



AS WE SEE IT

An integrated ecosystem approach for assessing the potential role of cultivated bivalve shells as part of the carbon trading system

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ABSTRACT: The role of bivalve mariculture in the CO₂ cycle has been commonly evaluated as the balance between respiration, shell calcium carbonate sequestration and CO₂ release during biogenic calcification. However, this approach neglects the ecosystem implications of cultivating bivalves at high densities, e.g. the impact on phytoplankton dynamics and benthic–pelagic coupling, which can significantly contribute to the CO₂ cycle. Therefore, an ecosystem approach that accounts for the trophic interactions of bivalve aquaculture, including dissolved and particulate organic and inorganic carbon cycling, is needed to provide a rigorous assessment of the role of bivalve mariculture in the CO₂ cycle. On the other hand, the discussion about the inclusion of shells of cultured bivalves into the carbon trading system should be framed within the context of ecosystem goods and services. Humans culture bivalves with the aim of producing food, not sequestering CO₂ in their shells, therefore the main ecosystem good provided by bivalve aquaculture is meat production, and shells should be considered as by-products of this human activity. This reasoning provides justification for dividing up respired CO₂ between meat and shell when constructing a specific bivalve CO₂ budget for potential use of bivalve shells in the carbon trading system. Thus, an integrated ecosystem approach, as well as an understanding of the ecosystems goods and services of bivalve aquaculture, are 2 essential requisites for providing a reliable assessment of the role of bivalve shells in the CO₂ cycle.

KEY WORDS: Aquaculture · Bivalve · CO₂ · Carbon cycling · Carbon trading system

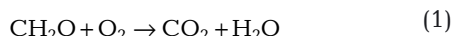
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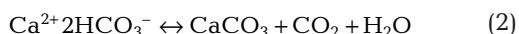
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Bivalve mariculture and the carbon cycle

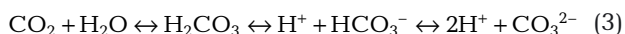
The role of bivalve mariculture in the carbon cycle is starting to generate attention in the scientific literature (e.g. Hicky 2009, Tang et al. 2011, Munari et al. 2013, Waldbusser et al. 2013), given the need to explore potential ways of stabilizing atmospheric CO₂ to control climate change (Le Quéré et al. 2009) while meeting the accelerating global demands for seafood. The role of calcifying marine organisms such as bivalves in the CO₂ budget has been commonly studied by measuring the balance between respiration and biogenic calcification (e.g. Chauvaud et al. 2003, Martin et al. 2006). The catabolism of ingested organic matter following:



and the formation of calcium carbonate (CaCO₃) by biogenic calcification:



both imply CO₂ release. These processes depend on pH, alkalinity, salinity and temperature (Millero 1995, Lerman & Mackenzie 2005, Dickson 2010, Mackenzie & Andersson 2013) and induce shifts in the seawater carbonate system:



The balance between respiration, shell calcium carbonate sequestration and CO₂ release in biogenic calcification has been used to suggest the role of several invasive molluscs as CO₂ generators (e.g. Chauvaud et al. 2003, Martin et al. 2006, Mistri & Munari 2013). Recently, Munari et al. (2013) applied the same concept (Fig. 1) to conclude that mussel farming is a significant additional source of CO₂ to seawater, and thus shell formation cannot be part of the carbon trading system.

We are concerned about the application of this approach to cultured populations, which are farmed and harvested with the aim of providing a key coastal ecosystem service, i.e. high-quality protein for human consumption. Specifically, there are 2 aspects that should be included in the discussion to evaluate the inclusion (or not) of shells from cultured bivalves in carbon trading systems: (1) an ecosystem approach, considering the effects of cultured populations and not the budget of a single individual, is needed to assess the bivalve's role in the carbon cycle, and (2) this holistic approach should also consider that bivalves are a combination of tissue and shell, both of which require energy expenditure for maintenance and growth; consequently, the CO₂ released through

respiration should be proportionally split between both components. Therefore, it is critical that any assessment of the inclusion of bivalve shells in carbon trading systems, which requires a specific CO₂ budget for shells and not for the whole organism, also considers the division of CO₂ fluxes between shell and tissue. Finally, indirect effects of bivalve culture on the ecosystem, such as mitigation of eutrophication and enhancement of primary production through increased water clarity and nutrient turnover, should be also considered, given their potential effects on the CO₂ cycle.

