FISHING FOR PROTEINS

How marine fisheries impact on global food security up to 2050. A global prognosis

Content

Summary of the Study ## Background

The world's population is growing and caring for it is now placing the earth's natural resources under severe pressure. One of the most pressing questions concerning the future centres on the food security of what will soon be nine billion people: how will we all have enough to eat? Can we change fishing and agriculture in such a way that they will feed us but their negative effects on the environment will remain limited to an absolute minimum? Will we be in a position to resolve distribution issues fairly and peacefully?

According to estimates, global food requirements are set to double in the next 35 years. From a technological perspective, it seems possible that enough food can be produced for up to 10 billion people (Evans 1998). In terms of calories, farmers around the world harvest around one-third more food than is needed to feed the world's population (BMEL 2015). Nevertheless, around a billion people go hungry every day. Their hunger is the result of a distribution problem and is a consequence of poverty and not of the lack of food availability.

Something that is lacking in some regions is needlessly wasted in others: globally, around 30 to 40% of all food along the production and supply chain ends up in the bin (WWF 2015). The possibility of expanding cultivated land for the agricultural production of staple foods seems very unlikely; on the contrary, this option has reached its limits, or has already exceeded them in many areas. Many farming systems generate huge harvests of products like corn, rice, cereals and meat while simultaneously degrading resources such as soil and water.

And what about fish? Fish plays a hugely important role in global food security. It provides more than 3.1 billion people with at least 20% of their animal protein but above all it is an important source of fatty acids and micronutrients (Thilstedt et al. 2016; FAO 2016; Béné et al. 2015). Fish currently supplies 17% of all the protein consumed in the world. This share will continue to grow because the rising income of consumers is accompanied by an increase in demand for high-quality fish (World Bank 2013). In addition to its importance as a source of food, fish is also of great socioeconomic importance: approximately 500 million individuals throughout the world make their living in some shape or form in the fishing industry (FAO 2014).

Yet the state of global fish stocks is cause for concern. Among the scientifically assessed fish stocks, 31% are considered to be overfished and another 58% to be yet fully fished (FAO 2016; Costello et al. 2016). A further increase in fishing pressure could gravely jeopardise the health of the fully fished stocks (FAO 2016).

In WWF's view, the discussion about supplying the world's population with high-quality protein neglects the fact that both food productions systems – the sea and the land – are closely interconnected and in terms of their capacity and natural limits must be viewed as one. Protein-rich soya is used in fish food whereas fish meal and fish oil are in turn part of the animal food of pigs and poultry. Marine catch rates can obviously not be increased, they have in fact been stagnating for almost 30 years. The demand for fish is currently much greater than can be covered by marine fish alone and already today half of all fish in the world is farmed or comes from aquaculture. This branch of the food industry, which has grown hugely over the last 40 years, requires both sea and land (see the box: Aquaculture).

The purpose of fishery management is to safeguard fish resources and ensure their sustainable and environmentally friendly use in the long term. It is the responsibility of policy makers to ensure that this happens. A number of researchers are convinced that this management must be improved significantly to strengthen global food security and prevent the imminent collapse of fish stocks (Pauly et al. 2005; Worm et al. 2006, 2009; Branch 2008; Branch et al. 2010; Allison et al. 2012; Quaas et al. 2016). Such reforms in management could prove very costly in the short term. However, the measures would be ultimately worthwhile if stocks were to reach a healthy size again (Quaas et al. 2012; Sumaila et al. 2012). Consistent, effective fishery management that pursues an ecosystem-based approach, ensures enforcement of the rules, severely restricts illegal fishing and embeds the concept of sustainable management in all fisheries will improve the global fish supply. This is vital in meeting the continuing growth in demand for fish and maintaining marine biodiversity and ecosystem functions (Worm et al. 2009; Froese and Proelss 2010). After all, healthy fish stocks can only live in healthy seas.

In this study, WWF is seeking to find and consolidate answers to three questions:

» What is the maximum quantity of fish that can be obtained from the seas in 2050 under sustainable conditions?

