Good Food Institute

Building climate policy momentum for alternative seafood

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Executive summary

Our one shared ocean plays a critical role in climate change mitigation, absorbing emissions as well as excess heat from those emissions. But threats to our ocean, like overfishing, are likely to mount with growing populations and the associated demand for seafood. By the end of this decade—recognized as the UN Decade of Ocean Science for Sustainable Development—global seafood production is expected to grow by 14 percent.[1] Neither wild-capture fishing nor fish farming can scale to meet the growing demand without threatening the health of the ocean and rivers, further contributing to the challenges facing a finite planet with a now rapidly changing climate. Alternative seafood—made from plants and cultivated from cells—may offer the world a chance to produce seafood without transforming critical aquatic habitats and mitigate the climate impacts of global seafood consumption.

Today, seafood is a critical source of animal protein and nutrition, globally eaten twice as often as poultry and three times as often as beef.[2] This is likely to increase, as standards of living rise around the world: most people are projected to qualify as middle income by 2050[3] (with the most rapid growth of the middle class taking place in Asia[4]), and seafood demand increases with income.[5] However, both wild-capture and aquaculture practices vary from highly responsible to highly problematic. Many conventional sources of seafood are overfished, and illegal, unreported, and unregulated (IUU). As conventional production methods undertake reform to keep pace with the global appetite for seafood, alternative seafood may help increase supply while minimizing climate impacts.

Alternative seafood takes two main forms: plant-based and cultivated. Plant-based seafood is made from plants, algae,[6] or fungi, while cultivated seafood is produced by directly cultivating the muscle and fat cells of fish, mollusks, or crustaceans.

Evaluating the climate benefits of alternative seafood requires comparing alternative seafood emissions to emissions from conventional seafood, meats, and other proteins. Fishing vessel fuel use is the primary driver of emissions for capture fisheries. The production of aquafeed is the main source of aquaculture emissions. To date, a limited number of studies compare conventional seafood and other center-of-the-plate proteins to alternative proteins.[7] Scientific methods vary by study, and few researchers have been able to examine impacts across the full value chain from production to consumption. Nonetheless, current research indicates that:

- Plant-based meat (assumed to be representative of plant-based seafood) has a greenhouse gas (GHG) footprint one-third less than conventionally farmed fish and three-quarters less than farmed crustaceans. However, scaled, efficient fisheries (such as purse seine tuna fishing) may remain less emission-intensive than plant-based seafood (Figure 5).[8]

- Cultivated meat (assumed to represent the upper limit of cultivated seafood emissions in this analysis) using conventional energy sources is projected to have emissions greater than most conventional seafood products but lower than the most emissions-intensive forms of conventional seafood (Figure 6, Figure 7).[9,10]

- Emerging forms of renewable energy are projected to substantially decrease cultivated meat/seafood emissions, putting them on par with the footprints of the least emissions-intensive conventional seafood that use grid power/fossil fuels (Figure 6, Figure 7). (Life cycle analyses that compare impacts using renewables across both conventional and alternative modes of seafood production are not yet available.)[11,12]

- Models currently project that cultivated seafood is likely to require less energy than cultivated red meat and poultry. Seafood cells tolerate production at lower temperatures than cultivated terrestrial meats because fish cells exhibit better tolerance to hypoxia (oxygen deprivation), high buffering capacity (resisting changes in pH), and importantly, the ability to grow at a low temperature.[13]

Alternative seafood may be particularly important for the United States, which imports about 65 percent[14] of its seafood and where per-capita seafood demand is rising, resulting in a projected seafood deficit. Neither domestic wild-capture fisheries, which are stable, nor mariculture (ocean farming) operations, which currently face complex permitting processes to expand into federal waters, are likely to meet this deficit. U.S. production of alternative seafood could improve the resilience of the domestic seafood supply, with the potential co-benefit of new domestic seafood employment. Production of alternative seafood in the United States could also reduce the supply chain risks associated with imports, which are growing in the face of greater sourcing-transparency requirements and climate-driven disruptions. These risk reductions include: assuring legal provenance of international seafood, compliance with U.S. laws that protect marine mammals, and protection against fraudulent product labeling.

The U.S. 2021 recommitment to the Paris Climate Agreement—matched by more ambitious emissions-reduction targets and a renewed focus on climate change in domestic policy—created new opportunities for alternative seafood. To help fulfill climate commitments, U.S. policymakers can:

1. Increase public investment in relevant research to advance alternative seafood and recognize such initiatives as climate solutions.

2. Ensure a clear, efficient regulatory process: alternative seafood should not be subject to regulatory requirements that exceed the norms for conventional proteins.

3. Level the playing field for alternative seafood producers for a fair, competitive marketplace with equitable labeling laws for all types of protein, including alternative meats.

4. Increase investment in both methods and fieldwork to quantify how various forms of ocean (and diverse landscapes) production affect sequestration, GHG releases, and warming potential.

Additionally, disclosure and transparency of conventional and alternative protein emissions could further incentivize the adoption of alternative seafood. To realize the full climate benefits of alternative seafood, investment in renewable energy infrastructure is a priority (especially for cultivated seafood), as are policies that assure that all protein producers receive comparable government incentives and support.

Introduction

As the global human population, average longevity, and affluence all grow, seafood demand also increases.[15,16,17] However, the capacity of ocean, coastal, and freshwater systems to feed our growing population is finite. While the sustainability and social responsibility of fisheries and aquaculture are incrementally improving, the capture or farming, processing, and transport of the global seafood supply still contribute to climate change. Simultaneously, climate change may threaten the productivity of stocks and will shift their distributions. Rising ocean temperatures are also likely to escalate conflicts over maritime boundaries and shared stocks[18] while altering access to traditional fishing grounds. These climate impacts present a food security risk because seafood is important for nutrient provisioning globally (e.g., vitamin B12 and DHA omega-3 fatty acids). There are particular risks to vulnerable populations, where 1.39 billion people (19% of the global population) may face seafood-driven nutrient deficiencies because fish currently make up more than 20 percent of their intake of animal-derived foods by weight.[19]

Advances in food and agricultural science coupled with a growing appetite for affordable, nutritious, sustainable, and socially responsible seafood have sparked plant-based and cultivated seafood innovations. Plant-based seafood is produced from terrestrial plants, algae, or fungi to mimic the sensory and, in some cases, nutritional attributes of conventional seafood. Cultivated seafood—also referred to as cellular aquaculture or cell-cultured seafood—is cultivated from the muscle and fat cells of wild fish, molluscan, or crustacean species. Cultivated seafood producers feed cells the same nutrients they would receive inside a fish (amino acids, sugars, salts, vitamins, fats, and other key nutrients) to grow seafood without growing the entire animal.

> *The United States can continue to be a global leader on alternative protein science and these technologies can play an important role in combating climate change and adding resiliency to our food system.*
>
> **– U.S. House Appropriations Chair Rosa Delauro**

This paper explores what is currently known about the climate impacts of all forms of seafood, trends in production, and how these may relate to U.S. domestic climate policy challenges or aspirations, specifically:

1. How conventional seafood generates its main emissions and how practices that reduce emissions from aquaculture and wild capture fisheries might interact with the emergence of alternative seafood.
2. How alternative seafood can support work to address the climate crisis.
3. What policy, industry, and nonprofit engagement would advance these novel alternatives in the marketplace, particularly in the United States.

Climate allies and policymakers have the opportunity to bolster their own climate action priorities by supporting alternative seafood. Advancing alternative seafood as a climate solution may also help address a multiplicity of global challenges including biodiversity loss (please see New blue foods for biodiversity), nutrition, global health, and food security.

Greenhouse gas emissions: Seafood in the context of food systems

Food production[20] is responsible for 34 percent of global GHG emissions and has significant effects on the planet's elemental cycles of carbon, nitrogen, phosphorus, and water—all of which affect climate regulation as well.[21] Agricultural land use and associated land conversion drive 71 percent of these emissions, with the remainder coming from supply chain activities like retail, transport, consumption, fuel production, waste management, industrial processes, and packaging.[22] Without question, the impact of agriculture is substantial, as it directly affects more than 70 percent of the earth's surface and uses 40 percent of the world's ice- and desert-free land.[23,24] Across the agricultural system, red meat has the greatest climate footprint of the main forms of protein, and the global production of conventional meat (beef, pork, mutton, chicken), as well as seafood, is rising (Figure 1).[25,26,27]

In the United States, seafood consumption has increased by approximately two pounds per person per year since 1970—with shellfish doubling in popularity.[28] However, global capture fisheries production, which currently supports U.S. imports, is limited. Yet, long-term trends continue to be relatively stable, with worldwide catches fluctuating between 86 million tonnes and 93 million tonnes per year since the late 1980s.[29] Optimistically, supply from capture fisheries is projected to reach an upper limit of about 100 million tonnes.[30] However, while the United Nations Food and Agriculture Organization (FAO) conservatively characterizes global fisheries as stable, they also recognize that global catch has declined by 0.38 million tonnes per year since 1996. Other estimates indicate that global production has been falling by as much as ~1 percent per year since 1996, which is three times faster than FAO's estimates.[31] Either way, these trends are worrisome in terms of the ability of wild fisheries to support future demand for fish.

