Ocean acidification on carbonate chemical disruption and its implications for marine calcifiers and shellfish farming

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Abstract

Mollusc aquaculture is a lucrative business experiencing tremendous output growth in Europe and beyond. In recent years, there has been discourse over the extensive environmental advantages of this method of food production. An area of concern in Mollusk Aquaculture (MA) is the generation of calcareous shells ($CaCO_3$). The formation of mollusc shells has occasionally been characterized as a reservoir for atmospheric CO_2, as it sequesters carbon in a solid crystalline state. More comprehensive carbonate chemistry modeling, incorporating simultaneous variations in seawater CO_2, pH, soluble inorganic carbon, and overall alkalinity, indicates that calcification is a net CO_2 supply to the atmosphere. The discourse surrounding the inclusion of MA respiration in carbon footprint modeling suggests that more comprehensive knowledge is necessary before incorporating shellfish farming into carbon trading systems and footprint assessments. This study demonstrates that regional variations in the marine carbonate ecosystem can influence the quantity of CO_2 emitted per unit of CaCO production. The carbonate chemistry modeling indicates that a coastal mussels farm in southern Portugal emits approximately 0.3 g of CO_2 per gram of $CaCO_3$ shell produced. In contrast, a similar farm on the coastline of the Baltic Ocean would generate up to 34% more CO_2 per gram of $CaCO_3$: $CaCO_3$ g-CO_2. This regional heterogeneity must be considered if MA is incorporated into future carbon pricing systems and the manufacturing expansion strategy.

Keywords: Ocean acidification, Carbonate chemical disruption, Marine calcifiers, Shellfish farming

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Introduction

Aquaculture (Verdegem *et al.,* 2023) persistently increases its proportion of worldwide marine consumption by weight. Since marine fisheries productivity has stagnated since the 1990s, the significance of farming for the future of world food security is now widely acknowledged. Molluscs (Bita, Balouch and Mohammadian, 2021) constitute a substantial segment of contemporary aquaculture output, including around 23% of the total global yield, equating to 17.2 million metric tons by live weight in 2015. While East Asia now dominates worldwide fish production, the European Union possesses a vital sector, with the first value of sales from aquaculture reaching €4.8 million in 2013. Mollusks constituted 29% of the whole value. In along with volume of production, sustainable molluscan aquaculture is significant because: 1) it necessitates no supplementary feed or clean water; 2) it offers a highly nourishing and protein-rich food origin; 3) uncomplicated cultivation methods can eliminate the need for energy-intensive procedures; and 4) in various aspects, such as nutrient cycling, molluscan culture can be neutral or even ecologically advantageous to the ecosystem around it. Such factors are essential due to worries regarding food and energy availability, imminent freshwater limitations, and an increasing number of people. Farming of shelled mollusks is categorized as a possibly viable and low-impact "food source of the future" that is now being promoted. Recent academic and technological developments, including offshore farming, coordinated multi-trophic aquaculture, and land-based recirculating structures, present opportunities for the sector's ongoing expansion. Numerous facets of molluscan aquaculture remained inadequately researched (Ngandjui *et al.,* 2024). The comprehension of the possible environmental impacts, both beneficial and detrimental, must align with the swift expansion of this sector to ensure its long-term health (You *et al.,* 2025).

A frequently neglected feature of shelled Mollusk Aquaculture (MA) (Malešević *et al.,* 2023) is the impact of intense production on the surrounding seawater carbonate network. Climate change experts have rigorously examined carbon dioxide (CO_2), the marine carbon cycle, and Ocean Acidification (OA) (Salloum, Guo and Scanes, 2025), and academics and the aquaculture sector now acknowledge their effects on the development of calcareous-shell-producing species (Zhang, Chen and Cohen, 2010). The generation of natural calcium carbonate (CaCO), the energy requirements of the calcification procedure, and heterogeneous consumption/breathing all affect localized carbonate science, and their intricate interrelations remain poorly comprehended within the aquaculture framework (Valenza and Cheminod, 2020).

