DNV

WHEN TRUST MATTERS

OCEANS' FUTURE TO 2050

MARINE AQUACULTURE FORECAST

2021 Edition

DNV in aquaculture

DNV has been working with ocean industries for more than 150 years and is a leading third-party assurance and risk-management service provider for the aquaculture industry. With the purpose of safeguarding life, property, and the environment, our services support the industry in meeting regulatory requirements and industry standards that are driven by multiple goals such as cost effectiveness, safety, and environmental sustainability. DNV is owned by a foundation and is trusted by a wide range of customers to advance the safety and sustainability of their businesses.

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Foreword

There is little doubt that marine aquaculture could play a critical role in securing supplies of food for a global population that will exceed nine billion by 2050. For the industry to grow sustainably, operators, governments and investors need trusted information on which to base business cases, supportive policies, and financial and technical due diligence.

This first Marine Aquaculture Forecast developed by DNV responds to that need by delivering our 'best estimate' of the developments to 2050.

As a key provider of risk management and assurance services to the industry across its complete value chain, we are keenly aware of the complexity of making a long-term projection. Our analysis considers not just population growth, but societal trends and changes in living standards to estimate future demand for food. We then consider the ability of marine aquaculture to meet this demand by taking advantage of a range of technology options and addressing several risk factors, not least of which are ecological concerns.

We forecast a more than doubling of marine aquaculture production from 30 million tonnes gross weight per year today to 74 million tonnes in 2050. That means marine aquaculture will match the present output of capture fisheries, which is not expected to grow further because it has already reached its sustainability limits. Molluscs will remain the most farmed species by live weight. However, finfish production, with its more favourable live to edible weight ratio, will grow faster than molluscs.

Our forecast supports the view that future demand for seafood can only be met sustainably with a wave of technological innovation in marine aquaculture. Growing production at the rate we envisage require innovation on many fronts, including technologies that both intensify production and address concerns such as fish health, pressure on inshore marine spaces, and environmental impacts.

Responding to these concerns, innovative production technologies for high-value finfish species will gain significant market shares. We forecast 10% of production capacity for finfish marine aquaculture being onshore in 2050, and 13% offshore. Lower costs due to accumulated experience will drive uptake of new fish-farming technologies.

We expect large regional differences in output by mid-century. South East Asia will see continued growth of finfish marine aquaculture in sheltered waters. Offshore fish farming will gain a strong foothold in Greater China, Europe, and Latin America. Onshore farming of marine species will come to fruition in Greater China,

Europe, and North America, with some smaller capacities in high-income countries in the Middle East and OECD Pacific.

This Marine Aquaculture Forecast will be followed later in 2021 by a more comprehensive Ocean Forecast for a broader set of ocean-related activities.

This is the Decade of Ocean Science for Sustainable Development, and we are ever mindful of the fact that forecasting is not an exact science. However, it is a valuable tool for an industry that needs to navigate a difficult, but potentially very rewarding, passage between the goals of ocean health and ocean wealth.

We welcome your comments and will use them to further enhance our work. Let me also use this opportunity to thank the many people and organizations that have provided input to this report prior to its publication.

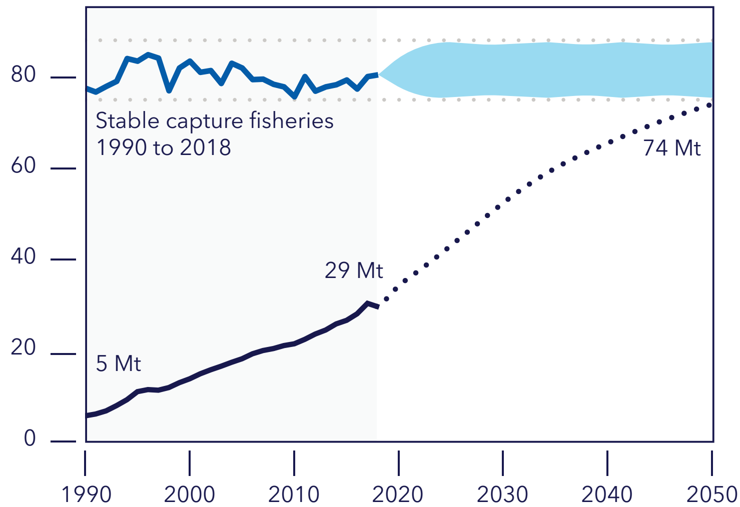
REMI ERIKSEN, Group President & CEO, DNV

Highlights 2050

Global marine aquaculture production approaches same level as capture fisheries by mid-century

- Marine aquaculture production more than doubles in response to rising living standards and dietary shifts coupled with capture fisheries having reached limits for sustainable catch.

Global marine aquaculture production
Units: million tonnes (Mt) in live weight*



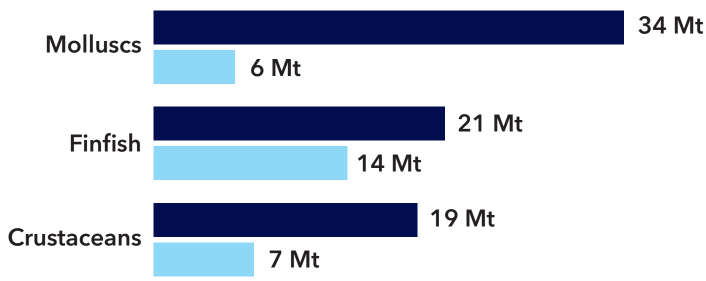
Capture fisheries
Marine aquaculture

*Excludes seaweed

Finfish most important contributor to world food supply from marine aquaculture

- Finfish accounts for more than 50% of the edible weight provided by marine aquaculture.
- Future focus will be on high-value species currently farmed, rather than large-scale farming of new species.

Marine aquaculture production by species in 2050

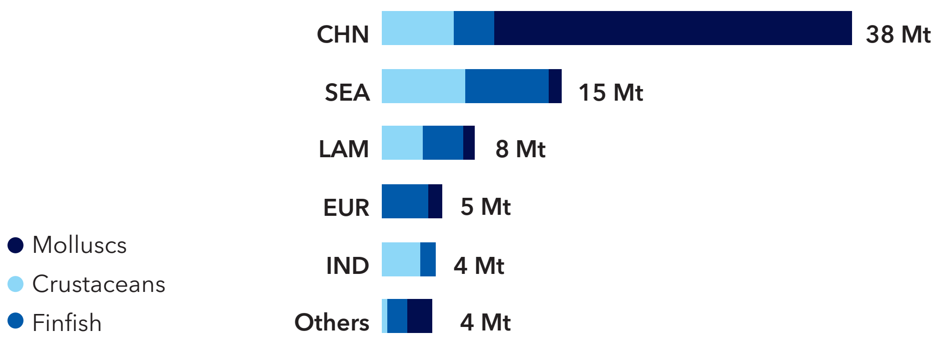


Live weight
Edible weight

Asia keeps its dominant position with 80% of global production

- South East Asia will produce the most finfish and crustaceans while Greater China is the largest producer of molluscs.
- Latin America overtakes the output of Europe through increased production of both finfish and crustaceans.

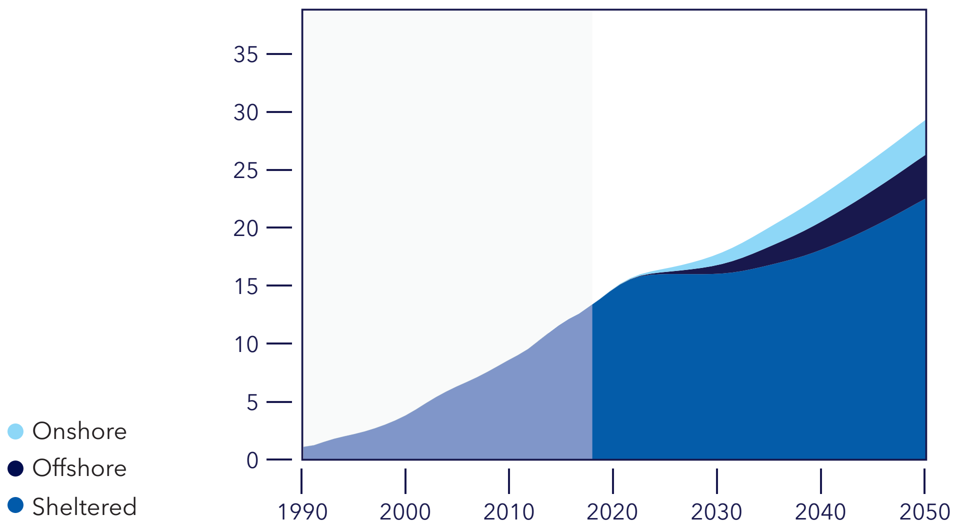
Regional production in live weight in 2050



New offshore and onshore production technologies for finfish will gain traction and market share

- Lower costs due to accumulated experience will drive technology uptake.
- Greater China, Europe and Latin America will lead the way.

Globally installed finfish production capacity
Units: million tonnes



Setting the scene

With world population heading beyond nine billion by 2050, two billion more mouths will need secure sources of food that underpin healthy diets and can be sourced sustainably. Meeting all these criteria is an important objective within the ongoing Decade of Action for the UN Sustainable Development Goals (SDGs).

The barriers to succeeding are considerable. Food security is vulnerable to conflict, disease, mismanagement, climate change and, currently, economic fallout from the COVID-19 pandemic (FAO et al., 2020). The need for dietary shifts is clear from the rising challenge of obesity, micronutrient deficiency, and public health concerns over unbalanced diets globally (UN Global Compact, 2020). The environmental sustainability of our food systems must stay within the safe planetary boundaries for the environmental processes that regulate the state of the Earth system (Willett et al., 2019).

The ocean can play a significant role in helping to meet these challenges. Covering 71% of the planet, it could produce up to six times more food than today, according to the High Level Panel for a Sustainable Ocean Economy (Costello et al., 2020); but only if we manage both fisheries and marine aquaculture more sustainably.

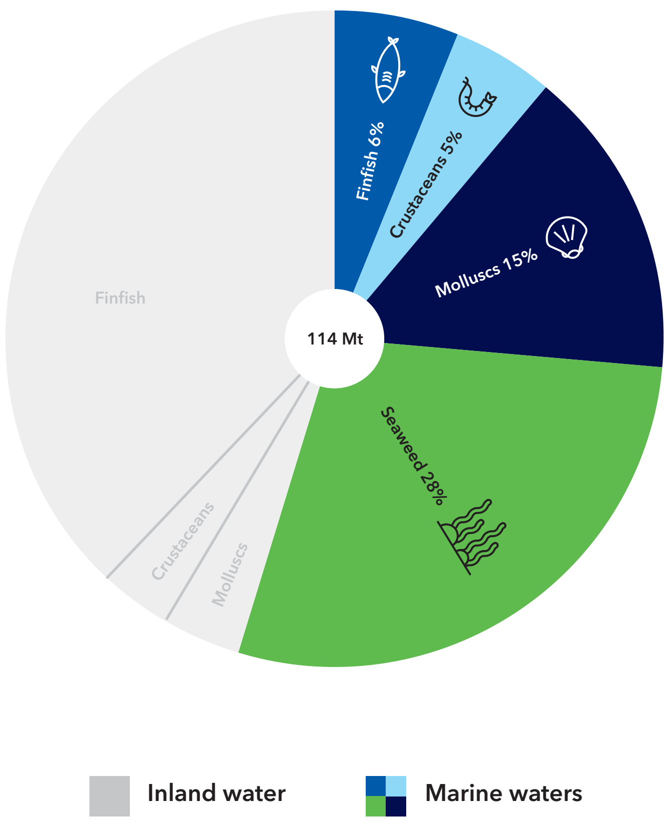
Technology, ocean health, and foresight are key

Technologies in use, under development, and yet to be invented will play a part in marine aquaculture's contribution to feeding the world. The technologies include innovative and more productive physical systems, better methods of disease control, and approaches to prevent or minimize the industry's environmental impacts. Some of these trends highlight that to be productive, the ocean must also be healthy. Threats to ocean health are substantial and growing. Climate change, pollution and marine littering, habitat destruction, overfishing and poor governance are among the direct and indirect threats (UN Global Compact, 2019).

To invest in marine aquaculture, companies, public policymakers, and other stakeholders need to know what the future holds (see box). What will the demand for seafood be? How much of that demand will be met from marine aquaculture production? How much of that production will be finfish, and how much shellfish? Which regions will see the largest growth and eventual production levels of various seafood from marine aquaculture? What production technologies will be introduced to meet the increase in production?

Reliable forecasts support investment

Most future increases in food production from the oceans will need to come from marine aquaculture, as there are limited opportunities for sustainable growth in capture fisheries (Costello et al., 2020). Marine aquaculture is hence key to a global food system meeting the SDGs while taking advantage of healthy and productive oceans. In turn, demand for seafood can only be met sustainably through technological innovations in marine aquaculture (DNV, 2018). Examples include new fish and shrimp vaccines, alternative feedstocks, digitalization and automation of operations, new production technologies offshore and onshore as well as multipurpose platforms. Forecasting demand, supply, and geographical trends is important for determining what types and scale of infrastructure will be needed for the industry to grow; what regulatory issues will arise; and what incentives may work best in achieving policy outcomes. Investors and public policymakers need trustworthy information for long-term decision making.



Current status of global aquaculture production

Global aquaculture production was 114 million tonnes (live weight) in 2018. More than half (55%) came from four main species groups farmed in marine waters – finfish, crustaceans, molluscs, and seaweed. The remaining part of aquaculture are aquatic animals farmed in inland waters, primarily freshwater. This production is outside the scope of this marine aquaculture forecast.

Seaweed and molluscs contribute most in terms of weight, and China is by far the main producer. When considering protein content and market value, however, both marine finfish and crustaceans have more significant shares. These higher-value species groups are also more internationally traded than seaweed and molluscs, which are both largely used in local food-supply chains.

Our forecast of the most likely evolution of these and other market and technology trends between now and mid-century is published as marine aquaculture continues its rapid growth of recent decades. Investors have seen demand for seafood rise in line with growth in population and living standards over this period. Rising consumer awareness of seafood's health benefits compared with red meat is another driver of demand. Aquaculture has a lower feed-conversion ratio than other meat production sectors. This resource-efficient production means fish will become an even more important protein source (FAO, 2020c).

Making marine aquaculture sustainable

Marine aquaculture is facing numerous challenges to its track record as a sustainable ocean industry, however. Disease outbreaks in farmed fish and concerns about reduced fish health, challenge the intensification of farming practices. Increasing infection pressure on wild species can threaten biodiversity. Aquaculture of fed species of fish and crustaceans can contribute to water pollution by discharging large amounts of nutrients. Fed aquaculture comes with the additional challenge of finding new sources of fish feed that do not overexploit wild fish stocks or compete for agricultural products and/or land that could otherwise be used to grow food for people. Competition with industrial and recreational uses of ocean space increases as aquaculture grows.

Solutions to the sustainability challenges of the industry include introducing knowledge-based methods to improve aquaculture management. These methods include new production technologies that move fish farming onshore or further offshore (DNV, 2018), and permitting the production of molluscs and seaweed delivering ecosystem services (Costello et al., 2020). Bringing marine fish farming into facilities onshore or further out to sea represents opportunity for growing wholly new industries that service marine aquaculture (see text box). Exploiting the filtering and carbon sequestration mechanisms of molluscs and algae enables marine aquaculture to contribute to restoring ocean health. Marine aquaculture like this could in some cases enhance wild fisheries by creating artificial habitats and nursery grounds for fish (Stuchtey, et al., 2020).

Fish farms test the water offshore

Offshore aquaculture is seeing farm locations become more exposed on the way to eventually being complete offshore installations in open rough waters. Few species can potentially be farmed offshore. Some key questions are: can a species live in the harsh conditions; are relevant technologies available; what are the economics; will the infrastructure and logistics be in place; and what national strategy plans and policies support or hinder offshore farms? Developments are nevertheless underway for some finfish (DNV, 2018). Offshore cage systems are producing salmon and cobia, whose high value means they can absorb the extra investment involved in going offshore. Locations that have featured in pioneering work in recent years include Australia, China, Faroe Islands, Norway, and Panama. Other finfish species could follow in the coming years.

Havfarm 1, Nordlaks, Norway

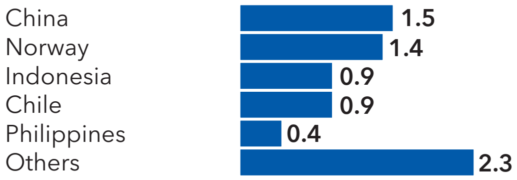
"Bringing marine fish farming into closed facilities onshore or further out to sea represents opportunity for growing wholly new industries."

