem and the climate.	Global
Ionising radiation potential	IRP		
Ozone depletion potential	ODP		
Fossil depletion potential	FDP	Describe the excessive use of non-renewable resources such as fossil fuels and metals.	Global
Metal depletion potential	MDP		
Water depletion potential	WDP	Measures unsustainable water use and impact on freshwater resources	Local/ Regional
Freshwater ecotoxicity potential Marine ecotoxicity potential Terrestrial ecotoxicity potential	ETP	Assesses assesses the potential damage caused by chemicals to natural ecosystems.	Global
Human toxicity potential	HTP	Assessment of the long-term effects of chemical pollution on human health.	Local/ Regional
Freshwater eutrophication potential Marine eutrophication potential	FEP MEP	Measures the accumulation of nutrients in aquatic and terrestrial ecosystems, leading to the phenomenon of eutrophication.	Local/ Regional
Particulate matter formation potential	PMFP	Considers particulate matter emissions and their contribution to air pollution with adverse effects on human health	Local/ Regional
Photochemical oxidant formation potential	POFP	Assesses the formation of tropospheric ozone, which has negative effects on health and vegetation.	Regional
Terrestrial acidification potential	TAP	Assesses the acidification potential of terrestrial and marine ecosystems due to emissions of sulphur and nitrogen oxides.	Regional

adjusting the diesel consumption from 10% to 90%. The duration of the mussel growth cycle was modelled by considering a range of growth periods from 1 to 3 years. This range was chosen to represent potential variations in environmental conditions, such as water temperature and nutrient availability, that could influence the time required for mussels to reach commercial size. The same factors can influence the productivity rate, which was also modelled by considering a range of 100 to 500 t of fresh mussels per km^2. The relationship between each farming parameter and its environmental impact was analysed across all impact categories using the same LCA methodology as for the baseline scenario.

2.5. Carbon, nitrogen, and phosphorus sequestration integration in LCA assessment

To consider carbon, nitrogen and phosphorous sequestration in the GWP and EP potential, the study of Van der Schatte Olivier et al. (2021) was used as reference for the data on the concentration of these elements in the shell and flesh. Quantification of carbon sequestration in shell calcification (Eq. 1) is complex and there is no consensus on the most appropriate approach, as the process may drive release of carbon dioxide from the relatively stable pool of dissolved bicarbonate in seawater (Ware et al., 1992; Morris and Humphreys, 2019). Eq. (1):

$$Ca^{2+} + 2HCO_3^- \leftrightarrow CaCO_3 + CO_2 + H_2O \quad (1)$$

We followed the method described by (Zavell et al., 2023), which assumes that for each mole of CO_3^- absorbed during calcification, 0.6 mol of CO_2 is released to the atmosphere. Hence, the carbon sequestration potential (CSP) in the shells of 1 kg of fresh mussels was calculated using Eq. (2).

$$CSP = \left[\left(\frac{C_{shell}}{AW_C}\right) \times MW_{CO_2}\right] \times 0.4 = \frac{g_{CO_2}}{kg_{fresh\ mussel}} \quad (2)$$

Where C_{shell} is the carbon content (g) in the shells of 1 kg of fresh mussels, AW_C is the atomic weight of carbon (12.011 u) and MW_{CO2} is the molecular weight of carbon dioxide (44.01 g/mol).

The CO_2 released during respiration and in the organic content of pseudofaeces and faeces has not been included in the balance. Also, the carbon in mussel meat was excluded, as this is not considered long-term sequestration. Before integrating the carbon sequestration potential into the estimate of Total Global Warming Potential (GWP_T), the CO_2 eq. sequestered during shell calcification was assigned impact factors, established by the ReCiPe Midpoint (H) method. This approach applies the same characterization principle used for emissions, whereby CO2 equivalents are calculated using the corresponding impact factor, ensuring consistency within the LCA framework.

The total GWP of 1 kg of fresh mussels, expressed as CO_2 equivalent, was calculated using Eq. (2).

$$GWP_T = GWP_{LCA} - (CSP \times IF_{CO_2}) \quad (3)$$

Where GWP_{LCA} is the contribution of the farming phase to climate change, CSP is the carbon sequestration potential from shell formation, and IF_{CO2} is the impact factor for carbon dioxide in marine environments, equal to 1.

Mussels also incorporate nitrogen and phosphorus into their tissues, predominantly in the form of organic nitrogen (amino acids) and phosphorus (phosphoric acid), which are essential components of their biomass. The total amount of nitrogen and phosphorus sequestered in both flesh and shell were calculated from Van der Schatte Olivier et al. (2021) and for each element different impact factors were applied, equivalent to the amount of nitrogen, or phosphorus required to produce the same effect per kilogram of input, based on the environment they are released into. Phosphorus was assigned to freshwater eutrophication potential, while nitrogen was linked to marine eutrophication potential, although this remains a theoretical division as both can lead to eutrophication phenomena in both environments (Dodds and Smith, 2016; Conley et al., 2009; Ryther and Dunstan, 1971).

The total EP, expressed as nitrogen (MEP_T) or phosphorus equivalent (FEP_T), was calculated using Eq. (4), (5).

$$MEP_T = (N_{shell} + N_{meat}) \times IF_N \quad (4)$$

$$FEP_T = (P_{shell} + P_{meat}) \times IF_{organic\ P} \quad (5)$$

Where N_{shell} and N_{meat} are the nitrogen content (g) in the shell and meat, respectively, and IF_N is the impact factor for nitrogen in its organic form in marine environments (=1.43). P_{shell} and P_{meat} are the phosphorus contents (g) in the shell and meat, respectively, and IF_P, (=0.32) is the impact factor for phosphorus in its organic form in freshwater environments.