Aquaculture is growing in response to the increasing global demand for seafood. Of the overall production of aquatic animals, 89 percent (157 million tonnes from fisheries and aquaculture together) were used for apparent[32] human consumption, while 16 of the remaining 20 million tonnes were destined for non-food uses, to produce mainly fishmeal and fish oil.[33] Aquatic animals are important to global food security, and currently represent 15.3 percent of the global non-plant protein, with the remainder coming from terrestrial animals, milk, and eggs.[34]

FAO projects aquaculture production to increase 22 percent from 2020 to 2030, becoming 59 percent of all seafood available for human consumption.[35] However, the growth in aquaculture production is decelerating: the average annual growth rate of 4.2

percent (2010 to 2020) is projected to decrease to only two percent between 2020 and 2030 (Figure 2).[35] FAO attributes this slowdown to:

- broader adoption and enforcement of environmental regulations;
- reduced availability of water and suitable production locations;
- increasing outbreaks of aquatic animal diseases related to intensive production practices; and
- decreasing aquaculture productivity gains.[35]

If aquaculture growth does not keep pace with increased demand (particularly given consumption levels recommended by health authorities[36]), many countries may experience seafood deficits, higher prices,[37] and the potential for protein or micronutrient insecurity which are already deficits in diets of the poor.[38,39]
Furthermore, there may be real limits on producing food from aquatic systems—alternative seafood can be an important tool for addressing these. Industrial production of even relatively climate-neutral ocean crops such as seaweed and shellfish may disrupt nutrient cycling in the ocean,[40] which is estimated to be 60 times more trophically efficient than land. Since energy and nutrients pass much more efficiently up the food web in aquatic systems, there are stricter limits on production from the sea than on land.[41] These limitations mean that we should not assume that the historical expansion of terrestrial farming can ecologically proceed in a similar way in the ocean. Furthermore, freshwater systems and coastal zones are already highly coveted for multiple uses and may not be prioritized or remain fit for aquaculture and mariculture.[42] There is a great opportunity to convert the large, available biomass of terrestrial plants into alternative seafood via land-based production systems.[43]

Conventional seafood: Key drivers of emissions

GHG emissions are commonly measured with life cycle assessments (LCAs), which are quantitative and transparent frameworks that examine the environmental impacts of products or services from the extraction of raw materials through to their disposal. The debate about best practice in LCAs has led to consensus-building efforts among users and stakeholders such as the European Platform on Lifecycle Assessment[44] and internationally standardized methods such as ISO 14040,[45] which defines the scope and goals of LCAs consistently but does not specify detailed analysis methods.

Therefore, LCAs remain critical but imperfect and evolving tools. Fewer LCAs for seafood exist than for terrestrial agriculture.[46] Most food system LCAs also focus heavily on production emissions (harvesting/fishing)[47] but omit emissions from the other stages in the value chain such as boat building, processing, cold storage, export, and beyond. In fisheries, the most current research consolidates information on impacts across nutrient cycles and shows how different forms of farmed and wild seafood compare to each other and, occasionally, conventional meats.[48] Although more data are needed, we have a broad, if still basic, understanding of the key drivers of emissions for wild-capture fisheries and aquaculture.

Emissions from wild-capture fisheries

The overall contribution of fisheries to global GHG emissions appears to be relatively small in absolute terms. However, conventional seafood emissions are poorly documented,[49] and most estimates do not account for blue carbon released from the ocean floor. Fuel use is believed to be the primary driver of fisheries' GHG emissions: an estimated 60 to 90 percent of total lifecycle GHG emissions in fisheries are the direct result of vessel fuel consumption. Parker and colleagues[50] estimated that fisheries consumed 40 billion liters of fuel in 2011 and generated a total of 179 million tonnes of CO_2-equivalent GHGs, which corresponds to approximately four percent of global food production emissions. However, fuel and associated emissions vary up to 200-fold depending on the fishery and the type of gear used,[51] target species, fish behaviors such as schooling, transport to and from fishing grounds, skipper behavior, and more. Half of capture fishery products for human consumption are estimated to have a CO2-eq kg protein that falls below pork emissions, while the other half ranges from the lowest bound of pork emissions into the range of beef cattle and lamb emissions (Figure 3). New hybrid-electric and battery-powered pure electric boat designs show GHG emissions savings and favorable lifecycle cost savings,[52] but remain far from widespread in terms of commercial deployment. Other emissions-heavy aspects of current seafood supply chains include transporting fresh products by air,[53] some types of packaging,[54] and some refrigerants.

Current LCAs do not account for the release of blue carbon from the ocean floor, which has unknown effects on GHG emissions for active, bottom-contact gear. Calculations from research in 2021 estimated that bottom trawling may release as much as 1.5 billion metric tonnes (1.5 Pg) of aqueous CO_2 sequestered in seafloor sediments annually: this is comparable to the volume of CO_2 released on land through farming.[55,56] It is also not clear what fraction of this CO_2 moves across the water interface to become a GHG that drives atmospheric warming directly. Regardless, in-water release of seabed CO_2 reduces the capacity for ocean surface waters to sequester carbon from the atmosphere and pump it into deep ocean environments.[57] And while acidification reduces the ability of shellfish and reef invertebrates to calcify hard structures, there also is preliminary evidence that it increases the mineralization of fish cartilage and may boost algal growth. Climate-induced changes in ocean acidity will therefore disrupt carbon circulation as well as long-evolved and complex physiological and ecological relationships.[58]

Emissions from aquaculture

Aquaculture contributes approximately five percent of total agricultural GHGs[59] and 0.49 percent[60] of global GHG emissions. Aquatic animals convert feed more efficiently than terrestrial livestock and do not typically release enteric methane from digestion (although methane may be released from hypoxic pond conditions).[61] Yet, even the lowest-impact aquaculture systems exceed emissions associated with plant-protein production.[62,63]

Production and transport of aquafeed ingredients (e.g., fishmeal, fish oil, and land crops such as beans, peas, wheat, canola, and flaxseed) are the main drivers of aquaculture emissions.[64] Overall, fishmeal-based aquafeed has higher impacts on the environment than plant protein-based feed, but different aspects of ingredients drive diverse climate impacts. For example, global warming potential and acidification potential relate to the fossil-fuel energy used to generate feed inputs, while eutrophication potential is most related to run-off of fertilizers used on crops,[65] and land conversion/use can be substantial for feeds that use soybean or other crops from newly expanded fields.[66] Secondary aquaculture impacts include nutrient pollution and eutrophication from farm-based energy use and fertilizers.[67] Feed and energy use depend on the nature of the production systems and generally increase with intensive methods, such as closed containment for highly carnivorous species.[68]

Emerging research assesses land use and conversion in aquaculture climate analyses as well. Where land conversion for production occurs—particularly in coastal zones that naturally house high-carbon-sequestration habitats (e.g., mangroves with large below-ground carbon stocks), which can sequester up to ten times the carbon of tropical forests[69]—conversion and subsequent use of that land can result in serious emission footprints, exceeding even conventional beef production.[70] Although some aquaculture systems can have low land requirements[71] or may convert fisheries or agricultural byproducts into edible protein, the GHGs from the lowest-emission forms of aquaculture are greater than those from plant-protein production, driven mainly by land use change as well as crop product and feed transport (Figure 4).[72] Enabling greater direct consumption of plant proteins through plant-based seafood could help prevent further land conversion for fed aquaculture and reduce greenhouse gas emissions.

Alternative seafood: emissions relative to conventional proteins

Drawing comparisons between emissions from conventional and alternative seafood is challenging for several reasons. First, conventional seafood emissions are poorly documented:[73] the highly diverse and widely traded nature of seafood means that existing analyses do not account for potentially meaningful portions of footprints, particularly the rapid transport of fresh products, while the average transport emissions of future alternative seafood are unknown. Also, as noted in the wild capture fisheries section above, GHG emissions from conventional and bottom-trawled seafoods like groundfish and shrimp may underestimate the release of GHGs through seabed disturbance. More LCA work on seafood and all proteins is particularly important given the incredible diversity of seafood (more than 33,000 species consumed globally)[74] and seafood production methods,[75] compared to the limited number of terrestrial species (primarily cattle, pigs, lamb, and chickens), which may also differ substantially in emissions based on production location and methods.

At present, few scientific publications compare the emissions of conventional proteins with alternative proteins at scale, and none are available based on the actual production of cultivated seafood. The most holistic analysis available comes from a 2020 paper by Santo et al., which reports on six available peer-reviewed studies that provide environmental impact data for plant-based proteins and three for cultivated proteins. By also incorporating gray literature from published reviews and a conference presentation, the authors examined the emissions of plant-based and cultivated seafood relative to various conventional proteins.[76]

Plant-based seafood

Plant-based seafood is a broad category that includes ingredients from an array of plant-based sources. In supplemental materials, Santo et al. document a list of the primary protein inputs used in commercially available plant-based seafood.[77] These include textured wheat and whey protein, vital wheat gluten, soy protein isolate or concentrate, various pea proteins (lentil, fava bean, navy bean), chickpea flour, and mycoprotein from fungi that are used in popular, highly processed products such as filets, slices, and finger formats. Plant-based seafood may also be minimally processed (e.g., whole tomatoes flavored or charred to mimic tuna). Regardless, where it has been quantified for plant-based meat patties, processing accounts for only an additional 13 to 26 percent of plant-based meat's climate impact.[78,79]

For plants, emissions vary dramatically with production method and location, making it important to assess the climate impact of a specific production system, rather than using the limited values currently available in the primary or gray literature. Wheat, for example, emits the greatest GHGs from the use of electricity and fuel in some countries using particular farming methods, while at other country-sites, the main GHGs come from residue burning, direct effects of synthetic fertilizers, or the manufacture of fertilizers.[80] Similar emissions differences are seen in fisheries. For instance, the GHGs associated with skipjack tuna are notably low for purse seine fishing but rival beef when fished using troll gear elsewhere.[81] In contrast, beef emissions from different countries are driven consistently from enteric fermentation, regardless of location.[82]