Marine waters: overview of species groups and regional breakdown of production in 2018

Million tonnes

Finfish

- Encompasses diverse aquatic species having backbones, gills, and fins.
- Finfish represents 85% of total marine capture production measured in edible food.
- Atlantic salmon tops the list of finfish marine aquaculture in both value and quantity.

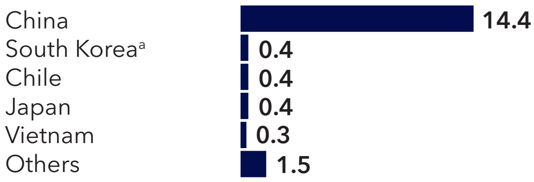


Crustaceans

- There are more than 50,000 described species of crustaceans.
- Shrimp, lobsters, and crabs are major food species, while smaller crustaceans like krill are integral to many food webs.
- Whiteleg shrimp is the most widely farmed crustacean.

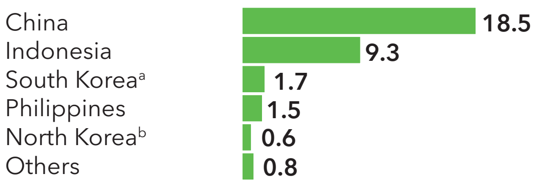
Molluscs

- Includes snails, octopus, squid, clams, scallops, oysters, and chitons.
- Found in some of the earliest human habitation sites in southern Africa over 100,000 years ago.
- Humans have likely included molluscs in their diet and as material resources for thousands of years.



Seaweed

- Plant-like organisms that generally live attached to rocks or other hard substrata in coastal areas.
- Also known as macroalgae.
- Classified into three broad groups based on pigmentation: brown, red, and green.
- Use as food dates to the fourth century in Japan and the sixth century in China.



a. Republic of Korea
b. Democratic People's Republic of Korea

Our approach

We have asked ourselves: what will be the future demand for seafood towards 2050, and how will this be met? To try to answer this, we have developed this forecast, providing a systemic and balanced view of marine aquaculture production between now and mid-century.

Marine aquaculture is defined as the part of aquaculture that takes place in salt water, either in the ocean or in the adjacent coastal zone. This report offers insight into the future of marine aquaculture with the purpose of supporting strategy and decision making. In contrast to scenario-based outlooks, we present a single 'best estimate' model-based forecast and discuss the sensitivities of key outcomes to assumptions applied in our analysis. The work is part of DNV's broader commitment to provide insight and transparency into the growth of the 'blue economy'. We do this through foresight activities that consider the interlinkages between industries, and the barriers to productivity that arise from global ocean health challenges. This report on marine aquaculture is DNV's first forecast focusing on key aspects of these interlinkages. It will be followed by more comprehensive studies looking at a broader set of ocean-related activities.

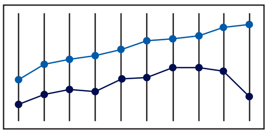
" The basis for our forecast for the future of marine aquaculture is a system dynamics simulation model mirroring key supply-demand relationships."

The basis for our forecast for the future of marine aquaculture is a system dynamics simulation model mirroring key supply-demand relationships. The most important feedback loops included in the model are shown in the illustration on page 13. The forecast starts by considering the number of people that need food globally. We present the outlook for protein demand towards 2050 while taking into account population growth and changes in living standards. We also consider growing concerns about health and sustainability, which will impact food preferences.

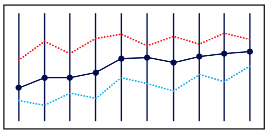
From the resulting demand for protein, the model forecasts production of marine animals and marine plants, and the investments required for marine and coastal supporting infrastructure. The supply of seafood from marine aquaculture is modelled for finfish, molluscs, crustaceans and seaweed. Production costs are derived from investment and operating costs, including feed costs, for marine aquaculture production facilities. This creates a baseline for seafood prices that influence future demand relative to other sources of food.

The model is populated with data from various sources: databases providing historical time series for supply and demand; industry reports; scientific articles; and, the judgement of domain experts. A full reference list and the key data sources are included in the back of our report.

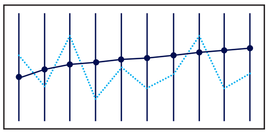
The scope of our forecast is limited by the following factors:



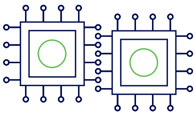
Our best estimate, rather than the future we want.



We forecast a single future as opposed to scenario-based analyses developed in other reports.



We focus on long-term dynamics rather than short-term imbalances and corresponding cyclical market behaviours. For example, we do not consider developments over intervals shorter than a year.



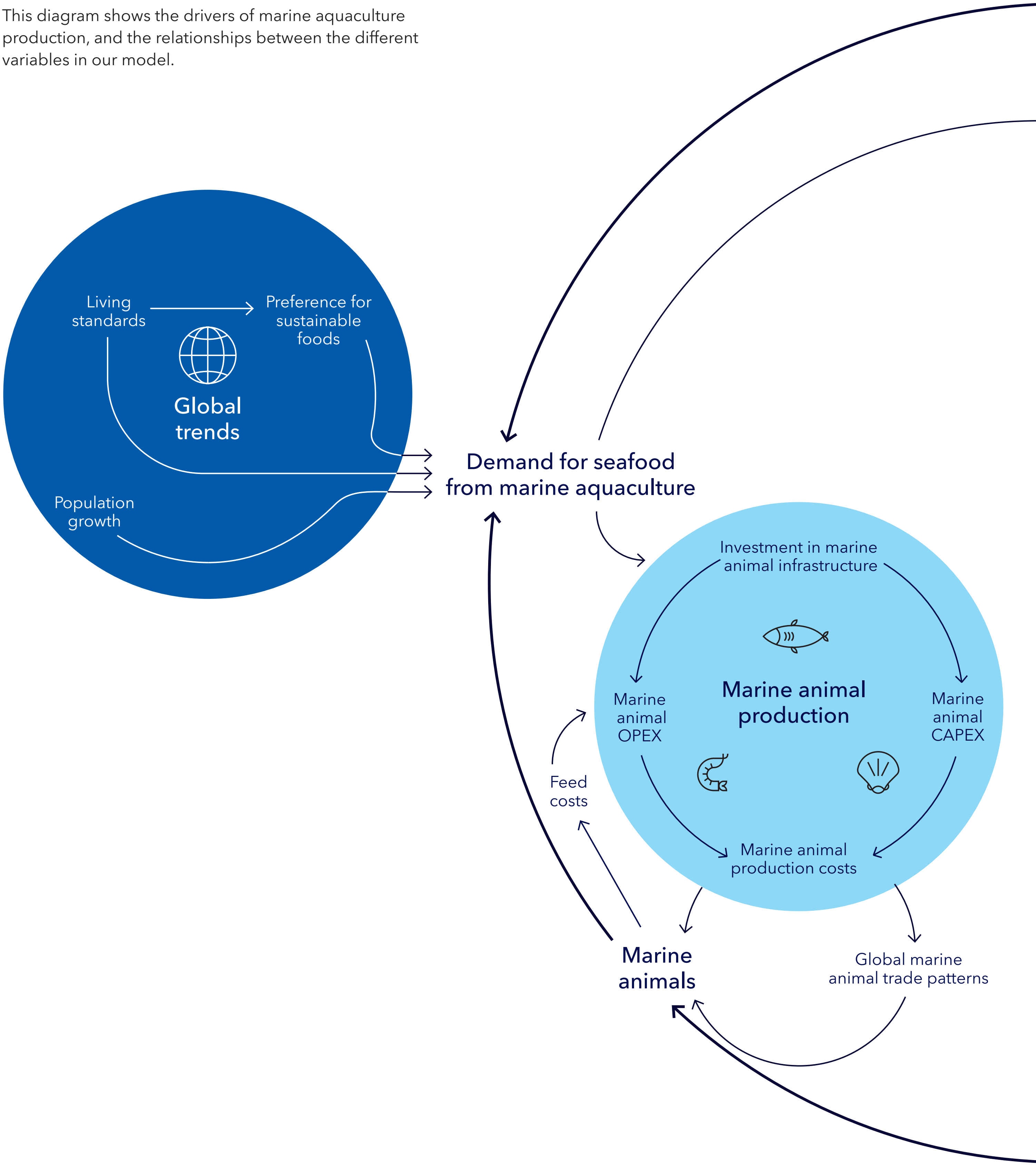
We model continued development of industries that already exist at pilot stage and beyond, rather than including unproven technologies.

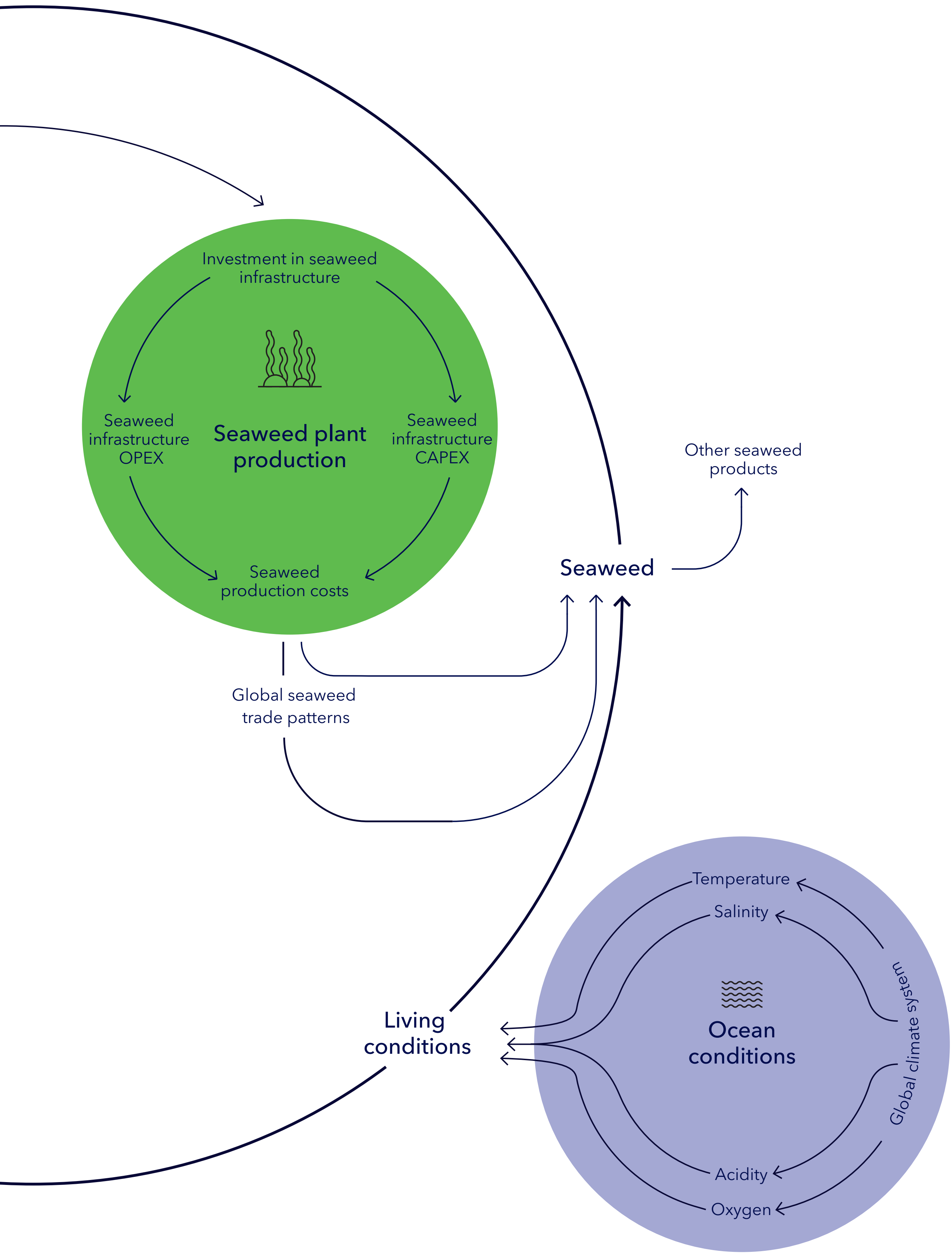
We include main policy trends, and exercise caution on untested commitments.

We model consumer behaviour based on changes in costs and sustainability.

Simplified overview of our system dynamics simulation model

This diagram shows the drivers of marine aquaculture production, and the relationships between the different variables in our model.





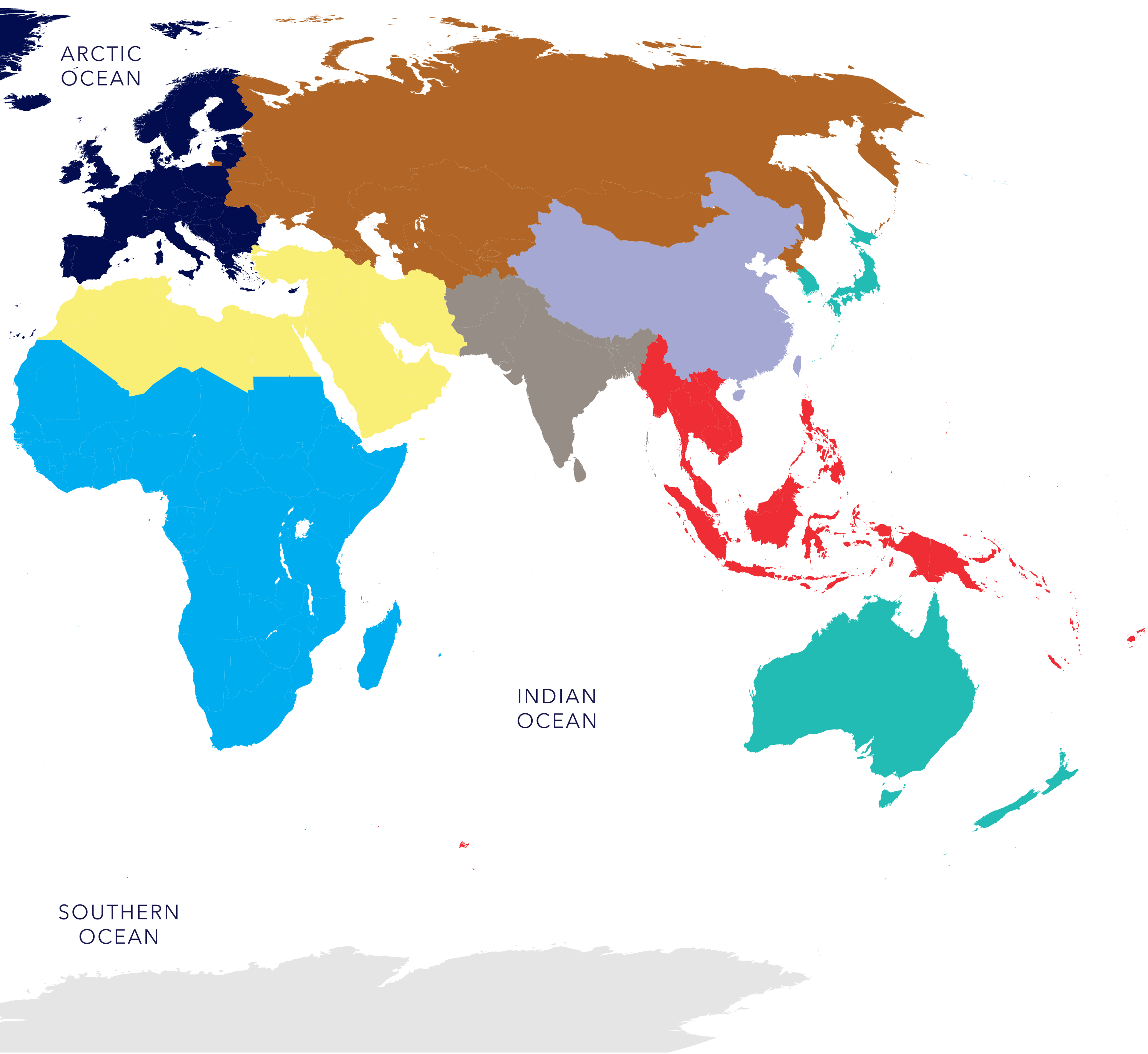
Investment in seaweed infrastructure
Seaweed infrastructure OPEX
Seaweed plant production
Seaweed infrastructure CAPEX
Seaweed production costs
Other seaweed products
Seaweed
Global seaweed trade patterns
Temperature
Salinity
Global climate system
Ocean conditions
Living conditions
Acidity
Oxygen

Our regional breakdown

Key socioeconomic drivers for our aquaculture analysis – for example, population and living standards – are derived for the 10 regions shown in the map. In our model, these regions are further divided by their proximity to the different ocean basins: Arctic, Atlantic, Indian, Pacific, and the Southern Ocean.