Fig. 3. Pedigree matrix for Ecoinvent data quality.

3. Results

3.1. LCA results of offshore mussel farming

Impact values and relative units, for all categories are shown in Table 4.

The processes causing impacts can be divided into five groups: boat use (boat production and maintenance), diesel consumption, PPE use, farming plant (longline installation and farming unit) and bags for storage (Fig. 4). The construction of boats and their maintenance is relevant only in some categories, such as MDP, HTP and WDP which account for about 14.6%. Impacts from use of PPE and bags are also very low or negligible, despite their short life span. In contrast, diesel consumption predominates in almost all impact categories, except for the land use, MDP and WDP categories, where its contribution is minor. In ETP and HTP, the contribution of diesel consumption to emissions is 30% and 46%, respectively, while for other categories is the main source of emissions (79–98%).

Looking at the results of the impact of the farming plant, it is possible to divide the full range of impact categories into those that are unaffected (ODP, PMFP, POFP, AP), those that are impacted to a lesser extent (GWP, FDP, MEP, IRP) and those where the farming plant is the main emitter (FEP, MDP, ETP, HTP, WDP and Land Use as an indirect effect resulting from the production and disposal of raw materials). The impact of farming plant is given by the sum of the longline construction and use impact and farming unit ones. The main impactful factors in construction are metal extraction and production, as 31 t of steel are used. The effect of metal end-of-life is negligible, as only transportation and sorting are included. Longline construction also involves a high use of plastics, (145 t); while production of this material has low environmental costs, its disposal has a higher contribution to possible total emissions. Farming units affects, to a lesser extent, the ETP, MEP and HTP categories (7–16%), otherwise it mainly affects Land use (79%). Indeed, the impact category 'land use' includes environmental impacts

Table 4
Impact values associated with farm production of 1 kg of fresh live mussel.

Impact category	Acronym	Impact value	Unit
Agricultural land occupation/ transformation potential	Land use	9.45×10^{-3}	m^2*year
Climate change potential	GWP	2.91×10^{-1}	kg CO_2 eq.
Fossil depletion potential	FDP	9.82×10^{-2}	kg oil eq.
Ecotoxicity potential	ETP	1.53×10^{-3}	kg 1,4-dB eq.
Marine Eutrophication potential	MEP	2.33×10^{-4}	kg N eq.
Freshwater Eutrophication potential	FEP	1.47×10^{-5}	kg P eq.
Human toxicity potential	HTP	1.68×10^{-2}	kg 1,4-dB eq.
Ionising radiation potential	IRP	2.16×10^{-2}	kg U_{235} eq.
Metal depletion potential	MDP	8.45×10^{-3}	kg Fe eq.
Ozone depletion potential	ODP	4.91×10^{-8}	kg CFC-11 eq.
Particulate matter formation potential	PMFP	1.94×10^{-3}	kg PM10 eq.
Photochemical oxidant formation potential	POFP	6.02×10^{-3}	kg NMVOC
Terrestrial acidification potential	TAP	5.53×10^{-3}	kg SO_2 eq.
Water depletion potential	WDP	1.24×10^{-1}	m^3

