MARINE AQUACULTURE AS A TOOL FOR CLIMATE MITIGATION

A summary of the current state of the science

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Table of Contents

Key Messages

- The Paris Climate Agreement called for efforts to limit global warming to 1.5°C above pre-industrial levels. To meet this goal, we must reach net zero global carbon emissions by 2050 (IPCC, 2018).

- Human population is projected to reach 9.7 billion by 2050 (United Nations, 2019) and the global demand for meat will rise by 73-88% (FAO, 2011; Searchinger, 2018).

- Several papers and reports published in the last three years call for future meat production to shift away from terrestrial livestock and towards seafood, which is more climate-friendly than most other meat products (Searchinger et al., 2018; Irz et al., 2018; Froehlich et al., 2018; Costello et al., 2019; Hoegh-Guldberg et al., 2019; Willet at al., 2019; Dundas et al., 2020; Capron et al., 2020).

- Life cycle assessment (LCA) is a method used to quantify the environmental impacts of food systems. Impact categories can include energy use, greenhouse gas (GHG) emissions, land use, water use, biodiversity impacts, etc. per functional unit of protein produced. Various LCA studies published in the last three years suggest that the GHG emissions from aquaculture production are comparable to emissions from poultry and pork production and significantly lower than production of ruminants like beef, sheep, and goats (Bohnes et al., 2018; Hilborn et al., 2018; Capron et al., 2020; MacLeod et al., 2020).

- Wild capture fisheries production peaked in the mid-1990s and has remained relatively steady in the decades since then. Any significant increase in seafood production will need to come from aquaculture, which is the fastest-growing global food sector (FAO, 2020).

- Well-managed marine aquaculture development could increase the resiliency of our food system to future environmental, social, and economic shocks, including the impacts of climate change (Griffis and Howard, 2013; Troell et al., 2014; Gentry et al., 2017; Cottrell et al., 2019; Capron et al., 2020).

- Certain types of marine aquaculture, such as seaweed farming, have the potential to sequester carbon and may be used as a tool to mitigate global warming by removing CO_2 and from the atmosphere (Krause-Jensen and Duarte, 2016; Duarte et al., 2017; Froehlich et al., 2019).

- In addition to carbon sequestration, marine aquaculture can provide other ecosystem services such as improving water quality, regulating ocean acidification, protecting coastlines, providing habitat for other species, and more (Froehlich, Gentry, and Halpern, 2017; Van der Schatte Oliver et al., 2018; Alleway et al., 2018 Gentry et al., 2019.

Introduction

Scope of report

The 2015 Paris Climate Agreement called for efforts to limit global warming to well below 2.0°C above pre-industrial levels, with an ideal target of no higher than 1.5°C above pre-industrial levels. In 2018, the Intergovernmental Panel on Climate Change (IPCC) published a landmark report that detailed the emissions reductions necessary to meet this 1.5°C goal. According to this report, global net anthropogenic CO_2 emissions must decline by 45% from 2010 levels by 2030 and must reach net zero by 2050 (IPCC, 2018). As of April 2021, 190 nations and the European Union are parties to the Paris Agreement and are working towards eventual net zero emissions. This includes the United States. Just this month, President Biden invited 40 world leaders to his Leaders Summit on Climate to discuss the urgency and economic benefits of stronger climate actions.

This report explores the climate impacts of marine aquaculture against this backdrop of climate mitigation as a global and domestic priority. It is based on a series of interviews with scientists and marine aquaculture experts and a comprehensive review of existing scientific literature (peer-reviewed studies, white papers, and government reports, etc.) related to the climate impacts of farming finfish, shellfish, crustaceans, and seaweeds. Particular attention was paid to papers and reports published in the last decade; many were published in just the last three years. The goal of this report is to present the state of the science, synthesize the existing literature, and summarize key themes.

Defining marine aquaculture

Aquaculture is the farming of aquatic organisms, including finfish, mollusks, crustaceans, and seaweeds. Most aquaculture farms are in freshwater, in ponds, rivers, and other inland water systems; 62.5 percent of the world's aquaculture production comes from freshwater systems (FAO, 2020). The rest comes from marine aquaculture, or mariculture, which is done in ocean waters. Marine aquaculture farms can be in shallow coastal waters or many miles offshore. They may use net pens, submersible cages, lines tethered to the seafloor, or a myriad of other farming methods.

Aquaculture is the world's fastest growing food sector and currently provides just over half of the seafood consumed globally. According to the Food and Agriculture Organization of the United Nations, wild capture fisheries production–fish and other seafood caught in the ocean and freshwater systems–peaked in the mid-1990s and has remained level in the decades since then (FAO, 2020). During that time, aquaculture production has increased to meet the growing seafood demand (Fig 1).

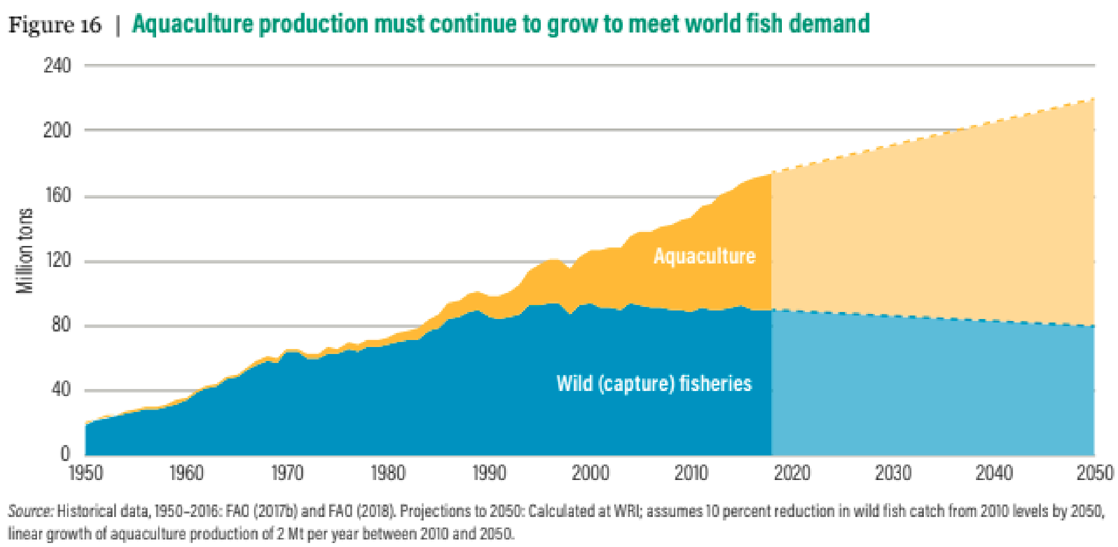


Figure 1. Wild capture fisheries and aquaculture production from 1950-2018; projected production through 2050 (FAO, 2020)

Given aquaculture's current and projected contributions to the global food system, questions have been raised about its impacts on the environment and climate. It has been the focus of many research studies, especially in recent years, though many questions remain. Here, we focus on just one of them: How does marine aquaculture fit into the climate change conversation?