Our regions are also roughly consistent with those of the Organisation for Economic Co-operation and Development (OECD), namely Europe, North America, and OECD Pacific (Australia, Japan, South Korea, New Zealand). When presenting graphs in the report, we primarily show the regions of greatest relevance to our discussion and results.

- North America (NAM)
- Latin America (LAM)
- Europe (EUR)
- Sub-Saharan Africa (SSA)
- Middle East and North Africa (MEA)
- North East Eurasia (NEE)
- Greater China (CHN)
- Indian Subcontinent (IND)
- South East Asia (SEA)
- OECD Pacific (OPA)



Global demand for marine aquaculture

Using population growth estimates to calculate how much food will be needed up to 2050, we forecast demand for protein from animals and seaweed from marine aquaculture. We identify regions that can expect the biggest growth and levels of demand for these products, and predict the amount of seaweed required for non-food uses. We discuss the drivers behind these need-to-know trends for private and public stakeholders in the industry.

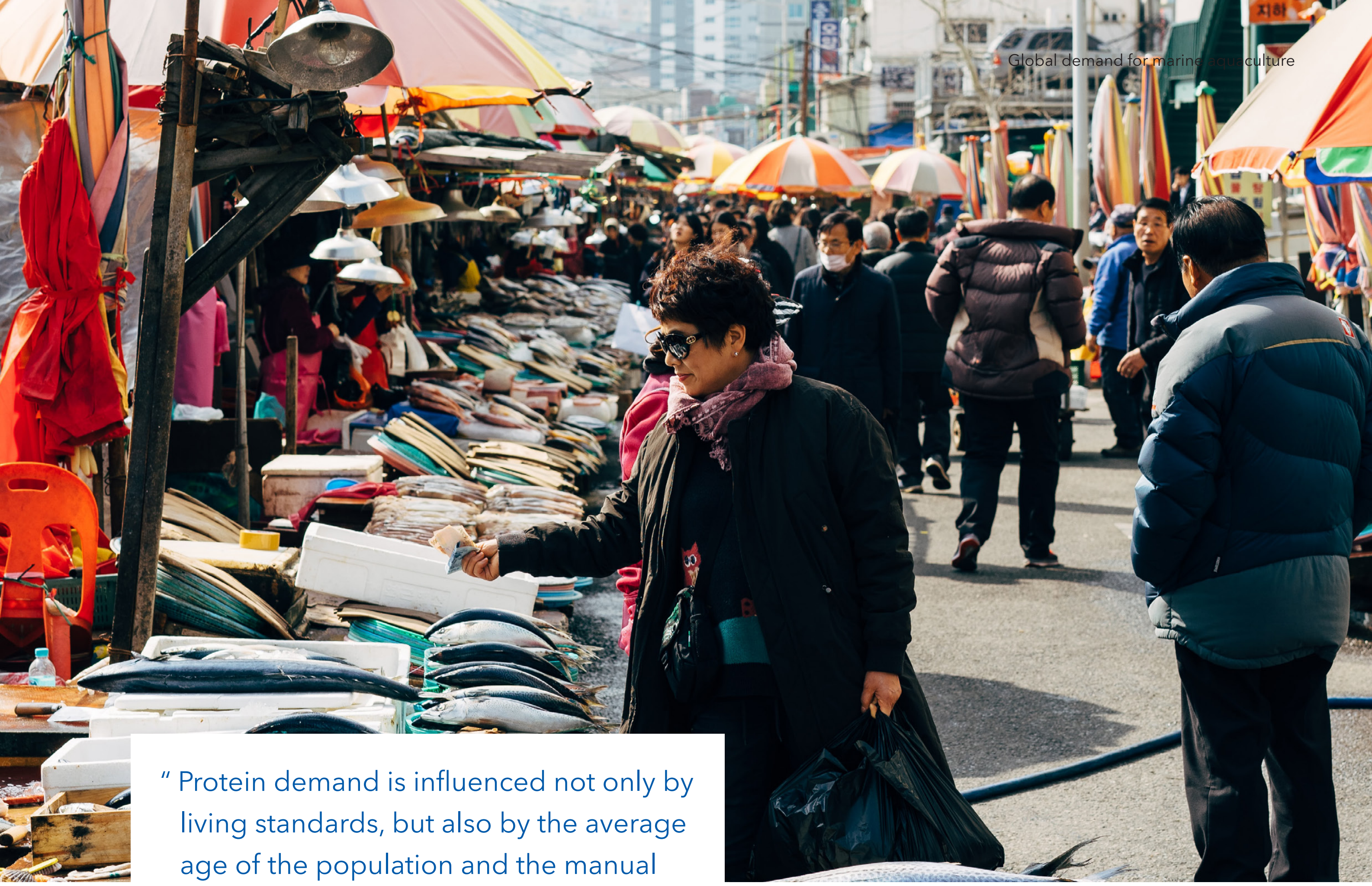
Population growth will differ among regions, chiefly because fertility rates decline with rising prosperity. Compared with the current UN (2019) population estimate of 7.5 billion, global population will increase more than 25% to 9.4 billion by 2050. It will grow most in the Indian Subcontinent, reaching almost 2.3 billion by mid-century (see Figure 1). Greater China's population peaks in the late 2020s at almost 1.5 billion then slowly declines, while Europe's remains at about 540 million.

Living standards as forecasted by DNV (2020) reflects that as gross domestic product (GDP) per capita rises, productivity growth and consequently living standards are growing less strongly. The strongest relative growth is found in less developed regions (see Figure 2).

Our framework reflects this through rising living standards driving up food consumption. Using protein consumption per person as an indicator, this relationship is strongest in developing regions (see Figure 3). On this measure, China and South East Asia have seen the strongest growth over recent decades. Half of the global increase of protein uptake since 2000 has been in Asia. This trend is expected to persist in the 2020s, with continued growth in per capita protein consumption in the Indian Subcontinent and, especially, South East Asia. Greater China surpassed OECD per capita levels of protein consumption in the mid-2010s, but we now see signs of saturation there and expect plateauing at North America levels in a couple of years.

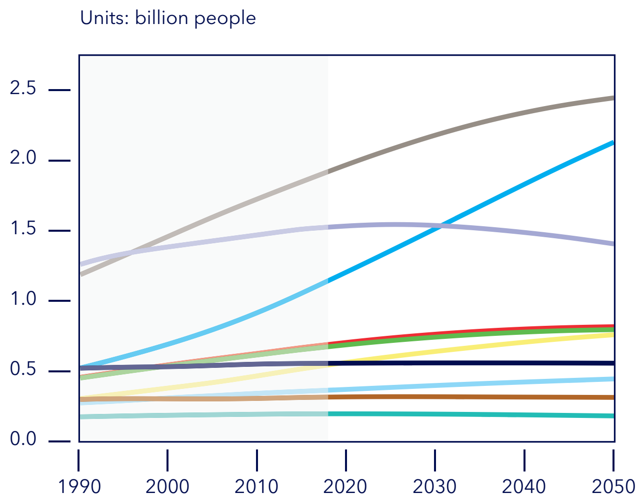
Protein demand is influenced not only by living standards, but also by the average age of the population and the manual labour intensity of the workforce. De-industrialization and consequently less manual labour have contributed to stabilization of demand across OECD member states. This helps to explain the recent growth in other regions, such as in China, where the primary and secondary sectors have seen and will continue to see growth. In developed regions like North America and Europe, protein demand per person is already plateauing, and has even declined in OECD Pacific. These trends are caused by various factors. For example, as their basic protein needs are already met, consumers are increasingly emphasizing health and food sustainability in their food preferences.

The lowest food consumption is observed in Sub-Saharan Africa and Indian Subcontinent at only 60 grammes of protein per capita per day (g/capita-day) in 2018, and this will rise to about 70 g/capita-day at the end of the forecast period. This is still above what the World Health Organization (WHO) recommends as a minimum daily intake (WHO, 2007). They refer to a safe protein intake of 0.75 g/kg per day, i.e. around 45 g/capita-day for an average person in these regions. Hence, rampant yet declining malnutrition is not primarily a consequence of low average protein consumption but is related to calorie and other nutrient deficiencies. Though diminishing, these non-protein deficiencies will not disappear by 2050.



" Protein demand is influenced not only by living standards, but also by the average age of the population and the manual labour intensity of the workforce."

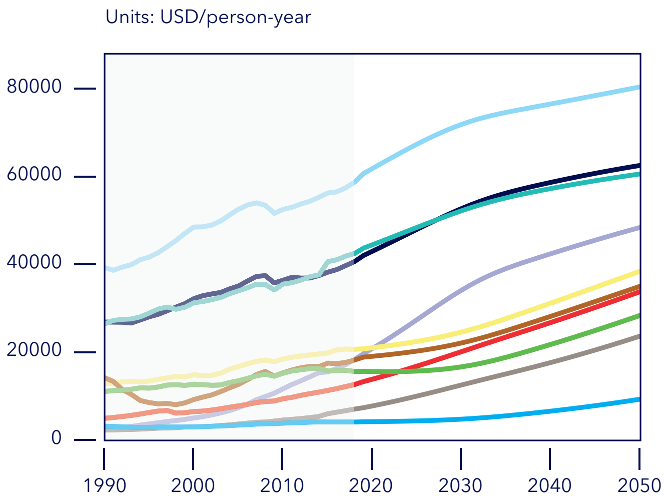
Figure 1 Population by region



Historical data source: UN (2019), Forecast: Wittgenstein Centre for Demography and Global Human Capital (2018)

IND
SSA
CHN
SEA
LAM
MEA
EUR
NAM
NEE
OPA

Figure 2 GDP per capita by region



Historical data source: World Bank (2018), Gapminder (2018)

NAM
EUR
OPA
CHN
MEA
NEE
SEA
LAM
IND
SSA

Figure 3 Protein consumption per person

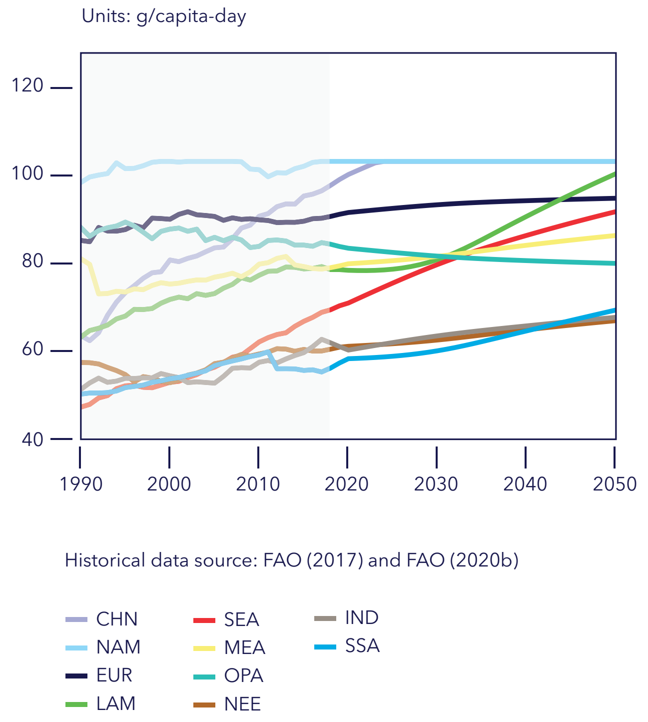
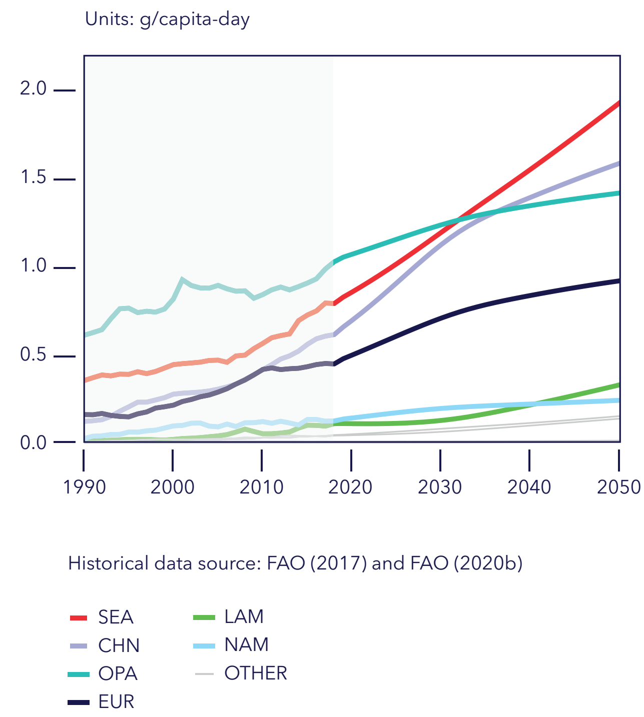


Figure 4 Marine aquaculture protein consumption



In sum, improved living standards will ensure that average global protein consumption per person grows by more than 10% between 2018 and 2050. It follows that global protein consumption will increase by over 35% by mid-century for a near-25% population growth.

How will this demand growth be met in a world already beyond its planetary boundaries (Randers et al., 2019)? Protein consumption will be met by plants and meat, both land- and sea-based. Based on a behavioural science approach, we let consumers weigh future costs and sustainability against their historical preferences for their current diet mix. Historical food preferences reflect proximity to food sources, taste preferences, and food culture factors. To measure sustainability, we consider the findings of the EAT-Lancet Commission (Willett et al., 2019) with regard to what constitutes a healthy diet from a sustainable food system. Based on reported environmental effects per serving of food produced, we establish a simple sustainability index for alternative protein sources, including seafood (aquaculture and fisheries) as well as terrestrial plants and meats. The index accounts for greenhouse gas emissions, land use, energy use, acidification and eutrophication.

Marine aquaculture

Marine aquaculture competes with both capture fisheries and freshwater aquaculture. The latter category accounts for over half of current aquaculture in protein terms, but is not part of our forecast due to our ocean focus. We forecast that growth of marine aquaculture will be stronger than for wild catch, which is already beyond its sustainable catch for many species and will not grow further. The estimated constraint on capture fisheries, given that all species are produced at maximum sustainable yield (Costello et al., 2020), is similar to the currently reported production levels (FAO, 2020c).

Figure 4 shows our forecast of protein consumption per capita sourced from marine animals produced by marine aquaculture. Marine animals include species of finfish, crustaceans, and molluscs, with great variation in their biological characteristics, subsequent usage in food preparation, and farming methods. We treat seaweed demand separately as non-food uses are an important demand driver (Naylor et al., 2021).

Our result shows Asia continuing to dominate demand for marine aquaculture products. South East Asia and Greater China more than double their demand towards 2050, both passing OECD Pacific after 2030. In contrast, the OECD Pacific region will see a very slow growth in marine aquaculture protein consumption. Outside Asia, Europe has the highest per capita consumption in 2050, at about half of the demand in South East Asia. Strong growth is also evident in Latin America, bypassing North America as consumers of seafood from marine aquaculture, but from a very low initial level.

Putting the predicted consumption estimates into perspective, one meal in which the 'meat' comes from marine animals requires around 150 g meat/person. From this, it follows that a typical meal of finfish will contribute approximately 30 g of protein, but less if the meal consists of molluscs. Note that there are huge differences in consumption within each world region, as proximity to local production is a factor that drives consumption of seafood from marine aquaculture in coastal communities globally (Naylor et al., 2021).

Seafood consumption patterns are also driven by food availability, taste preferences, and culture. For this reason, the split of marine animal consumption into finfish, crustaceans, and molluscs varies among regions, with climate also determining the species being farmed. We explore the production patterns for the species groups in more detail in the next section, taking into account their differences in edible yields and protein intensity, the impact of global trade, and corresponding food waste along the fish supply chain.

" South East Asia and Greater China more than double their demand towards 2050, both passing OECD Pacific after 2030."

