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Carbon Budgeting as a Tool for Carbon Credit Generation in Sustainable Aquaculture

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Abstract

Aquaculture is the second-fastest growing food production sector worldwide, providing critical aquatic food products to meet increased demand in the international market for seafood. The GHG emissions created from aquaculture operations can be attributed to several sources, including the energy used during the production of feed, the energy needed to operate the farm and the energy used in fuel consumption and waste disposal. Researchers can calculate the total greenhouse gas emissions associated with an aquaculture operation using the carbon budget method and determine the total environmental impact of those operations. Carbon accounting is an innovative way for aquaculture to create a market for carbon credits when it reduces carbon emissions. This paper presents two methods for estimating carbon emissions from feed consumption, electrical consumption and fuel consumption using simple calculation methods. The authors explore how sustainable aquaculture systems such as integrated multi-trophic aquaculture systems, renewable energy use and environmentally sustainable feed production will provide potential carbon credits for aquaculture producers. By participating in carbon markets and trading systems, organizations are financially compensated for their efforts to help mitigate climate change through reduced emissions. The integration of a carbon budgeting with a carbon credit system provides aquaculture systems to adopt and implement environmentally sustainable operating practices with corresponding economic benefits.

Keywords: Carbon budgeting, Carbon credits, Aquaculture sustainability, Carbon footprint, Greenhouse gas emissions

Introduction

Aquaculture has developed into the most rapidly expanding food production industry throughout the world while it serves as an essential component for maintaining global food security because wild fish populations continue to decline and people consume more seafood (FAO, 2022). The fast growth of aquaculture operations has created environmental problems because these activities produce greenhouse gas emissions through their feed production processes, energy needs, fuel consumption and waste decomposition activities (Li *et al.*, 2025). The activities produce various gases including carbon dioxide, methane and nitrous oxide which all contribute to climate change.

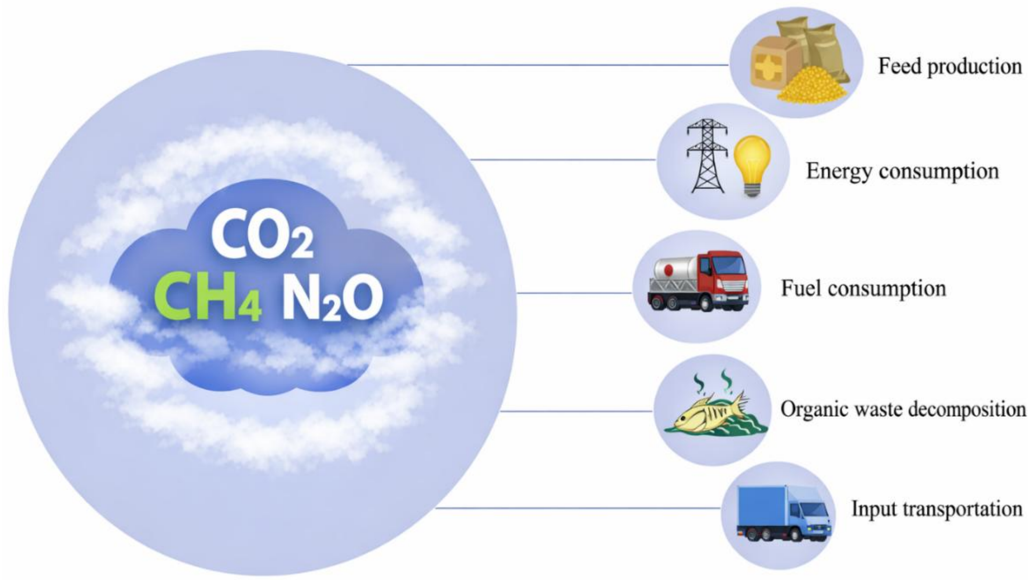

Figure 1. Sources of Greenhouse gases in Aquaculture

The main greenhouse gas emissions in aquaculture systems come from two sources which include feed production and energy consumption (Li *et al.*, 2025; MacLeod *et al.*, 2020). The anaerobic process in aquaculture ponds enables microbial decomposition of organic waste to generate both CO_2 and methane emissions (Boyd *et al.*, 2010). The Paris Agreement together with other global initiatives aims to limit global warming under 2 °C while reaching 1.5 °C as the ideal target for climate change mitigation (UNFCCC, 2015). The target requires all production sectors including aquaculture to reduce their greenhouse gas emissions by significant amounts. The carbon footprint serves as an essential concept for environmental impact assessment because it calculates total greenhouse gas emissions which occur throughout a product's or activity's entire production process (Wiedmann & Minx, 2008). Aquaculture carbon footprint analysis uses Life Cycle Assessment (LCA) to measure emissions throughout the complete production process which consists of feed production,

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farming operations, processing and transportation (Li *et al*., 2025). The framework allows organizations to treat carbon credits and carbon markets as vital financial tools which assist them in reducing emissions while advancing sustainable aquaculture practices.