Non-renewables—Conventional meat versus plant-based meat

Assuming that the emissions associated with plant-based seafood are not substantially different from data currently available from other forms of plant-based meats (e.g., plant-based beef and chicken), projected emissions using a conventional energy mix will be substantially lower than emissions from conventionally produced beef (mean of 42 kg CO_2e/100g protein) and dairy cattle (15 kg CO_2e/100g protein), and 2–3 kg CO_2e/100g protein lower than means for conventional pork and chicken emissions (Figure 5).[83] LCAs associated with producers of plant-based meats indicate promising results:

1. Eating a plant-based meat meal (Morning Star patties) results in a 58 to 77 percent reduction in CO_2 emissions, compared to a conventional meat-containing meal.[84]
2. Comparing the Beyond Burger to a 2017 beef LCA by Thoma et al., the Beyond Burger generates 90 percent fewer GHG emissions and requires 46 percent less energy.[85]
3. The Impossible Burger's global warming potential is 89 percent lower than a conventional beef burger, according to an LCA by Quantis.[86]

Results were calibrated based on product weight rather than unit of protein, and results would benefit from protein-based comparisons in order to make direct nutritional comparisons.

Non-renewables—Conventional seafood versus plant-based meat	Santo et al. reported that the median GHG footprint of plant-based seafood was 34 percent and 72 percent lower than those of farmed fish and farmed crustaceans, respectively, per 100 grams of protein (Figure 5). Of the three seafood categories reported, only wild tuna had a footprint less than plant-based products.[87] As noted in the wild capture fisheries section above, GHG emissions from conventional and bottom-trawled seafoods like groundfish and shrimp may also be underestimated, further increasing the potential emissions benefits of plant-based alternatives.
Mixed—Conventional seafood (non-renewables or renewables) versus plant-based meat (renewables)	No LCAs are currently available projecting emissions of plant-based meat using renewables, therefore it is not possible to compare renewable-produced plant-based meat emissions with capture fishing using conventional energy sources. Similarly, projections are not available modeling the production of wild or farmed seafood based on renewable energy, so it is not currently possible to perform a direct renewable-based comparison between conventional seafood and plant-based seafood. A number of plant-based substitutes are derived from plant products that may have corollary biodiversity or habitat benefits, unrelated to CO_2 emissions. Legumes, as a common ingredient in plant-based foods, can improve soil fertility by fixing atmospheric nitrogen for plants.[88] Plant-based meat also results in 51 to 91 percent less nutrient pollution in aquatic systems, with median savings of 75.5 percent compared with conventional meat.[89]

Cultivated seafood

Cultivated seafood's footprint will be driven by the energy used in the manufacturing process at scale, which will differ substantially depending on whether power comes from renewables or from traditional fossil fuels (e.g., diesel or coal). At this time there are no scientific analyses comparing the projected emissions of cultivated seafood directly to conventional seafood that account for expected shifts to renewables for both. Therefore, current comparisons must be extrapolated from projected cultivated meat emissions. Using cultivated meat's projected emissions as a cultivated seafood proxy likely overestimates cultivated seafood emissions because marine cells can be grown at lower temperatures than terrestrial meat cells.

The substantial range of estimates for projected cultivated meat production (Figure 5) reflects some of these uncertainties: the projected GHG footprint of cultivated meats varies from 0.9 to 36.3 $kgCO_2e$/100 g protein (median: 5.6 $kgCO_2e$/100 g protein).[90] The existing research on emissions from center-of-the-plate proteins must grapple with non-standardized accounting units: manuscripts variously use edible weight, live weight, and protein weight. Nonetheless, the most current information available indicates that:

Non-renewables—Conventional meat versus cultivated meat:

Sinke et al. project that emissions[91] of cultivated meat produced with traditional power will be substantially lower than emissions from conventionally produced beef and dairy cattle and are expected to be in the range of current conventional pork at about 14 $kgCO_2e$/kg of edible product (Figure 6).[92,93] Using different units, Santo et al. also show beef (42 $kgCO_2e$/100 g protein) and dairy cows (15 $kgCO_2e$/100 g protein) emitting substantially greater CO_2/weight of protein relative to cultivated meat (5 $kgCO_2e$/100 g protein) on average (Figure 5).[94] They also show mean cultivated meat (alternative seafood proxy) emissions as approximately equivalent to pork, and slightly greater than chicken, consistent with the Sinke et al. results.

Non-renewables—Conventional seafood versus cultivated meat:

Cultivated meat production with non-renewables is currently projected to have emissions greater than conventional seafood production, with rare exceptions. Sinke et al. project that emissions from scaled cultivated meat production with conventional energy would be about 14 kgCO2e/kg edible weight. This footprint is greater than the emissions of most farmed and wild seafood species as calculated by Gephart et al. which range from ~3.5-12 kgCO2e/kg edible weight—with farmed fish averaging on the lower end of this range and wild fish on the upper end. Rare exceptions in both categories[95] may emit close to 20 kgCO2e/kg which exceeds projected emissions for CM.[96,97] Santo et al. also showed that the median projected footprint of cultivated meat using conventional power is greater than farmed fish or wild tuna but was 17 percent lower than farmed crustaceans.[98]

Mixed—Conventional seafood (non-renewables) versus cultivated meat (renewables):	With increased energy decarbonization (where cultivated meat production uses renewable energy) and with scaling assumptions,[99] Sinke et al. project emissions of approximately 3–4 $kgCO_2e$/kg edible cultivated meat product (Figure 6). This would place cultivated meat produced with renewable power in the lower range of most farmed fish (e.g.) (Figure 7, a) and below the emissions of most wild fish (Figure 7, b), when compared to the results of Gephart et al.
Renewables—Conventional seafood versus cultivated meat:	While Sinke et al. model the emissions of both conventional and cultivated terrestrial meat production using renewables, no LCAs are currently available projecting the footprint of capture fishing using renewable power or electric boats to compare with the work of Sinke et al.

The takeaway here is that the climate benefits of cultivated seafood are highly dependent on scaling renewable energy. Warming considerations aside, alternative seafood offers important environmental benefits relative to conventional seafood production. For example, Gephart et al. note that emissions data alone fails to reflect holistic ecological impacts including biodiversity. For instance, some types of seafood with relatively low emissions pose the greatest risk of entanglement and bycatch to marine mammals. (Please see New blue foods for biodiversity for a deeper exploration of this topic.)

Both cultivated and plant-based seafood also enable the possibility of more distributed, local seafood production without the same safety-at-sea risks experienced in capture fisheries. Conventional seafood also has long and complex supply chains, and alternative seafood production facilities could theoretically be established almost anywhere in the world, including inland regions and socio-economically disadvantaged communities in need of environmentally just economic opportunities. Local producers could cater to regional demands, reducing transport times, distance, and, consequently, GHG emissions. Whether these potential energy and emissions savings offset other more energy-intensive aspects of cultivated seafood production, like the increased amount of automation, remains to be seen. However, the movement in the United States and around the world towards renewable energy and decarbonization promises to reduce the carbon footprint of both cultivated seafood and other modes of seafood production.

Alternative seafood and domestic policy priorities

Climate goals established by the current administration in the United States, including increasing the use of renewables, broader GHG accounting processes, and redirecting financial flows to climate solutions, are highly consistent with greater production and consumption of alternative seafood. Similarly, these new policy objectives could be bolstered by scaling alternative seafood production using renewable power, providing new forms of domestic employment, and decreasing the national GHG footprint.

Alternative seafood can advance domestic policy priorities for seafood

Per-capita seafood demand is rising in the United States, providing a substantial opportunity to increase national seafood production and bolster domestic industry through alternative seafood since U.S. capture fisheries are at or above production capacity[100] and federal waters are regulated in a way that does not currently make them easily available for aquaculture. As a result of these constraints, the United States imports between 62 and 65 percent of its seafood, making it the world's largest seafood importer.[101] Thus, increasing the domestic seafood supply is important for U.S. food independence and security—especially as climate change may create additional pressures for both capture fisheries and aquaculture production.

The seafood industry is particularly vulnerable to instability because it has long supply chains and is a highly traded global commodity.[102] Shortages at any one of many nodes in the supply chain increase risk. In a dramatic example, during the Covid-19 pandemic, infected crew, curtailed processing capacity, and restricted transport infrastructure caused significant, highly variable disruptions.[103] The U.S. seafood industry is adapting rapidly to risks, and diversifying seafood portfolios to include alternatives could be a key adaptation strategy. Large brands like Bumble Bee have invested in joint ventures with alternative producers[104] and some retailers are rapidly adding alternatives to their offerings.[105]

Trends in U.S. seafood consumption indicate that the same advantages that have favored aquaculture imports may further favor alternative seafood. Americans increasingly consume a small number of imported and farmed products from industries that have consolidated over the last 30 years. This trend currently confers a competitive advantage to aquacultured products because fewer systems (e.g., processing and marketing) are needed for a smaller number of product categories, and the same could be true for alternative seafood.[106] Alternative seafood research, development, and scaling may only be necessary for a relatively limited number of key domestic seafood species.[107] Further, polling demonstrates that Americans prefer domestic seafood, signaling potential marketing opportunities for domestically produced alternative seafood.[108]

For the United States, sourcing seafood is becoming more difficult, particularly from capture fisheries. Regulators have the substantial challenge of governing seafood operations, along with associated inspections and food safety assurance procedures for both domestic and international products—which only grow more complicated in the face of climate-driven disruptions. Sourcing climate-resilient alternative seafood domestically could alleviate the cost and burden of regulation, which includes ensuring legal provenance via traceability systems,[109] compliance with U.S. laws that protect marine mammals,[110] and prevention of fraudulent product labeling.[111]

Climate policy and domestic engagement can advance alternative seafood

A number of international agreements aim to address global climate change and guide the development of domestic climate policy. The Paris Agreement requires countries to outline and prepare their climate actions, known as nationally determined contributions (NDCs), to limit global temperature rise to 1.5°C. The Biden administration explicitly defined a "whole-of-government" approach to the climate crisis and committed to strategies[112] that forecast important U.S. climate policy shifts.[113] This government has set the stage to reduce the use of fossil fuels while supporting renewables, infrastructure, equitable food production, and nature-based climate solutions—all good news for alternative seafood.