Figure 5 Seaweed plant consumption

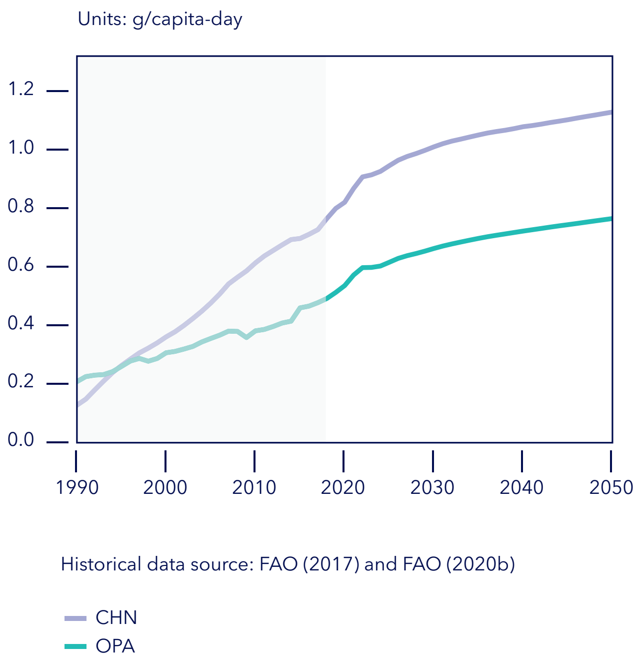
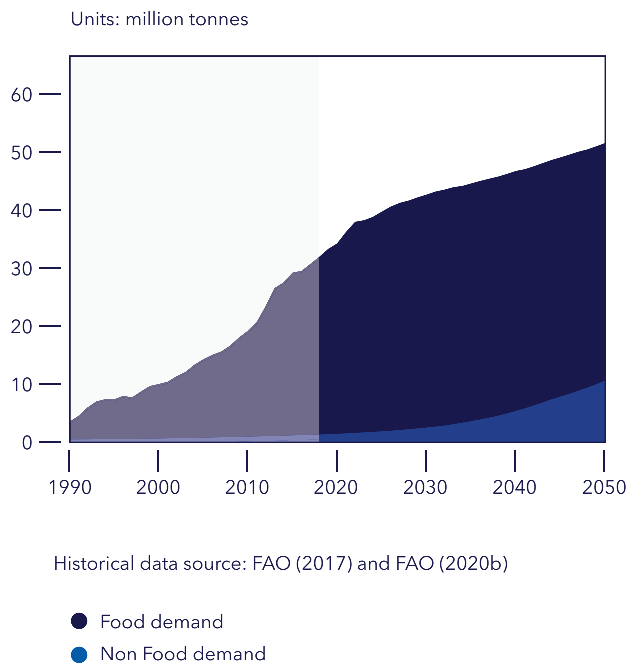


Figure 6 Seaweed demand



Demand for seaweed

Microalgae and macroalgae produce oxygen and absorb carbon dioxide through photosynthesis; they have the same function in the ocean that trees and plants have on land. Macroalgae, also called seaweed, grow 10 times faster than terrestrial plants, and need significantly less area to produce an equivalent amount of biomass. The application of seaweed for non-food uses is increasing. In addition to human food consumption, seaweed is used in a wide range of product applications such as animal feed, pharmaceuticals, bio-packaging, cosmetics, bio-stimulants, biofuels, and valorization of ecosystem services.

As consumers focus increasingly on a healthier, more sustainable diet, and with growing appreciation of the health benefits associated with seaweed, demand for seaweed as food has grown significantly (FAO, 2018c), but solely in Greater China and OECD Pacific. We use a similar model to that described for marine animals to reflect the food demand for seaweed. East Asia is where the current action is (see Figure 5). Greater China and OECD Pacific were responsible for more than 99% of seaweed production in 2018 (FAO, 2020c). Demand for seaweed outside these regions will remain negligible despite increasing health and sustainability concerns.

Non-food seaweed demand

The food business is the strongest contributor to seaweed demand, and our analysis tells that although sustainability concerns will increase, they will have no effect in eight regions. The result is that global demand for seaweed will grow more slowly than GDP to 2050. The degree of demand growth depends on production costs and prices, which are linked to new technologies being applied for production.

> " ...global demand for seaweed will grow more slowly than GDP to 2050."

For non-food seaweed demand, we use a much simpler forecasting method based on proven product application (FAO, 2018b) and sector-specific annual growth rates. We find that non-food products' share in total global seaweed demand will grow more strongly than the share for food uses. The share for non-food will rise from 4% of cultivated seaweed tonnage in 2020 to approximately 20% in 2050 (see Figure 6).

Key assumptions

Population growth: Our assumptions are based on population projections from the Wittgenstein Centre for Demography and Global Human Capital (2018).
Income: We base our GDP per capita growth forecast on the inverse relationship between the level of GDP per capita and its growth rate. We follow the assessment of GDP per capita as described in DNV's Energy Transition Outlook (DNV, 2020).
Relationship between food demand and living standards: Our forecast of marine aquaculture food consumption to 2050 is partly based on a best-estimate regression that uses GDP per capita as the independent variable, and UN Food and Agriculture Organization (FAO) estimates of consumers' daily protein consumption as the dependent variable. Cost and sustainability concerns are increasingly modifying this relationship. We then convert protein to harvested gross weight of edible foods by factoring in their protein intensities and what fraction of each species group is non-edible.
Impact of costs and sustainability: Relative costs and sustainability of foods impact the desirability of alternative sources of protein. Consumer preference for sustainability grows with improving living standards.

Marine aquaculture production

Sourcing seafood from the ocean will be transformed between now and 2050 as production from marine aquaculture grows quicker than supplies of food from capture fisheries. Marine aquaculture production, excluding seaweed, more than doubles by mid-century based on estimated regional demand for its products.

Marine aquaculture production, excluding seaweed, will grow from 30 million tonnes per year (Mt/yr) in 2018 to 74 Mt/yr in 2050, closing in on the output of marine capture fisheries (see Figure 7). We also forecast that seaweed production will rise from 30 Mt/yr to 50 Mt/yr over the same period (see Figure 8). We therefore predict that global marine aquaculture production will reach around 124 Mt/yr in mid-century. In comparison, freshwater aquaculture produced 51 Mt/yr in 2018 (FAO, 2020c).

> " ...production of aquatic animals will grow to 74 Mt/yr in 2050, closing in on the output of marine capture fisheries."

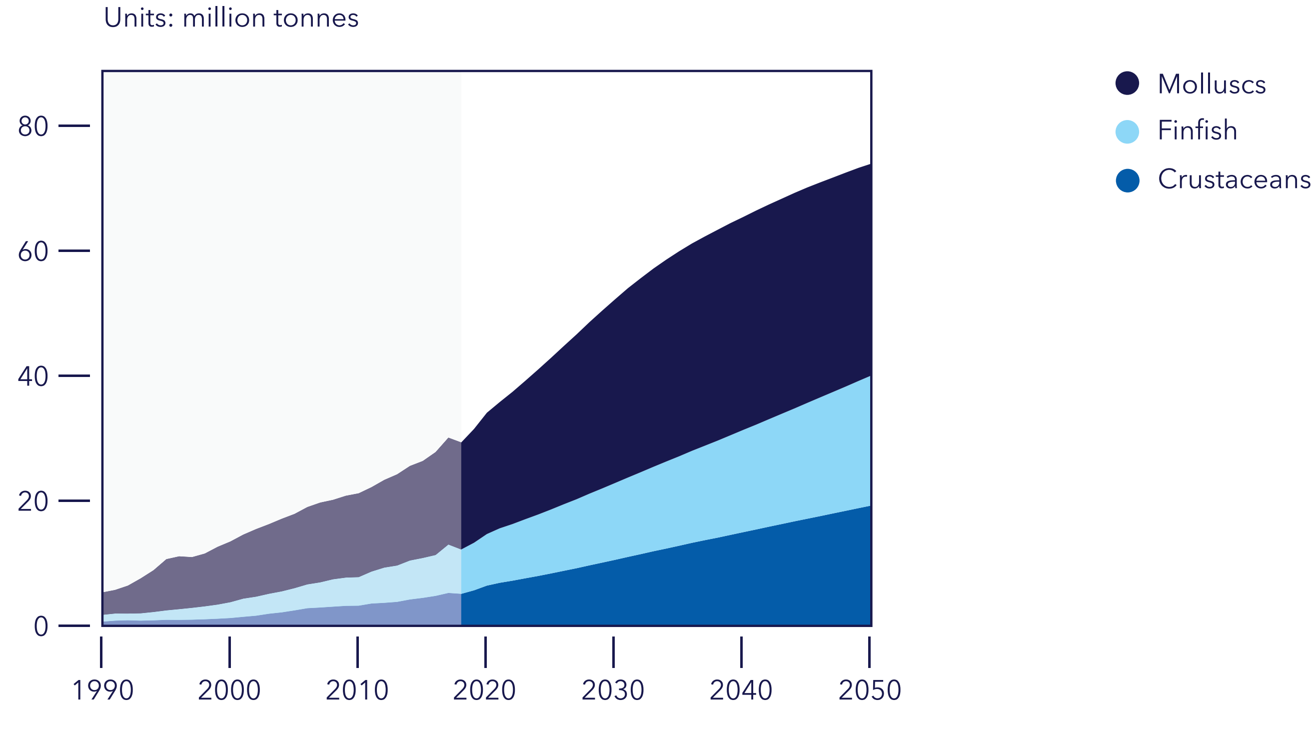
Marine capture fisheries production in 2018 was at 84 Mt/yr, while inland capture fisheries produced 12 Mt/yr (FAO, 2020c). Production from capture fisheries is already at or beyond the limits of what can be sustainably harvested, depending on the species captured. Overfishing – including illegal, unreported and unregulated fishing and bycatch – remains a major problem, and climate change is believed to have continuing detrimental effects on catch potentials globally (FAO, 2018a). With optimal fisheries management, the maximum sustainable yield of the marine capture fisheries has been estimated at 89 Mt/yr in 2050 (Costello et al., 2020).

Figure 7 shows the mix of species groups in marine aquaculture. Finfish produced by global marine aquaculture will reach 21 Mt/yr by 2050, tripling from 7 Mt/yr in 2018. Production of molluscs starts to plateau in the 2040s and reaches 34 Mt/yr in 2050, while crustacean production almost quadruples from 5 Mt/yr to 19 Mt/yr in 2050.

These changes cause minor shifts in the shares in total production for the species groups farmed. Finfish moves from 24% to 28% of total production from marine aquaculture, while crustaceans rise from 17% to 26%. Finfish and crustacean farming require input from production of feed. This suggests that the fish feed market will need to support 40 Mt/yr of fed marine aquaculture production compared with approximately 12 Mt/yr in 2018.

Lobster farm, Vietnam

Figure 7 Global production by species group



Historical data source: FAO (2020a)

Figure 8 Production of seaweed

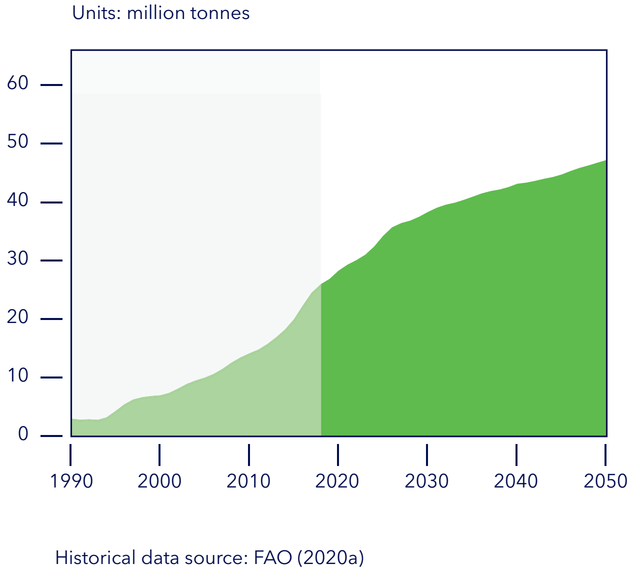
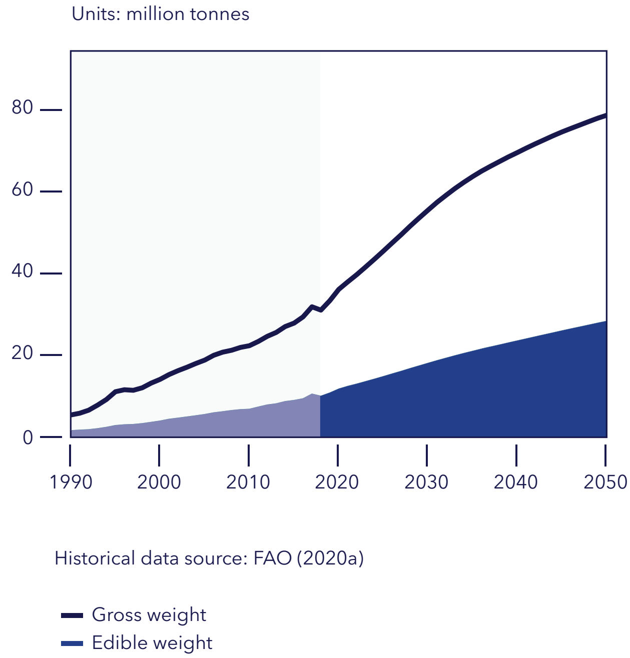


Figure 9 Global production comparing live and edible weight



Seaweed production

With production less than doubling from 30 Mt/yr to 50 Mt/yr (Figure 8), seaweed will most likely see a far slower growth trajectory than marine aquaculture of marine animals. We acknowledge that this is highly uncertain as seaweed farming is currently receiving a lot of attention in markets that currently produce very little, and the growth potential could be substantial.

World food supply

The outlook for marine aquaculture looks slightly different when we consider its impact on world food supply, even though we find a global shift in how seafood is sourced. When considering the edible food weight, marine aquaculture of marine animals will contribute around 27 Mt/yr in 2050 (see Figure 9), of which approximately 50% comes from finfish. The reason for this is the much higher edible-live weight ratio for finfish compared with shellfish (molluscs and crustaceans) (Edwards et al., 2019). A world food supply addition of 27 Mt/yr implies that an average person eats approximately 3 kg of seafood from marine animals sourced from marine aquaculture in 2050, ranging from more than 9 kg/person in Greater China, to around 5 kg/person in Europe, to almost nothing in Sub-Saharan Africa.

The estimate of the contribution to world food supply from marine capture fisheries is around 50 Mt/yr in 2050 (Costello et al., 2020; FAO, 2020c). Hence, wild catch will constitute approximately 65% of the food supply from the ocean, while the share from farmed marine animals will increase from 20% to around 35% towards 2050. This implies a large change in sourcing for the global seafood market.

Diversity of species

A future in which marine aquaculture production takes a larger share in total seafood output is likely one in which a smaller number of species are consumed. While more than 400 species of marine animals are farmed for human consumption, 20 species contribute more than 80% of production from marine finfish, and the dominance of the most-produced species of crustaceans and molluscs

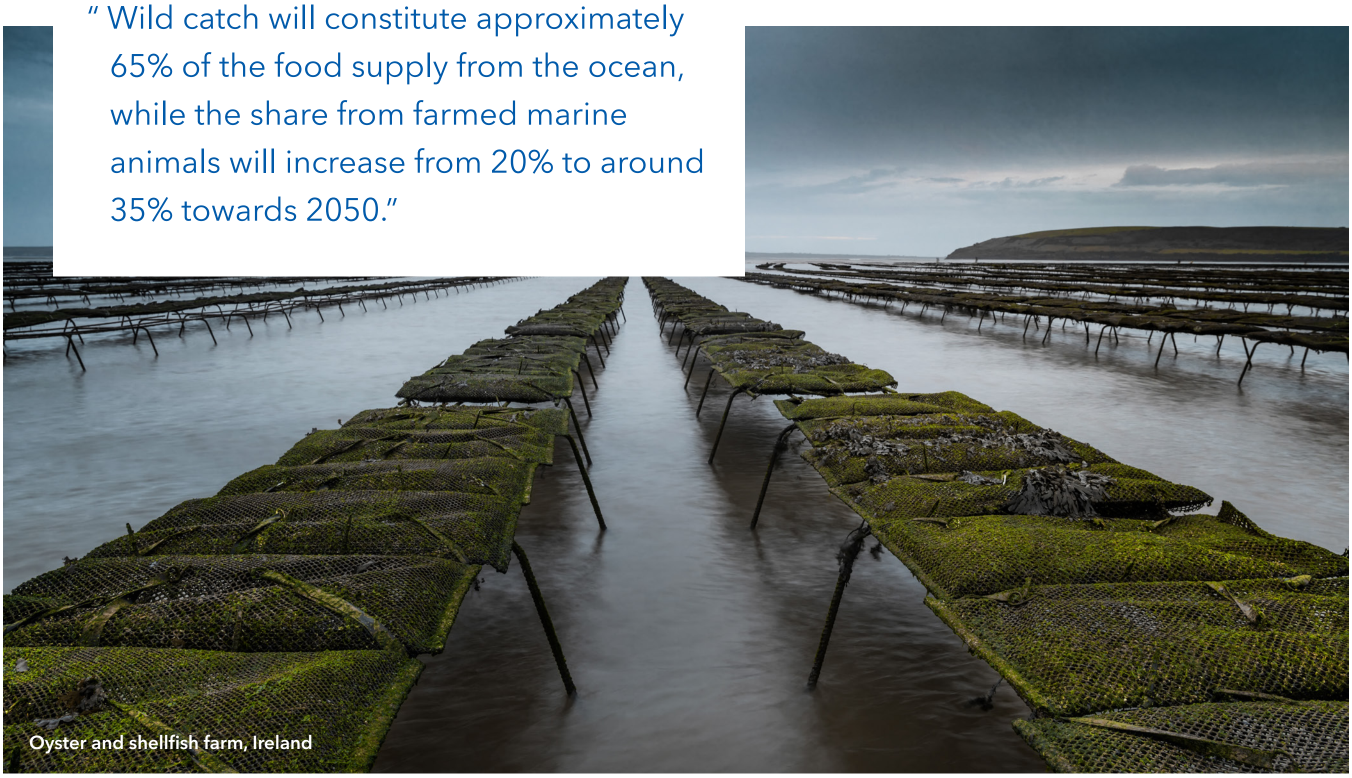
Species group			
Edible share of live weight	65%	38%	17%
Protein content of edible weight	21%	23%	13%

is far greater (FAO, 2020c). On the other hand, the FAO reports more than 1,700 species caught by fisheries (FAO, 2020c). Further diversification of capture fisheries to prevent overfishing of certain fish stocks is seen as a key to improving sustainability (Costello et al., 2020).