Ecosystem approach: the need for an integral analysis

The cultivation of bivalves at high densities can exert a significant effect on flows of matter and energy in coastal marine ecosystems (Dowd 2003) (Fig. 2). The most obvious effect of introducing a large biomass of filter-feeders is related to phytoplankton. Bivalve filtration activity may exert a top-down control of phytoplankton populations (Dame 1996, Dame & Prins 1998, Escaravage & Prins 2002, Newell 2004, Prins & Escaravage 2005, Petersen et al. 2008), to the extent that phytoplankton depletion can compromise bivalve performance when cultured at high densities (Bacher et al. 2003, Ferreira et al. 2007, Duarte et al. 2008, Rosland et al. 2011) and under certain hydrodynamic conditions (Aure et al. 2007, Saurel et al. 2013). During the feeding process, phytoplankton and particulate organic matter are consolidated into pseudofaeces (un-ingested), and faeces (undigested), which sink to the bottom and redirect part of the pelagic energy flow towards benthic food webs (Newell 2004). Remineralization of nutrients in pseudofaeces and faeces in the water column and mostly in the benthos (Grant et al. 1995,

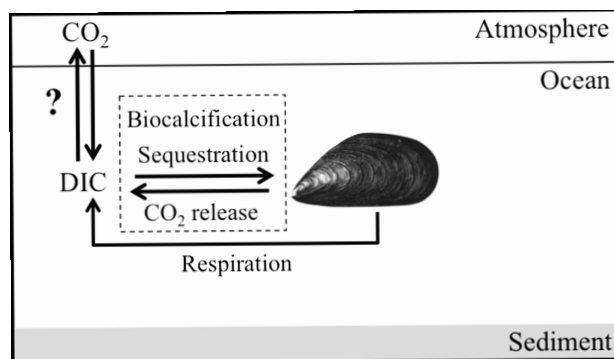


Fig. 1. Chemical approach to the inorganic carbon cycle in mussel culture. DIC: dissolved inorganic carbon

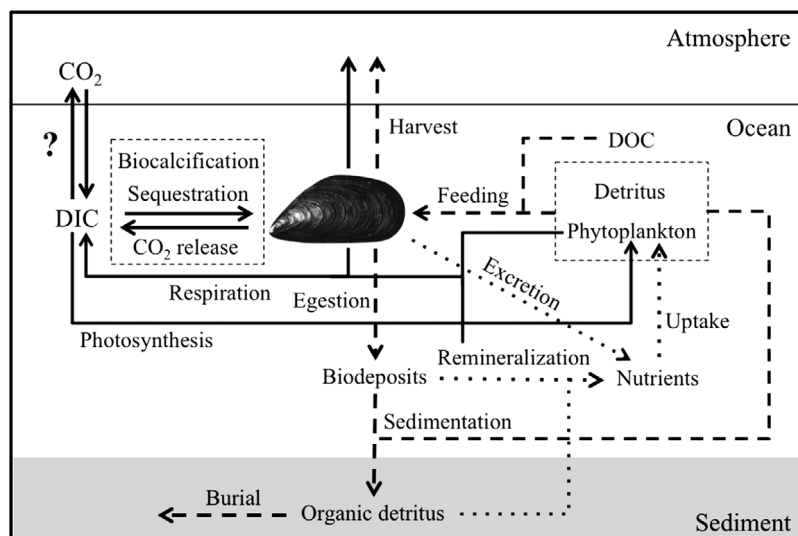


Fig. 2. Ecosystem approach to carbon cycling (continuous and dashed lines for inorganic and organic carbon, respectively) and feedbacks of mussel aquaculture on the pool of inorganic nutrients (dotted line). DOC (DIC): dissolved (in)organic carbon

Newell 2004, Carlsson et al. 2010, Jansen et al. 2012), as well as bivalve ammonia excretion, can accelerate the nitrogen cycle (Dame et al. 1991, Cranford et al. 2007). The ecological significance of nutrient regeneration consists of a relaxation of nutrient limitation for phytoplankton, which may result in enhanced primary production (Smaal 1991, Prins et al. 1995). Therefore, cultured shellfish can also exert a bottom-up nutrient control on phytoplankton populations (Ogilvie et al. 2000, Cranford et al. 2007, Trottet et al. 2008, Froján et al. 2014), which is considered to be an important feedback of bivalves on their own food source (Smaal et al. 2001). The remineralization of pseudofaeces and faeces also releases CO₂ and alters benthic–pelagic coupling, processes that should be accounted for in an ecosystem approach.