» How will fish demand develop gloablly and regionally up to 2050?

» How will these projections affect the consumption of fish? For example, do we face the threat of a fish protein gap?

Aquaculture

Growing numbers of people are eating increasing volumes of fish. In order to meet the growing worldwide demand, fish is also farmed. In fact, were it not for the strong expansion in aquaculture seen in recent decades, the demand for fish could not have been met as the yields from global marine fishery have been stagnating for around 30 years. With an average annual growth of 9% since 1970, aquaculture is the fastest growing branch of the global food industry. The Food and Agricultural Organization of the UN (FAO) calculated total aquaculture production of over 90 million tons in 2014. Today, more than half the edible fish consumed in the world is farmed.

However, the enormous growth in the farmed sector is problematic for several reasons. For one thing, aquaculture is overwhelmingly practised in countries that have little or no statutory frameworks for regulating aquaculture or protecting the environment. For another, it causes major marine pollution, if chemicals, food remains, faeces and medications from the open cages reach the rivers and seas.

Feeding predatory fish in breeding facilities requires primarily wild fish; herbivorous fish rely more on agricultural protein. In the past, as a result of the construction of facilities for shrimp farming in the coastal regions of tropical and subtropical countries, valuable habitats like mangrove forests were lost. Their destruction had huge consequences for the operation of coastal ecosystems, coastal protection and fishing.

In this study, we are focusing on the future of fish from the sea. The future of aquaculture is dealt with in a separate report.

Fish in the Diet

The unique combination of high-quality protein and important nutrients makes fish an exceptionally valuable food. For one thing, it is a good source of animal protein – 150 g of fish provides approximately 50 to 60% of an adult's daily

requirements. It also provides fatty acids, vitamins and other vital nutrients like iodine and selenium, which do not exist in this quantity or variety in any other cereal or meat (Beveridge et al. 2013; Kawarazuka and Béné 2011; WOR2 2013). Food diversity and quality are important elements in the fight against hunger and malnutrition. Poverty is correlated with an excessive intake of staple foods like rice, corn and cereals and an insufficient share of proteins, fats and nutrients.

Fish is frequently the only available and affordable source of animal protein in the coastal regions of developing countries. In a worldwide comparison, rather less fish is consumed in poorer countries (approximately 10 kg per capita per year), whereas the per capita consumption of around 22 kg per year in Asia, North America and Europe is higher than the global average of 20 kg. This reflects the various factors that affect fish consumption: how available fish is, how expensive it is, whether there are dietary traditions in relation to fish and how developed the country is. Generally, the lower the income, the lower the consumption of fish.