Improvements in production efficiency and economies of scale lead us to believe that future marine aquaculture production will drift towards increasing focus on high-value species currently farmed, rather than large-scale farming of new species. This is supported by FAO data showing that leading species have become more dominant in production figures since the 1990s (FAO, 2020a). This is particularly so in the OECD regions despite growth in the total number of cultured species, with much of Asia maintaining a more mixed-species approach (Metian et al., 2019). For example, improved breeding and feeding practices for the most valuable species make it more efficient to optimize production systems than to diversify and experiment with new species. We expect current key species to continue dominating production, and possibly increase their domination. However, trending towards less species diversity could increase biological risks from diseases that threathen to wipe out entire monoculture production systems (Metian et al., 2019)

When generalizing to the three species groups in this outlook for marine aquaculture, we model biological parameters based on proxy species for each of these groups, letting the proxies represent all marine aquaculture production in each region. Examples of such proxies include Atlantic salmon for finfish in Europe and the Americas, and whiteleg shrimp for crustaceans in Latin America and most of Asia. A detailed quantitative analysis of the production dynamics for individual species is beyond the scope of this study.

" Wild catch will constitute approximately 65% of the food supply from the ocean, while the share from farmed marine animals will increase from 20% to around 35% towards 2050."



Oyster and shellfish farm, Ireland

Regional production

The importance of marine aquaculture as a source of food supply and as an industrial activity differs globally. Most marine aquaculture production will remain concentrated in a few regions, notably dominated by Asia, which produces 80% of all output of marine animals. Within Asia, Greater China and South East Asia are the front-runners, and maintain a 70% share of global output towards 2050. The dominance of these two regions would increase even further if seaweed farming was added in.

" Asia produces 80% of all output of aquatic animals."

Figure 10 shows the production of marine animals in the regions that we forecast to produce more than 1 Mt/yr in gross weight in 2050. We expect Greater China to maintain its dominance towards then as its production doubles to 38.4 Mt/yr. South East Asia will be the second largest producer of marine aquaculture in mid-century, more than tripling its gross production from 4.5 Mt/yr in 2018 to 14.7 Mt/yr. When looking at the production in edible tonnes, Greater China produces 9.4 Mt/yr, and South East Asia 7.2 Mt/yr, in 2050 (Figure 11). Note that as molluscs contribute a large share of the output from Greater China, the role of marine aquaculture in securing food supply is easily overestimated.

Outside Asia, the biggest producers in 2050 are Europe and Latin America. We find that Latin America almost quadruples its marine aquaculture production, reaching 7.5 Mt/yr in 2050. This region thereby overtakes Europe as the leading producer outside Asia, as European production only doubles, from 2.5 Mt/yr in 2018 to 5.2 Mt/yr in 2050. The gap between Latin America and Europe is reduced when we look at the regional contributions to food supply, as Latin America will see a considerable increase in shrimp production. Where Latin American production in edible weight terms is 3.6 Mt/yr in 2050, Europe will contribute 2.8 Mt/yr to food supply.

Figure 10 Gross production by region

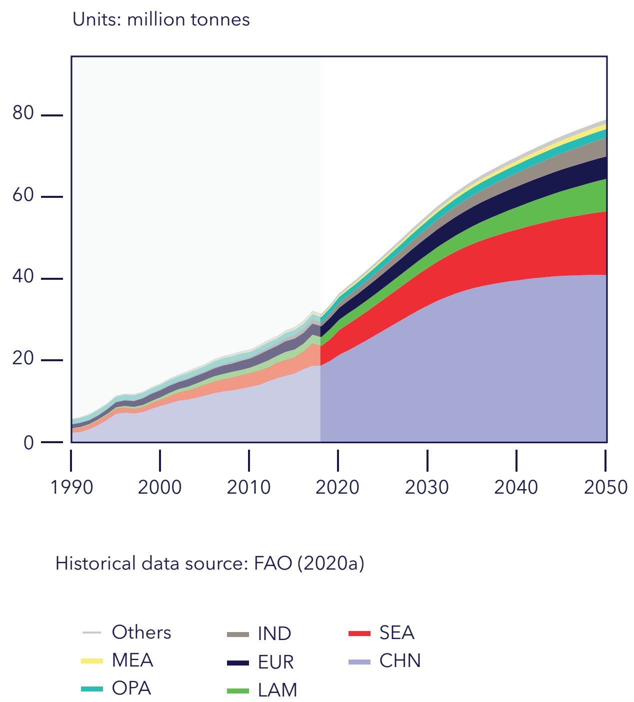
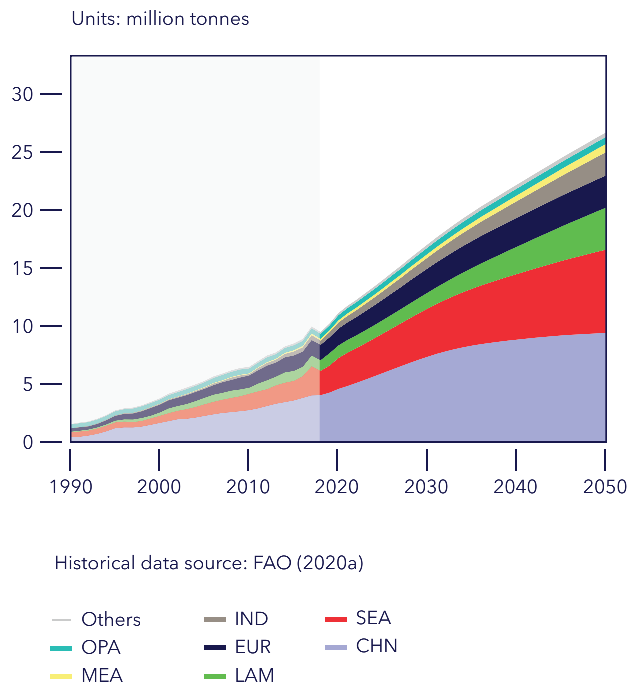


Figure 11 Production by region in edible weight



Mussel farm, Bulgaria

Figure 12 Finfish production

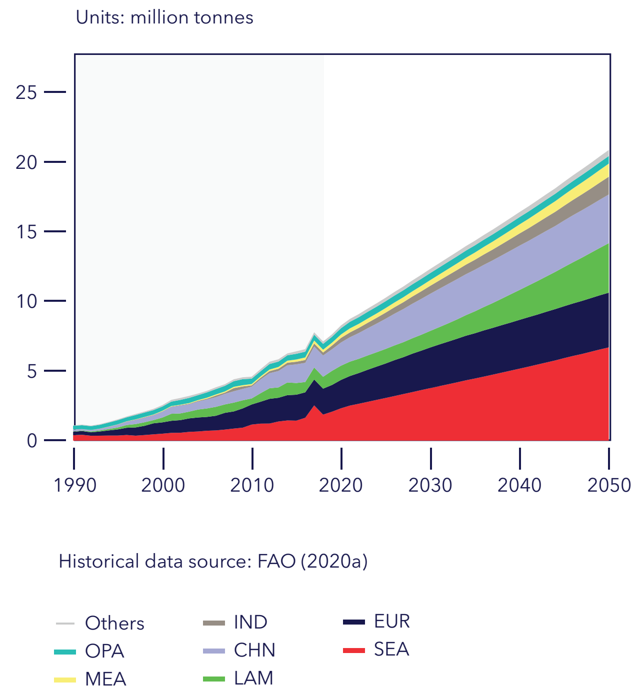
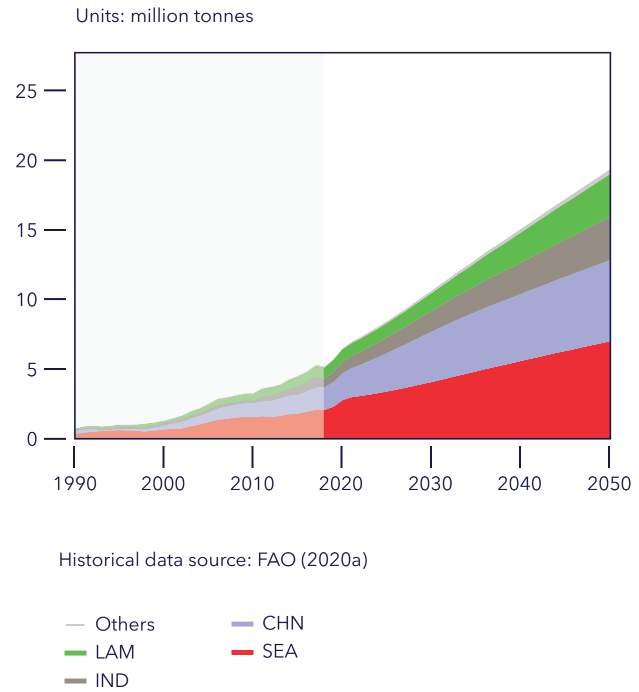


Figure 13 Crustacean production



Production and trade of high-value species

The economics of marine aquaculture are closely linked to the global fish trade. High-value products like salmon and shrimp are heavily traded, whereas many low-value goods from marine aquaculture never enter international markets (Naylor et al., 2021), but contribute to the local food supply. Our model accounts for trade flows between the 10 regions, so that the export of salmon from Norway to the US is captured as part of the trade flow between Europe and North America. Intraregional trade, e.g. between Canada and the US, is counted as part of the North America to North America trade flow.

Among the largest exporters in value terms in 2018, besides China, we find several large producers of salmon and shrimp, such as Chile, Norway, Thailand and Vietnam (FAO, 2020c). The economic importance of exports of salmon and shrimp for many countries suggests that a more detailed dive into the regional production forecasts for high-value species of finfish and crustaceans is warranted.

Figure 12 shows our production forecast for finfish from marine aquaculture, with regions producing less than 0.5 Mt/yr clustered in the 'Other regions' category. The region producing the most finfish in 2050 is South East Asia, where we forecast an output of 6.7 Mt/yr. European finfish production will grow from 1.8 Mt/yr to 3.9 Mt/yr in 2050.

Greater China, currently the third largest finfish producer and producing 3.5 Mt/yr in 2050, will be overtaken by Latin America, where we forecast that production will quadruple to 3.6 Mt/yr.

" European finfish production will grow from 1.8 Mt/yr to 3.9 Mt/yr in 2050."

It is likely that most of the European finfish production will be salmon, as it currently dominates production with about 80% of the regional finfish output. Our forecast thereby indicates that the frequently cited Norwegian ambition to increase marine aquaculture production from 1.2 Mt/yr in 2010 to 6 Mt/yr in 2050 is unlikely to be achieved. This result is consistent with other recent 'most likely' views on the development of the salmon farming industry (PwC, 2021).

A doubling of production in region Europe is still a significant growth in market size when we consider the economic impact. If we assume that the 3.9 Mt/yr of finfish is sold in 2050 at the current salmon price of 6 USD/kg, the size of the European salmon market will grow from around 11 billion (bn) USD/yr to 23 bn USD/yr. This implies that exports of European salmon to the rest of the world will be worth around 4 bn USD/yr.

For the economies of smaller countries like Norway, intraregional exports are much more important, but our model has insufficient granularity to provide accurate estimates for this. However, if we assume that Norwegian salmon trade grows at the same pace as European marine aquaculture in general, then a fair estimate of Norway's finfish export value is around 18 bn USD/yr, up from slightly more than 7 bn USD/yr in 2018 (Chatham House, 2020). Note that our forecasting model does not consider the dynamics of short-term price variations in fish products.

Shellfish production (molluscs and crustaceans) towards 2050 will be dominated by Asia, with Greater China contributing more than 80% of mollusc production. We forecast that a strong growth in Chinese mollusc production until 2030 will be increasingly substituted by finfish and crustacean production. Parts of the forecasted growth in mollusc production may come from integrated multi-trophic aquaculture (Naylor et al., 2021).

" Shellfish production (molluscs and crustaceans) towards 2050 will be dominated by Asia, with Greater China contributing more than 80% of mollusc production."

Compared to the little-traded molluscs, which are mainly produced in Greater China, crustacean farming is much more equally divided among regions in tropical climate zones (Figure 13). Like for finfish, South East Asia will be the leading producer, with an output of 7 Mt/yr in 2050. South East Asia is followed by Greater China at 5.8 Mt/yr in mid-century, with Latin America and the Indian Subcontinent both producing around 3.1 Mt/yr. The Indian Subcontinent exhibits particularly strong growth, increasing five-fold to 2050.

As a widely exported product, farmed crustaceans are important to local economies. At shrimp prices of 10 USD/kg, South East Asian production of shrimp is valued at 70 bn USD/yr in 2050, considerably higher than the estimated value of the European salmon market. However, the crustacean market has recently been severely affected by boom-bust cycles induced by price fluctuations following disease outbreaks; hence, this estimate is highly uncertain (FAO, 2020c).

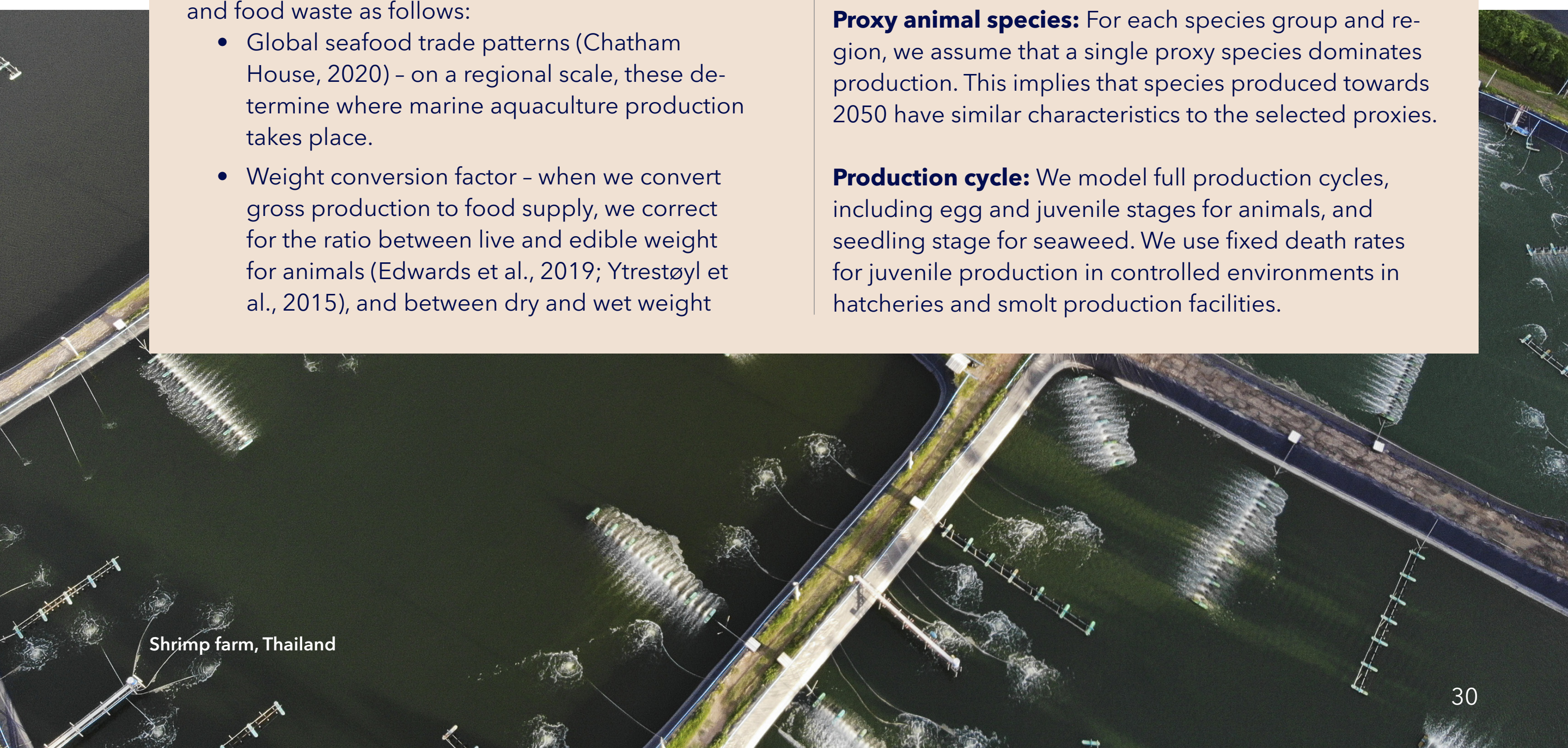
Key assumptions

Demand-supply balance: The growth in marine aquaculture production is determined by demand driven by increasing living standards, production cost trajectories, and sustainability awareness. Linking demand and supply, we correct for regional exports and imports, protein content per live weight, and food waste as follows:

- Global seafood trade patterns (Chatham House, 2020) – on a regional scale, these determine where marine aquaculture production takes place.
- Weight conversion factor – when we convert gross production to food supply, we correct for the ratio between live and edible weight for animals (Edwards et al., 2019; Ytrestøyl et al., 2015), and between dry and wet weight for seaweed. When making the additional leap to demand for seafood proteins, we also correct for protein content per unit of edible weight.
- Waste from farm to fork – considering food waste in the fish supply chain from production to the consumer table lets us match our demand predictions with historical production reports.