Four themes emerged from a review of the scientific literature: (1) marine aquaculture can produce climate-friendly protein to feed a growing population while producing fewer emissions than land-based protein production, (2) marine aquaculture development can increase the resiliency of the global food system to environmental shocks including the impacts of climate change (3) certain types of marine aquaculture have the potential to mitigate global warming by sequestering carbon, and (4) in addition to carbon sequestration, marine aquaculture can provide other ecosystem services and help boost resilience of coastal ecosystems.

Potential Climate Benefits of Marine Aquaculture

Marine aquaculture as a climate-friendly protein source

As nations work to reduce carbon emissions, human population continues to grow. The United Nations predicts that in 2050, the year that global emissions should reach net zero, the world population will be about 9.7 billion (United Nations, 2019). This population increase—which will add about 2 billion people to the current population—will require a significant increase in global food production. Global demand for meat protein alone is expected to increase by about two-thirds; exact estimates range from 73-88% (FAO, 2011; Searchinger, 2018). Given that agriculture and associated land use currently accounts for about a quarter (24%) of global greenhouse gas emissions, meeting the increased demand for meat and other food products while also reducing emissions presents a challenge (IPCC, 2014). Several high-profile reports have discussed this challenge and presented potential ways to address it.

One such report, published by the World Resources Institute, World Bank Group, and United Nations in 2018, focuses on opportunities and policies for meeting food, land use, and GHG emissions goals in 2050 (Searchinger et al., 2018). One of its five top-line recommendations is to increase fish supply through improved wild fisheries management and aquaculture. It notes that wild capture production has peaked, and that future supply of fish and seafood will increasingly need to come from aquaculture production.

Another report, published by the EAT-Lancet Commission in 2019, brought together 37 leading scientists from around the world to answer the question "Can we feed a future population of 10 billion people a healthy diet within planetary boundaries?" (Willet et al., 2019). It recommends a shift towards healthier, low GHG emission diets that largely consist of vegetables, fruits, whole grains, legumes, nuts, and unsaturated oils, include a low to moderate amount of seafood and poultry, and include no or a low quantity of red meat, processed meat, added sugar, refined grains, and starchy vegetables. It states that future expansion of seafood should come from aquaculture, which could help steer production of animal source proteins towards reduced environmental effects and enhanced health benefits

The High Level Panel for a Sustainable Ocean Economy (Ocean Panel), an initiative established in 2018 by 14 world leaders to develop an action agenda for transitioning to a sustainable ocean economy, has published several relevant reports. One, published in 2019, is one of 16 "Blue Papers" commissioned by the Ocean Panel to summarize the latest science and state-of-the-art thinking about ocean sustainability (Costello et al., 2019). This report considers the status and future trends of food production through capture fisheries and mariculture, and it identifies opportunities for action to transition to more sustainable and abundant food production from the ocean. The authors suggest that marine aquaculture could be one of the most ecologically sustainable forms of future food production. They note that food production from the sea, whether through capture fisheries or mariculture, is advantageous from a climate change perspective for two reasons: (1) production does not directly drive land conversion like land-based food systems (e.g., conversion from forests to farms), and (2) GHG emissions associated with production are lower than emissions from terrestrial animal production.

Another Ocean Panel report, also published in 2019, explores how the ocean can help mitigate global warming and describes a series of recommendations for action from the Ocean Panel (Hoegh-Guldberg et al., 2019). One of the areas of action identified in the report has to do with a dietary shift away from land-based protein sources and towards low carbon ocean-based protein from fisheries and marine aquaculture. The authors note that food from the sea, produced using best practices, can have some of the lowest GHG emissions per unit of protein produced of all protein sources. They estimate that a dietary shift towards seafood could reduce emissions by as much as 0.94 GT CO_{2eq} (carbon dioxide equivalent emissions) by 2030, and by as much as 1.24 GT CO_{2eq} by 2050. However, they also note that global analyses of the complete climate footprint of aquaculture are lacking.

Efforts to analyze aquaculture's carbon footprint have mostly been done through life cycle assessment (LCA), which is a method used to quantify the environmental impacts associated with each stage of a commercial product's life cycle from the extraction and processing of raw materials all the way through manufacturing, distribution, and sometimes through final recycling and disposal. Comprehensive "cradle to grave" LCA assesses all of these steps, from the very first step to the final disposal, while "cradle to gate" LCA stops at the point the product leaves the production or manufacturing facility. When it comes to food products, LCA uses a functional unit (e.g., 1kg of edible product) and considers impact categories such as greenhouse gas (GHG) emissions, energy use, land use, freshwater use, biodiversity impacts, etc.

Bohnes et al. conducted a critical review of 65 aquaculture LCA studies and found that, across all studies, average carbon emissions were 4.4 tons of CO_{2eq} per ton of seafood produced (Bohnes et al., 2018). Hilborn et al. reviewed 148 LCA studies of animal source foods including livestock, aquaculture, and wild capture fisheries, and compared four metrics of environmental impact: energy use, GHG emissions, release of nutrients, and acidifying compounds (Hilborn et al., 2018). They found that GHG emissions were lowest for mollusk aquaculture and small pelagic fisheries, with salmon aquaculture, chicken production, and large pelagic and whitefish fisheries also emitting less than 1kg CO_{2eq} per 40g of protein produced. Catfish, tilapia, and shrimp aquaculture generated higher GHG emissions, and beef production generated the highest of any animal protein source. Those authors concluded by noting that all food production has environmental costs, and they called for more comparison between the costs of fish production and the costs of land-based livestock production.

A 2020 paper compared global GHG emissions from aquaculture, wild fisheries, and livestock sectors and found that the emissions intensity (GHG emissions per unit of edible output) of aquaculture production is comparable to that of chicken and pork production and lower than emissions from cattle, sheep, and goat production (MacLeod et al., 2020; Fig. 2).