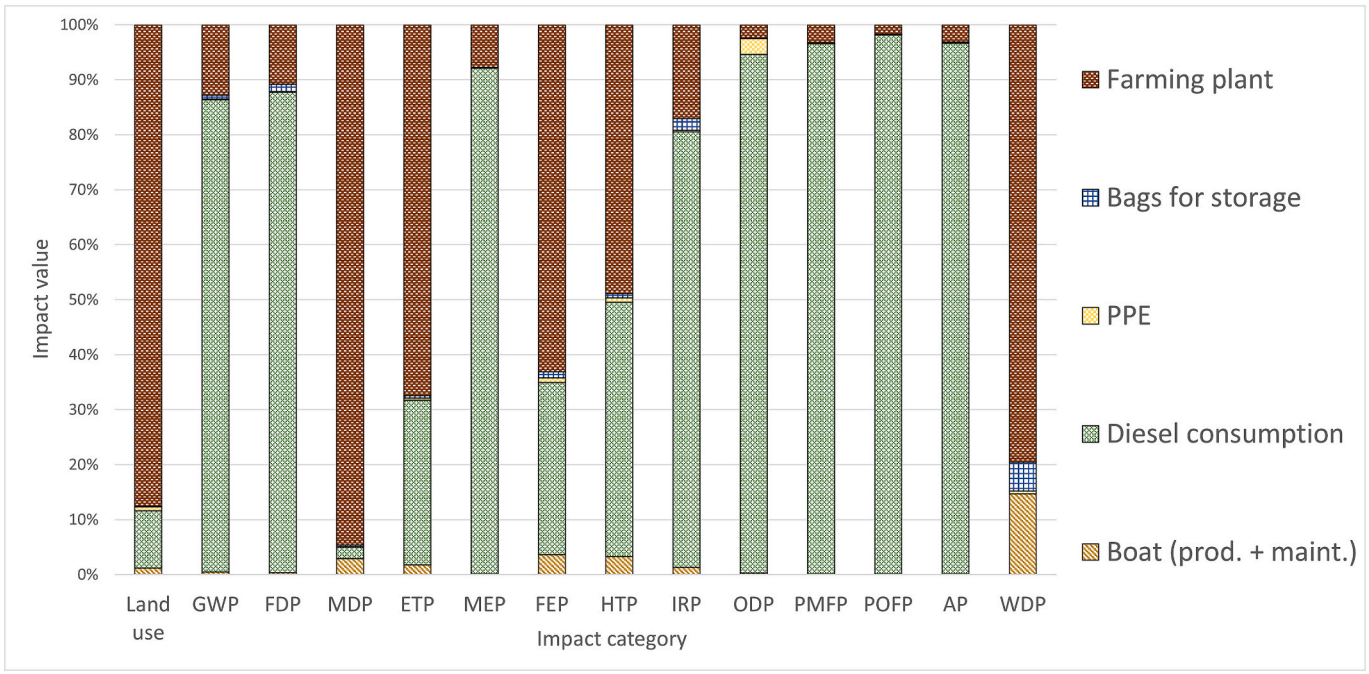


Fig. 4. Flow contributions in all impact categories (F.U. 1 kg of fresh live mussels). Global warming potential (GWP), fossil depletion potential (FDP), metal depletion potential (MDP), ecotoxicity potential (ETP), eutrophication potential (EP), human toxicity (HTP), ionising radiation potential (IRP), ozone depletion potential (ODP), particulate matter formation potential (PMFP), photochemical oxidants formation potential (POFP), acidification potential (AP) and water depletion potential (WDP).

resulting from the use of land for various purposes, including those not directly related to mussel farming. Therefore, in addition to the occupation of marine areas, which has an insignificant impact on land use, it is essential to consider the indirect impacts related to the production of raw materials. In this case, the cultivation of cotton for socks production is the most significant factor (Fig. 5).

The reliability of the results was confirmed by the Monte Carlo analysis, which was performed using 1000 iterations and a 95% significance level.

MC analysis shows a high uncertainty level for categories related with environmental toxicity phenomena, ETP and HTP (Table 5). Looking at the MC means, for both ETP and HTP the calculated impact values (Table 4) are smaller than the MC mean and the uncertainty analysis reveal a positive asymmetric distribution. These results are the natural consequence of the high flow uncertainties of plastic production, which are closely related to the impact of these categories. Categories IRP and Land Use, also present quite high uncertainty, as there is a bias between the MC means and the calculated values for these categories (+14% and + 7%, respectively). Other categories present a very low uncertainty values (CV 0.5–8%) demonstrating high reliability of the

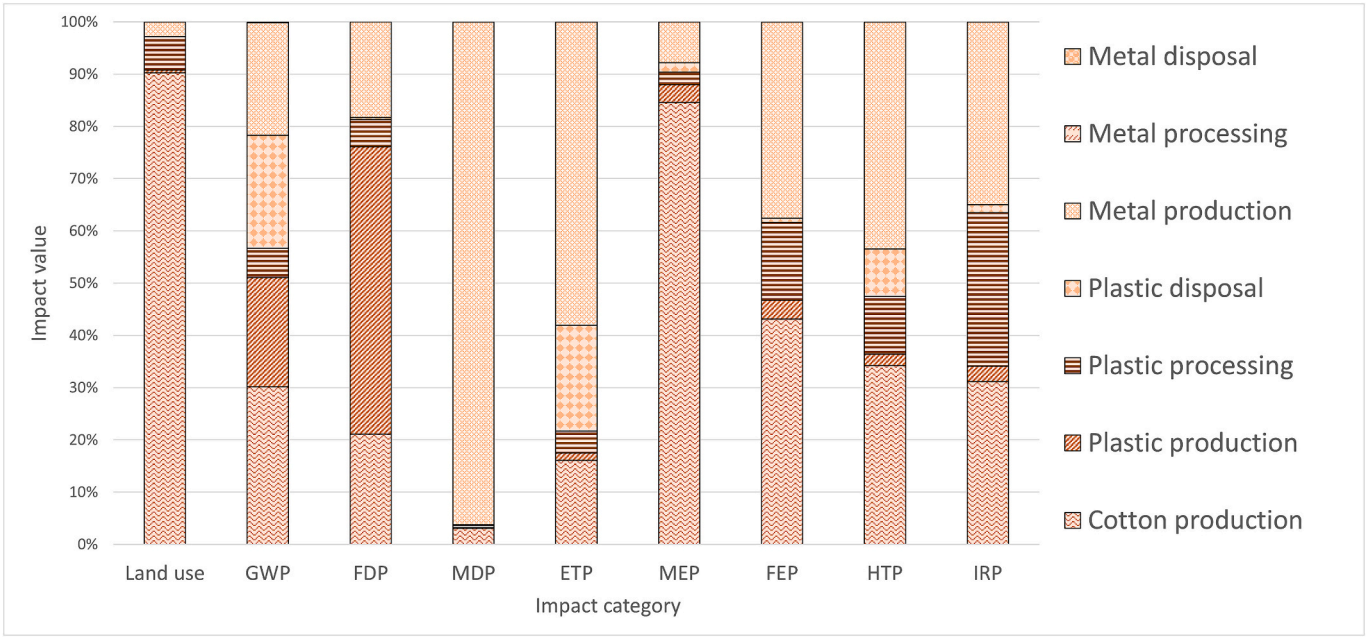


Fig. 5. Flow contribution of farming plant material in the affected impact categories.

Table 5
Results of uncertainty analysis. (SD: standard deviation, MC mean: Monte Carlo mean; CV: variation coefficient).