The World Health Organization (WHO) recommends the regular consumption of fish – one to two portions a week (WHO 2002).[1] With an average portion size of 150 g, this results in a worldwide recommended annual consumption of 11.7 kg fish per capita. Several national nutrition guidelines were also analysed for this study. They operate within a similar range, averaging 10.6 kg of fish per capita per year (see Table 6 in the appendix).
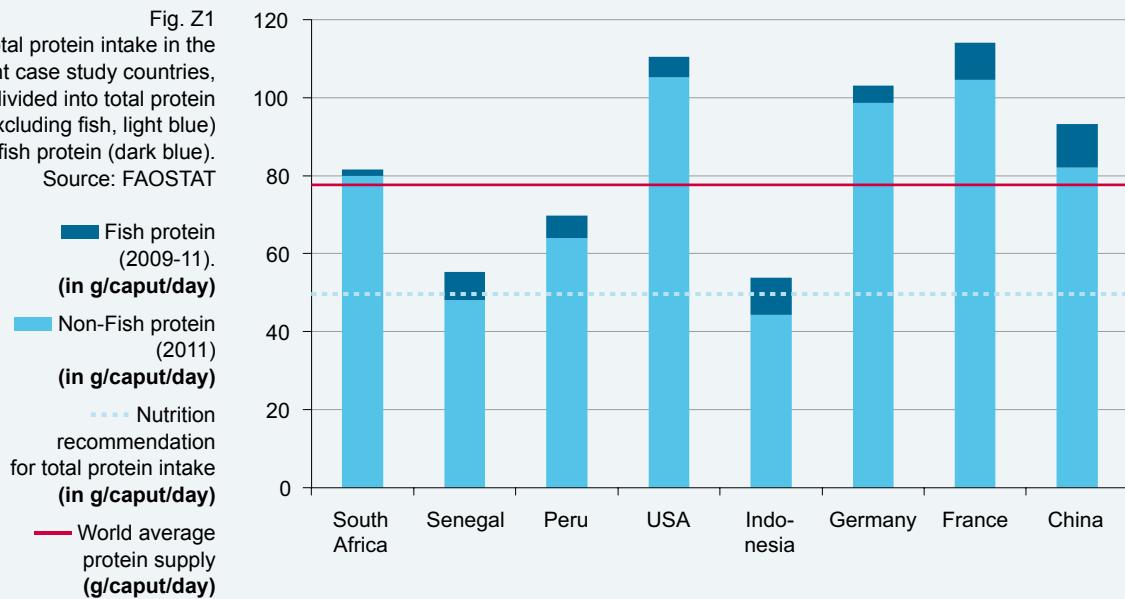
However, this rough guideline only applies in Africa and Latin America; all other regions in the world consume significantly more fish (Figure Z1). Globally, an average of more than 20 kg of fish is currently consumed per capita per year (FAO 2016). The average German also consumes roughly 14 kg of fish per year, more than the recommended intake.[2] In general, Germans eat too much protein. Depending on the individual age group, they consume between 130 and 160% of the recommended amount (MRI 2008). We are thus eating more protein and more fish than we really need. As the world's population grows and the population density constantly increases in coastal areas, the question arises of whether we are satisfying our need for fish at the expense of those who actually need it. Viewed at a global level, fish is already distributed unequally and too much fish per capita is eaten in the Northern hemisphere.

Staple foods like corn, rice and other cereals account for a large share of the dietary pattern of poor people. The consumption of fish is important in correcting the imbalance between calories and protein. Fish is generally not only cheaper than other animal protein but is also often a basis of local and/or traditional recipes. In countries like Senegal or Indonesia, fish accounts for up to 40% of the total intake of animal protein.

In absolute figures, the consumption of animal protein in developing countries is lower than in developed countries. However, the share of animal protein in total protein is growing very rapidly. This is due primarily to economic development and the way in which developing countries in Africa and Asia are 'catching up'. If we make a distinction between fish and meat in the consumption of animal protein, it becomes clear that the contribution made by fish to the supply of animal protein has fallen slightly since 1990 – primarily in favour of meat.

In poor countries, where fish is traditionally eaten, rising income leads to an increase in the consumption of meat and higher-quality fish species. Conse-

Fig. Z1
Total protein intake in the eight case study countries, subdivided into total protein (excluding fish, light blue) and fish protein (dark blue).
Source: FAOSTAT

■ Fish protein (2009-11). **(in g/caput/day)**

■ Non-Fish protein (2011) **(in g/caput/day)**

···· Nutrition recommendation for total protein intake **(in g/caput/day)**

— World average protein supply **(g/caput/day)**

quently, small pelagic fish (those that live in the open sea between the surface of the water and the bottom of the sea) are replaced by larger demersal species.

Between 1990 and 2012, the consumption of wild-caught fish remained almost constant while the consumption of fish cultivated through aquaculture increased five-fold. In 2015, half the volume of fish produced for human consumption came from aquaculture, compared with just 5% in 1962 and 37% in 2002 (FAO 2015).

From a global perspective, there is enough food to feed everyone in the world. If we also take the current protein supply as a basis, there is no protein gap. Food distribution problems are actually at the heart of hunger issues.