Specific stakeholders in the fishery industry have proposed that the development of shelled MA function as a CO_2 sink, facilitating the net elimination of carbon from the environment and its subsequent storage in CaCO shells (Sengupta and

Deshmukh, 2024; Reddy and Qureshi, 2024). It is firmly proven that the creation of CaCO is, in fact, a source of CO_2, which is intensified from a holistic organism viewpoint by breathing. Mollusc farming is hence a net CO_2 source procedure, as shown by a recent study unique to aquaculture. The impacts of intensive MA on carbon cycling have been examined at an ecosystem-wide level. Research indicates that differentiating between tissue and shell output in MA facilitates the incorporation of shell manufacturing into carbon trading systems by accounting for CO_2 fluxes. CO_2 emissions from tissue formation are regarded as a function of food manufacturing, whereas $CaCO_3$ shell creation is viewed as a by-product (Ravshanova *et al.*, 2024). The research utilizes a marine carbonate framework to enhance the comprehension of the alterations in carbonate chemistry, mainly linked to calcification in MA (Karo *et al.*, 2024; Kumar and Sunil, 2024).

OA often denotes the reduction in oceanic pH and the concomitant alterations in Dissolved Inorganic Carbon (DIC) (Moor *et al.*, 2022) chemical structure due to the inhalation of ambient CO_2. The ocean functions as a vast reservoir for CO_2, absorbing around 32% of anthropogenic CO_2 emissions, leading to a notable rise in OA. The acidity of the ocean's surface has grown by around 27% since 1870, leading to a pH decrease from 8.3 to 7.9. A one-unit reduction in pH signifies a tenfold escalation in acidity due to the logarithmic structure of the pH scale. As atmospheric CO_2 levels increase, the quantity of CO_2 the seawater takes will rise, leading to increased acidity (Devaki, Ramganesh and Amutha, 2024; Shimazu, 2023).

The carbon biochemistry of the seawater is defined by the percent pressure of CO_2 (pCO_2), total acidity, pH, and the amount of inorganic carbon that is dissolved, encompassing carbon monoxide, sulfuric acid, ions of bicarbonate, and calcium ions (Mitra and Shah, 2024). As acidity levels rise, carbonate ions diminish, adversely affecting species that utilize carbonate to form CaCO structures, such as corals, snails, crustaceans, and plankton (Shutler *et al.,* 2024). The predominant form of carbonate of soda utilized by organisms is agate or limestone; a reduction in carbonate leads to a diminished aragonite saturation level (Qarag) or calcite saturation status (Scal) (Vakhguelt and Jianzhong, 2023), indicating that the formation of skeletons composed of aragonite or calcite becomes actively more challenging. Additional research suggests that certain calcifying animals, like mollusks and coral reefs, preferentially utilize alternative forms of dissolved inorganic carbon (e.g., bicarbonate) over bicarbonate for calcifying, with rising proton levels exerting a greater influence on the calcium process (Müller and Dupont, 2024). The Southeast is abundant in highly profitable creatures that calcify and utilize CaCO to construct their shells and bones. Reefs composed of shellfish are predominant organisms in coastal areas and are especially susceptible to acidity (Feng, Sun and Yan, 2023; Agarwal and Yadhav, 2023).

Materials and Methods

Calcification, Breathing, and CO_2

DIC in saltwater is the total amount of aqueous CO_2 and the carbonates and calcium ions it generates through reaction. Total Alkalinity (TA) measures the ability of saltwater to retain DIC in balance with a specific ambient pCO_2. The saltwater pCO_2 can be derived from DIC and TA, representing the ambient CO_2 that would exist in balance with a particular specimen of seawater. The disparity between saltwater and ambient pCO levels is seldom zero, influencing the net direction of air-sea CO trade, where elevated seawater levels result in net CO transport from sea to air. A process that consumes DIC and/or elevates seawater TA, reducing seawater CO_2 and inducing a compensatory CO_2 flow into the ocean. This type of device is referred to as a 'CO_2 sink'. Conversely, a procedure that elevates DIC and/or diminishes TA increases seawater pCO_2. This facilitates sea-to-air CO_2 transport and can be characterized as a CO_2 'source'. Calcifying (i.e., CaCO production) consumes both TA and DIC from the ocean in a 2:1 balanced ratio. The CO source impact from TA loss surpasses the CO sink impact from DIC loss, resulting in a net rise in saltwater pCO_2, which makes it a net CO_2 source. The source's intensity can be measured as a function of the fundamental seawater biochemistry. The breakdown of CaCO enhances seawater's potential to sequester CO by elevating TA. However, the concomitant increase in DIC only partially utilizes this augmented capacity, resulting in an imbalance that can facilitate CO_2 absorption from the environment.