Impact category	SD	MC mean	Median	CV	Unit
Land use	1.78×10^{-3}	1.01×10^{-2}	9.85×10^{-3}	19%	m^{2}*a
GWP	6.67×10^{-3}	2.90×10^{-1}	2.89×10^{-1}	2%	kg CO_2 eq.
FDP	2.36×10^{-3}	9.77×10^{-2}	9.71×10^{-2}	2%	kg oil eq.
ETP	1.28×10^{-3}	2.41×10^{-3}	2.15×10^{-3}	86%	kg 1,4-dB eq.
MEP	5.51×10^{-6}	2.34×10^{-4}	2.34×10^{-4}	2%	kg N eq.
FEP	6.47×10^{-6}	1.85×10^{-5}	1.69×10^{-5}	35%	Kg P eq.
HTP	2.98×10^{-2}	3.26×10^{-2}	2.56×10^{-2}	> 100%	kg 1,4-dB eq.
IRP	7.67×10^{-3}	2.45×10^{-2}	2.19×10^{-2}	36	kg U_{235} eq.
MDP	6.88×10^{-4}	8.76×10^{-3}	8.71×10^{-3}	8%	kg Fe eq.
ODP	2.30×10^{-10}	4.92×10^{-8}	4.92×10^{-8}	0.5%	kg CFC-11 eq.
PMFP	3.09×10^{-5}	1.94×10^{-3}	1.94×10^{-3}	2%	kg PM10 eq.
POFP	1.05×10^{-4}	6.02×10^{-3}	6.02×10^{-3}	2%	kg NMVOC
TAP	7.17×10^{-5}	5.54×10^{-3}	5.54×10^{-3}	1%	kg SO_2 eq.
WDP	1.06×10^{-2}	1.36×10^{-1}	1.36×10^{-1}	8%	m^3

calculated results.

3.2. Effects of mussel farming on climate change and eutrophication potential

One limitation of Life Cycle Assessment (LCA) is the inherent challenge in analyzing dynamic systems, such as marine ecosystems. In the case of mussel farming, this type of analysis often excludes biological factors related to the organism, which can be crucial for assessing its interactions with the surrounding environment. To address this limitation, LCA has been supplemented with data on carbon, nitrogen, and phosphorus sequestration to assess the overall contribution of mussel farming on climate change potential and marine or freshwater eutrophication potential. The carbon in shells of 1 kg of fresh mussel is 0.046 ± 0.002 kg, which is equivalent to a carbon sequestration potential of 0.068 kg CO_2 eq. The LCA on farming phase estimated the GWP from production of 1 kg of fresh mussel as 0.29 kg CO_2 eq. When including the estimated contribution of carbon retained in shells, the resulting GWP is 0.22 kg CO2 eq. per kg (Table 6).

The analysis calculated Marine Eutrophication Potential for N as -9.27×10^{-3} kg N eq kg^{-1} of mussel flesh, and Freshwater Eutrophication Potential for P as -0.29×10^{-3} kg P eq kg^{-1}, while the contribution of the shell is relatively low. LCA analysis estimated Eutrophication Potential (EP) as result of mussel farming materials and processes as 0.23×10^{-3} Kg N eq. and 0.01×10^{-3} Kg P eq. kg^{-1} of whole mussels.vHence, the total EP potential of mussel production is negative, and is calculated as -9.71×10^{-3} Kg N eq. kg^{-1} and -0.29×10^{-3} Kg P eq. kg^{-1}.

Table 6
Effects of the mussel farming process and nutrient sequestration in mussel flesh and shells on GWP and EP.

Kg of live mussel	GWP (Kg CO_2 eq.)	MEP_T (Kg N eq.)	FEP_T (Kg P eq.)
Shell	−0.068	-0.67×10^{-3}	-0.01×10^{-3}
Flesh	/	-9.27×10^{-3}	-0.29×10^{-3}
Farming	+0.291	$+0.23 \times 10^{-3}$	$+0.01 \times 10^{-3}$
Total	**+0.223**	$\mathbf{-9.71 \times 10^{-3}}$	$\mathbf{-0.29 \times 10^{-3}}$

3.3. Modelling influence of farm operational and production variables on LCA results

Diesel consumption during the cultivation cycle is due to the need to travel to the cultivation site and to carry out activities on the boat, such as socking and de-clumping. As the fuel consumption of these activities cannot be counted separately, it has been included in the annual consumption. Location of a farm (distance from port) will influence fuel consumption for transit to the farm site but not farm management operations once at the site. In this context, the values shown in the sensitivity analysis represent variations applied to the baseline fuel consumption. Relative to the calculated values in the present study, considering lower use of diesel (between 10% and 90%), it is evident that this parameter has a linear correlation with the emissions of all impact categories, except for WDP (see Table S1). However, the scale of this effect depends on the relative contribution that diesel consumption has on each category.

Considering the impact categories land use, GWP and ETP as examples, a 10% reduction in diesel results in approximately 1%, 9% and 3% reduction in total emissions reduction, respectively (Fig. 6). This means that, although a more distant farm may result in an effective increase in greenhouse gases, in other impact categories, the distance of the farm from the coast is a less important influencing factor. For some impact categories, such as ecotoxicity, the effect of farm distance from port is negligible.

On a broader geographic scale, environmental conditions such as water temperature and phytoplankton concentration may be expected to affect productivity per spatial unit or duration of the growth cycle, even if farms use identical equipment. Therefore, the effects of varying these two parameters were investigated. The productivity range considered was from 1000 to 2600 t of fresh live mussels km^{-2} per two-years production cycle, assuming the density of production header lines is unchanged, considering that the production rate of offshore mussel farming in the case study presented here was 1760 t km^{-2}. Unlike the trend in the reduction of diesel use, the effect of the production rate is the same for each category, but it does not have a linear trend (Fig. 7). This means that small variation in production could have a greater effect on emission reduction. This trend is correlated with factors that are partly influenced by the production rate and others that are not, such as boat maintenance.