The global average supply of protein was 79 g per capita per day in 2011, while the average protein requirement was 49.6 g per capita per day. The latter figure was calculated on the basis of the recommended 0.8 g per kilogram of body weight and the average weight of a person in 2011 (62 kg). Measured against the WHO's recommended intake, the 79 g corresponds to an oversupply of protein of around 30%.

Figure Z1 shows the protein supply in the countries that were selected as examples for this study: South Africa and Senegal, Peru and the USA, China and Indonesia, Germany and France. The height of each bar represents the total supply of protein, subdivided into dark blue areas for fish and light blue areas for other proteins.

The New Fish Dependence Index

Our fish dependence index measures the level of dependence on fish as a source of income and nutrition (especially protein). It is based on the composition of a number of factors: a) food security (incidence of malnutrition in % of the population); b) fish consumption (share of fish in the total consumption of animal protein in %); c) national catch quantity per capita; and d) gross domestic product (GDP) (in USD; capacity to replace fish by other protein-rich food). See section 2.5 for further details on the index.

Fig. Z2
Overview of global
fish dependence.

- high
- medium high
- medium
- low
- no data
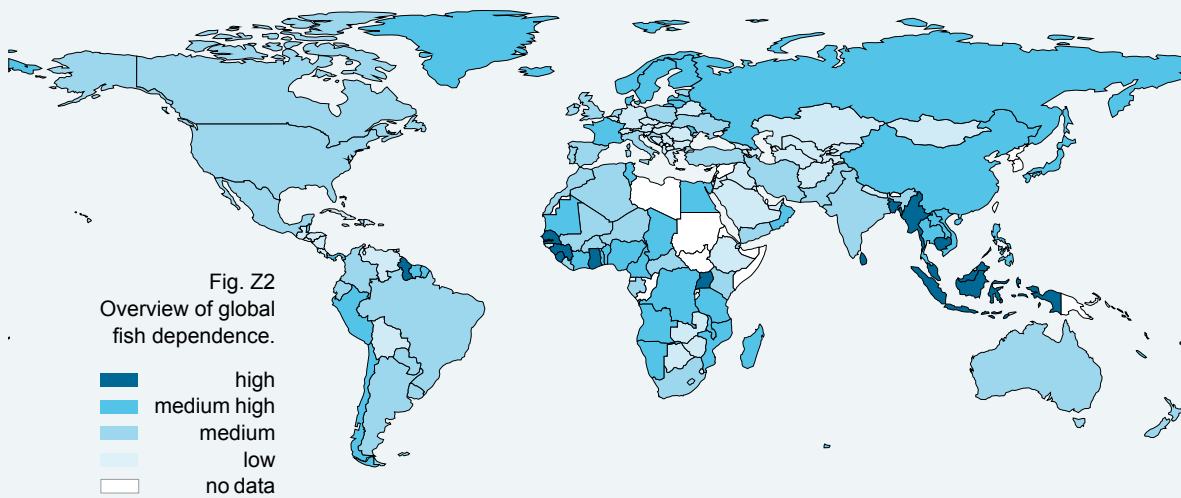
In Figure Z2, we link the country-specific situation of food (in)security and the general situation regarding health and hunger with the value of fish and fisheries to the country's socioeconomic status and the livelihoods of its citizens in order to describe the fish dependence of individual countries. The index shows that countries with a high share of fish in their diet are particularly dependent on fish. More importantly, however, these countries (in dark blue) are precisely the countries that tend to have a large fisheries sector and are neither wealthy nor particularly food secure.