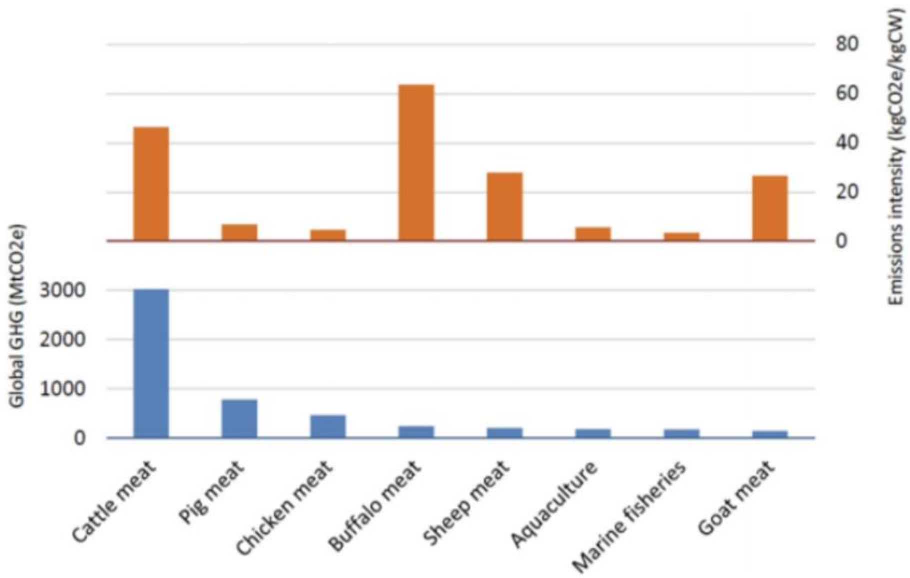


Figure 2. Total global emissions and emissions intensity of aquaculture (2010), terrestrial meat (2010), and marine fisheries (2011) (MacLeod et al., 2020)

Other recent papers have modeled the climate impacts of feeding the 2050 population through a business-as-usual approach to animal protein production, i.e., maintaining current ratios of livestock production vs. fisheries and aquaculture production, vs. a higher ratio of seafood production. One found that a shift towards seafood protein could spare millions of hectares of land (Froehlich et al., 2018). Another found that filling the future protein production gap with aquaculture instead of meat could save give billion metric tons of CO_2 emissions (Capron et al., 2020). A paper that focused specifically on oyster aquaculture found that if just 10% of the protein from beef consumption in the U.S. was replaced with protein from oysters, the GHG emissions savings would be equivalent to 10.8 million fewer cars on the road (Ray et al., 2019).

Contribution to a more climate-resilient and shock-resilient food system

Shocks such as geopolitical strife and extreme weather events pose a significant threat to global food security. Improving the resilience of our global food system is especially urgent under climate change, which is projected to increase the frequency and duration of shocks (Cottrell et al., 2019). Some recent studies suggest that an increase in well-managed marine aquaculture production could help make our global food system more resilient to future environmental, social, and economic shocks, including the impacts of climate change (Gentry et al., 2017). For example, marine aquaculture systems that can be moved throughout the water column may be more resistant to marine heatwaves that force fish to migrate and harm less-mobile species (Capron et al., 2020). There have even been suggestions that some marine aquaculture may benefit from climate-related impacts such as warmer water temperatures (Griffis, 2013), though the impact of climate change on marine aquaculture production is beyond the scope of this report. A 2014 paper by Troell et al. explored the potential for increased aquaculture production to enhance resilience of the global food system in the face of increased resource scarcity and climate change (Troell et al., 2014). The authors concluded that the present diversity of aquaculture systems, which includes a wide range of cultured species, feed ingredients, and feed practices, contributes important elements of stability to the global food system. However, they note that the ability of increased aquaculture to add resilience to global food systems will depend largely on how the sector develops in terms of species, composition, feed inputs, and system design and operation.

Potential for mitigation through carbon sequestration

Marine aquaculture has climate change mitigation potential beyond its role in the global food system. Seaweed aquaculture, the farming of marine macroalgae, can be used as a carbon sequestration tool and is often discussed alongside other blue carbon conservation and restoration strategies such as planting seagrasses and restoring coastal wetlands (Ahmed et al., 2016; Krause-Jensen and Duarte, 2017). By one recent estimate, seaweed aquaculture has the potential to mitigate about 1500 tons of CO_2 per square km per year (Dundas et al., 2020).

Seaweed aquaculture could play a possible role for carbon offsetting or in carbon markets. A 2019 study by Froehlich et al. discussed seaweed aquaculture's potential as a tool to offset carbon emissions from agriculture (Froehlich et al., 2019). The authors considered average nutrient levels and temperature suitability for various seaweed species and found a substantial area (about 48 million km^2 around the world) that is suitable for seaweed farming but largely unfarmed. To fully offset global agricultural emissions, seaweed farming would need to ramp up significantly, taking up 15% of the suitable ocean area and doubling the area of wild seaweed. The authors note that this is not realistic, and that seaweed offsetting is not a silver bullet when it comes to climate change mitigation. However, it could be a viable option for certain countries or regions. For example, California could offset emissions from its entire agricultural sector by farming just 3.8% of U.S. waters on the West Coast, or 0.065% of all suitable global waters.

Other ecosystem services

Carbon sequestration, as discussed above, is one example of an ecosystem service. Marine aquaculture can provide other ecosystem services, some of which can help mitigate the ocean impacts of climate change. A 2017 study suggested that with a more strategic focus, marine aquaculture has great potential to provide ecosystem services, such as improving water quality and reducing GHG emissions, while supplementing wild capture for food (Froehlich, Gentry, and Halpern, 2017). A 2019 study presented a literature review of 129 peer reviewed papers on marine aquaculture's ecosystem services (Gentry et al., 2019). That paper lists regulation of ocean acidification, protection of coastal ecosystems, and carbon sequestration among potential services of finfish, bivalve, crustacean, and seaweed farming (Fig. 3).

Table 1 Ecosystem services pertaining to mariculture that were included in this analysis

Service category	Service	Potential species providing service
Provisioning	Augment wild fisheries catches	Bivalves, Fish, Algae
Regulating	Carbon sequestration	Bivalves, Algae
	Acidification regulation	Algae
	Coastal protection	Bivalves, Fish, Algae
	Nutrient removal	Bivalves, Algae
	Improve water clarity	Bivalves, Algae
Habitat and supporting	Provision of artificial habitat	Bivalves, Fish, Algae
Cultural	Livelihoods	Bivalves, Fish, Algae, Crustacea
	Tourism	Bivalves, Fish, Algae, Crustacea

Figure 3. Ecosystem services provided by marine aquaculture (Gentry et al., 2019)

Climate-related ecosystem services are mostly provided by bivalve and seaweed aquaculture, while finfish aquaculture plays a larger role in complementing wild capture production. Some studies have explored the potential benefits of integrated multi-trophic aquaculture (IMTA), through which different species from different trophic levels are farmed together. Ahmed et al. suggested that the "greening of aquaculture" through practices like IMTA could fit into a larger blue carbon initiative to mitigate and enhance resilience to climate change (Ahmed et al., 2016). More recently, Capron et al. suggested that high-protein seafood and macroalgae-for-biofuel could be grown together on the same structure through IMTA (Capron et al., 2020). Through IMTA, one aquaculture system could potentially provide multiple ecosystem services while also providing a climate-friendly source of food.

Conclusion

As nations work towards global net zero emissions, marine aquaculture should be part of the conversation. The scientific literature tells us two main ways it can be a powerful mitigation tool. First, marine aquaculture can produce climate-friendly protein that does not drive land conversion and has lower GHG emissions than livestock production. Secondly, marine aquaculture can provide ecosystem services such as sequestering carbon, buffering ocean acidification, and protecting coastal habitats. Some farming methods, such as IMTA, maximize ecosystem services while also producing high-protein, climate-friendly seafood.