The interactions between bivalves, carbon flow and nutrient cycling are complex, and understanding the magnitude of direct and feedback interactions between cultured populations and phytoplankton, particulate organic carbon, dissolved organic carbon and nutrient dynamics is crucial for understanding the inorganic carbon budget. As mentioned above, bivalve grazing can have a top-down effect on phytoplankton growth and production, particularly in light-limited systems, by decreasing turbidity, continuously grazing larger algal cells, and facilitating a shift to faster growing algal species (Prins et al. 1995). In nutrient-limited systems, bivalves exert a bottom-up control on the phytoplankton by retaining nutrients in the system and increasing the rate of nutrient

cycling and consequently nutrient availability (Dame et al. 1991, Smaal 1991). For example, mesocosm studies with the clam *Mercenaria mercenaria* show that a relatively low abundance of clams can double primary production and alter phytoplankton community structure (Doering & Oviatt 1986, Doering et al. 1989). The progressive increase of bivalve retention efficiency from small to large particles (Strohmeier et al. 2012) can also result in increased picophytoplankton abundance (Olsson et al. 1992, Vaquer et al. 1996, Cranford et al. 2008, Froján et al. 2014) with related effects on the local rate of carbon uptake by phytoplankton. As bivalve populations increase to high levels, a point will eventually be reached where grazing on phytoplankton begins to reduce primary production, and consequently CO₂

uptake by phytoplankton (Smaal et al. 2013). In addition, local ecosystem characteristics can exert critical effects on carbon budgets. For example, in deep fjord-type systems, the sedimentation of aquaculture wastes would transfer carbon to deep waters, potentially reaching the sediment (Sepúlveda et al. 2005), which can be considered as a carbon storage compartment. On the other hand, vertical fluxes of organic matter towards the seafloor in shallow environments may, depending on bivalve stocking and hydrological conditions, significantly affect habitat characteristics and infaunal communities in the vicinity of the farm (e.g. Mirto et al. 2000, Hargrave et al. 2008, Cranford et al. 2009, Guyondet et al. in press), concomitantly affecting benthic–pelagic coupling and the CO₂ cycle. This local variability is also reflected in the differential fluxes of CO₂ between estuaries and the atmosphere depending on estuarine topography, hydrodynamics, terrestrial organic carbon budget and magnitude, and stoichiometry of nutrient inputs (Laruelle et al. 2010, Bauer et al. 2013). In addition, bivalve anaerobic metabolism (de Zwaan & Wijsman 1976), which depends on local conditions and/or culture technique (intertidal vs. subtidal), may also affect CO₂ fluxes. Therefore, a rigorous assessment of the role of bivalve aquaculture in the CO₂ budget should be based on an ecosystem approach that accounts for the complex trophic interactions involving dissolved and particulate organic and inorganic carbon cycling, as well as local and seasonal variability.

Ecosystem services: attributing respired CO₂ to tissue or shell

According to the most recent predictions, the world's current human population of 7.2 billion is projected to reach 9.6 billion by 2050 (UN 2013). Constraints on the availability of freshwater and land plants and animals to feed this projected population increase can be overcome by enhancing the contribution of the ocean to food production (Duarte et al. 2009). This contribution must be achieved by (1) the recovery of wild fisheries and adjusting the global fishing effort to sustainable levels (Pauly et al. 2002), and (2) farming the ocean while maintaining environmental health and sustainability (Marra 2005, Byron & Costa-Pierce 2013). The need for supplemental feeds to grow farmed species is one of the major constraints to aquaculture development (FAO 2012), and one of the challenges to improving aquaculture sustainability (Naylor et al. 2000). However, one-third of the world's farmed seafood harvested from animals in 2010 was achieved without the use of feed, through the production of animals from the second trophic level: bivalves (14.2 million tonnes, 23.6% of world aquaculture production) and filter-feeding carp (9.6 million tonnes) (FAO 2012). In detail, 89% of global production of marine bivalves (clams, cockles, mussels, oysters and scallops) came from aquaculture in 2012 (www.fao.org/fishery/statistics/en). Consequently, the main ecosystem good provided by shellfish aquaculture is meat production, and shells should be considered by-products of this human activity. Therefore, it is important to independently quantify the role of tissue and shell in the CO₂ cycle.

Most of the energy consumed by bivalves is invested in maintenance, tissue growth, and reproduction rather than shell growth, the energetic cost of which is limited to producing the conchiolin matrix that allows precipitation and shell formation. There are not strong conclusions in the literature regarding the fraction of total energy that is invested in this matrix, in part because any estimation is highly dependent on environmental conditions such as salinity and temperature. Hawkins & Bayne (1992) estimated that *Mytilus edulis* could spend more than 20% of the energy that is available for growth (Scope For Growth; Winberg 1960) on shell formation. This matches the calculations of Duarte et al. (2010), who estimated that *Mytilus galloprovincialis* could invest an average of 20 to 28% of the energy that is available for growth in shell formation. In addition, mussels invest differing amounts of energy into shell for-

mation in different habitats (Rodhouse et al. 1984). In intertidal and bottom culture, mussels invest more of the energy that is available for growth towards producing relatively thick shells compared to mussels cultivated in suspended structures, which could be related to feeding conditions (Aldrich & Crowley 1986), hydrodynamics (Steffani & Branch 2003) and predation pressure (Lowen et al. 2013). As explained above, in the same way that not all the energy consumed by mussels is used for shell formation, not all the CO₂ released through respiration should be attributed to shell formation. It is critical to split this CO₂ flux between tissue and shell, because the ultimate goal is to determine the potential inclusion of shells rather than whole cultured individuals in the carbon trading system. This reasoning is based on the assumption that humans culture bivalves with the aim of producing food, not sequestering CO₂.