Modelling of the effect of production cycle duration (time from seed to harvest) considered a range between 1 and 3 years. The relationship between cycle duration and the impact of production is directly proportional and linear. However, the increase or decrease in emissions per unit of time is very different depending on the category considered (Fig. 8). The most strongly influenced categories are FDP, MDP, MEP and WDP; while for the other categories the variation in emissions is very small or negligible. For example, each one year increase in production duration resulted in only 5% increase in CO_2 emissions, as the overall diesel consumption from boat operations is spread across a longer time span rather than increased. Instead, for the FDP and EP categories, there is an increase or decrease of 5.8% and 12.6%, respectively, for every 3-month change in the duration of the production cycle. This is the result of their greater sensitivity to increases in the use of lubricating oil for the boat maintenance and the allocation of use of farm equipment.

4. Discussion

The Life Cycle Assessment (LCA) conducted on offshore mussel farming in Lyme Bay, UK, offers a comprehensive and detailed evaluation of the environmental sustainability of this pioneering form of shellfish aquaculture that can also inform more generally the relative

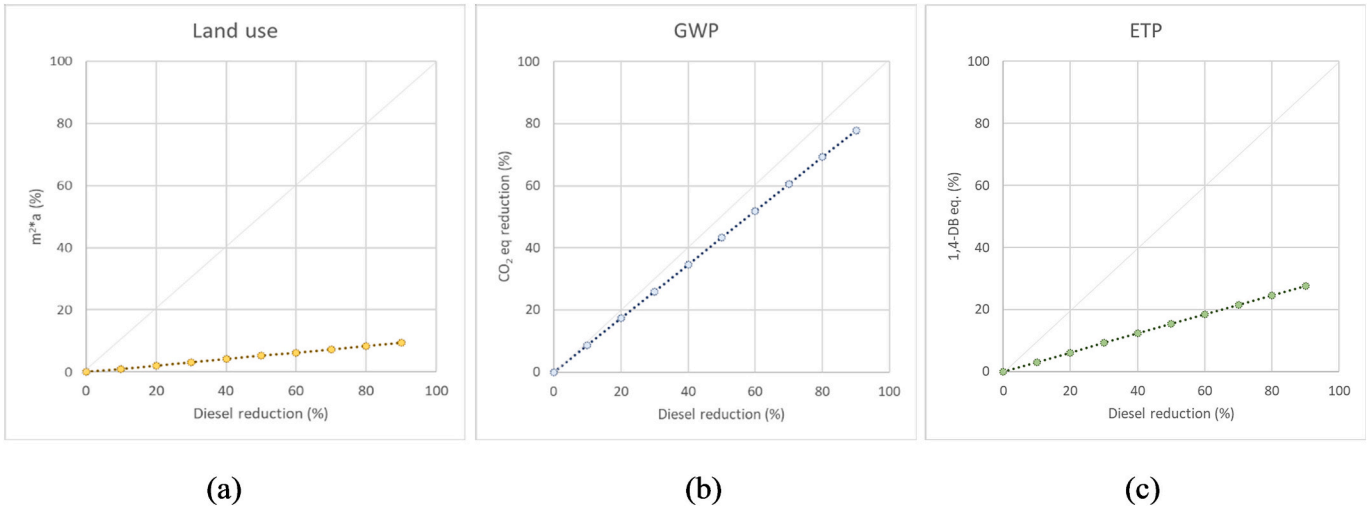


Fig. 6. Sensitivity analysis of diesel reduction on a) land use potential, b) global warming potential, c) eutrophication potential.

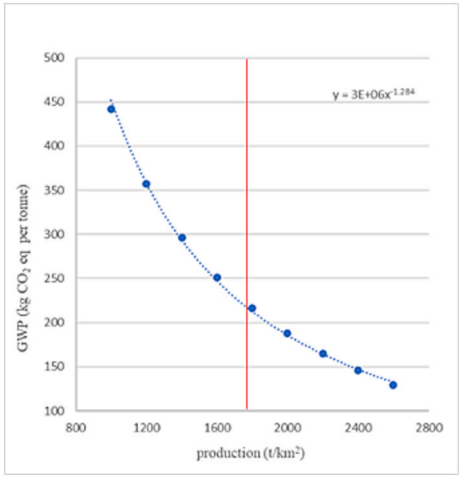


Fig. 7. Sensitivity analysis of GWP in relation to productivity rate (F.U. 1 ton of fresh live mussel); red line represents the productivity rate applied in the present study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

impacts of future expansion of shellfish farming offshore. The primary objective of the study was to assess the overall environmental effects of mussel farming, considering factors such as resource use, greenhouse gas emissions, and other significant environmental impacts. In this case study, the GWP of farmed mussels was within the range of previous studies for a range of European mussel production systems (Table 7), with results confirming that offshore mussel farming can be a highly sustainable solution for food production, particularly when compared to meat production or other aquaculture products. (Williams et al., 2006;

Table 7
Comparison of Global Warming Potential (CO_2 eq Kg^{-1} whole fresh mussels) for a range of mussel farming systems.

Location	Farming method	Kg CO_2	Reference
U.K. – Lyme Bay	Offshore rope culture	0.291	Present study
U.K. - Scotland	Inshore rope culture	0.131–0.252	McGoohan, 2022; Fry, 2012
France - Brittany	Inshore Bouchot culture	0.325	Aubin et al., 2018
Sweden - west coast	Suspended culture	0.048–0.092	Frösell, 2019
Spain - Galicia	Raft culture	0.220	Iribarren et al., 2010
Italy - North (Ferrara)	Offshore suspended culture*	0.055–0.137	Tamburini et al., 2022 and 2020
Italy - North (Venice)	Offshore suspended culture*	0.410	Abbadessa, 2023
Algeria	Suspended culture*	0.404	Lourguioui et al., 2017
Denmark	Not specified	0.072	Frösell, 2019