The magnitude of the prospective CO source induced by calcium can be evaluated using ocean temperatures, salinity, and carbonate biochemistry, utilizing the variable. It quantitatively represents the supplementary decrease in DIC necessary, about the quantity of DIC transformed into CaCO, to ensure no net alteration in seawater pCO_2. Thus, it indicates the prospective CO_2 emissions from molluscan calcium. The term 'potential' is employed because, although the introduction of DIC and TA immediately establishes the pCO_2 gradients necessary for facilitating air-sea CO_2 trade, the actual procedure of CO_2 exchange requires many months to a year to re-establish equilibrium in the surface marine mixed layer after a disturbance. The total magnitude of the CO sink resulting from CaCO dissolving is equivalent to Φ. Breathing serves as a source of CO more naturally than hardening. This mechanism emits CO into the ocean water, hence elevating DIC levels. In contrast, autotrophic activity serves as a CO_2 sink. The modest TA alterations linked to these procedures complement the DIC variation regarding their influence on the ocean as a CO_2 supplier or sink.

Results

Quantity and Price Volatility

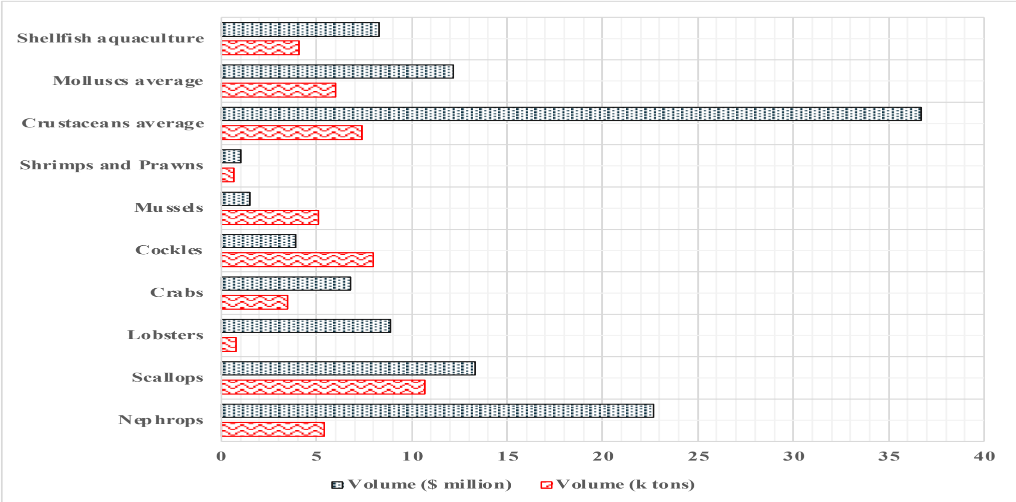

Figure 1: Production and consumption analysis.

The production and consumption of lobsters in the UK exhibit greater volatility than molluscs (Figure 1). Twenty-year statistics on production indicate that volatility is most significant for scallops in terms of volume generated. At the same time, it is highest for Nephrops regarding the value of landings. Considering that oysters and Nephrops are the predominant shellfish varieties generated, the fluctuations in quantity and value suggest that the UK is significantly vulnerable to the OA. The percentage of wild-caught oyster relative to total fishery (fin-fish + oyster) generated annually by the UK varied from 55% in Wales to 92% in England, indicating the financial significance of the shellfish industry across all areas (Figure 2).