Carbon Credits and Carbon Trading

A carbon credit serves as proof that one metric tonne of carbon dioxide equivalent (CO_2-e) has been removed from the atmosphere (IPCC, 2021). The carbon markets allow organizations to sell their excess credits which they earned through emission reductions that exceed mandatory requirements to entities that have surpassed their permitted emission levels. The cap-and-trade system stands out as the most prevalent carbon pricing system because it enables governments to establish total emission limits while allowing emission permit trading (Stavins, 2008). Companies receive or purchase emission allowances and must ensure that their total emissions do not exceed the allocated limit. Companies can sell to other organizations the permits that are left if they manage to cut down on emissions. Multiple regions operate carbon trading markets which include the European Union Emissions Trading System (EU ETS) (European Commission, 2023) and similar systems in countries such as China, Japan, Canada, South Korea and New Zealand.

The process of carbon offsetting functions as a carbon credit mechanism that allows organizations to achieve their carbon reduction goals through emissions cuts at one site which balance out their total emissions from other sites (Schneider *et al*., 2019). Carbon offsets typically support projects that reduce greenhouse gases through initiatives that include renewable energy projects, energy-efficiency improvements and ecosystem restoration. The implementation of these mechanisms in aquaculture systems would provide financial incentives that encourage farmers and companies to implement both low-carbon technologies and sustainable farming methods.

Carbon Credit Opportunities in Aquaculture

Aquaculture practices have the ability to create carbon credits because they decrease greenhouse gas emissions and they enhance carbon dioxide absorption through their operations.

1. **Integrated Multi-Trophic Aquaculture (IMTA)**

The Integrated Multi-Trophic Aquaculture (IMTA) system demonstrates two benefits by using one species' waste as feed for another species to create better waste management and decreased environmental damage (Chopin *et al*., 2012). The system allows simultaneous cultivation of finfish, seaweeds and shellfish. Seaweeds absorb dissolved nutrients and carbon dioxide through photosynthesis, while shellfish filter organic particles from the water. The system demonstrates two benefits by creating better waste management operations and decreasing environmental damage. The IMTA systems achieve high nutrient retention performance because they can absorb most carbon and nutrients which exist in aquaculture feed materials. Aquatic plants provide an effective method for oceanic carbon storage because seaweeds through photosynthesis process absorb carbon dioxide and convert it into biomass which they store (Duarte *et al*., 2017).

2. Sustainable Feed Development

In regards to the impact on aquaculture's carbon footprint, feed production has been noted as one of the highest contributors to aquaculture's negative impact (Li *et al*., 2025). While many current feed production methods have been used for years (such as fish meals), there are several new options available to producers, including the use of plant-based ingredients, insect meal and microbial proteins. These sustainable feed innovations will potentially reduce carbon emissions associated with the production of feeds. Aquaculture may also reduce its overall carbon footprint by using two different approaches to reducing the carbon associated with producing feed, including decreasing feed conversion ratios (FCR) and improving feed utilization efficiency.

3. Energy-Efficient Aquaculture Systems

Energy is used to provide aeration to aquaculture systems, to circulate water through aquaculture systems and to pump water into aquaculture systems; as a result of this use of energy, aquaculture systems contribute significantly to greenhouse gas emissions (Boyd and McNevin, 2015). By using alternative, renewable energy sources (e.g., solar, wind) to run the equipment used in aquaculture facilities, producing aquaculture will also contribute to reducing greenhouse gas emissions leading to energy-efficient aquaculture systems. By managing their resources properly, aquaculture facilities allow for the sustainable production of aquaculture through greater efficiency in resource utilization while promoting the sustainable operation of aquaponics (aquaculture and hydroponics), biofloc technology and recirculating aquaculture system (RAS).

Feed production represents one of the largest contributors to aquaculture’s carbon footprint (Li *et al*., 2025). Sustainable feed innovations, such as plant-based ingredients, insect meal and microbial proteins, can significantly reduce emissions associated with feed manufacturing. Aquaculture production can reduce its carbon emissions through two methods which involve decreasing feed conversion ratios (FCR) and making feed consumption more effective.