The scientific literature is also full of recommendations to shift global diets towards seafood and to increase marine aquaculture production in a way that is thoughtful and strategic. Responsible marine aquaculture development has real potential to feed a growing human population, increase the resilience of the global food system to shocks, and mitigate climate change. It is a tool that should be used.

Summaries of Key Publications

Ahmed, N., Bunting, S. W., Glaser, M., Flaherty, M. S., & Diana, J. S. (2016). Can greening of aquaculture sequester blue carbon? *Ambio, 46*(4), 468-477. doi:10.1007/s13280-016-0849-7

Ahmed et al. suggest that "greening of aquaculture" could be a component of sustainable coastal management that could reduce blue carbon emissions and sequester blue carbon. They define greening of aquaculture as embracing an Ecosystem Approach to Aquaculture (EAA), Integrated Aquaculture-Agriculture (IAA), and/or Integrated Multi-Trophic Aquaculture (IMTA). The authors suggest that if one fourth of degraded mangroves and seagrasses were restored by the greening of aquaculture, 25% of coastal ponds were converted to IAA, and shellfish production increased by 25%, it could be possible to sequester 97 million tons of additional blue carbon annually. This is a low number compared to annual carbon emissions (9.73 billion tons in 2014); they recognize this and suggest greening of aquaculture could be part of a larger blue carbon initiative.

Themes: blue carbon, carbon sequestration, coastal ecosystems, IMTA

Alleway, H. K., Gillies, C. L., Bishop, M. J., Gentry, R. R., Theuerkauf, S. J., & Jones, R. (2018). The Ecosystem Services of Marine Aquaculture: Valuing Benefits to People and Nature. *BioScience, 69*(1), 59-68. doi:10.1093/biosci/biy137

Alleway et al. discuss the potential ecosystem services of finfish, shellfish, and macroalgae mariculture. These include provisioning services (food and medicinal resources), regulating services (nutrient cycling, water filtration, etc.), habitat services (providing habitat for other species), and carbon sequestration. The authors suggest that well-designed macroalgae mariculture could be purposefully developed as a climate change mitigation strategy and that there is global potential for expansion of mariculture activity.

Themes: ecosystem services, sustainable aquaculture planning

Barange, M. C., Bahri, T. L., Beveridge, M. U., Cochrane, K. U., Funge-Smith, S. U., & Poulain, F. U. (Eds.). (2018). *Impacts of climate change on fisheries and aquaculture: Synthesis of current knowledge, adaptation and mitigation options*. Rome, Italy: Food and Agriculture Organization of the United Nations.

This 2018 FAO report includes a section on global carbon emissions of wild fisheries and aquaculture. In 2012, fishing vessels emitted 172.3 million tons of CO_2, about 0.5% of total global emissions that year. The aquaculture industry emitted 385 million tons of CO_2 in 2010; this was around 7% of the emissions from land-based agriculture. The energy use of protein production per unit mass of fish is comparable to chicken and is much less than that from other land-based livestock such as pork and beef.

Themes: climate change, GHG emissions of fisheries and aquaculture

Bohnes, F. A., Hauschild, M. Z., Schlundt, J., & Laurent, A. (2018). Life cycle assessments of aquaculture systems: A critical review of reported findings with recommendations for policy and system development. *Reviews in Aquaculture, 11*(4), 1061-1079. doi:10.1111/raq.12280

This is a peer-reviewed critical review of 65 life cycle assessment (LCA) studies of aquaculture systems. LCA is a tool commonly used to assess the environmental sustainability of food production systems. It quantifies impacts of those systems on different impact categories such as ecosystems, human health, natural resources, and climate change. Bohnes et al. found that across the 65 LCA studies, the average carbon emissions were 4.4 tons of CO_{2eq} per ton of seafood produced. Given that average annual global fish consumption is 20kg per capita and that about half of that fish is farmed, the authors calculate an aquaculture impact of 44kg CO_2 per year per capita. This is approximately 0.6% of the annual climate change impacts of an average person. The authors note that recirculating aquaculture systems (RAS) have higher energy demand and climate change impacts than other forms of aquaculture.

Themes: LCA, impacts of food production, GHG emissions

Capron, M. E., Stewart, J. R., Nyeurt, A. D., Chambers, M. D., Kim, J. K., Yarish, C., . . . Hasan, M. A. (2020). Restoring pre-industrial CO2 levels while achieving Sustainable Development Goals. doi:10.1002/essoar.10503397.4

This paper describes the potential for total ecosystem aquaculture (TEA) to produce high-protein seafood and macroalgae-for-biofuel. TEA is a form of IMTA that consists of permanent, flexible reefs floating at ocean depth for optimal macroalgae growth. TEA can produce finfish, shellfish, and crustaceans in addition to macroalgae. The authors note that protein demand is expected to double by 2050 and that the average GHG impact of meat is about 17 metric tons of CO_{2eq} per metric ton of meat, while the average GHG impact of seafood is about three metric tons of CO_{2eq} per metric ton of seafood. A business-as-usual approach in both meat and seafood production could produce 13 billion metric tons of CO_{2eq}. If meat production stays the same and we instead fill the protein gap with aquaculture production, it would produce eight billion metric tons of CO_{2eq}, saving five billion metric tons of CO_{2eq} emissions.

Capron et al. suggest that seafood could improve human health, especially in developing countries where, as temperatures rise in the tropics, crops are failing and food micronutrients are dropping. They also note that TEA systems can be moved throughout the water column, making them more resistant to marine heat waves that force fish to migrate and harm less-mobile species. In these ways, TEA can contribute to a more climate-resilient food system.

Themes: IMTA, GHG emissions, climate-resilient food systems

Costello, C., Cao, L., & Gelcich, S., et al. (2019). *The Future of Food from the Sea*. Washington, DC: World Resources Institute.

This is one of 16 “Blue Papers” commissioned by the High Level Panel for a Sustainable Ocean Economy. This paper considers the status and future trends of food production through capture fisheries and mariculture at regional and global scales, and it identifies opportunities for action to transition to more sustainable and abundant food production from the ocean. The authors suggest that sustainable mariculture could be one of the most ecologically sustainable forms of future food production. They note that food production from the sea, whether through capture fisheries or mariculture, is advantageous from a climate change perspective for two reasons: (1) production does not directly drive land conversion like land-based food systems (e.g., conversion from forests to farms), and (2) GHG emissions associated with production are lower than emissions from terrestrial animal production.