The importance of policy in transforming commodity systems and diets may not always be well recognized, but goals, programs, legal structure, and priorities set by governments can either bolster existing norms or allow for interruptions.[114] After policy realignment, broadened regulatory tools allow new forms of production, scaling, and consumer access. These types of transitions have occurred in different regions for broad consumption of products such as milk, farmed tilapia, and chicken.[115]

By supporting alternative seafood, the administration and Congress can advance progress to fulfill the United States' commitments under the Paris Agreement. The proposals below represent opportunities to leverage alternative seafood as a solution that simultaneously advances renewable energy, food security, monitoring and science, sustainable agriculture, stronger ocean management, and the realignment of financial flows to support emissions reductions.

1. Increase public investment in relevant research

Policymakers can catalyze climate-smart food production by making significant investments in the most climate-friendly forms of seafood production. Governments have sparked transitions in energy, computer processing, and food systems by providing public funds to support research and development. Relative to other critical climate solutions, alternative protein research is sorely underfunded. As of 2021, only $360 million had been awarded to alternative protein research and development (R&D)—just 0.004 percent of the $2.5 trillion invested in renewable energy over the past decade.[116,117] Agencies are funding climate solutions, and clarifying and confirming support for alternative protein research represents a leadership opportunity for policymakers. As U.S. House Appropriations Chair Rosa DeLauro said, "The United States can continue to be a global leader on alternative protein science, and these technologies can play an important role in combating climate change and adding resiliency to our food system."[118]

At the United Nations Climate Change Conference COP26, the United States and the United Arab Emirates jointly launched the Agricultural Innovation Mission for Climate initiative (AIM4C),[119] which seeks to unite national governments to increase and accelerate global investment in climate-smart agriculture over the next five years. Alternative proteins, including alternative seafood, should be a critical part of global climate collaboration, and countries like the United States can operationalize their carbon-reduction commitments by working with others to fund foundational open-access research into crop varieties and processing methods. In the United States, these investments can be made through existing programs like the U.S. Department of Agriculture's Agricultural Research Service or through competitive grants awarded to university research centers. Careful thought will need to be given to how any alternative protein technologies are patented or privatized with respect to equity considerations for seafood-dependent and developing fishing nations.

2. Level the playing field for alternative seafood

Alternative seafood should benefit from the same advantages that policymakers confer on conventional seafood in the United States, allowing growth of the alternatives as a sector to support the U.S. seafood supply while minimizing climate impacts. In practice, this means that producers should have fair access to progressive subsidies, and allocations should be informed by contributions to the United States' NDCs. Under this framework, responsibly produced seafood (alternative or otherwise) could receive government funds for demonstrating best practices, which would shift support away from harmful subsidies associated with illegal, destructive, or emission-intensive practices.[120,121]

Likewise, alternative proteins should be able to use familiar food terms (e.g., veggie burger, oat milk, or plant-based sausage) on labels—terms that communicate what these foods replace and how they fit into culinary customs. In 2020, the EU considered restrictive legislation that would have banned producers from using terms like "burger" and "sausage" to label plant-based meat options.[122] Meanwhile, plant-based dairy labels in Europe have been so restricted: familiar terms like “milk” and “cheese” cannot be used for plant-based options, even when used with appropriate qualifiers such as “vegan.” Some state policymakers backing this same kind of legislation in the U.S. have been explicit that labeling proposals are designed to support the interests of animal agriculture.

The FDA currently has an opportunity to clarify labeling standards,[123] reaffirming that plant-based and cultivated seafood producers comply with law and policy when they use seafood terms or imagery on their labels. Seafood labels must allow alternative products to fit into the existing culinary culture on a fair footing with conventional seafood.

3. Ensure a clear, efficient regulatory process

Alternative seafood should not be subject to regulatory requirements that exceed the norms for conventional proteins. This is especially important for cultivated seafood, which has not yet received regulatory clearance in the United States. The FDA should exert its regulatory authority fairly and ensure that safe, properly labeled cultivated seafood can come to market without unduly onerous regulatory requirements. At an international level, the Codex Alimentarius (“Food Code”) Commission can help develop guidance or model regulations for cultivated seafood that assists other nations in developing their own fair regulatory frameworks. Simultaneously, the two multilateral organizations that convene Codex—the UN Food and Agriculture Organization and the World Health Organization—should continue to provide international forums for regulators and subject-matter experts to share information about production processes and preventative controls, particularly in jurisdictions such as Singapore that are advanced in regulating alternatives.

4. Fund alternative seafood as a component of food justice

The current administration has explicitly recognized the intersection of food, production, equity, and justice. Policymakers are being asked to increase national food security while also creating good-paying jobs and climate-positive careers in underserved communities. Emerging policy priorities can support partnerships to strengthen local food economies through the growing alternative protein industry. State and local governments can provide fiscal incentives to site alternative seafood production in areas with affordable land and job scarcity, including where they can be co-located with other agricultural production or facilitate the economic transition away from reliance on fossil fuel extraction. Production of fresh alternative seafood far from rivers and oceans could provide nutritional benefits while reducing transport footprints.

5. Support inclusive, full-cost carbon accounting tools for NDCs

The United States’ NDCs include commitments to “support nature-based coastal resilience projects” and “increase sequestration in waterways and oceans by pursuing ‘blue carbon.’”[124] Shifting seafood production away from the ocean and coasts offers an excellent opportunity for nature-based solutions that reduce emissions footprints either by avoiding conversion that releases GHGs or through remediation of environments such as seagrass, mangroves, and estuaries, which all have great carbon-capturing potential. In addition to serving as vital wildlife habitat, these types of rewilded seascapes can also serve to buffer high-value and high-use coastal areas from increasingly extreme climate events.

Administration (NOAA) is working with the Environmental Protection Agency (EPA) on an updated accounting process for coastal blue carbon to better assess wetlands, include coastal or marine habitats that are currently omitted, and analyze how fishing, sea-filling, or other disturbances affect GHG emissions. NOAA and EPA should be funded to collect emissions data in the field (rather than rely on modeling) to assess the carbon footprints of different management practices and to bridge gaps in measuring emissions associated with transformation, transport, retail, and distribution.[125] For instance, international shipping and aviation are not currently included in NDC accounting processes and are vital to the international trade of conventional seafood, which may be transported farther than future scaled and regional production of alternative seafood. These types of emissions need to be accounted for to assure progress toward the NDCs. By creating more accurate and comprehensive accounting tools, these agencies could encourage the private sector to reduce and offset certain capture fisheries, allowing markets to more easily shift toward producing more alternative seafood.

6. Grow blue carbon credit trading

Monetizing carbon sequestration in aquatic systems can incentivize the decommissioning of unprofitable fishing grounds and shift consumers toward alternatives. Blue carbon trading is in its infancy but shows promise and general carbon credit projects are projected to increase by a factor of 15 by 2030.[126]

For instance, in 2020, updated government methods[127] covering mangroves, tidal wetlands, and salt marshes increased the scope of eligible projects, which should allow more sequestration-based projects to move to market. Questions remain about how to ensure the permanence of blue carbon sequestration, particularly with the rise of climate disturbance. Like fire devaluing forest carbon assets, storms or hot water events may impact the value of marine credits. Cross-referencing these environments with the coastal protection they provide could help prioritize projects from a joint mitigation and security perspective. It would be useful for both researchers and NOAA to map blue carbon assets across all marketable categories, particularly seagrass.

There are also opportunities for government and academic researchers to formalize new accounting methods to be used outside the shallow coastal zone (e.g., recent work by Sala et al. estimating trawl gear emissions)[128] and to account for how reducing destructive fishing could allow more carcasses to naturally sequester carbon at depth.[129] Researchers calculate that the transition from terrestrial animal agriculture to plant-based diets by 2050 could sequester enough carbon dioxide to meet the Paris Agreement emissions budget for a 66 percent change of staying under 1.5 degrees of warming.[130] Similar analyses could quantify the carbon sequestration opportunity to shift away from the most destructive/emission-intensive forms of fishing and toward scaled adoption of alternative seafood.