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4. Ecosystem-Based Aquaculture

The implementation of nature-based aquaculture solutions through mangrove restoration and seaweed farming leads to enhanced carbon sequestration and additional ecosystem benefits. The restoration of coastal ecosystems that support aquaculture activities enables the storage of substantial carbon quantities within sediments and vegetation which assists in long-term climate change mitigation efforts.

Carbon Budgeting in Aquaculture

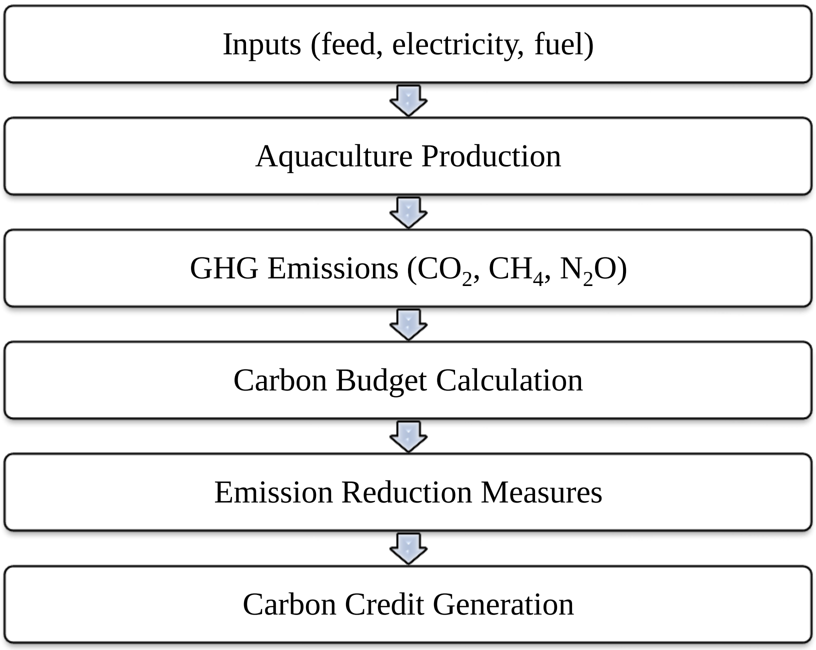

Figure 2. Conceptual framework of carbon budgeting and carbon credit generation in aquaculture systems.

Aquaculture produces carbon emissions, which can be assessed using carbon budgeting techniques (Li *et al.*, 2025). Major sources of emissions from aquaculture production are typically feed production, electricity and fuel consumption.

Activity	**Unit**	**Emission Factor**	**Source**
Electricity consumption	kWh (kilowatt-hour)	0.82 kg CO_2 / kWh	IPCC
Diesel consumption	litre	2.68 kg CO_2 / litre	IPCC
Petrol consumption	litre	2.31 kg CO_2 / litre	IPCC

Aquafeed production	kg feed	1.5 – 3.0 kg CO_2 / kg feed	Life Cycle Assessment (LCA) studies

Table 1. Emission factors used for estimating carbon emissions from aquaculture inputs

A. Feed Carbon Emissions

CO_2 emission (kg) = Feed usage (kg) × Emission Factor

Typical emission factor = 1.5-2.0 kg CO_2 per kg feed

Example:

Feed usage = 1000 kg

CO_2 emissions = 1000 × 1.5-2.0 = 1500-2000 kg CO_2

B. Carbon Emissions from Electric Power

Carbon dioxide is produced as a result of electric power generation and consumption. The CO_2 emissions within this section can be found by using the following calculation:

CO_2 emission (kg) = Electricity usage (kWh) x Emissions Factor

The estimated amount of carbon dioxide emissions from 1 kWh of electricity generated in India is approximately 0.82kg of CO_2 (IEA, 2022).

Example:

Electricity usage = 500kWh

CO_2 emissions = 500 x 0.82 = 410kg CO_2

C. Carbon Emissions from Fuel

Carbon dioxide can be produced through the use of fossil fuels for motor vehicles and other kinds of equipment. CO_2 emissions for fuel can be calculated using the following formula:

CO_2 emission (kg) = Fuel used (litres) x Emission Factor.

The estimated emissions from fuel can also be determined by using common emission factors applied to greenhouse gas emissions across various emissions accounting methods and frameworks. The emission factor for diesel fuel is approximately 2.68 kg of CO_2 from burning each litre, while the emission factor for petrol is approximately 2.31 kg of CO_2 per litre of fuel

(IPCC, 2019).