Themes: sustainable food production, land use, GHG emissions

Cottrell, R. S., Nash, K. L., Halpern, B. S., Remenyi, T. A., Corney, S. P., Fleming, A., . . . Blanchard, J. L. (2019). Food production shocks across land and sea. *Nature Sustainability, 2*(2), 130-137. doi:10.1038/s41893-018-0210-1

Cottrell et al. looked at 53 years of food production data from crop, livestock, aquaculture, and fisheries sectors to better understand how shocks (geopolitical strife, extreme weather events, etc.) occurring in one food sector can create challenges among others. They note that shocks can pose a significant threat to global food security and call for increased investment in food systems research to improve resilience to shocks. This research is especially urgent under climate change. In their analysis, the authors suggest that increased aquaculture could increase resilience to external shocks in vulnerable nations and note that barriers that limit industry growth must be overcome.

Themes: food security, shock-resilient food systems

Davis, K. F., Gephart, J. A., Emery, K. A., Leach, A. M., Galloway, J. N., & D’Odorico, P. (2016). Meeting future food demand with current agricultural resources. *Global Environmental Change, 39*, 125-132. doi:10.1016/j.gloenvcha.2016.05.004

Davis et al. evaluate the resource demands and GHG emissions of future food production by considering agriculture’s water, nitrogen, carbon, and land footprints and investigate whether an increase in environmental burdens can be avoided. They conclude that a transition away from terrestrial animal products—especially ruminants—and towards seafood and plant products is an important strategy for reducing the environmental impacts of the food system.

Themes: GHG emissions, environmental impacts of protein production

Duarte, C. M., Wu, J., Xiao, X., Bruhn, A., & Krause-Jensen, D. (2017). Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation? *Frontiers in Marine Science, 4*. doi:10.3389/fmars.2017.00100

In this paper, the authors discuss the climate change mitigation and adaptation benefits of macroalgae farming. Current mitigation benefits include carbon sequestration and food production with a reduced CO_2 footprint, while future mitigation benefits could include biofuel production to replace fossil fuels, reduction of methane emissions via additive in cow feed, and replacement of synthetic fertilizer. Adaptation benefits include shoreline protection via dissipation of wave energy, buffering of ocean acidification, and oxygen inputs to coastal waters.

Themes: macroalgae, climate mitigation, climate adaptations, carbon sequestration

Dundas, S. J., Levine, A. S., Lewison, R. L., Doerr, A. N., White, C., Galloway, A. W., . . . White, J. W. (2020). Integrating oceans into climate policy: Any green new deal needs a splash of blue. *Conservation Letters, 13*(5). doi:10.1111/conl.12716

Dundas et al. provide policy recommendations that would integrate oceans into climate initiatives focused on the energy and transportation sectors, food security, and habitat restoration. They suggest that sustainable aquaculture, when paired with sustainable wild capture fisheries, has the potential to increase food security, sequester CO_2, provide protein with a low carbon footprint, and stimulate economic activity in both coastal and inland communities. Specifically, the authors note that aquaculture production of lower trophic level species (e.g., shellfish) produces less CO_2 per kg of protein than most forms of terrestrial meat production and that seaweed aquaculture has the potential to mitigate about 1500 tons of CO_2 per square km per year while producing food with an excellent source of dietary fiber, protein, and a variety of micronutrients.

Themes: food security, carbon sequestration, GHG emissions

Froehlich, H. E., Gentry, R. R., & Halpern, B. S. (2017). Conservation aquaculture: Shifting the narrative and paradigm of aquacultures role in resource management. *Biological Conservation, 215*, 162-168. doi:10.1016/j.biocon.2017.09.012

In this paper, Froehlich, Gentry, and Halpern define “conservation aquaculture” as aquaculture done for the purpose of managing and/or protecting a natural resource. They discuss current benefits of conservation aquaculture and suggest that, with a more strategic focus, aquaculture has great potential to provide ecosystem services, such as improving water quality and reducing GHG emissions, while supplementing wild capture for food. The authors note that LCA studies are revealing aquaculture's potential to provide protein with lower GHG emissions, reduced land-use, and reduced freshwater use than other animal protein production, and they call for more monitoring and measuring of aquaculture's ecological outcomes so we may better understand its conservation potential. They predict that, given divisive public perceptions, aquaculture will not receive the benefit of the doubt when it comes to environmental impacts. They suggest that long-term, stronger connections to conservation objectives may help build public trust around aquaculture.

Themes: ecosystem services, conservation, GHG emissions, land use

Froehlich, H. E., Runge, C. A., Gentry, R. R., Gaines, S. D., & Halpern, B. S. (2018). Comparative terrestrial feed and land use of an aquaculture-dominant world. *Proceedings of the National Academy of Sciences, 115*(20), 5295-5300. doi:10.1073/pnas.1801692115

Here, Froehlich et al. used models to consider how a shift away from meat and towards cultured seafood would change pressure on feed-crop requirements, and how that might translate to changes in area and location of land use for crops and grazing. They modeled three different scenarios, each set in 2050 when human population is expected to reach 10 billion: (1) the additional 2050 meat demand is met by business-as-usual production, meaning more meat than seafood, (2) additional demand is met entirely by aquaculture with current trends of freshwater and marine production, and (3) additional demand is met by predominantly marine aquaculture production. They found that a shift towards cultured-seafood dominant diets could reduce annual feed-crop requirements by 598.7 (scenario 2) to 564.7 (scenario 3) million tons compared with business-as-usual (scenario 1). In other words, millions of hectares of land could be spared by a shift away from meat and towards more seafood protein.

Themes: animal feed, land use, human diets

Froehlich, H. E., Afflerbach, J. C., Frazier, M., & Halpern, B. S. (2019). Blue Growth Potential to Mitigate Climate Change through Seaweed Offsetting. *Current Biology, 29*(18). doi:10.1016/j.cub.2019.07.041

Here, Froehlich et al. discuss seaweed aquaculture's potential as a tool to mitigate carbon emissions from agriculture. They considered average nutrient levels and temperature suitability for various seaweed species and found a substantial area (about 48 million km^2) that is suitable for seaweed farming but largely unfarmed. To fully offset agricultural emissions, seaweed farming would need to ramp up significantly, taking up 15% of the suitable ocean area and doubling the area of wild seaweed. The authors note that this is not realistic, and that seaweed offsetting is not a silver bullet when it comes to climate change mitigation. However, it could be a viable option for certain countries or regions. For example, California could offset emissions from its entire agricultural sector by farming just 3.8% of the West Coast exclusive economic zone, or 0.065% of all suitable global waters.