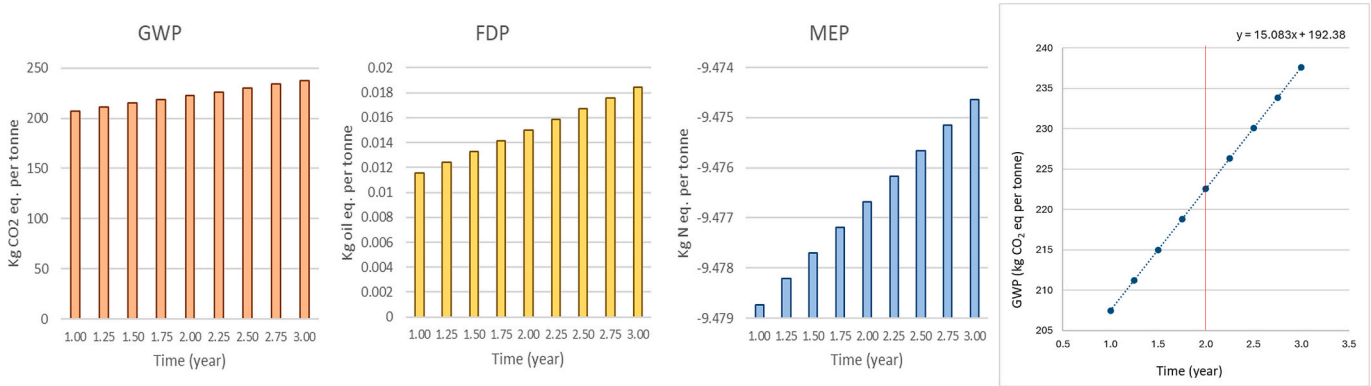


Fig. 8. Sensitivity analysis of (a) GWP, MEP and FDP in relation to production cycle duration; and (b) focus on GWP variation; red line represents the production cycle duration applied in the present study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Pelletier et al., 2009; Carboni et al., 2019. This is an important finding, as it assesses the balance between the environmental advantages of bivalve aquaculture against the additional costs associated with operating in more distant open sea locations (Röckmann et al., 2017; Buck, 2017). This is partially because mussels are filter-feeding organisms that rely on naturally occurring phytoplankton in the water column and therefore do not require external feed inputs, a major source of environmental impact in livestock and fed aquaculture systems. Although Lyme Bay is a highly favourable environment for mussel farming, the more challenging conditions and higher energy demands of offshore installations require careful attention to operational sustainability. One of the most significant findings is the role that diesel fuel consumption plays in the overall environmental impact of mussel farming, especially in relation to GWP. Clearly, distance from port and vessel fuel efficiency are important considerations in optimising the sustainability of offshore farming operations. However, the modelling indicates that the scale of this impact is highly sensitive to variation in production (per unit area), mussel growth rates and meat yield (kg^{-1} of whole mussel). This is significant, as geographic and year-year variation in environmental factors, such as seawater temperature and chlorophyll-a concentrations, may influence the length of the growing cycle, productivity or both (Taylor et al., 2021; Holbach et al., 2020). This has implications for interpretation of the results for the study site in Lyme Bay; for example, the most recent annual harvest results (3000 t in 2024, Offshore Shellfish Ltd. *pers comm*) were 30% higher than the annual production data applied in the present study (2200 t), though with largely the same resource inputs. This implies that the LCA impact categories, for the same operation, can be substantially reduced as production efficiency increases, and that offshore mussel farming can compare even more favourably with all other mussel production systems, despite the additional environmental costs of operations. The effects of growth rate and production on environmental impacts are also more generally relevant to sustainability of offshore mussel farming in future locations; it will be commercially advantageous to select sites with conditions that will support high growth rates, which is likely also to reduce environmental impacts of the farm operations. Farming in productive offshore waters also tends to produce higher-value mussels with a high meat yield relative to total weight (Kapetsky and Aguilar-Manjarrez, 2013). In the present study, we have considered 1 kg whole fresh mussels as the functional unit as this allows comparison with other shellfish farming LCA studies. However, if based on a functional unit of 1 kg of shucked meat, the GWP of offshore farmed mussels is inversely related to meat yield, ranging from 0.45 to 0.89 Kg Kg^{-1} for 50% and 25% meat yield, respectively. This illustrates the potentially relatively lower environmental impact of edible food production in offshore mussel farming systems and the important influence of timing of harvesting on the environmental sustainability of the product, given the seasonal variation in meat yield that is characteristic in farmed shellfish.

* Suspended mussel culture in the northern Adriatic uses individual tubular polypropylene nets/socks to support mussel growth, rather than the continuous mussel rope systems developed for more exposed conditions, as described in the present study.

LCA is a useful tool to inform improvements in environmental performance. Overall, our results are consistent with other studies of longline mussel farming, that have highlighted the importance of energy consumed during farm operations and the role of plastic use in overall sustainability. GWP of mussel farming may be reduced by use of more operationally-efficient vessels; this strategy is particularly promising in the light of emerging technologies that offer more sustainable solutions for maritime transport. In the present study, we have also considered the environmental costs of the materials used in vessel construction, which have not been included in most previous LCA studies of shellfish aquaculture due to their long life and consequently relatively low impact (Lorenzo et al., 2024; Tamburini et al., 2022). Although steel boats are more common in aquaculture, the trend to replacement with more durable aluminium construction may lead to disadvantages in increasing emissions from production of raw aluminium, as well as advantages in reduction in vessel weight and less fuel consumption (Hayman et al., 2000). However, it is worth noting that in the present study we considered the worst-case scenario, i.e. production from virgin primary aluminium, even though it is more common to use recycled metals as a component of boats. The materials used in farming equipment, particularly steel, aluminium and plastic components, also play a role in the overall environmental impacts, though these are mitigated by equipment durability and long life usage. For plastic materials, for example ropes, the main challenge remains in end-of-life management, with disposal by incineration as biological fouling prevents recycling, whereas metals are assumed to be recycled.