7. Break down scientific silos around seafood

As climate change strains protein production, policymakers need information to help them co-optimize decisions for human health, sustainability, and climate.[131] The fragmented seafood science and management landscape[132] encompasses fisheries management, ocean health, human health, international development, and social justice, among others—each associated with different missions and priorities. By developing more holistic analyses and establishing standard units for comparative work spanning land and water, researchers across government, academia, and nonprofits can break down existing scientific silos. This would help inform the food and nutrition security literature, funding decisions, and policy priorities, which often exclude or overlook seafood,[133] including alternative seafood. A number of different groups may be interested in the climate benefits of alternative seafood, and by providing cross-cutting analyses, researchers can illuminate alternative seafood's potential as a solution to many climate-related policy needs. Importantly, food, health, and climate systems analysts in government, academia, and the private sector can help identify the greatest-common-good options to inform strong policy processes for blue foods.[134]

8. Include human well-being in climate reporting

Analyses capable of supporting a wide array of human-relevant and climate-aligned policies have the potential to highlight the strengths of alternative seafood. A report by the Index Initiative—which aims to clarify how leading seafood companies contribute to the Sustainable Development Goals (SDGs)—identified the seafood sector as one of fifteen in which improvements could advance multiple SDGs and sustainable development as a whole.[135] Research on U.S. consumer preferences also indicates that consumers are most concerned about health risks like mercury, radiation, and plastics; then labor and slavery; and finally, environmental impacts like habitat damage and bycatch.[136] Alternative seafood creates an opportunity to address all three sets of concerns at the same time. Food system researchers should prioritize analyses that encompass both GHG emissions and human health and well-being (such as health and nutrition with environmental impacts). The European Union recently generated this type of work in a "Consumer Footprint," which uses LCAs aligned against five key SDGs[137] to assess the consumption impacts of various products, including food. Approaches like these, which are different forms of multifactor LCA and LCSA[138] assessments, may well highlight the benefits of alternative seafood and create opportunities to fund climate and public health policy goals simultaneously.

9. Collaborate with the domestic agriculture sector

The Biden administration’s recommitment to the Paris Agreement presents opportunities to develop the bioeconomy. Policymakers can seize this opportunity to serve the common needs of multiple constituencies: for example, supporting plant-based seafood producers would provide increased markets for the domestic growers of pulses and grains commonly used as alternative seafood ingredients. Traditional domestic farmers may consider growing key base ingredients for alternative seafood such as peas, soybeans, and wheat in particular, as well as grains, tubers, seeds, and nuts.[139] Plant-based meat companies can also create a robust market for farmers of specialty crops tailored to particular "seafood" textures and flavors, such as tomatoes, eggplants, and seaweed, used either directly as "meat" or as important flavorings. Indoor agriculture operations may consider the opportunities in algal oils, yeast, and fungi, among other high-value crops, that require controlled environments. U.S. producers may receive greater income by producing these ingredients relative to their current income growing commodity crops. In all cases, policymakers should create a level playing field for the diverse forms of agriculture in the United States and should support policies that protect fundamental production needs such as soil health and ocean health.

The activities below are particularly relevant to the private sector and nonprofits working in markets-based conservation, and which need to examine the benefits of alternatives relative to conventional seafood or other types of center-of-the-plate proteins. The production of alternatives on privatized croplands and in the controlled conditions of production facilities may offer a number of important supply chain benefits that reduce the risks that often challenge open-access harvesting and production from wild systems. Extreme climate events that increase these risks and decrease supply chain stability will mount. It is therefore timely to compare how these changing dynamics affect investments and may redirect financial flows and market tools for seafood.

10. Create impact investment-friendly comparisons of the emissions from alternative seafood to other forms of protein

Impact investment vehicles that finance seafood may be able to advance their mission by investing in alternative seafood. At present, investors and impact funds are navigating how best to assess climate impacts via standardized, feasible environmental, social, and governance (ESG) frameworks[140] and such reporting remains voluntary for most funds. This currently makes it challenging to compare conventional seafood production fairly with alternatives. (See Appendix I for research recommendations.) However, Bloomberg Intelligence estimates that by 2025, a third of global assets will be managed for ESG value, so collaboration between seafood experts and fund managers to create standardized ESG frameworks for seafood—that also encompass alternative production processes—could stimulate the inflow of investment from green funds and other social-good finance that should consider climate performance as a key metric.

11. Include climate accounting in voluntary seafood standards and expand the scope to cover alternative seafood

Voluntary standards influence both major retailers' buying specifications and fisheries agencies' management and monitoring. At present, no standard-holding organizations include alternative seafood within the scope for certification, and climate accounting is generally limited or is not evaluated, even for sustainability-based seafood standards. For example, the Marine Stewardship Council is a public proponent of climate action but has not formally integrated GHG emissions requirements into its standard. A number of aquaculture standards-holding organizations, including the Aquaculture Stewardship Council, do require producers to track energy use but do not evaluate operations based on emissions. Incorporating climate accounting into standards that operationally link production practices to consumer markets is vital to showcase the cross-cutting benefits of alternative seafood to the private sector. Researchers have outlined processes for nonprofits and standard holders to incorporate carbon footprints into ecolabels and sustainable seafood guides[141] and these could be applied to alternative seafood as well.

Conclusions

Plant-based and cultivated seafood represent dynamic innovation opportunities to advance domestic solutions for the climate crisis. Plant-based seafood may be particularly important for rapidly addressing climate goals given how efficiently plants produce high-value protein: the global transition to plant-rich diets provides a 50 percent chance of meeting the Paris goal to prevent a 1.5-degree increase in global temperatures relative to pre-industrial levels.[142] Cultivated seafood—particularly if scaled based on renewables—represents a low-emission alternative to the highest-emission forms of seafood that may retain the sensory and nutritional profile of seafood while facilitating consumer shifts toward climate-friendly and healthy diets. However, to fully realize this potential and its climate benefits, investment in renewable energy is critical to supporting infrastructure for the manufacture, distribution, and scaling of alternative seafood.

Large-scale shifts in commodity systems and diets have taken place when publicly funded technological innovation is available to the private sector to scale up under supportive state and international policy regimes.[143] Given this precedent, investing public funds in pre-competitive processes to advance alternative seafood is particularly important to capitalize on the climate benefits that these new forms of protein production are projected to offer at scale. At the same time, conversations to address equity considerations that will arise in the face of seafood with privatized intellectual property—that has the potential to compete with a publicly accessible livelihood option in capture fisheries, particularly in the global South—should not be ignored.

Alternative seafood is an innovation with the potential to provide healthy, geographically distributed, and nutritionally dense protein, while relieving pressure on ocean ecosystems in the face of expanding human populations. We encourage policymakers, members of the private sector, and solution-oriented organizations to consider the exciting potential available in alternative seafood as an emerging climate and biodiversity solution with compelling investment opportunities.

Appendix I: Research recommendations

Governments, universities, and the private sector should work collaboratively to fund and conduct research that is likely to accelerate progress on reducing the climate impacts of conventional protein production by shifting toward plant-based and cultivated seafood alternatives, which will ensure more information from neutral third parties. Building on recommendations by Santo et al., areas of needed research include:

- A standardized framework for reporting the outputs of seafood LCAs to reduce cross-study methodological inconsistencies, including breakdowns of the specific greenhouse gasses associated with the production of different products, in addition to the singular footprint reported in carbon dioxide equivalents.[144, 145]
- LCAs that examine how the specific physiological properties of cells from different marine products—which may behave differently in culture from other types of meat—correspond to differences in emissions, if any.
- LCA methods and field data to quantify the effects of emissions from highly subsidized fishing gear with known negative climate impacts.
- LCA methods and field data to quantify the effects of emissions from the decomposition of organic matter in aquaculture ponds, which creates hypoxic conditions that can result in substantial emissions of methane, nitrous oxide, nitrogen dioxide, ammonia, and other gases.[146] Methane and nitrous oxides are potent greenhouse gasses that disproportionately contribute to warming.
- LCAs that examine if and how emissions for the most common ingredients used in plant-based seafood (e.g., konjac powder, pea starch, pulses, seaweed powder, alginate) differ from those used in other types of plant-based meat substitutes.
- Multidimensional impact analysis that addresses social considerations such as workers' rights alongside the climate impacts of alternative and conventional seafood.
- Research to quantify the impact of technological developments and the scaling of operations in the production of plant-based and cultivated seafood.
- Outreach material for U.S. farmers, disseminating research on optimal growing zones for key alternative seafood ingredients to include conventional farmers and producers of aquafeed ingredients in the opportunity of alternative seafood.
- Regional maps of U.S. seafood preferences and analysis of the potential for local/small-scale bioreactors to embed alternative proteins in regional food systems and bioeconomies.
- Scientific models projecting how climate change will affect and be affected by overall seafood production in the short, medium, and long term via increased water temperatures, ocean acidification, and extreme weather events.
- Research examining how population trends and climate shifts may affect key regions supplying U.S. seafood imports, and on what timescales, would help inform the urgency of increasing domestic seafood production.
- Research that projects emissions from alternatives over sufficient durations to examine the inclusive implications of potent but short-lived GHGs such as methane, versus gasses such as CO_2 with lesser but longer-lasting warming potential to assess acute needs to reduce global warming as well as long-term climate stability.
- Methods to promote the most accurate and up-to-date data from startups without compromising competitive considerations.

Appendix II: Figures and tables

Table 1: Summary of values estimated by eye from figures cited in the text.