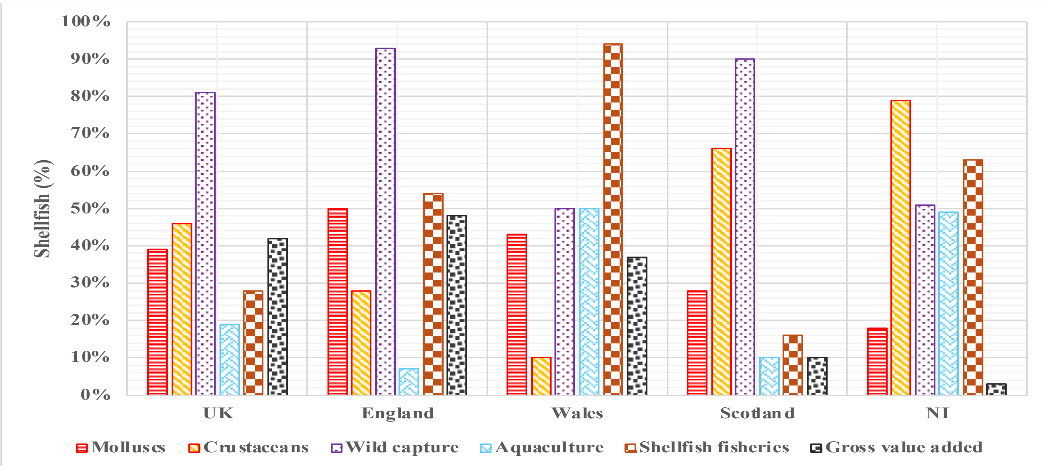

Figure 2: Shellfish production analysis.

The statistics indicate that England (52%) and Wales (41%) are more susceptible to the impacts of OA due to molluscan output. In contrast, Northern Ireland (74%) and Scotland (62%) are more at risk from crustacean development. Results indicate that of the four autonomous governments, Wales is likely to face the most significant impacts of OA, given that 92% of its aquaculture output comprises oyster. If OA similarly affects both caught in the wild and fish farming, shellfish. If the decline of shellfish harvesting corresponds to the reduction in calcification rates caused by OA, then the sea acidity will significantly affect the UK shellfish business.

Comprehensive Economic Ramifications of OA

In 2020, the value of arrivals by UK ships into UK ports was £69 billion for molluscs and £164 billion for crabs. The Net Present Value (NPV) for molluscs, corrected to current values with a 4.7% discounted rate and projected until 2150, is £1900 million, while for crustaceans it is £4500 million. This presumes the absence of alterations to the existing economic and natural circumstances.

Although projected future income deficits are less significant than present ones due to the compounded effects of rising income and investment return rates, evidence indicates that the financial impacts of OA might be considerable. The values range from £750 billion to £1500 billion for molluscs and from £1200 billion to £2800 billion for crustaceans, contingent upon the emission event and the biological reaction (Fig. 3). Utilizing region-specific OA forecasts for the British Isles, an atmospheric pCO_2 of 710 ppm in 2120, with a pH spectrum of 7.5-8.5 and an average pH of 7.9, represents a medium emissions situation. Conversely, an atmosphere pCO_2 of 1000 ppm in 2150, with a pH range of 7.2-8.5 and a center pH of 7.8, illustrates a higher emissions scenario, indicating that vessel earnings will decline by 12-29%. These reductions will not be uniformly distributed throughout the UK devolved areas. Wales is projected to incur the most significant losses from molluscan manufacturing, estimated at 15-35%, whilst Scotland faces the most crucial potential loss from crustacean collection, ranging from 23-45% of the net present value of wild-caught shellfish. Wales will be among the most significantly affected devolved governments, losing 31-57% of the entire shellfish NPV.