According to this index, Senegal, for example, appears to be particularly dependent on fish. At the same time, Senegal is also an example of the complexity reflected in this statement. According to estimates based on FAO figures, approximately one million people are directly or indirectly dependent on fishing in the country. Fish accounts for 44% of animal protein intake but just 12% of total protein. If the global recommendation of 11.7 kg of fish per person per year is taken as a reference, the annual average per capita consumption of 24 kg of fish in Senegal is 'too much'. At 60 g per capita per day, protein supply is also above the required value of 49 g. Thus, on the one hand, a moderate decline in fish intake would not lead to a protein gap in Senegal. Nevertheless, 10% of the population is undernourished and fishing is the main source of income in rural coastal regions (Thiao et al. 2012). So even though the protein supply would be sufficient, a shrinking fisheries sector would probably see an increase in poverty and hunger in the coastal regions (Lam et al. 2012) with the potential consequence of political instability.

Fish Demand and Fish Supply

We wanted to know which regions in the world can meet their requirements through their own production now and in the future and where there is a growing dependency on imports to meet demand. To do this, we subdivided the world's seas into 64 large marine ecosystems (LMEs). These 64 ecosystems supply up to 95% of the annual global fish catch (Sherman et al. 2009) and present quite specific challenges for regional, and in some cases, multinational management. Then we calculated whether the fish catches in these regions in 2010 were able to meet the local demands of people in the neighbouring countries for fish. To this end, we drew on the data from the Sea Around Us project conducted by the University of Vancouver (Sea Around Us database).
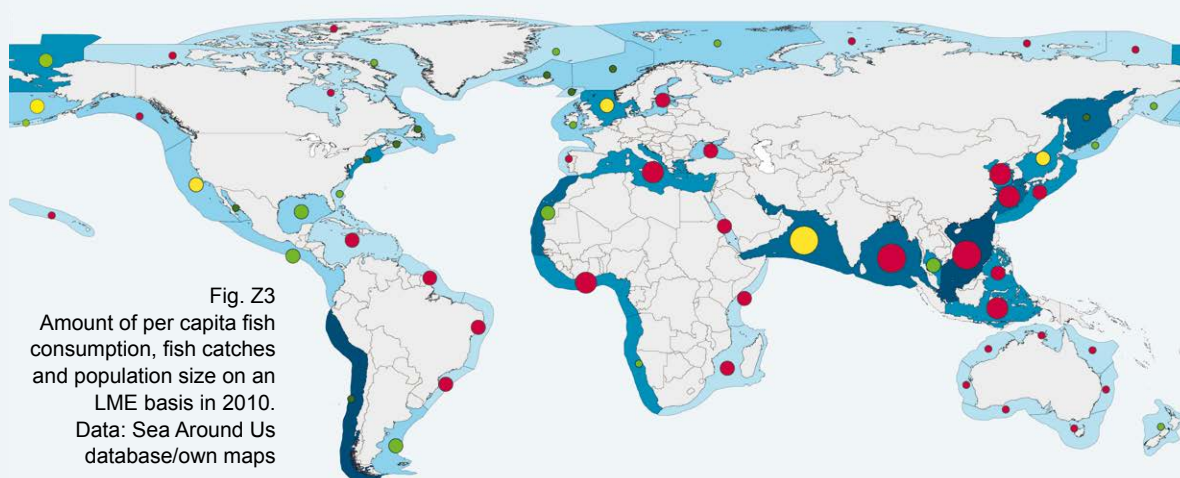
Fig. Z3
Amount of per capita fish consumption, fish catches and population size on an LME basis in 2010.
Data: Sea Around Us database/own maps

Pop. 2010 Scenario (mn)

●	> 50
●	50–150
●	150–500
●	500–1,000

Fraction

🟥	0–80%
🟨	80–100%
🟩	100–500%
🟩	> 500%

Catches (mn tons)

	no data
	0.01 – 0.60
	0.61 – 1.50
	1.51 – 4.00
	4.01 – 8.00
	8.01 –12.86

Figure Z3 shows the LMEs. The productivity of the regions differs significantly: red or yellow means 'does not supply enough fish to meet local demand'; light green and green mean 'supplies enough/more than enough fish to meet local demand'.