Themes: macroalgae, mitigation, carbon sequestration, carbon offsetting

García, B. G., Jiménez, C. R., Aguado-Giménez, F., & García, J. G. (2016). Life Cycle Assessment of Gilthead Seabream (Sparus aurata) Production in Offshore Fish Farms. Sustainability, 8(12), 1228. doi:10.3390/su8121228

This seems to be the only published LCA study of offshore finfish aquaculture not done via IMTA. The authors applied LCA to the production of gilthead seabream in an offshore fish farm (depth of 30-50m) on the Spanish Mediterranean coast. They considered operations related to the production cycle in the offshore facility (e.g., feed, emissions due to fish metabolism, fuel consumed by vessels), the cages and anchoring system, and manufacturing process and raw material used for fish feed. Impact categories included global warming, ozone layer depletion, and cumulative energy demand, among others. The authors found that fish feed, especially the raw material used, had the greatest environmental impact (48% of the overall impact). Fuel consumed by vessels contributed 35% of the impact, nitrogen and phosphorous release from fish metabolism contributed 12%, and the cages and anchorage systems contributed 5%. They conclude that increasing feed efficiency and improving feed formulation could lead to a significant reduction in potential environmental impact.

Themes: LCA, finfish, offshore

Gentry, R. R., Froehlich, H. E., Grimm, D. D., Kareiva, P. S., Parke, M. U., Rust, M. U., . . . Halpern, B. U. (2017). Mapping the global potential for marine aquaculture. *Nature Ecology; Evolution, 1*(9), 1317-1324. doi:10.1038/s41559-017-0257-9

In this landmark paper, Gentry et al. map the biological production potential for marine aquaculture across the globe, finding vast areas in nearly every coastal country that are suitable for aquaculture. The authors conclude that the total landings of all wild-capture fisheries could be produced using less than 0.015% of global ocean area for aquaculture and suggest that well-managed marine aquaculture development could increase the resiliency of our food system to future environmental, social, and economic shocks. To realize the global potential for marine aquaculture, social, economic, and governance hurdles must be overcome. The authors specifically mention the United States, where regulatory inefficiency and uncertainty have limited marine aquaculture's development.

Themes: climate-resilient food systems, aquaculture potential

Gentry, R. R., Alleway, H. K., Bishop, M. J., Gillies, C. L., Waters, T., & Jones, R. (2019). Exploring the potential for marine aquaculture to contribute to ecosystem services. *Reviews in Aquaculture, 12*(2), 499-512. doi:10.1111/raq.12328

Here, Gentry et al. conduct a literature review of 129 peer reviewed papers that describe marine aquaculture's ecosystem services, including carbon sequestration, regulation of ocean acidification, coastal protection, and more. The table below summarizes the ecosystem services and species covered by the reviewed papers. The authors concluded by calling for more research focused on how expansion of marine aquaculture will affect these services.

Table 1 Ecosystem services pertaining to mariculture that were included in this analysis

Service category	Service	Potential species providing service
Provisioning	Augment wild fisheries catches	Bivalves, Fish, Algae
Regulating	Carbon sequestration	Bivalves, Algae
	Acidification regulation	Algae
	Coastal protection	Bivalves, Fish, Algae
	Nutrient removal	Bivalves, Algae
	Improve water clarity	Bivalves, Algae
Habitat and supporting	Provision of artificial habitat	Bivalves, Fish, Algae
Cultural	Livelihoods	Bivalves, Fish, Algae, Crustacea
	Tourism	Bivalves, Fish, Algae, Crustacea

Themes: ecosystem services, carbon sequestration

Griffis, R., & Howard, J. (Eds.). (2013). Oceans and Marine Resources in a Changing Climate: A technical input to the 2013 National Climate Assessment. Washington, DC: Island Press.

This report was developed by NOAA and is one of a series of technical inputs to the 2013 National Climate Assessment. It states that aquaculture stocks are expected to be more resilient to climate change than wild stocks due to selective breeding and vaccination and that aquaculture could potentially reduce some climate impacts on wild stocks and ecosystems through a net removal of CO_2 from the oceans. It suggests that certain aquaculture species may actually benefit from climate-related changes such as higher water temperatures.

Themes: climate change, resilience

Hilborn, R., Banobi, J., Hall, S. J., Pucylowski, T., & Walsworth, T. E. (2018). The environmental cost of animal source foods. *Frontiers in Ecology and the Environment, 16*(6), 329-335. doi:10.1002/fee.1822

This paper is cited often in discussions about impacts of protein production. Here, Hilborn et al. conducted a literature review of 148 LCA studies of animal source foods including livestock, aquaculture, and wild capture fisheries, and compared four metrics of environmental impact (energy use, GHG emissions, release of nutrients, and acidifying compounds) of the protein sources. GHG emissions were lowest for mollusk aquaculture and small pelagic fisheries, with salmon aquaculture, chicken production, and large pelagic and whitefish fisheries also emitting less than 1kg CO_{2eq} per 40g of protein produced. Catfish, tilapia, and shrimp aquaculture generated higher GHG emissions, and beef production generated the highest of any animal protein source. The authors conclude by noting that all food production has environmental costs, and that these costs vary greatly between different animal proteins. Though the environmental impacts of wild fisheries and aquaculture have been the topic of much discussion in recent years, these impacts are rarely compared to the environmental impacts of terrestrial proteins.

Themes: LCA, environmental impacts of food systems, GHG emissions

Hoegh-Guldberg, O., et al. (2019). *The Ocean as a Solution to Climate Change: Five Opportunities for Action*. Washington, DC: World Resources Institute.

This report explores how the ocean can help mitigate the impacts of climate change and describes a series of recommendations for action from the High Level Panel for a Sustainable Ocean Economy. One of the areas of action identified in the report has to do with a dietary shift away from land-based protein sources and towards low carbon ocean-based protein from fisheries and aquaculture. The authors note that food from the sea, produced using best practices, can have some of the lowest GHG emissions per unit of protein produced of all protein sources. They estimate that a dietary shift towards seafood could contribute potential mitigation between 0.34 and 0.94 GT CO_{2eq} by 2030, and between 0.48 and 1.24 GT CO_{2eq} by 2050, relative to business-as-usual projections. However, they also note that global analyses of the complete GHG footprint of aquaculture are lacking, and many systems that make up a large portion of global production have not been sufficiently assessed.

Themes: mitigation, GHG emissions, food systems

Irz, X., Leroy, P., Réquillart, V., & Soler, L. (2018). Fish in Climate-Friendly and Healthy Diets. *Marine Resource Economics, 33*(4), 309-330. doi:10.1086/699882

Irz et al. used a model to simulate how a rational consumer urged to consume more fish would modify his diet and then explored the health and climate outcomes of that modification. (The climate impacts were based on LCA study data related to GHG emissions.) They also compared the impacts of promoting fish consumption against the impacts of urging consumers to eat less meat overall. The authors concluded that raising fish consumption generates more health benefits and climate benefits than reducing meat consumption overall. They ultimately recommend climate-friendly and healthy diet recommendations that send a positive message urging people to add more fish into their diets.

Theme: GHG emissions, food systems, climate-friendly diet

Klinger, D. H., Levin, S. A., & Watson, J. R. (2017). The growth of finfish in global open-ocean aquaculture under climate change. *Proceedings of the Royal Society B: Biological Sciences, 284*(1864), 20170834. doi:10.1098/rspb.2017.0834

Klinger, Levin, and Watson estimate the potential of open-ocean finfish aquaculture globally under climate projections. They compare growth potential for three species (Atlantic salmon, gilthead seabream, and cobia) across regions, considering physical, biological, and technical constraints. They find that areas with existing aquaculture industries are likely to see increases in growth rates due to global climate change and in areas where climate change may alter growth potential, adaptations measures such as selective breeding can offset production losses.