Study	Unit type	Units *numerical*	Farmed	Wild	Alternative meat
Gephart et al. 2021	Edible weight	$kgCO_2e\ t^{-1}$	*tighter credible intervals* **Range:** 3K–18K (fish) **Mean:** 7K–8K	*wider credible intervals* **Range:** 4K–21K **Mean:** 9–10K	n/a
	Live weight (Fig S10)	$KgCO_2e\ t^{-1}$	**Range:** 1K–10K **Mean:** 3–4K	**Range:** 1.5K–11K **Mean:** 4K–6K	n/a
Parker & Tyedmers 2014	Live weight	$kgCO_2e\ kg^{-1}$	**Range:** 2–5 **Median:** 2.5	**Range:** 2.5–8.5 **Median:** 5	n/a
Poore & Nemecek 2018	Protein weight	$kgCO_2e$ 100g $protein^{-1}$	**Mean:** 4.8 (fish) **Mean:** 11.9 (crustaceans)	n/a	n/a
Santo et al. 2020	Protein weight	$kgCO_2e$ 100g $protein^{-1}$	<u>Fish</u> **Range:** 2.5–9.5 **Mean:** 5 <u>Crustaceans</u> **Range:** 4–24 **Mean:** 12.5	<u>Tuna</u> **Mean:** 1.5	<u>Plant-based</u> **Range:** 0–6 **Mean:** 2 <u>Cultivated</u> **Range:** 2–32 **Mean:** 5.5
Sinke et al. 2023 Scope 1 = direct emissions from owned or controlled sources Scope 2 = indirect emissions from purchased energy Scope 3 = indirect emissions upstream and downstream in the value chain	Edible weight	$kgCO_2e\ kg^{-1}$	n/a	n/a	Cultivated (conventional energy/average energy mix, scope 1,2, and 3) 14.4 Cultivated (renewables, scope 1 and 2, conventional/ average energy mix scope 3) 4.1 Cultivated (renewables, scope 1, 2, and 3) 2.9

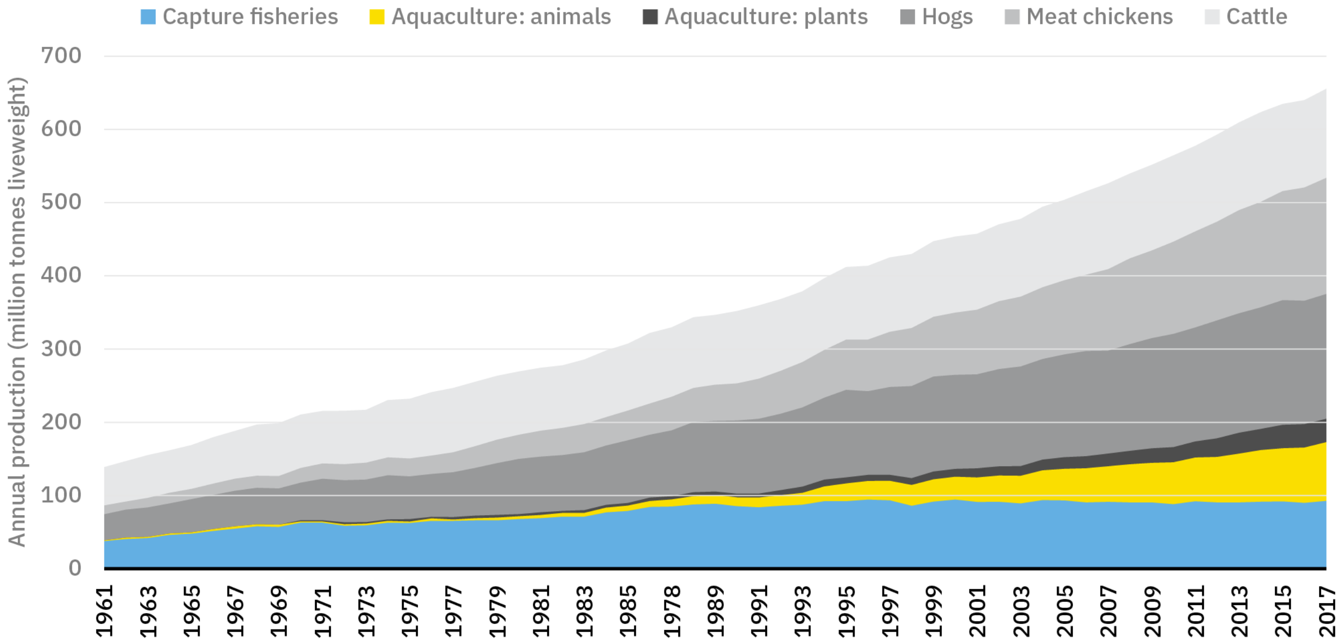
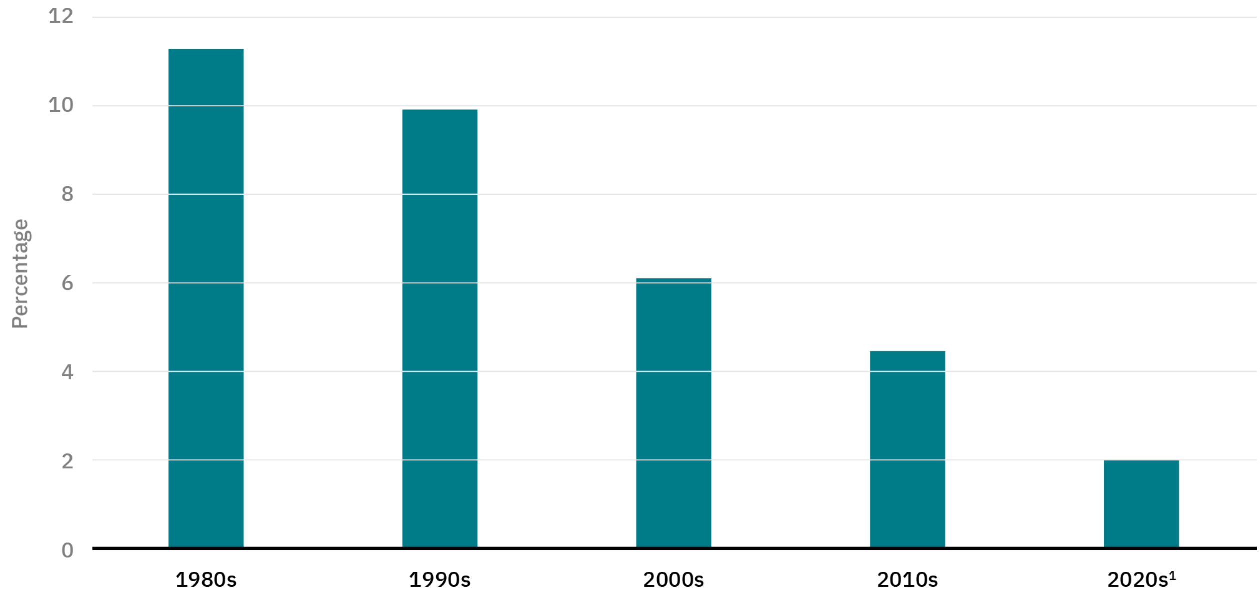


Figure 1. Global production of conventional meat and seafood is rising. However, global capture fisheries production is limited: global catch has declined by 0.38 million tonnes per year since 1996 according to FAO. To fill the gap, aquaculture is growing in response to the increasing global demand for seafood.

Adapted from MacLeod et al, this figure represents, "World production of capture fisheries, aquaculture, and pig, chicken, and cattle meat from 1961 to 2017." (https://www.nature.com/articles/s41598-020-68231-8, Figure 1)