Proxy animal species: For each species group and region, we assume that a single proxy species dominates production. This implies that species produced towards 2050 have similar characteristics to the selected proxies.

Production cycle: We model full production cycles, including egg and juvenile stages for animals, and seedling stage for seaweed. We use fixed death rates for juvenile production in controlled environments in hatcheries and smolt production facilities.



Shrimp farm, Thailand

New production technologies gain traction

We forecast growth in the use of new production technologies for fish farming. Towards 2050, high-value finfish species like salmon will increasingly be farmed in offshore structures or in closed containment systems in the sea or on land. These trends are driven by lower production costs, following initial investments enabled by favourable incentive schemes.

The predicted growth in marine aquaculture production comes with increasing pressure on coastal and nearshore production sites, where the industry already faces competition from other uses and threatens biodiversity. At the same time, the oceans provide ample space for increasing food production (Gentry et al., 2017) if this can happen further from shore in an environment characterized by deeper water, higher waves, and more severe winds. Efforts to intensify production of several high-value species are underway worldwide.

Several technology trends will contribute to efficiency gains possible in marine aquaculture. The continued focus on genomics and development of new vaccines will be important enablers for ensuring a robust fish population, better suited for their environment. Digitalization, including improved monitoring and decision support, enables improved production control, with advantages ranging from fish welfare to product quality. Automating operations decreases the need for manning on fish pens, reducing operating costs and improving safety. Development of closed containment systems for sheltered water will also increase the production efficiency and reduce the environmental impact. Among trends with potential to improve the efficiency of marine aquaculture, we focus our analysis on the impact of new production facilities offshore and onshore.

High-value finfish species like salmon and cobia, which can justify higher investment costs, are already farmed in exposed locations in countries like Norway and China, but still in relatively small quantities (DNV, 2018). Facilities in development and plans also exist for land-based production facilities, particularly for salmon. For shrimp, intensification has so far been troublesome, with increased stocking density in more advanced coastal facilities being linked with disease outbreaks and high mortality. Access to financing for more capital-intensive farming systems in the producing countries represents a barrier to intensifying production of crustaceans. Offshore mollusc and seaweed aquaculture are being researched and tested in pilot projects, and we find small volumes of investments in high-tech seaweed production in industrialized countries.

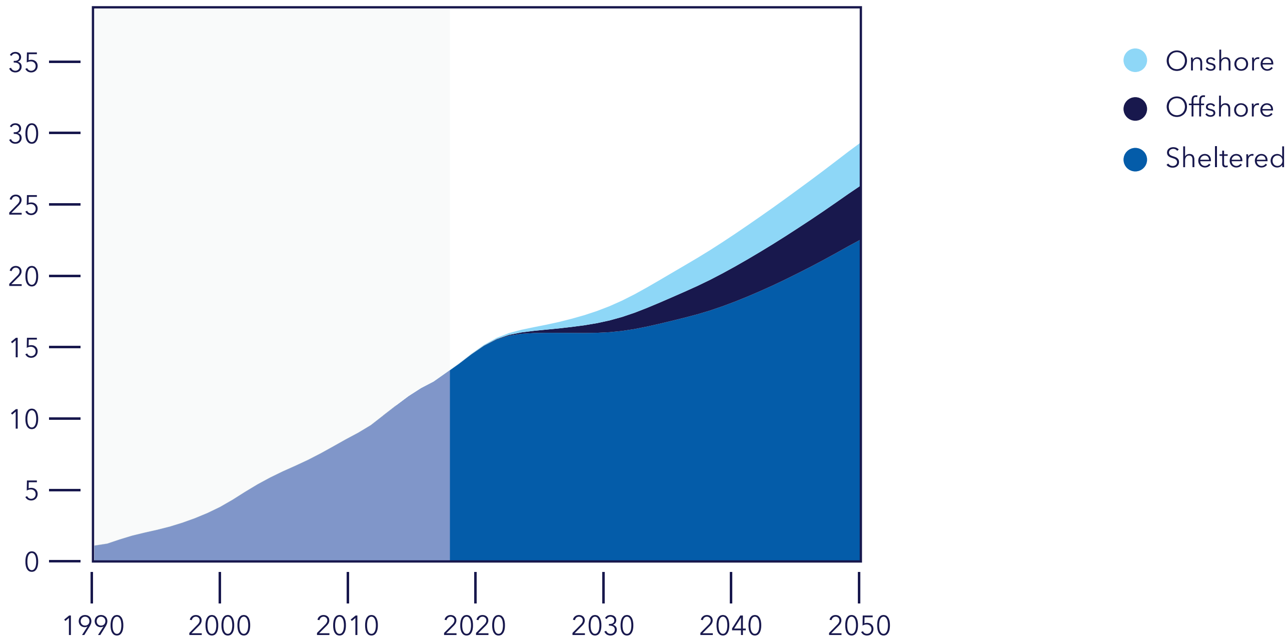
The use of new production technologies for finfish so far looks the most promising. We forecast a shift towards more technically advanced systems for high-value species of finfish between now and 2050, with production moving both offshore and onshore. The analysis of production technologies considers installed capacity and the utilization of this towards production. We estimate higher utilization factors for the emerging technologies.

Havfarm 1, Nordlaks, Norway

> " We forecast a shift towards more technically advanced systems for high-value species of finfish between now and 2050, with production moving both offshore and onshore."

Figure 14 Globally installed finfish production capacity

Units: million tonnes



Historical data source: FAO (2020a)

Fish farming moving offshore

As the most attractive locations for conventional net pens in sheltered waters fill up, fish farmers are looking at increasing production capacity further out to sea. In exposed and offshore localities, improved water quality, reduced animal densities, and less infection pressure can positively impact fish welfare, and additional economies of scale can be achieved. Moving fish farming to exposed locations, and eventually offshore, requires the use of larger, more complex production facilities, and fish that are robust against a harsh marine environment. Design and operation of more complex production facilities like offshore fish farms will draw heavily on existing ocean engineering competence, including rigorous hydrodynamic and structural analyses, and risk management practices. Offshore fish farming may also instigate changes in aquaculture logistics as production scales and distance to shore increases, thereby creating a market for support vessels different from those operating in marine aquaculture today. In some cases, offshore aquaculture represents an opportunity for suppliers, service providers, and shipowners to reduce their dependency on the oil and gas sector.

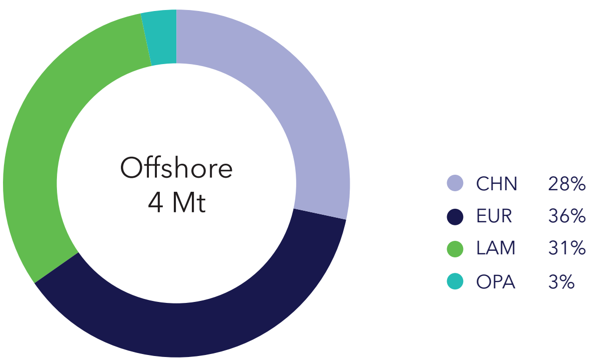
Offshore structures for aquaculture are already operating in Norway and China, with Norway providing a financial incentive by waiving licencing fees for companies that introduce novel technical solutions to fish farming (DNV, 2018). The concepts for offshore fish farming that have been proposed so far vary immensely. They range from structurally advanced versions of conventional cages, to closed containment systems in the sea, to ship-shaped structures, and even offshore fish farms integrated with multipurpose platforms and offshore energy production (Chu et al., 2020; Stuchtey et al., 2020). We expect that installations for offshore marine aquaculture will standardize, driven by the need for regulatory compliance. Standardization will also create a path forward for learning and efficiency gains to reduce future investment costs.

Fish farming moving onshore

Following the advent of recirculating aquaculture systems, market players also increasingly grow marine fish in onshore facilities. These systems are used for the full grow-out cycle incorporating the saltwater phase, having previously been used only to prepare juvenile finfish for transfer to seawater. This trend has also been driven partly by the need for larger, sturdier smolts when farming fish in exposed environments. Onshore grow-out operations aim to improve control of living conditions and to optimize production. These facilities can be placed closer to important consumer markets, thereby reducing transportation costs and streamlining supply chains (Liu et al., 2016), but require cheap, reliable energy. A major biological concern is related to the build-up of lethal concentrations of hydrogen sulphide gas, which is more probable due to seawater use in production plants.

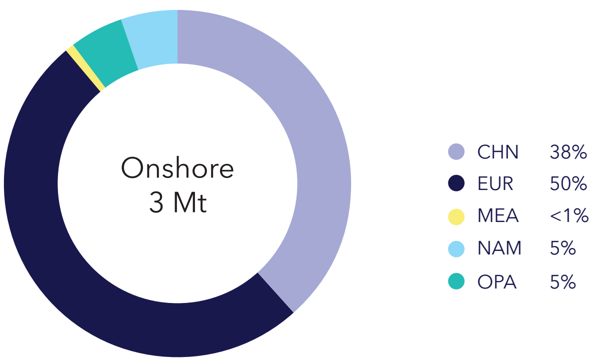
> " We expect that installations for offshore marine aquaculture will standardize, driven by the need for regulatory compliance."

Figure 15 Forecasted share of offshore finfish production capacity by region in 2050



Historical data source: FAO (2017) and FAO (2020b)

Figure 16 Forecasted share of onshore finfish production capacity by region in 2050



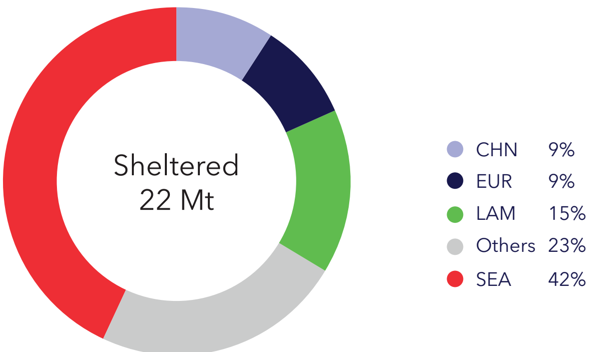
Historical data source: FAO (2017) and FAO (2020b)

Changes in production technology

Figure 14 shows global installed capacity for finfish marine aquaculture distributed among the three future modes of production. We forecast around 10% of the production capacity for finfish marine aquaculture being offshore in 2050, with around 13% offshore. We forecast that the strongest growth in offshore and onshore finfish production capacity will be between now and the mid-2030s, with a relatively steady level of finfish production capacity in sheltered waters. Hence, the growth in these technologies will be characterized by a rapid ramp-up and subsequent stabilization. We still acknowledge the significant uncertainty surrounding uptake of these technologies and note that experience from future production cycles will have a major effect on investments.

We project that offshore fish farming will gain a strong foothold in Greater China, Europe, and Latin America, with smaller capacities installed in OECD Pacific (Figure 15). Onshore farming of marine species will take place in Greater China, Europe and North America, with smaller capacities in high-income countries in the Middle East and OECD Pacific (Figure 16). In South East Asia, we forecast that production of marine finfish will primarily continue in conventional net pens in sheltered waters and coastal ponds. Figure 17 shows the shares of sheltered production by region in 2050. Overall, new fish farming technologies will be introduced mainly in regions that are already major producers of high-value species of finfish, such as salmon, tuna, or cobia.

Figure 17 Forecasted share of sheltered finfish production capacity by region in 2050



Historical data source: FAO (2017) and FAO (2020b)

" Onshore farming of marine species will take place in Greater China, Europe and North America, with smaller capacities in high-income countries in the Middle East and OECD Pacific."

Figure 18 Seaweed production capacity

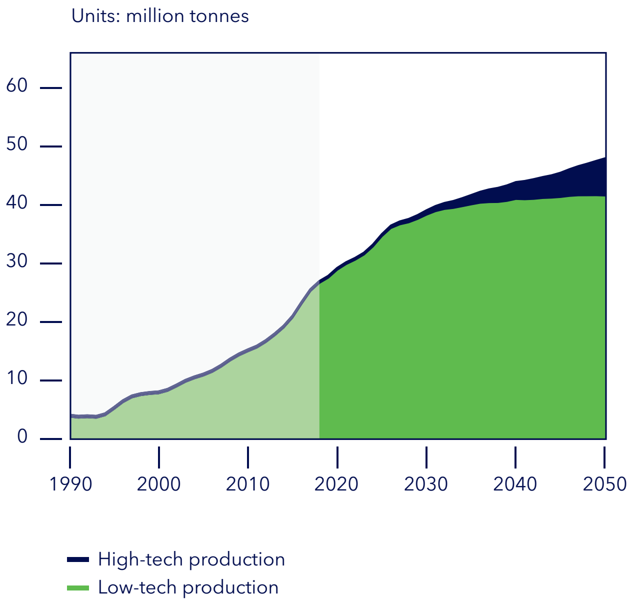
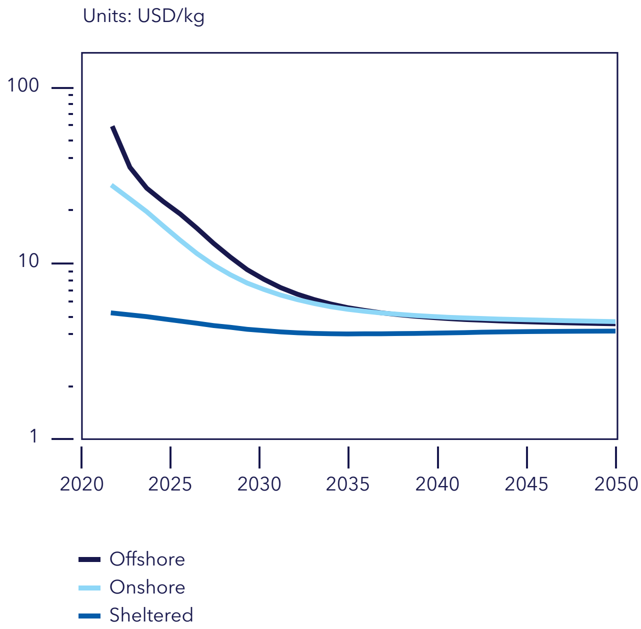


Figure 19 Production costs per kg harvest



Industrialized seaweed production

We are also observing growing interest in seaweed production in developed countries. Current farming practices are very labour-intensive; so, new technologies that reduce manual labour are a prerequisite for the industry's development in high-cost countries. Moreover, yields can be improved by moving from unidimensional longline cultures to two-dimensional or three-dimensional textile structures on which the seaweed can grow, thereby increasing the returns. Industrialization through multi-trophic cultures where seaweed and molluscs take up nutrients from the discharge from fish farming, thereby providing ecosystem services, represents another growth opportunity (Naylor et al., 2021).