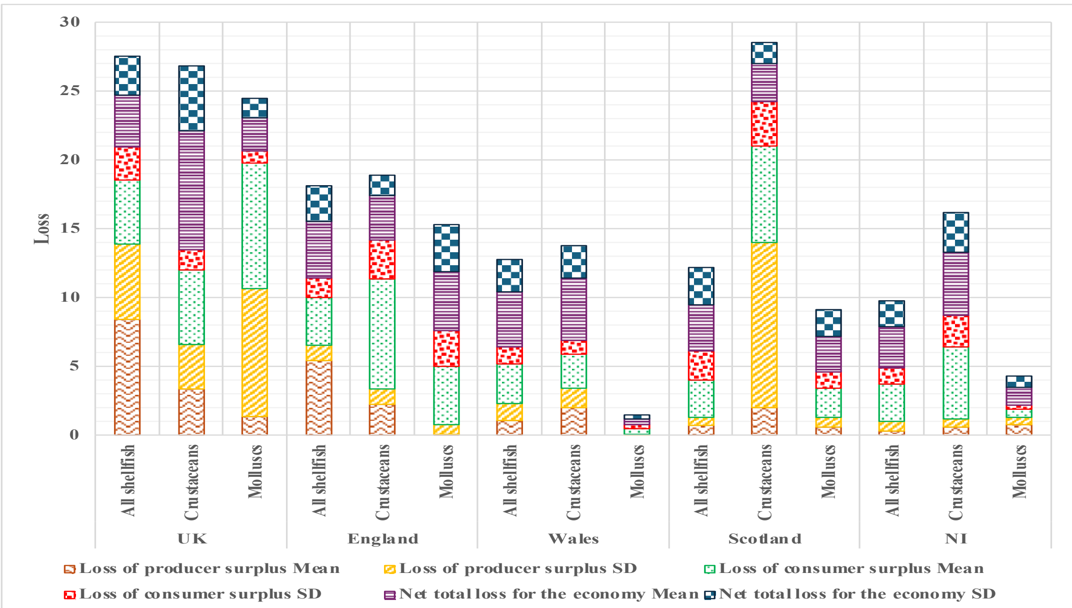

Figure 3: Production and consumption analysis of species.

Figure 3 illustrates the comprehensive possible damage to the consumer and producer surplus and the net loss for the financial system resulting from OA on shellfish output in the UK and its devolved governments. Although crustaceans are anticipated to exhibit significantly stronger resilience to OA than molluscs, the substantial production and consumption of Nephrops and brown crustaceans in the UK indicate that the overall economic losses due to OA will surpass those associated with MA. Findings suggest an average overall economic loss of £88 billion from crustacean manufacturing, as opposed to £39 billion for molluscan manufacturing and consumption. Due to the OA, England exhibits the most accumulated Gross Domestic Product (GDP) loss in shellfish manufacturing and eating among the four autonomous governments. In addition to the anticipated substantial financial losses from crustaceans manufacturing in Scotland, the declines to both manufacturers and consumers exceed for both mussels and crabs exhibit a relatively even split throughout globe.

Conclusion

The procedure of calcification, exemplified by mussels forming their $CaCO_3$ shells, serves as a net supply of CO_2 to the environment. The inherent regional diversity in ocean temperatures and the marine limestone system results in varying quantities of CO_2 emissions during $CaCO_3$ generation in various geographical regions. Initially, greater CO_2 is emitted by calcium in colder seas; in the eight study locations in Western Europe, the CO_2 produced per unit of calcium escalates by 33% from the southerly site to the highest (Baltic, Germany). Mussels' respiration releases additional CO_2. The quantity of CO released by existing mussel fields fluctuates, as various species—and even the same variety in disparate environments—generate differing amounts of CaCO while generating equivalent quantities of obtainable food. The research mainly analyzed the study's results on mussels due to their widespread cultivation in Western Europe. The results are pertinent to the broader bivalve MA sector and apply to all calcified mollusks such as oysters, scallops, and mussels. The findings hold significant consequences for assessing the possible value of shellfish farming in carbon pricing initiatives and should be considered when selecting sites for new mussel farms.

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