LMEs with several neighbouring countries (such as the Mediterranean, Caribbean Sea and Baltic Sea) appear to be less able to cover local demand, whereas LMEs with only one or a few neighbouring states perform better. Moreover, the highly productive LMEs in the North Atlantic and East Pacific are generally better able to meet local demand. This also applies to Europe, the East and West Coast of the USA and the western coast of Latin America. By contrast, fish production in the LMEs around Africa (with the exception of Northwest Africa) and along the Asiatic and Australian coasts is inadequate when compared to current demand.

The Bio-economic Model

Looking ahead to 2050, we are projecting future global fish catches and possible effects on fish consumption. As fish catches are generally affected by fishery activity and the productivity of stocks, we need to apply a bio-economic model to determine future catches. This model combines an ecological aspect, which describes the productivity of fish stocks, and an economic aspect, which describes the economic incentives for carrying out fishery activity and the distribution of fish catches across the markets.

The model is designed to explain how the total volume of fish catches changes in different economic and fishery management scenarios and how the total global catch is distributed in terms of regional catches and regional consumption quantities.

We based the modelling framework on various current fishery management systems. A new element of this approach is that we include interactions in the sea. The fish include predator and prey species and both are caught. Previous studies with comparable global research approaches ignored the biological interactions and either included all fish species in one model (World Bank 2009) or considered stocks that are biologically independent of one another (Quaas et al. 2016; Costello et al. 2016).

Results

For our projection we assume a Maximum Sustainable Yield (MSY) management scenario for all fisheries. The projection calculates the MSY, which provides an indication of the maximum contribution that global fish stocks could theoretically make in supplying the world's population with protein in 2050. The estimated MSYs for the global fish stocks using three different model approaches are presented below.
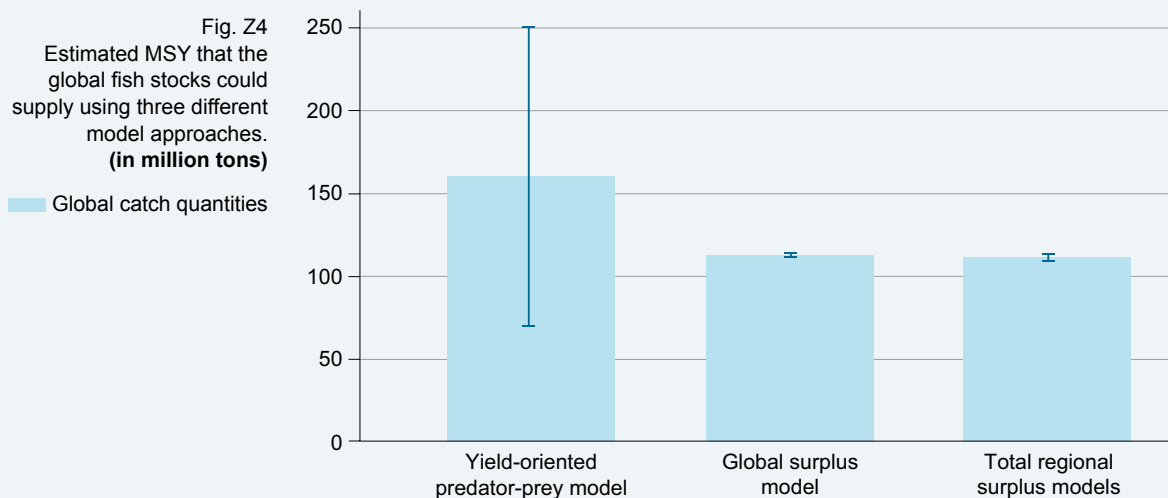
The first bar shows the global catch quantity for a purely yield-oriented predator-prey model. The first model determines the productivity of global fish stocks based on the interactions between the predatory and prey fish: only when the stocks of large predatory fish are depleted can the catch of their prey fish be increased significantly, thus increasing the total volume of the overall catch. Consequently, the objective of fishery management in this model is to maximise catch quantities. However, an MSY of 160 million tons in 2050 can in principle only be achieved at the expense of marine biodiversity. The increased catch quantity is accompanied by a high level of uncertainty (+/- 90 million tons). This is a typical effect following the destabilisation of the predator-prey balance. If all other target values for healthy seas as a prerequisite for healthy fish stocks are disregarded – for example intact habitats or the minimisation of unwanted bycatch – a higher catch quantity would be possible but would be neither desirable nor sustainable from an ecological perspective.