LCA is to some extent limited in only considering fixed processes as inputs, while commercial activities in the marine environment may also impact ecological processes and the condition of habitats that underpin ecosystem function and services, that are not quantified in the emissions categories. For shellfish aquaculture LCA, there is a lack of studies that fully integrate biological nutrient and carbon sequestration (Tamburini et al., 2022; Aubin et al., 2018; Filgueira et al., 2019) in calculating net global warming potential (GWP) and eutrophication potential (EP), in addition to emissions from fuel and materials. The importance of filter feeding bivalves in water quality control has long been recognised (e.g. Dame et al., 1980; Officer et al., 1982), playing an important role in ecosystem processes, such as the removal of particulate material that increases light penetration, stimulating benthic productivity and supporting this productivity with the transfer of nutrients from the water column to the benthos as waste products (pseudofaeces and faeces) (Peterson and Heck Jr., 1999; Shumway et al., 2003; Schröder et al., 2014). The harvest of mussels, removes from the aquatic environment, the net nitrogen and phosphorous retained in the flesh and shell (Van der Schatte Olivier et al., 2020, 2021), after metabolic losses due to respiration and biodeposition (Ferreira and Bricker, 2016; Nielsen et al., 2016). In the present LCA, we have applied estimation of nutrients retained in harvested shellfish in calculations of the eutrophication potential metric in LCA calculations, demonstrating net positive effects of mussel farming. The net removal of nutrients through mussel harvest, primarily nitrogen, with phosphorus playing a secondary role, was incorporated into the marine eutrophication category, as nitrogen is typically the limiting nutrient in coastal and estuarine systems. This approach aligns with ecological understanding that nutrient mitigation in marine environments is predominantly driven by nitrogen dynamics, whereas phosphorus plays a more central role in freshwater eutrophication. Our estimates of net nutrient removal in harvested mussels are very similar to that of Gephart et al. (2021) who reported 0.13 kg of N and 0.024 kg P were removed kg^{-1} of bivalve meat harvested. The net negative eutrophication potential identified in the present LCA is also consistent with the positive outcomes of practical trials of the use of cultured bivalves for nutrient remediation in coastal waters (Lindahl et al., 2005; Petersen et al., 2014; Taylor et al., 2019). However, we acknowledge that only accounting for nutrients removed with mussel harvest is a necessarily simplistic approach. The net effects of shellfish aquaculture on eutrophication are, to a large extent, dependant on farm location and hydrodynamic conditions, with greater effects seen in more enclosed, microtidal settings (Maar et al., 2023). However, quantification of overall net effects of bivalve shellfish on water quality is not easily accommodated in an LCA framework, requiring detailed ecological and modelling studies on a case-by-case basis. However, in general, mussel cultivation lines are spaced to facilitate efficient water exchange, preventing sediment and debris buildup beneath the ropes (Ögmundarson et al., 2011; Kotta et al., 2020), and the high-energy conditions of offshore sites ensure that waste does not accumulate, maintaining the environmental integrity of the surrounding area (Bridger, 2022). It is notable that in the well-mixed, dispersive, environment at the Lyme Bay study site, the scale and configuration of rope installations were designed to minimize negative effects on water flow and density of plankton, and recent studies have shown no evidence of

accumulation of organic sediments below the mussel farm (Mascorda-Cabre et al., 2024a), indicating that the focus on direct nutrient removal in LCA calculations is an appropriate approach in this setting. Coastal eutrophication, caused by excess nutrients, can lead to negative environmental effects such as harmful agal blooms, hypoxia and degradation of benthic communities. In the UK context, mussel farming may not necessarily contribute to mitigation of eutrophication in well-mixed offshore waters, where Good Environmental Status in relation to the standards of the Water Framework Directive may already have been achieved. However, the present results are clearly relevant to identified eutrophication problem areas, especially in enclosed embayments and estuaries, which are in many cases also important areas for shellfish aquaculture (Centre for Environment, Fisheries and Aquaculture Science, 2018).

Carbon sequestered in mussel shell potentially represents long-term carbon storage, whereas carbon in the meat is not considered long-term sequestration because it returns to the atmosphere when mussels are consumed. However, quantification of carbon sequestration in shell calcification is complex and there is no consensus on the most appropriate approach, as the process may drive release of carbon dioxide from the relatively stable pool of dissolved bicarbonate in seawater (Ware et al., 1992; Morris and Humphreys, 2019). We have adopted a conservative approach, as described by Zavell et al. (2023), which assumes that for each mole of CaO_3^- absorbed during calcification, 0.6 mol of CO_2 is released to the atmosphere, and hence net sequestration of 0.4 mol CO_2. In the present study, the GWP of offshore mussel farming (0.288 Kg CO_2eq kg^{-1}, whole live mussels) was largely attributable to diesel fuel consumption for operations and maintenance, and to a less extent the impact of boat construction and maintenance. While GWP is partially offset by carbon retained in shell formation (−0.068 Kg CO_2 eq kg^{-1} whole live mussels), this effect depends on the long-term fate of shell material. Where post-consumption pathways support long-term carbon storage, this contribution can represent a meaningful reduction in GWP, in this instance lowering the estimated value to 0.220 kg CO_2eq kg^{-1}. It is therefore important to emphasise that, within the boundaries of the present LCA, carbon sequestration associated with shell formation should be interpreted as a potential contribution to long-term carbon storage, contingent on downstream management practices (Jović et al., 2019; Summa et al., 2022). Although mussel shells are currently considered a low-value byproduct, they can be reintroduced as a raw material in numerous applications such as soil conditioners, aggregates, sources of biopolymers and calcium compounds for industrial and pharmaceutical applications (Naik and Hayes, 2019; Medina Uzcategui et al., 2022; Mititelu et al., 2022). Depending on the waste fate, the inorganic carbon contained in the shell can either contribute to long-term sequestration (soil conditioner, biocomposites, etc.) or be re-emitted into the atmosphere or aquatic environments as CO_2. As the post-consumption phases are not included within the system boundaries, this contribution cannot be accounted for directly as an offset to the global warming potential (GWP), but rather as a potential for long-term carbon sequestration.