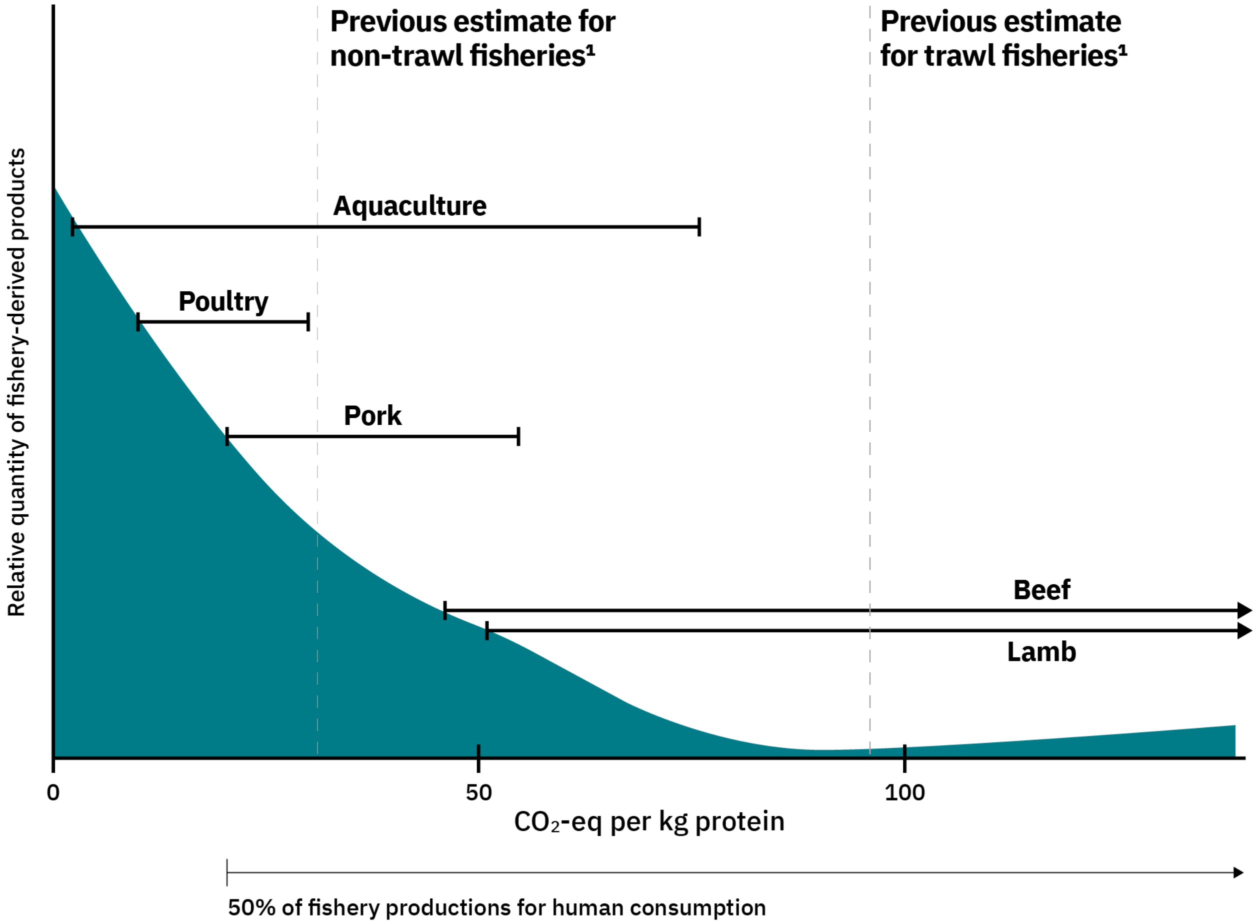


[1]2030 included in 2020s.
NOTE: Excluding algae.
SOURCE: FAO.

Figure 2. Growth in aquaculture production is decelerating: the average annual growth rate of 4.2% (2010 to 2020) is projected to decrease to only 2.0% between 2020 and 2030. FAO attributes this slowdown to:

- “broader adoption and enforcement of environmental regulations;
- reduced availability of water and suitable production locations;
- increasing outbreaks of aquatic animal diseases related to intensive production practices; and
- decreasing aquaculture productivity gains."

Adapted from the FAO State of the World Fisheries Report 2022, this figure represents, “Annual growth rate of world aquaculture, 1980-2030.” (https://www.fao.org/3/cc0461en/cc0461en.pdf, Figure 72, p. 215)



[1]Tilman, D. & Clark, M. Global diets link environmental sustainability and human health. Nature 515, 518–522 (2014).

Figure 3. Fuel and associated emissions vary up to 200-fold across fishery productions. As represented by data from Parker et al 2018, half of fishery products for human consumption are estimated to have a CO2-eq kg protein that falls below pork emissions, while the other half ranges from the lowest bound of pork emissions into the range of beef cattle and lamb emissions.

Adapted from Parker et al, this graph represents, "Carbon footprint of fishery-derived products for human consumption in 2011 compared to other sources of animal protein. Truncated for display purposes to include 98% of landings. Vertical partitions indicate previous generalized estimates for trawl and non-trawl fisheries, showing the percentage of global fisheries below (59%), within (32%), and above (9%) those estimates. Ranges for livestock systems have been previously published: aquaculture, 4-75kg CO_2 per kg protein; poultry, 10-30 kg CO_2 per kg protein; pork, 20-55kg CO_2 per kg protein; beef 45-640 kg CO_2 per kg protein; lamb 51-750 kg CO_2 per kg protein." (https://doi.org/10.1038/s41558-018-0117-x, Figure 3.)

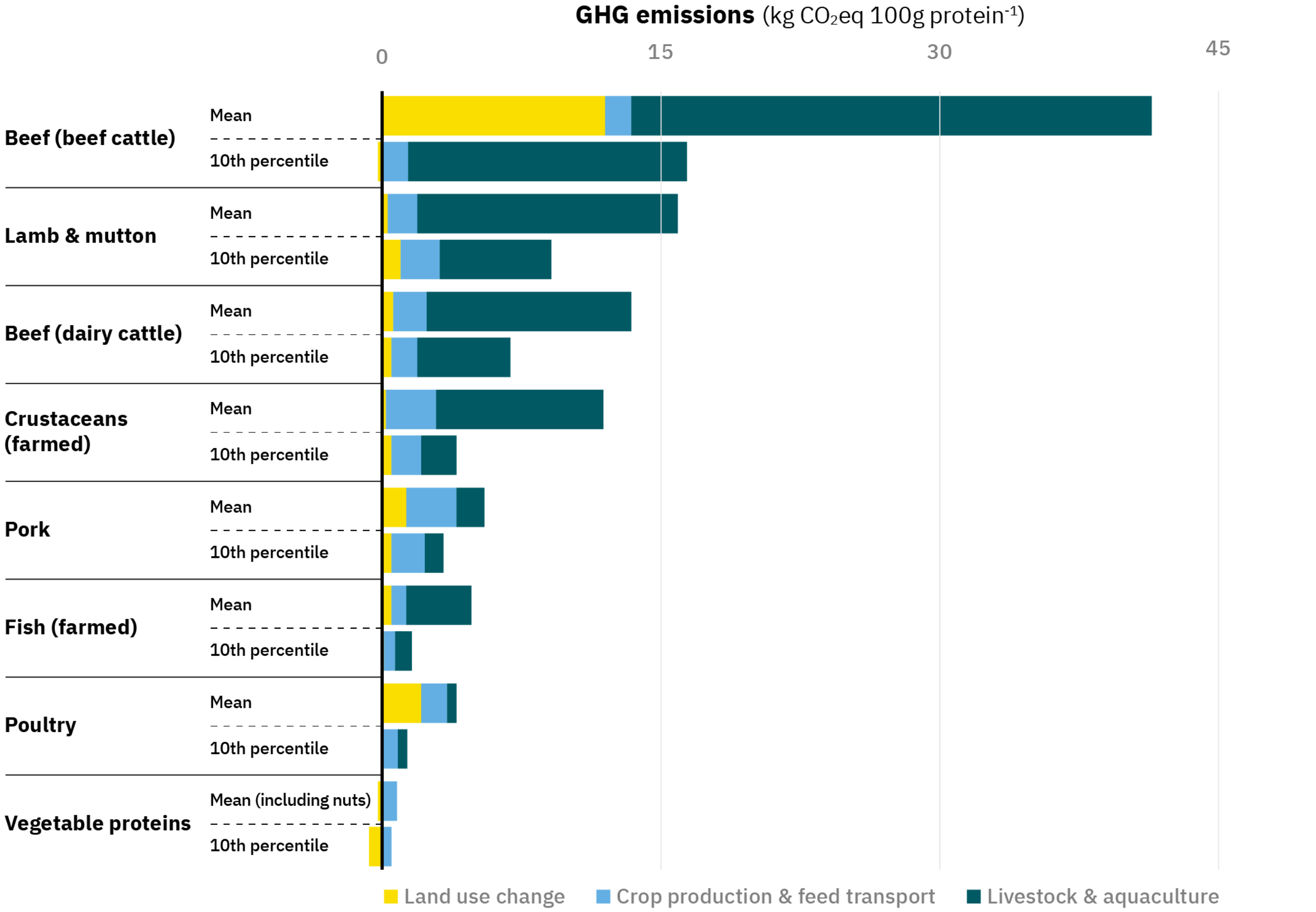


Figure 4. Vegetable proteins including pulses, nuts, and grains are a comparatively low-emissions source of protein-rich food. Plant-based meats use legumes (especially soy and peas) as primary inputs and require processing. These data do not represent emissions for the additional processing required for plant-based meat. Research by Heller et al. and Dettling et al. commissioned by Beyond Meat and MorningStar Farms respectively, found that additional processing accounts for 13%–26% percent of end product emissions.

Adapted from Poore and Nemecek 2018, the figure above represents, "Mean and 10th percentile GHG emissions of protein-rich products across three major production stages...To calculate 10th-percentile emissions by stage, the authors averaged across farms that have total emissions between the 5th and 15th percentiles, controlling for burden shifting between stages." (https://www.science.org/doi/10.1126/science.aaq0216, Figure 3)