The second and third bars, on the other hand, show a stable maximum catch for Schaefer surplus models. Such a model specifies that the utilisation rate may not be higher than the natural growth rate of renewable resources. We first calculated the surplus model for the entire sea and assumed one global stock (second bar); we then calculated it for the 64 individual LMEs (third bar) and assumed one stock for each of them. When added up, the result of the third model agrees with the result of the second model: both project around 112 million tons of fish for 2050. We use the surplus model to analyse the potential contribution that the LMEs could make to meeting the global and regional demand for fish protein.

We retrospectively calculated a total global catch of 101 million tons of fish for 2010. This means that current catch quantities cannot be increased by more than 10% in the future. Accordingly, marine resources already seem to be almost fully exploited.
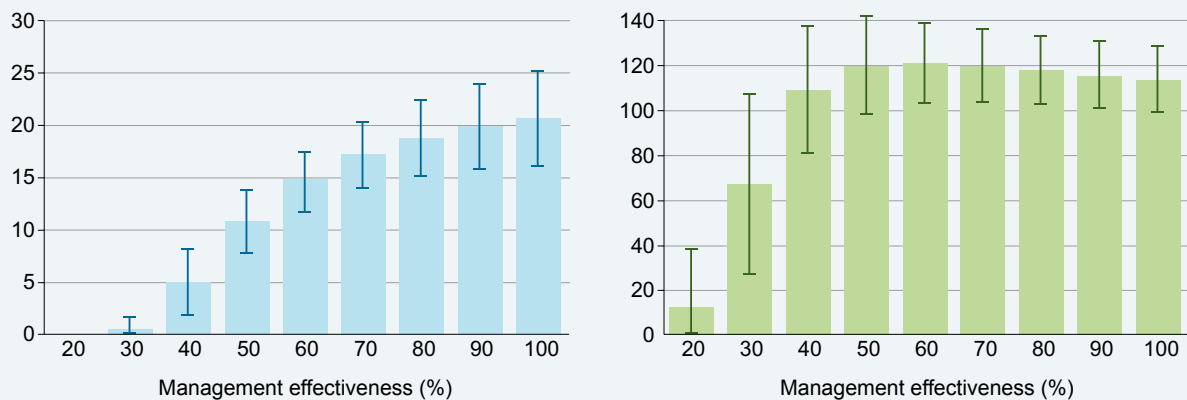
We also studied how various levels of fishery management effectiveness affect catch quantities. Our analysis concluded that if fishery management effectiveness reached 100%, marine biodiversity would be secured, global catches of predatory and prey fish would reach levels of 21 and 116 million tons, respectively, and a total of 137 million tons of fish would be caught sustainably (Figure 23).

If management took into consideration all potential effects of fishery activities on future fishing opportunities, 100% effectiveness would be achieved. Optimum management from an economic perspective would also stipulate the total allowable catch for individual stocks in such a way that it actually regulates and restricts fishery activities.

We come to the conclusion that only a management system that focuses on relationships in the ecosystem can meet the various needs of a sustainable fishing industry: to achieve high catch volumes while increasing ecosystem resilience by protecting marine biodiversity and habitats.

The effectiveness of fishery management is currently estimated at an average of between 50 and 60% (Mora et al. 2009; Watson et al. 2009; Quaas et al. 2016). There is thus considerable scope for development here. Current catch quantities could be maintained at this level of effectiveness. However, the large predatory fish would have to be heavily fished in order to reduce the pressure on smaller prey fish, thus allowing for slightly larger catches. In fact, that is currently common practice. Compared to the model of best-possible management, this would cause a loss of stability in the balance of the ecosystem and shift future fish consumption in the direction of prey fish.