In addition to food production, we cannot ignore other ecosystem services provided by farmed bivalves, beyond the discussion of carbon credits. One of the most important is the regulation of nutrient levels in coastal areas. Bivalves can be farmed in hyper-eutrophic coastal waters, which are prone to intense and harmful phytoplankton blooms. Feedbacks brought about by the grazing activity of farmed bivalves may reduce the intensity and duration of blooms, controlling the nitrogen cycle. Thus, bivalves have been suggested as a mitigation tool for coastal eutrophication (Rice 2001, Lindahl 2011, Petersen et al. 2014, Guyondet et al. in press; but see Cranford et al. 2007). Bivalve farming also plays an important role in benthic restoration (Dumbauld et al. 2009). Overall, 85% of oyster reefs have been lost globally (Beck et al. 2011), and dredging natural populations of mussels is still an ongoing fishery that, as with all dredging activities, may cause harmful impacts on benthic environments (e.g. Jennings & Kaiser 1998). Bivalve aquaculture can mitigate the pressure on these natural populations (Carranza et al. 2009, Dolmer et al. 2012), but may also represent a form of restoration of ecosystem services previously provided by overfished wild populations. Although shading from farming structures at the local scale can reduce light availability and consequently primary productivity (Skinner et al. 2014, M. Froján et al. unpubl. data), bivalve filtration activity can increase water clarity at the ecosystem level. The increase in light penetration and/or sediment nutrient enrichment promoted by cultured bivalves can also enhance the productivity of seagrass in shallow coastal ecosystems (Peterson & Heck 2001, Carroll et al. 2008), which may become an important carbon sink

(Duarte et al. 2013). A recent study conducted in Atlantic Canada showed a positive relationship between farmed oyster biomass and eelgrass, *Zostera marina*, biomass (A. Locke pers. comm.). The restoration of these services, e.g. water clarity and habitat, may also have effects on the CO₂ cycle. Another effect on habitat is related to the deployment of 3-dimensional physical structures in the ocean, which can provide refuge from predators and/or provide food sources for different species (McKindsey et al. 2011), ultimately altering species assemblages (Gibbs 2004), which can impact CO₂ fluxes. Therefore, the contribution of shellfish aquaculture to the CO₂ cycle and the associated implications on carbon trading systems must be viewed from a broad perspective, without neglecting to account for the provision of other ecosystem services. In fact, a comprehensive approach to the CO₂ budget must also include a life-cycle analysis of the commercialized product, as has been done for terrestrial farming (e.g. Smith et al. 2008, Garnett 2009), but that is beyond the scope of this study.

In conclusion, the balance between respiration, shell calcium carbonate sequestration and CO₂ release in biogenic calcification provides the most significant fluxes of the CO₂ budget in calcifying marine organisms from a chemical standpoint. Nevertheless, a comprehensive analysis of all forms of carbon, as well as significant ecological relationships, feedbacks, and habitats, are required to rigorously quantify the role of cultured bivalves in the CO₂ budget of coastal ecosystems. In addition to the need for an ecosystem approach, it is also important to understand the main role of shellfish aquaculture as providing food, i.e. a source of high-quality protein for human consumption. In this comment, we have not attempted to quantify the net contribution of bivalve aquaculture as a source or sink of CO₂, a determination that would be highly dependent on seasonality and local characteristics such as farming practices, temperature, phytoplankton populations, nutrients, and potential ecological feedbacks. On the contrary, we wish to highlight the need for an ecosystem approach to quantify the role of bivalve aquaculture in the CO₂ budget and, perhaps even more importantly, the need to understand that bivalve shells and not the whole bivalve (tissue and shell) are the potential product to be included in the carbon trading system. Accordingly, given that a specific CO₂ budget for shells rather than for the whole organism is required to evaluate the potential inclusion of shells in the carbon trading system, the CO₂ released in respiration for the whole individual (Eq. 1) must be proportion-

ally split between tissue and shell to construct this specific CO₂ budget for shells. Thus, an integrated ecosystem approach as well as an understanding of bivalves as a combination of tissue and shell are 2 essential requisites for providing a reliable assessment of the potential of bivalve shells as part of the carbon trading system.

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