Themes: finfish, production under climate change

Krause-Jensen D., Duarte C.M. (2016). Substantial role of macroalgae in marine carbon sequestration. *Nature Geoscience* 9: 737–742.

In this paper, Krause-Jensen and Duarte explore seaweed's potential for carbon sequestration. They find that it has significant potential and recommend that it be considered within blue carbon conservation and restoration strategies to mitigate climate change. This paper is often referenced in other papers that discuss the potential of seaweed farming as a tool to address climate change.

Themes: seaweed, carbon sequestration, climate mitigation

Macleod, M. J., Hasan, M. R., Robb, D. H., & Mamun-Ur-Rashid, M. (2020). Quantifying greenhouse gas emissions from global aquaculture. *Scientific Reports, 10*(1). doi:10.1038/s41598-020-68231-8

In this study, MacLeod et al. quantified the global GHG emissions from finfish, shellfish, and crustacean aquaculture for the year 2017. They used recent commercial feed formulations for the main species groups and geographic regions, which is important because it allowed for a more up to date analysis than previously existed in the academic literature. According to their results, global aquaculture accounted for about 0.49% of anthropogenic GHG emissions in 2017. The authors also compared global aquaculture emissions with emissions from livestock sectors based on 2010 data (the most recent year for which FAO has reported global livestock results). They found that the emissions per unit of edible output for aquaculture production are comparable to emissions from pork and chicken production and lower than emissions from cattle, sheep, and goat production. The table below summarizes the total emissions and emissions intensity of aquaculture compared to terrestrial meat production and wild capture fisheries.

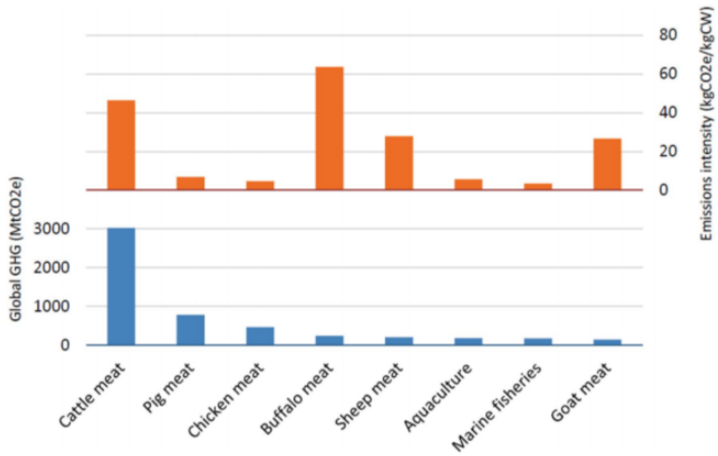


Figure 3. Total global emissions and emissions intensity of aquaculture (2010), terrestrial meat (2010) and marine fisheries (2011). Sources: Aquaculture—calculated in this study. Marine fisheries[5]. Cattle, pig, chicken, buffalo, sheep and goat meat[4].

Themes: GHG emissions of aquaculture, GHG emissions of terrestrial livestock

Nijdam, D., Rood, T., & Westhoek, H. (2012). The price of protein: Review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. *Food Policy, 37*(6), 760-770. doi:10.1016/j.foodpol.2012.08.002

Nijdam, Rood, and Westhoek analyzed 52 LCA studies of animal and vegetable sources of protein in order to compare land requirement and carbon footprint. They found that the carbon footprint of aquaculture ranged from 3-15kg of CO_{2eq} per kg of protein produced; this is based on 7 LCA studies. By comparison, beef's footprint was 9-129kg, pork's footprint was 4-11kg, poultry's footprint was 2-6kg, and seafood from fisheries had a footprint range of 1-86kg. The authors note that beef and seafood are both produced using a variety of systems, whereas pork and poultry production is more homogenous and had smaller footprint ranges.

Themes: LCA, GHG emissions

Parker, R. W., Blanchard, J. L., Gardner, C., Green, B. S., Hartmann, K., Tyedmers, P. H., & Watson, R. A. (2018). Fuel use and greenhouse gas emissions of world fisheries. *Nature Climate Change, 8*(4), 333-337. doi:10.1038/s41558-018-0117-x

Parker et al. quantify fuel inputs and GHG emissions for the global fishing fleet from 1990-2011 and compare GHG emissions from fisheries to those from agriculture and livestock production. They estimate that, between 1990 and 2011, average emissions per metric ton of fish landed increased by 21% due to increased harvests from fuel-intensive crustacean fisheries (e.g., lobster). The authors estimate that GHG emissions from fisheries were about 179 million metric tons of CO_{2eq}, which is about 4% of the total fishery, agriculture, and livestock emissions. They noted that, compared to other sources of animal protein, products derived from marine fisheries produced relatively low GHG emissions and that over half of fishery-derived products were estimated to produce fewer GHG emissions than the low end of emission ranges for pork, beef, and lamb. The average carbon footprint of fishery products is comparable to that of poultry production. This paper does not discuss aquaculture, but it is a good resource for information about GHG emissions of wild capture fisheries.

Themes: GHG emissions of wild capture fisheries

Ray, N. E., Maguire, T. J., Al-Haj, A. N., Henning, M. C., & Fulweiler, R. W. (2019). Low Greenhouse Gas Emissions from Oyster Aquaculture. *Environmental Science; Technology, 53*(15), 9118-9127. doi:10.1021/acs.est.9b02965

In this paper, the authors quantify GHG emissions from oyster aquaculture. They found that oyster aquaculture has less than 0.5% of the GHG cost of beef, small ruminants, pork, and poultry in terms of CO_{2eq} per kg of protein. The authors suggest that shellfish aquaculture may provide a low GHG alternative for future animal protein production and that if 10% of the protein from beef consumption in the U.S. was replaced with protein from oysters, the GHG savings would be equivalent to 10.8 million fewer cars on the road. This study is unique in that Ray et al. did not use LCA or modeling studies. Rather, they directly measured the CO_{2eq}, methane, and nitrous oxide released during aquaculture production of the Eastern oyster (*Crassostrea virginica*).