Example:

Fuel used = 100 litres diesel

CO_2 emissions = 100 x 2.68 = 268kg CO_2

Total Carbon Footprint

The total carbon footprint for the feed is calculated by adding all three types of carbon dioxide emissions, which include feed, electric power/energy and fuel emissions. The formula for this is as follows:

Total CO_2 = Feed CO_2 emissions + Electric CO_2 emissions + Fuel CO_2 emissions

Example:

Feed CO_2 emissions = 1800kg

Electric CO_2 emissions = 410kg

Fuel CO_2 emissions = 268kg

Total CO_2 = 1800 + 410 + 268 = 2478kg

Carbon Credit Calculation

Calculating carbon credits allows for the measurement of greenhouse gases that a project will reduce versus that of a baseline scenario. It measures what the emission levels would be if there was no sustainable practice implemented within a project and compares those emissions against the total emissions produced after the implementation. The end difference will equal a volume of carbon credits, where each carbon credit is equivalent to one metric ton of CO_2 emissions (known as CO_2 equivalents).

The calculation of the Carbon Credit award would be as follows:

Carbon credit = Baseline emissions − Actual emissions

{1 Carbon Credit = 1 Metric ton of CO_2 equivalent}

Example: Baseline Emissions = 5 Metric tons of CO_2.

Actual Emissions = 3 Metric tons of CO_2.

The project would have generated 2 Metric tons of CO_2 carbon credit(s).

Benefits of Carbon Credit Systems in Aquaculture

Implementing a carbon credit system for aquaculture has numerous advantages to the aquaculture sector with respect to environmental, economic, and social aspects of the aquaculture sector. The carbon credit system encourages producers to implement sustainable practices, thereby reducing greenhouse gas (GHG) emissions while improving the efficiency and environmental performance of their operations.

1. **Promote the use of low-carbon technologies:** Producers will be encouraged to adopt low-carbon technologies (e.g., energy-efficient aerators) will be encouraged to be used by

the producer and/or producer's farm through the implementation of low-carbon technologies to reduce GHG emissions from aquaculture operations.

2. **Provide financial incentives for sustainable aquaculture practices:** Anyone who participates in sustainable aquaculture practices will have the opportunity to earn carbon credits for the reduction of emissions as well as a marketplace for carbon credits.
3. **Assist climate and climate change mitigation:** The overall GHG emissions from aquaculture production will be reduced, which will contribute to a reduction in GHG emissions and assist global and national initiatives to limit global warming.
4. **Encourage advances in feed development and use, energy efficiency and farming systems:** A complete range of innovative technologies will be the introduced for example: biofloc systems, IMTA systems, RAS systems, alternative sustainable feed.
5. **Enhance the public perception of aquaculture and provide better environmental sustainability for the aquaculture industry:** Producers will enhance their image and demonstrate responsible resource use and pollution, GHG reductions and strengthen consumer confidence in responsible aquatic product production.

Challenges and Future Prospects

The implementation of carbon credit systems in aquaculture faces multiple obstacles despite its potential benefits. The carbon markets maintain their credibility through the accurate assessment and verification process which establishes greenhouse gas emissions (IPCC, 2021). The effective implementation process requires organizations to establish dependable monitoring systems with unified carbon accounting standards and open reporting frameworks. The diverse aquaculture systems which range from small-scale ponds to large offshore farms create challenges for establishing standard carbon accounting procedures. The carbon budgeting approaches need to be customized according to the specific requirements of different aquaculture systems.

The ongoing research efforts in carbon footprint evaluation together with the development of sustainable aquaculture technologies will enable aquaculture to enter international carbon markets.

Conclusion

Aquaculture makes an important contribution to global food supply, but it can also produce greenhouse gases from energy use, feed production and waste decomposition. Carbon budgeting is a method to quantify emissions associated with aquaculture activities. When combined with carbon crediting systems, these calculations can promote the use of climate-friendly practices in aquaculture, as well as motivate businesses to implement emission

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reduction measures. Sustainable aquaculture practices (e.g., integrated multi-trophic aquaculture, adoption of renewable energy sources, development of sustainable feeds, ecosystem restoration), can be effective ways for the aquaculture industry to decrease its carbon footprint. As climate change policies continue to evolve, there may be potential for aquaculture to be incorporated into carbon crediting markets in order to contribute to both environmental sustainability and economic resilience within the aquaculture sector.

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