Figure 18 indicates that traditional, artisanal production methods (low-tech) continue to dominate in regions already producing a lot of seaweed. This is due to low investment costs and relatively good and stable income potential. Future growth will primarily be driven by investments in high-tech production. There will be large growth in this mode of production, primarily in Europe and China, with later adoption elsewhere. The emergence of high-tech seaweed production will likely depend on a large degree of novel, automated harvesting methods.

" We foresee production costs per kg for offshore and onshore fish farming falling substantially in coming years."

Will new production technologies become competitive?

The competitiveness of new finfish production technology is evaluated using the per kg production cost, which is shown for European finfish in Figure 19. Currently, onshore and offshore production of marine species is much more costly. Hence, investments require greatly reduced logistics costs, consumers willing to pay substantial price premiums (Liu et al., 2016), or government subsidies (Stuchtey et al., 2020) for operations to be competitive. Logically, the high cost levels suggest that high-value species will be the focus of this development. Recent research (Tveterås et al., 2020) shows that exposed and offshore salmon farming is profitable at current price levels, albeit at a lower margin, if licensing fees are not imposed.

We foresee production costs per kg for offshore and onshore fish farming falling substantially in coming years. The most significant investments will be made in the 2020–2030 decade, coinciding in time with the most substantial cost reductions. Figure 19 shows production costs for offshore fish farming reaching 4.9 USD/kg in Europe by 2050. Production costs for onshore farming of marine species converge to a slightly higher unit-cost level at 5.1 USD/kg. Meanwhile, we estimate that sheltered finfish production will produce at 4.1 USD/kg. The cost difference between the most and least expensive production technologies for finfish remains at 20% in 2050, before accounting for differences in transportation cost. Factoring in logistics further reduces the cost advantage of conventional fish farming, as production facilities can be located closer to consumer markets.

> " Factoring in logistics further reduces the cost advantage of conventional fish farming, as production facilities can be located closer to consumer markets."

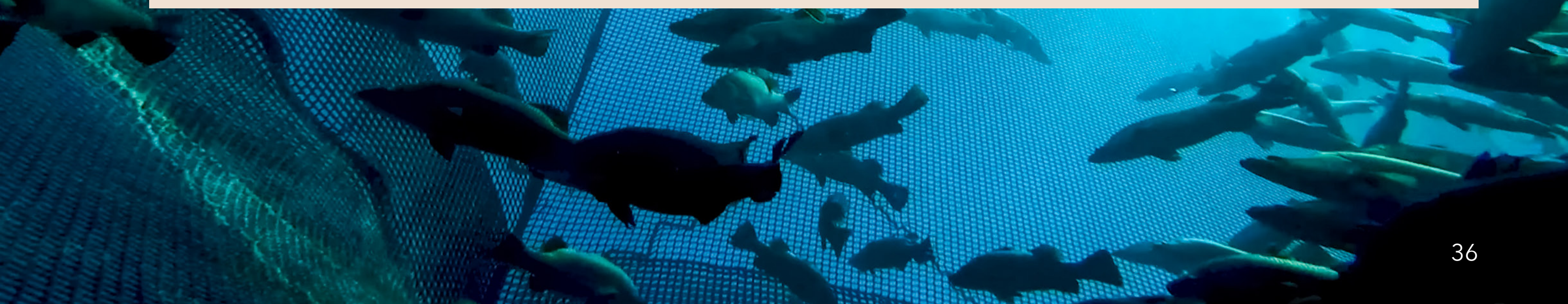
The main driver for the forecasted cost reductions is the accumulation of experience with the new production technologies. The relationship between accumulated experience and cost reductions is captured by a cost-learning curve. Cost-learning curves suggest that costs fall by a given fraction each time cumulative production capacity doubles. For emerging technologies that grow fast, cumulative production capacity will double often, meaning that the high unit costs will fall much more rapidly than for a mature technology. In this analysis, we assume that cost-learning curves estimated on cost data from Norwegian salmon farming (Guttormsen, 2002; Iversen et al., 2020; Statistics Norway, 2020) will hold for onshore and offshore fish farming alike. Furthermore, we assume that increasing capacity in one region influences learning and reduces costs globally.

Increases in feed costs, independent of type of production facility, also play a role in reducing the cost difference between conventional fish farming and new technologies. Feed costs are already the dominant component of per kg production cost (Iversen et al., 2020), and are expected to continue growing in the future (Naylor et al., 2021). Automated feeding systems, in tandem with other improvements in feed management from digitalization, may have a role in offsetting parts of the feed cost increase. However, this is not something considered in the model.

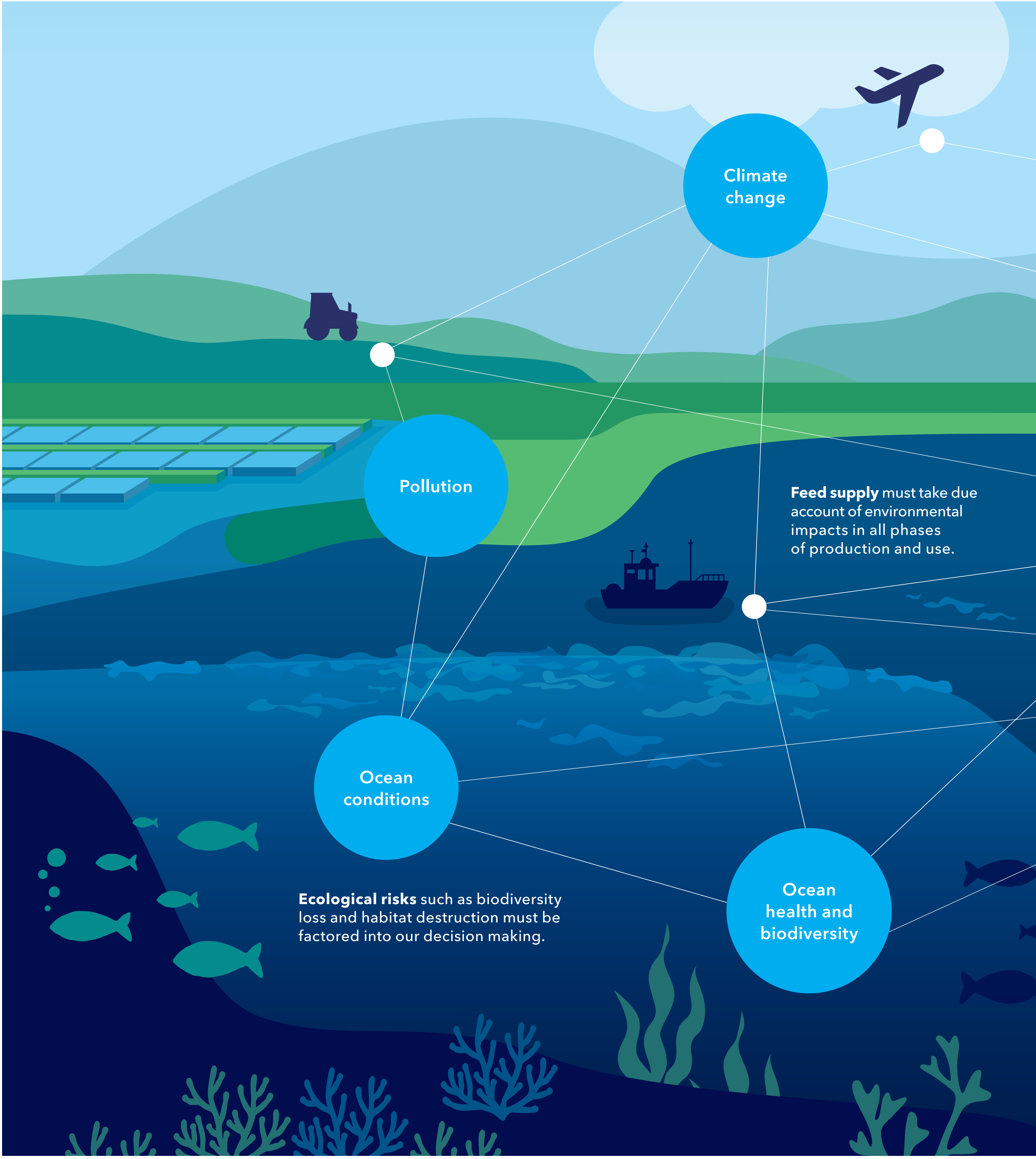
We also see evidence of cost-learning dynamics in the trends we estimate for capital expenditure. We forecast strongest growth in the current decade, with annual CAPEX in global finfish aquaculture growing to around 10 bn USD/yr in 2030, with little additional growth in yearly capital expenditures towards 2050. In Europe, finfish investments will be around 2.5 bn USD/year in 2050, of which approximately 25% is spent on offshore aquaculture. 2050 CAPEX for offshore aquaculture in Europe is close to the currently reported yearly investments in Norwegian aquaculture (Statistics Norway, 2020). Comparing this with other emerging ocean industries, our 2050 European CAPEX estimate for offshore aquaculture is only one-fifth of current investments in offshore wind in the region. Even as production triples with offshore and onshore production of finfish, marine aquaculture will be smaller than other emerging constituents of the blue economy.

Key assumptions

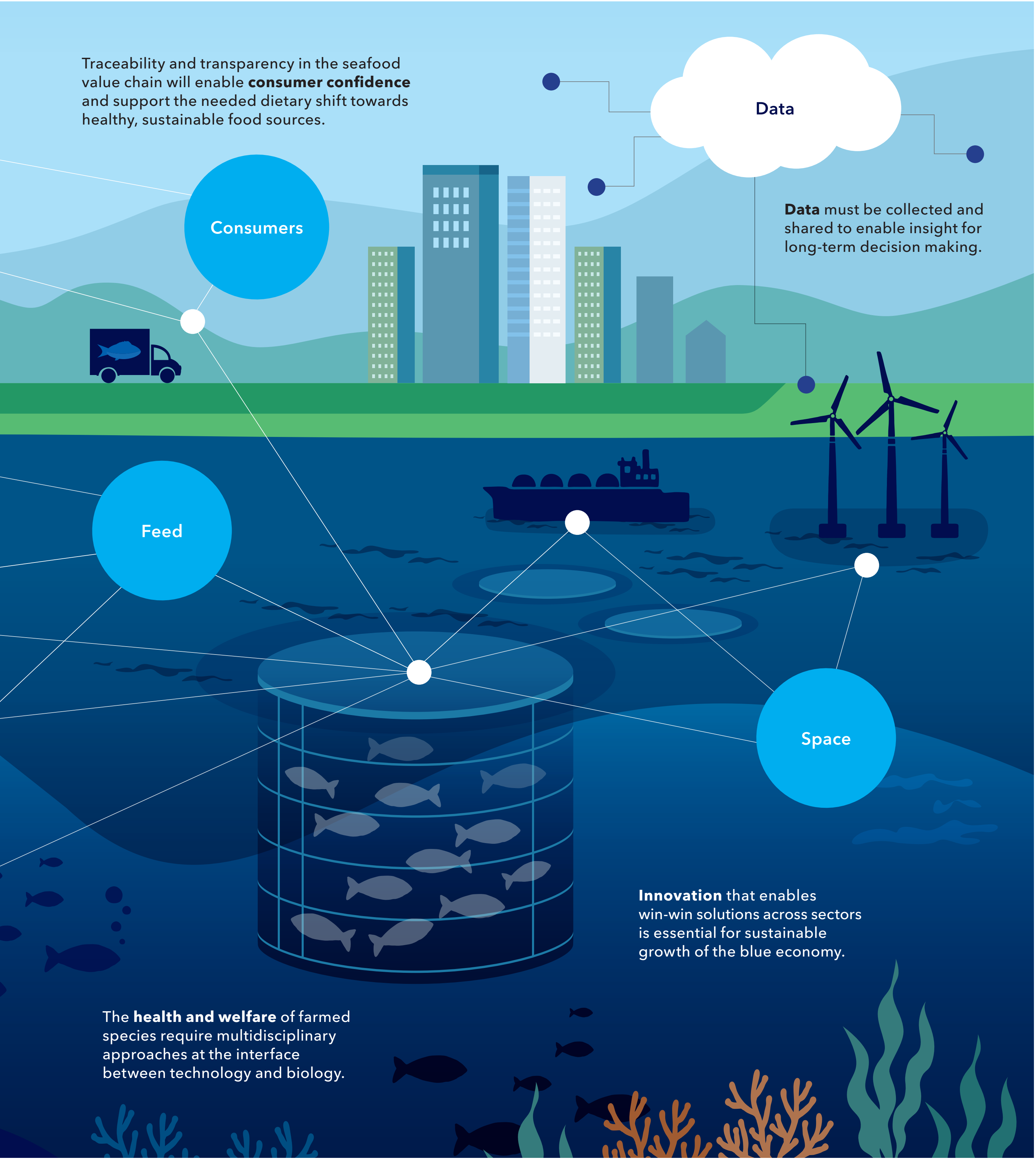
Onshore and offshore fish farming: By onshore, we mean fully onshore production cycles for marine fish, rather than the tendency to produce larger smolts. By offshore, we mean marine aquaculture using more advanced marine structures able to operate in harsher sea states. We do not make an additional distinction between exposed and offshore fish farming.
Cost estimation: These come from publicly available databases (Statistics Norway, 2020) and scientific articles (Engle et al., 2017; Iversen et al., 2020). For new technologies, costs are based on reference projects.
Reference projects: SalMar's Ocean Farm 1 off Norway is the reference for capacity and cost estimates for new offshores structures (Directorate of Fisheries, 2016). Capacity and cost estimates for onshore fish farming come from studies that provide detailed cost breakdowns (Bjørndal & Tusvik, 2018; Liu et al., 2016).
Cost-learning curves: Our estimates of learning rates per doubling of capacity are based on historical data for salmon production (FAO, 2020a), investment statistics in national accounts (Statistics Norway, 2020), and production costs (Guttormsen, 2002; Iversen et al., 2020). We assume these learning rates hold for emerging aquaculture technologies, and that the effect of learning is global.
Governmental influence on costs: The impact of taxation schemes on aquaculture varies by country and is considered implicit in the baseline cost estimates. The model includes subsidies to favour development of new technology, with OECD regions and Greater China being the most prone to subsidize seafood production (Stuchtey et al., 2020).
Spatial requirements and yield: We assume a direct relationship between aquaculture production quantities and the amount of area taken up by infrastructure. Measures of yield come from scientific literature (Engle et al., 2017; Gentry et al., 2017).



Sustainable growth of marine aquaculture



When forecasting marine aquaculture, a holistic approach is crucial to understand the **social**, **economic** and **environmental** issues, how they interact and how sustainability burdens may shift to other parts of the system.



Production of fish feed

The future growth of aquaculture is dependent on the availability of quality feed at affordable prices. About 80% of marine finfish and crustacean production depends on commercial compound feeds, and we expect this share to grow in the future. Feed production increased six-fold from 8 million tonnes in 1995 to 48 million tonnes in 2015. In 2015, about 38% of the feed was consumed by marine aquaculture (Tacon and Metian, 2015).

The feed industry, which was traditionally dependent on fishmeal and fish oil produced from wild capture fisheries, achieved this growth by moving to new ingredients. The major innovations in nutrient-based feed formulation allowed inclusion of plant-based ingredients (such as soy, canola, wheat, and legumes), animal by-products (blood meal, bone meal, feather meal), and supplementary ingredients like vitamin pre-mixes. This move substantially reduced the dependence on forage fish, and annual catch decreased from 23 Mt in 2000 to 16 Mt in 2017. Waste and trimmings from fish contribute one-third of the fish meal and fish oil supply (Naylor et al., 2021).

Assuming species-specific biological feed conversion ratios (net amount of feed used to produce one kg of fish), and accounting for where farming takes place, we estimate 60 Mt of feed is required to meet our forecasted demand in 2050. Challenges include availability of ingredients from sustainably sourced raw materials, competition, and cost. Aquafeeds account for less than 4% of total global animal feed and face tough competition for ingredients also used in terrestrial livestock feed, pet food, and the human food industry (Hua et al., 2019). Consumer acceptance and regulations are constraints in using animal by-products. Traceability of fishmeal and fish oil is still a challenge, and use of low-value species, mainly juveniles, in feed production in some Asian countries is a threat to biodiversity (Naylor et al., 2021).