Themes: GHG emissions of oyster farming, mitigation, GHG emissions of livestock

Ruiz-Salmón, I., Laso, J., Margallo, M., Villanueva-Rey, P., Rodríguez, E., Quinteiro, P., . . . Aldaco, R. (2021). Life cycle assessment of fish and seafood processed products – A review of methodologies and new challenges. *Science of The Total Environment, 761*, 144094. doi:10.1016/j.scitotenv.2020.144094

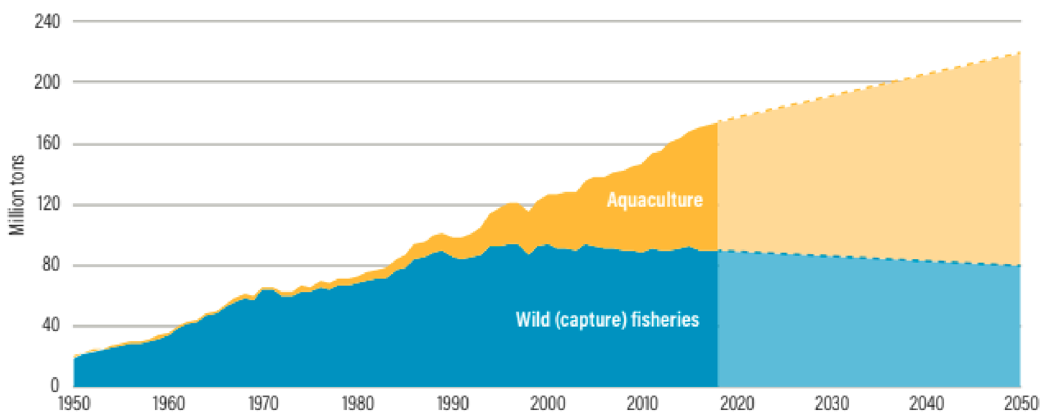
This paper described the LCA framework and its application to wild capture fisheries. The authors reviewed and analyzed 69 LCA-related publications, most of which were published in the last decade, focused on the extraction and processing of wild capture seafood products. They did not include aquaculture LCAs. They compared the methods used in various studies, noting that the use of different reference systems, system boundaries, and functional units make it difficult to compare and harmonize different studies. The authors recommended establishing rules and methods for seafood specific LCAs and suggested that, if designed correctly, LCA studies could help inform policies and strategies aimed at climate change mitigation, energy security, food security, and more. This study is relevant in that it addresses the importance and potential of LCA studies when it comes to future fishery management.

Themes: LCA, climate mitigation, food security, wild capture fisheries

Searchinger, T., Waite, R., Hanson, C., & Ranganathan, J. (2018). *Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050* (Synthesis Report) (E. Matthews, Ed.). Washington, DC: World Resources Institute.

This report from the World Resources Institute, World Bank Group, and United Nations focuses on opportunities and policies for meeting food, land use, and GHG emissions goals in 2050. It projects that fish consumption will rise 58% between 2010 and 2050 but notes that wild fish catch peaked at 94 million tons in the mid-1990s and has since stagnated or perhaps even declined. To make up the difference, the report proposes ways to improve wild fisheries management and to raise the productivity and environmental performance of aquaculture. One such recommendation is to expand aquaculture in marine waters, possibly further offshore. The figure below illustrates the increase in aquaculture production needed to meet seafood demand in 2050.

Figure 16 | **Aquaculture production must continue to grow to meet world fish demand**



Source: Historical data, 1950–2016: FAO (2017b) and FAO (2018). Projections to 2050: Calculated at WRI; assumes 10 percent reduction in wild fish catch from 2010 levels by 2050, linear growth of aquaculture production of 2 Mt per year between 2010 and 2050.

Themes: food systems, food security, seafood demand

Troell, M., Naylor, R. L., Metian, M., Beveridge, M., Tyedmers, P. H., Folke, C., . . . Zeeuw, A. D. (2014). Does aquaculture add resilience to the global food system? *Proceedings of the National Academy of Sciences, 111*(37), 13257-13263. doi:10.1073/pnas.1404067111

Troell et al. explore the potential for increased aquaculture production to enhance resilience of the global food system in the face of increased resource scarcity and climate change. They conclude that the present diversity of aquaculture systems, which includes a wide range of cultured species, feed ingredients, and feed practices, contributes important elements of stability to the global food system. However, the authors predict that the ability of increased aquaculture to add resilience to global food systems will depend largely on how the sector develops in terms of species, composition, feed inputs, and system design and operation. They suggest that if aquaculture is not designed to minimize environmental damages and social injustices, it is likely to make the global food system less resilient, not more.

Themes: climate-resilient food systems

Van der Schatte Olivier, A., Jones, L., Vay, L. L., Christie, M., Wilson, J., & Malham, S. K. (2018). A global review of the ecosystem services provided by bivalve aquaculture. *Reviews in Aquaculture, 12*(1), 3-25. doi:10.1111/raq.12301

In this study, the authors synthesize the evidence available on the ecosystem services provided by bivalve species commonly used in aquaculture. These include supporting services (cycling of nutrients through filter feeding, creation of sediment, increasing seabed roughness, and providing habitats for other organisms), provisioning services (provision of food and provision of materials such as fertilizer and grit for poultry), regulating services (biochemical accumulation, carbon sequestration, nutrient removal, and coastal defense), and cultural services (recreational fisheries, education and tourism, and spiritual benefits). The authors estimate that the global, non-food bivalve aquaculture services are worth between $2.95 billion and $9.99 billion per year.

Themes: ecosystem services, bivalve aquaculture

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., . . . Murray, C. J. (2019). Food in the Anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet, 393*(10170), 447-492. doi:10.1016/s0140-6736(18)31788-4

This is usually referred to as "The EAT-Lancet Report". It comes from the EAT-Lancet Commission, which brought together 37 leading scientists from around the world to answer the question "Can we feed a future population of 10 billion people a healthy diet within planetary boundaries?" According to the Commission, this report provides the first ever scientific targets for healthy diets and sustainable food production based on a broad review of the latest scientific literature. The report recommends a shift towards healthier, low GHG emission diets that largely consist of vegetables, fruits, whole grains, legumes, nuts, and unsaturated oils, include a low to moderate amount of seafood and poultry, and include no or a low quantity of red meat, processed meat, added sugar, refined grains, and starchy vegetables. It also notes that seafood provides about 3.1 billion people with 20% of their daily intake of animal protein, and states that future expansion of seafood should come from aquaculture, which could help steer production of animal source proteins towards reduced environmental effects and enhanced health benefits.

Themes: nutrition, climate-resilient food systems, seafood demand

Zhang, Y., Zhang, J., Liang, Y., Li, H., Li, G., Chen, X., . . . Liu, J. (2017). Carbon sequestration processes and mechanisms in coastal mariculture environments in China. *Science China Earth Sciences, 60*(12), 2097-2107. doi:10.1007/s11430-017-9148-7

This Chinese paper discusses the potential for seaweed aquaculture ("mariculture" in this paper) to sequester blue carbon and mitigate climate change. The authors explain the process through which seaweed aquaculture sequesters carbon and discuss the role of blue carbon sequestration in China's climate policies. They also suggest that blue carbon will be included in the future carbon market as a tradeable good.

Themes: seaweed, blue carbon, carbon sequestration, mitigation

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