Additionally, it is important to consider that mussel farming can also have positive effects on biodiversity (Van der Schatte Olivier et al., 2020). In the case of suspended mussel farming, cultivation lines and ropes provide hard substrates that support the formation of mussel colonies, that sustain diverse communities of sessile species, as well as attracting an array of mobile species such as fish, crabs, cephalopods, and invertebrates (Kristensen et al., 2015). Establishment of mussel farming also creates areas where impacts of fishing activity on the seabed may be reduced, promoting recovery. At the current study location in Lyme Bay, establishment of mussel farming has been shown to enhance habitat complexity and biodiversity in benthic habitats previous impacted by bottom-towed fishing activity (Mascorda-Cabre et al., 2021; Bridger et al., 2022; Mascorda-Cabre et al., 2024a), with associated benefits to commercially-exploited crustacean species (Stamp et al., 2024), while the mussel lines promote aggregation of pelagic fish species (Bridger et al., 2024).

Relative to terrestrial livestock farming, low-trophic marine aquaculture ranks among the most efficient food production systems in terms of energy, land and carbon inputs (Hilborn et al., 2018; Gephart et al., 2020). These systems are associated with substantially lower greenhouse gas emissions and place minimal demands on freshwater and terrestrial ecosystems (Nijdam et al., 2012; Hilborn et al., 2018; Gephart et al., 2021). Unlike fed aquaculture or land-based livestock farming, bivalve shellfish derive their nutritional requirements from ambient marine nutrients and particulate organic matter, thereby eliminating the need for external feed or chemical inputs. Despite requiring fewer resources, they provide nutrient-rich food containing high levels of protein, essential fatty acids, and trace elements (Wright et al., 2018; Hallström et al., 2019; Naylor et al., 2021). As such, dietary shifts towards such low-trophic marine species could promote both environmental sustainability and public health and also generate a suite of ecological co-benefits. The barriers to increasing bivalve shellfish aquaculture in coastal areas include limited availability of suitable sheltered sites, water quality and complex regulatory or licensing requirements (Debnath and Sahoo, 2020; Kluger and Filgueira, 2021; St-Gelais et al., 2022; Krause et al., 2022; Pinn and Le Vay, 2023). The results from the Lyme Bay case study demonstrate that movement of mussel production to more exposed offshore waters offers the opportunity for future increases in production, while retaining the excellent environmental performance of more traditional inshore mussel farming systems.

5. Conclusions

Offshore mussel farming is becoming established as a viable approach to expanding the sector, especially where opportunities for increased inshore production are limited. The present LCA study is a first analysis of the potential environmental impact of moving mussel farming offshore. A key finding is that the impacts of the commercial mussel farm studied fall within the previously reported range for mussel farms across Europe. While a limitation of the LCA analysis is dependence on underpinning data from a single site, the simple modelling undertaken provides an opportunity to consider more generally the influence of varying distance from port and productivity in other locations. Additional distance from port means that some key impacts such as GWP are associated with increased fuel consumption, compared to more inshore production sites. In the present case, this is to some extent mitigated by the high harvest yields at the study site, which could further improve with increasing production efficiency. Unlike other farming systems, the use of fuel and plastic materials for facility construction during the farming phase results in environmental impacts that can be mitigated by biological processes such as phytoplankton filtration and calcification. These processes lead to the sequestration of nitrogen, phosphorus, and carbon. However, while net nutrient removal in harvested biomass of bivalve shellfish is well established, with potential to reduce marine eutrophication in coastal systems, the long-term storage of carbon in shell material depends on the post-harvest pathways, and does not fully offset GWP. The impact of mussel farming on biogeochemical cycles can also vary depending on the environmental context and these conclusions must be considered alongside the site-specific nature of the analysis and the need to re-examine system boundaries when discussing long-term carbon sequestration. As offshore mussel farming becomes more widespread, it will be worthwhile studying environmental impacts over a wider range of environmental and operational conditions. The interactions between mussel farming and the surrounding ecosystem can provide additional positive environmental impacts such as habitat creation and increased biodiversity, as demonstrated by previous studies. The inability to integrate these aspects into the quantitative assessment is an inherent limitation of the LCA approach. However, it remains effective in allowing standardised comparison of food production systems and in assessment of change in

impacts as farming methods evolve. Overall, the results demonstrate that offshore mussel farming is a highly sustainable food production system, with environmental performance largely driven by operational efficiency, particularly fuel use, and potential for further impact reduction through optimisation of farming practices. This study reaffirms the high sustainability credentials of mussel farming, which provides a high-protein food source with lower environmental impacts than land-based animal production or fed aquaculture.

CRediT authorship contribution statement

Daniela Summa: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Julie Webb:** Writing – review & editing, Investigation. **Mark Walton:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Ben Winterbourn:** Investigation. **John Holmyard:** Writing – review & editing, Investigation. **Giuseppe Castaldelli:** Writing – review & editing. **Elena Tamburini:** Writing – review & editing, Supervision, Methodology, Investigation. **Lewis Le Vay:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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. Seafish provided grant funding to LLV, and supported coordination of project activities. If there are other authors, they 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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Data availability

Data will be made available on request.

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