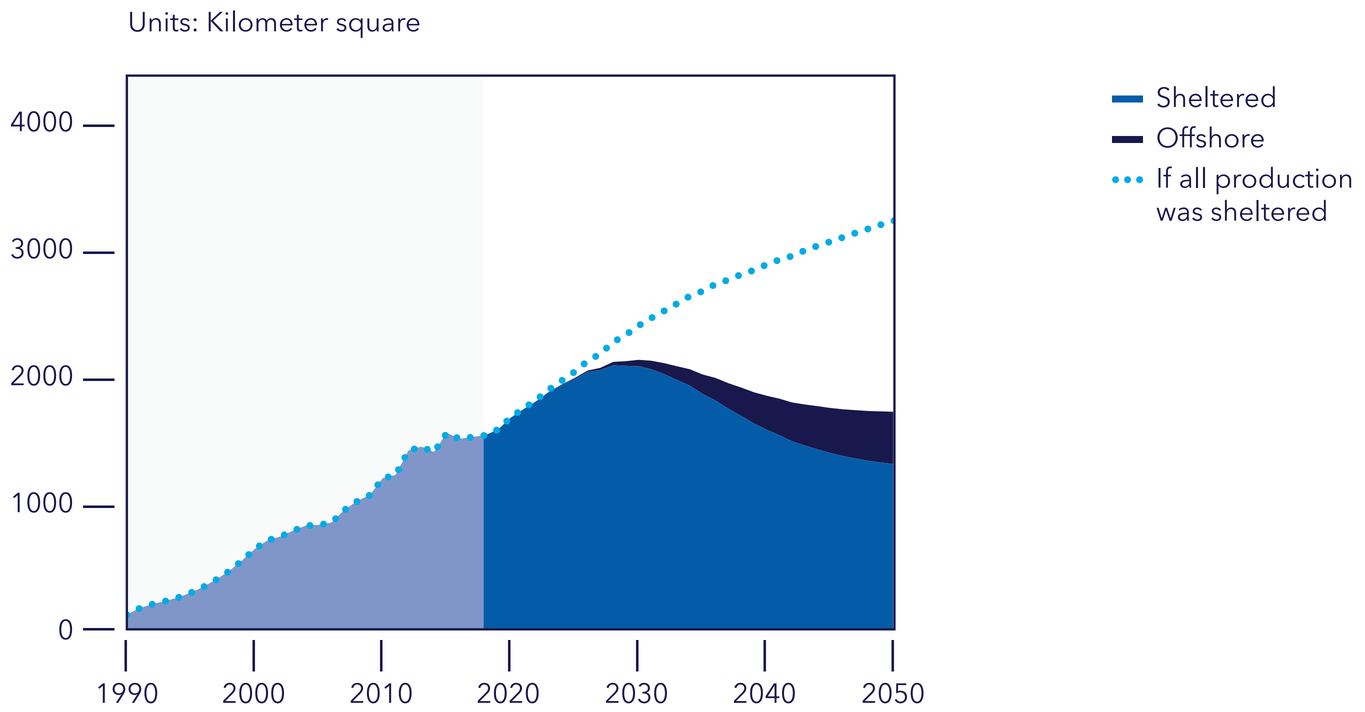
Future production of food from aquaculture will be determined by the scalability of new ingredients. Novel ingredient such as single-cell proteins, insect meal, and algae oil are among the potential candidates. Production costs for new ingredients will also be an important factor in determining large-scale use. Together with improvements in feeding practices, technology improvements in processing of both raw materials and feed will further enable wastage reduction and better utilization of resources.

Environmental impacts of fed aquaculture

The aquaculture value chain from farming of raw materials to consumption of seafood leaves a significant environmental footprint. 90% of the environmental impact from fed aquaculture production has been traced to the fish feed (Naylor et al., 2021). While feed production has shifted from use of forage fish to plant-based ingredients, deforestation remains a major issue in using soy- and palm-based ingredients. Continued effort to reduce habitat destruction for the cultivation of feed raw materials is critical. Reductions in use of fertilizers and pesticides in agriculture will also help minimize the environmental footprint of feed production.

" Future production of food from aquaculture will be determined by the scalability of new ingredients."

Figure 20 Marine space required for the European production of finfish



A considerable portion of the nutrients from uneaten feed and from fish faeces is discharged to the environment, and roughly a third of the feed consumed is discharged as fecal nutrients. Coastal pond farming of crustaceans may also impact on groundwater resources. Improvements in feeding practices and feed processing are necessary to minimize nutrient discharge. Additional solutions we foresee emerging are integrated multi-trophic aquaculture, with molluscs and seaweed feeding on the nutrient discharge (Naylor et al., 2021). Onshore farming of marine finfish does not contribute directly with discharge to the ocean, and opens pathways to circularity as waste products can be processed for use as agricultural fertilizer.

Space use in marine aquaculture

As expansion of marine aquaculture relies heavily on available area, it can increasingly come into conflict with other ocean uses. There is a need for marine spatial planning as an integrated approach for trading off the spatial requirements of competing ocean industries. Marine aquaculture needs balancing with other industries and marine life, bearing in mind topics such as economics, scientific knowledge, environmental impacts, and societal preferences (Costello et al., 2020). Without any gains in area efficiency, the area required by marine aquaculture would almost triple by mid-century. By scaling offshore production of finfish, the average finfish yield in marine areas can increase by around 10% to 850 tonnes of food per square kilometre (km^2). In comparison, mollusc and crustacean production is much less efficient in using space, with outputs of 500 and 400 tonnes of food per km^2 respectively.

For Europe, we estimate that approximately 1,700 km^2 will be occupied by marine aquaculture in sheltered and offshore waters. Due to investment in onshore and offshore finfish production, there is little growth in space use. This is less than half the area that would have been needed if the production happened entirely in conventional net pens. The estimated area footprint is similar to the current space occupied by the European offshore wind industry (Borrmann et al., 2018). Figure 20 compares the forecasted area requirement of European finfish production with a situation in which all production happens in sheltered, conventional net pens.


Ocean Farm 1, SalMar, Norway

The required marine area towards 2050 includes a significant amount of area offshore, where we foresee higher yield. While offshore production does require marine space, onshore finfish production has no footprint in the ocean but adds to pressure on available land resources.

Multi-use marine platforms are also increasingly discussed as a solution to marine spatial planning challenges. Co-existence of marine species within one unit of marine infrastructure is a first step in this direction, represented by integrated multi-trophic aquaculture. We note that emerging initiatives to co-locate marine aquaculture and offshore wind farms are a possible next step towards integrating several industries onto multipurpose platforms (Stuchtey et al., 2020).

These technology trends are most likely to take hold in Europe, the Americas, and Greater China. Spatial use is a large problem in Asian crustacean production, which is threatening pristine coastal environments like mangrove forests. Even though habitat conversion has decelerated after the turn of the century (Herbeck et al., 2020), nearly a third of the loss of mangroves in South East Asia between 2000 and 2012 is traced to aquaculture (Richards & Friess, 2016). As mangroves play an important role in carbon sequestration and in supporting biodiversity, removing them in favour of shrimp farming is unsustainable.

> " ...initiatives to co-locate marine aquaculture and offshore wind farms are a possible next step towards integrating several industries onto multipurpose platforms."

Further intensification of the Asian crustacean farming sector represents one pathway to reducing space use. Key barriers to intensifying shrimp farming have so far included increasing investment costs, and higher risk of disease outbreaks.

Biodiversity impacts

There are several additional biodiversity challenges beyond the use of forage fish to produce feed, and the occupation of coastal and marine space. With the high density of susceptible hosts in aquaculture facilities, the probability of pathogen propagation and clinical outbreaks is increased. Due to the open net pen structure of most marine aquaculture, disease outbreaks are a big threat to coastal wildlife. Marine aquaculture facilities can attract certain wild fish species, thereby becoming transmission hotspots (Dempster et al., 2009).

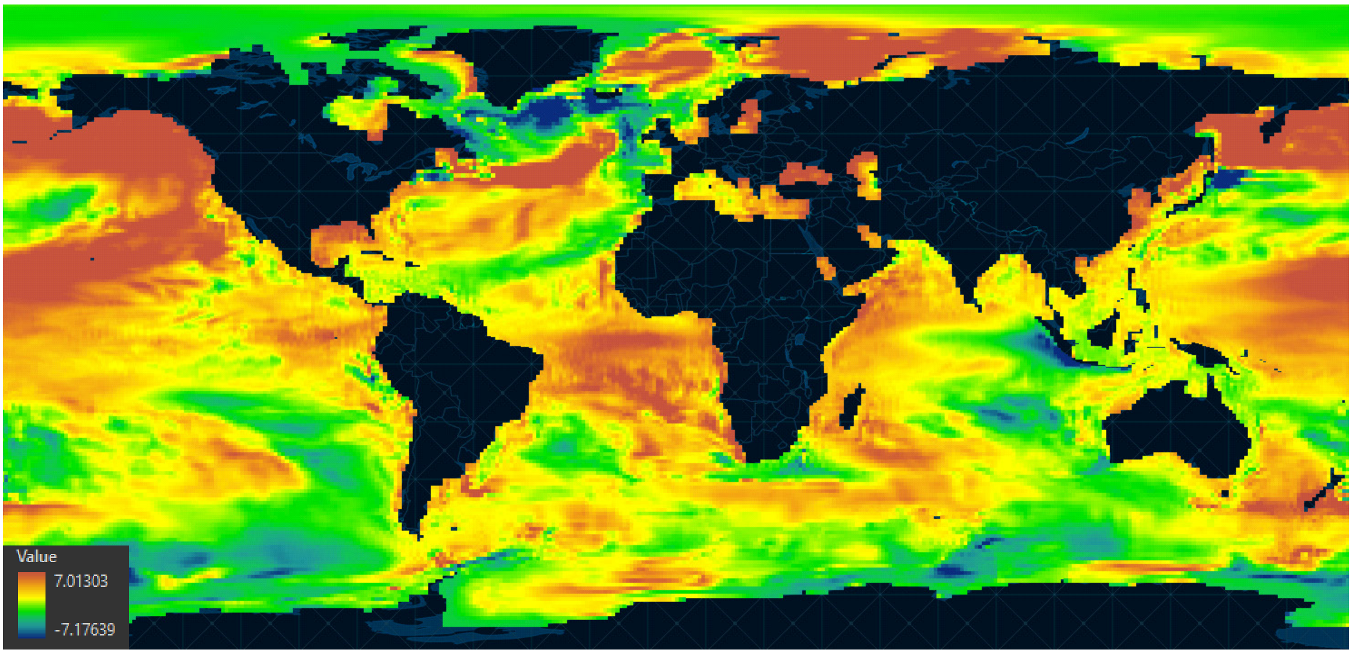
As a consequence of high infection rates, many operating countries still rely on intensive use of pharmaceuticals, including antibiotics, in their operations (Lulijwa et al., 2019). The continued use of therapeutics accelerates antimicrobial resistance in surrounding pathogens, as residues from oral administration through fish feed or immersion treatments often end up in the environment. This will further alter the composition of the normal bacterial flora of both farmed and wild animals, hence endangering local biodiversity.

In addition to spreading infectious diseases and parasites, fish escapes are also considered a major concern due to the risk of potentially devastating genetic interference with wild populations (Atalah & Sanchez-Jerez, 2020). Interbreeding of farmed and wild fish stocks could contribute to reduced survivability among the wild fish, increasing the risk of ecological collapse. For production of high-value species, the influence on wildlife is an important driver for development of closed containment systems in sheltered water, offshore aquaculture, and recirculating aquaculture systems onshore.

Estimating the economic impact of finfish mortality

If we in Europe alone assume a finfish mortality rate of 20% (Sommerset et al., 2021) and a price of 6 USD/kg, the annual financial loss by mid-century would reach approximately USD 6 billion.. Excluded from these numbers are the unreported but substantial losses due to reduced growth rates and resource utilization because of compromised fish health.

Figure 22 Delta average temperature for the period 2005 to 2050 (Degrees Celsius (°C) scenario: RCP 4.5)



Fish health and potential impacts from climate change

Throughout their life cycles, marine animals will encounter various health hazards, such as infectious diseases, changing environmental conditions, operational interventions, or system failures. As aquaculture production intensifies and animal density increases, infectious diseases tend to gain a foothold. This will force stressful interventions and treatments (e.g., delousing) increasing susceptibility to secondary infections and thereby contributing to increased mortality. Additionally, climate change towards 2050 will have an impact on ocean conditions and potentially worsen the situation.

Warming of the ocean (shown for the RCP 4.5 scenario in Figure 22), and the consequent reduction of dissolved oxygen, is expected to have a long-term impact on all marine life, as it will exceed the tolerance limits of numerous species (Deutsch et al., 2015). This will result in stress and increased metabolic demand, causing increased sensitivity to other stressors such as reduced oxygen and acidification (Pörtner & Peck, 2010), and will accelerate vulnerability to infectious diseases. Additionally, ocean acidification is critical for the early life stages of crustaceans and molluscs. It alters biomineralization pathways in calcifying organisms, thereby compromising the structural integrity of the shell (Fitzer et al., 2014).

Increasing deviation between the forecasted environmental parameters and the species' environmental thresholds leads us to expect rising mortality rates and declining growth rates towards 2050. However, it is hard to model these effects due to limited model granularity, particularly in fjords and near coastlines. Projections from coarse-scale climate models deviate significantly in areas known to have marine aquaculture production (Falconer et al., 2020). Caution is therefore needed when using such models to predict future outcomes for marine aquaculture. DNV's climate forecaster C-Gear applies a downscaling algorithm to cope with this issue. However, our system dynamics model will still face this challenge, as the water conditions in which marine aquaculture takes place vary a lot across our regions. Hence, climate-change impacts remain a considerable uncertainty in seafood's future.

Managing marine aquaculture under the threat of climate change is also dependent of measures that will increase the robustness of species. Mechanisms for adaptation include selective breeding, changing feeding practices, and application of new technologies. In coming years, continued development of new preventive measures – e.g., vaccines, genomics, and functional feeds – will thus be important contributors to mitigating these losses, reducing antibiotics use, and improving animal health. We also foresee digital transformation bringing us one step closer to precision farming with optimized production processes. Key trends to watch include improved sensor technologies and intelligent systems for disease detection and biomass control. The impact of climate change on marine life outside marine aquaculture is expected to be much more problematic, as indicated by the Intergovernmental Panel on Climate Change (IPCC (2019).

Transparency and traceability

Our marine aquaculture forecast provides an outlook to 2050 that will meet seafood demand from a growing world population if action is taken on key sustainability barriers in the next decade as discussed above. The sustainability challenges are complex, and the industry is taking active steps to achieve these through technology and innovation. However, this cannot be achieved by any industry actors in isolation, and collaboration, sharing of data, and trust among multiple stakeholders will be essential.

> " Sustainable marine aquaculture production depends on transparency and traceability throughout the entire value chain, including feed, to prevent negative environmental and social impacts."

Sustainable marine aquaculture production depends on transparency and traceability throughout the entire value chain, including feed, to prevent negative environmental and social impacts. Transparency and traceability together drive accountability, oversight and, ultimately, trust in the sustainability performance of the industry. The business case for full-chain traceability is strengthening, particularly in industrialized nations (UN Global Compact, 2020). Progress is being driven by consumer expectations, food safety concerns, and improved risk management in global supply chains, including a focus on human rights.

Consumers and other stakeholders will need reassuring that progress is being made and will demand access to information in order to trust their seafood suppliers.

Roles of policy and regulation

Global, regional, and national policies and mechanisms that encourage transparency, traceability, and sustainability in marine aquaculture must be put in place to accelerate these efforts (UN Global Compact, 2020). However, as highlighted in a recent review of global aquaculture, the wide diversity of aquaculture systems across species, geographies, producers and consumers makes it difficult to develop a single strategy to achieve sustainable and healthy products (Naylor et al., 2021). Future regulatory frameworks must be robust and underpinned by scientific knowledge to safeguard our oceans, but simultaneously flexible to avoid hampering innovation and further developments (Pretlove & Blasiak, 2018). Meanwhile, we see the industry using a number of private governance mechanisms – including standards, best practices, and certification schemes – across several sustainability areas. Such voluntary schemes, although fragmented across geographies, jurisdictions, and market sectors, strongly complement public governance regimes. They have an important role in filling governance gaps where current regulations are absent, weak, or poorly enforced, and often go beyond compliance to promote new norms of best practice (Pretlove & Blasiak, 2018).

The work with this forecast has revealed to us where there are significant data gaps, lack of quality data, or what further research is needed. Data and statistics published by organizations such as FAO are invaluable. Efforts towards modifying national accounts for sustainable ocean development, as highlighted by the High-Level Panel for a Sustainable Ocean Economy, will be critical (Fenichel et al., 2020). We also welcome business-to-business initiatives such as the global dialogue on seafood traceability promoting a unified framework for interoperable seafood traceability practices (UN Global Compact, 2020). By enabling value-chain transparency and product traceability, consumer preferences will shift towards sustainably produced seafood and shape trends in demand between now and 2050.

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This report has been prepared by a cross-disciplinary team in DNV Group Research and Development.

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