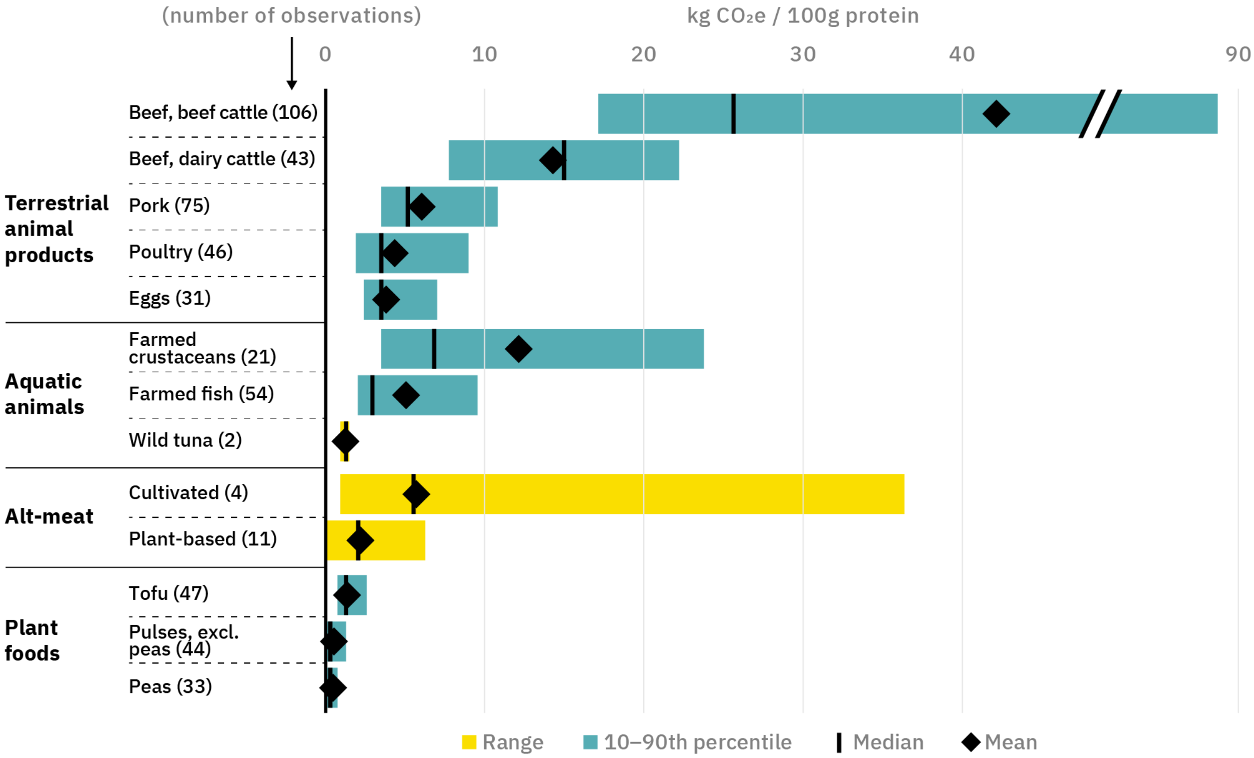


Figure 5. Assuming that the emissions associated with plant-based seafood are not substantially different from data currently available from other forms of plant-based meats (e.g., plant-based beef and chicken), projected emissions using conventional power will be substantially lower than emissions from conventionally produced beef (mean of 42 kg CO_2e/100g protein) and dairy cattle (15 kg CO_2e/100g protein), and 2–3 kg CO_2e/100g protein lower than means for conventional pork and chicken emissions.

Adapted from Santo et al 2020, this figure represents "Cradle to processing-gate GHG Emissions in kg CO_2 equivalent per 100 g of protein produced for different forms of protein." (https://doi.org/10.3389/fsufs.2020.00134, Figure 3).

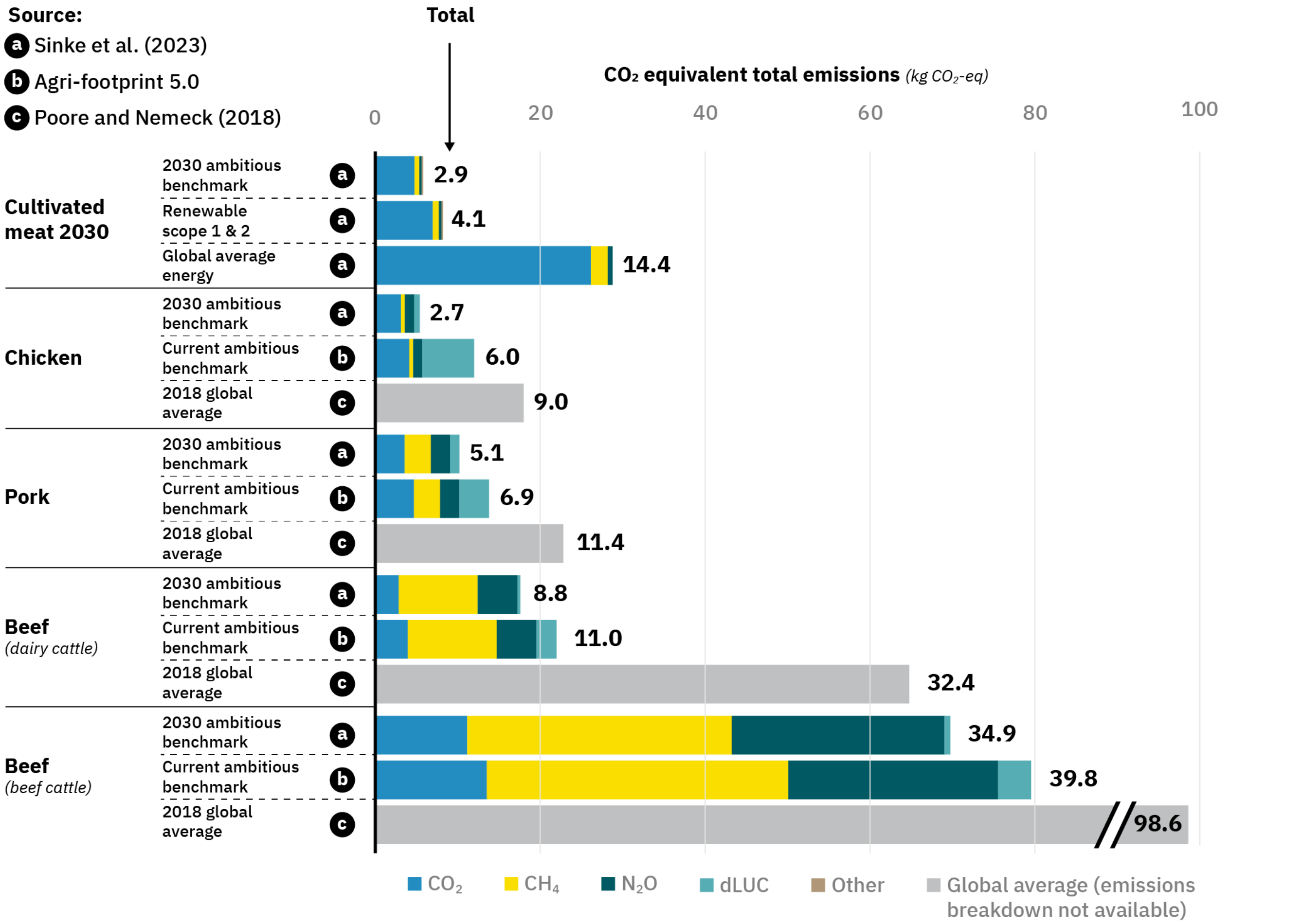


Figure 6. Sinke et al. project that emissions of cultivated meat produced with traditional power will be substantially lower than emissions from conventionally produced beef and dairy cattle and are expected to be in the range of current conventional pork at about 14 kgCO_2e/kg of edible product. With increased energy decarbonization (where cultivated meat production uses renewable energy) and with scaling assumptions, Sinke et al. project emissions of approximately 3–4 kgCO_2e/kg edible cultivated meat product.

Adapted from Sinke et al., this figure represents, "Carbon footprint and greenhouse gas emissions of cultivated and conventional meats." (https://doi.org/10.1007/s11367-022-02128-8, Table 2).

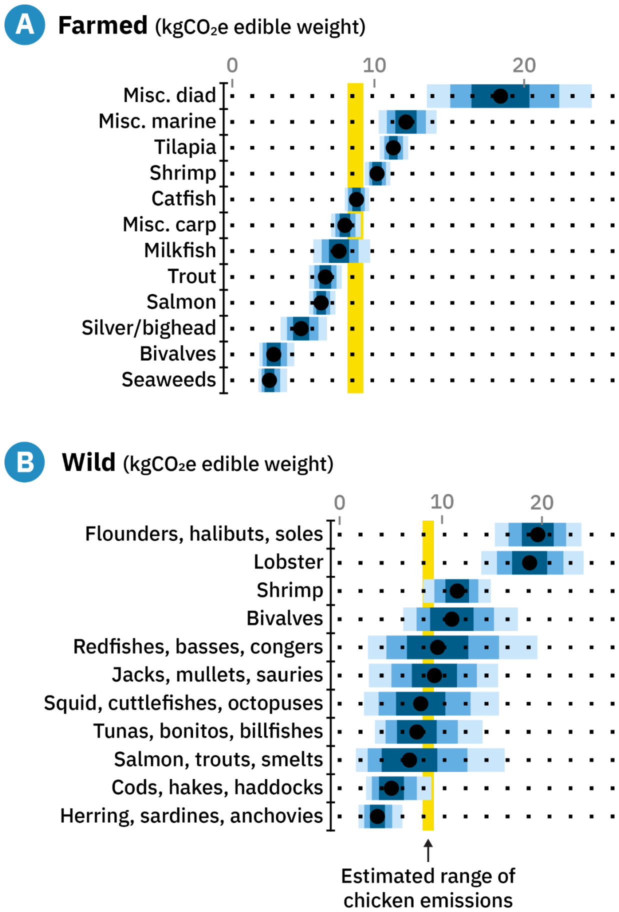


Figure 7. Sinke el al. project emissions from cultivated meat produced with renewable power to be 3–4 kgCO2e/kg edible cultivated meat product, landing in the lower range of most farmed fish (a) and below the emissions of most wild fish (b), when compared to the results of Gephart et al.

Adapted from Gephart et al, this figure represents (a) aquaculture GHG emissions (kg CO_2e) and (b) capture GHG emissions (kg CO_2e) both expressed in units of edible weight. The authors note, “Dot indicates the median, colored regions show credible intervals (i.e., range of values that have a 95% (light), 80%, and 50% (dark) probability of containing the true parameter value). [Yellow] band represents estimated chicken minimum to maximum range.” (https://doi.org/10.1038/s41586-021-03889-2, Figure 1).

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