If management effectiveness slipped below the current level, this would be expressed in a sharp reduction in the catches of both predatory and prey fish. This means that ensuring the maximum possible effectiveness of fishery management is critical for maintaining catch yields in the face of simultaneous increases in the global demand for fish.

In the last step, we analyse how the LMEs can help to cover the global requirement for protein. To do this, we use the estimates from the third model (surplus model for 64 LMEs) and compare them with projected regional fish consumption. We use international estimates of future socioeconomic development for the projections, e.g. population trend and economic growth (Shared Socioeconomic Pathways, SSP – see footnote 3).

In the SSP1 scenario with the lowest assumed population growth, the global fish supply in 2050 will be able to meet approximately 81% of the global requirements of what will then be almost 8.5 billion people. In the SSP3 scenario, where population growth is strongest, only 75% of fish requirements will be met by wild-caught fish by the same date.

It is generally assumed that the huge growth rates in aquaculture seen over the last 30 years were needed to meet the world's growing appetite for fish. In terms of numbers, half of the world's fish currently comes from aquaculture production. If the results of our projections are accurate and the volume of fish catches in 2050 could meet around 80% of the world's requirements, the need for further growth in aquaculture production would abate if the fish was distributed in a more equitable manner.

And the distribution problems are continuing to grow: fish consumption in the regions along the East Asian coast could decline significantly by 2050. Fish is traded globally and prices depend on global demand. If fish prices increase accordingly based on this demand, fish will become unaffordable for a large swathe of the population of LMEs along the East Asian coast. These people would have to switch to affordable alternative sources of protein and fish would be exported at a higher export price.

Key Findings of the Study and WWF Comments

1 According to the projections made by this study, it will on the one hand be possible to fish approximately 112 million tons of fish around the world in 2050 if the current moderate level of fishery management effectiveness remains the same. On the other hand this would risk the health of predatory fish stocks which will be fished too hard. This may cause a perilous destabilisation of the ecosystem. It would appear that marine resources are already close to fully exploited (2010: total catch of 101 million tons), leaving little room to increase catch volumes in the future.

There is only one way to increase global catch quantities that is both relevant and sustainable and thus meets the growing demand: fishery management must be improved significantly worldwide and any decisions made must place far greater emphasis on ecological interactions than has been the case to date. The interactions between predatory and prey fish is one such example. This type of differentiated, economically optimised and fully enforced management system could enable sustainable catches of approximately 137 million tons worldwide in 2050.

Improve Management

Fishing is exerting considerable pressure on fish stocks and their habitats in all areas of the world's oceans. WWF is committed to an ecosystem-based fishery management that safeguards the future of marine ecology and the human population. Part of this strategy is not only to conserve vital stocks of large predatory fish but also to protect habitats and endangered species. Total allowable catch limits are set to actually regulate the fishing industry. From the current perspective, this management model would constitute a major improvement in quality and one that is urgently required to make fishing sustainable. Ultimately, it would lead to more fish, which could then be distributed more equitably.

Illegal fishing, which accounts for an estimated 30% of the global catch, is evidence of a particularly damaging consequence of poor management. It reflects increased competition and higher demand accompanied by weak controls. The European Union has a particular responsibility to solve this problem. Firstly, EU Member States must be more consistent in implementing the existing regulation against illegal fish imports. Secondly, they must ensure that any fishing activity they conduct in waters outside the EU is both fair and sustainable. Furthermore, EU agreements with third countries must focus on prioritising regional fishing and first and foremost guarantee that local populations are provided with local fish.

2 If the quality of fishery management, at a minimum, stays at its current moderate level, there would be enough wild-caught fish available in 2050 (112 million tons) to theoretically supply each world citizen with 12 kg (per person per year). This roughly matches the average quantity currently recommended by the WHO and a large number of countries.

More 'Fish Fairness'

WWF considers that the belief that there is enough fish for everyone requires closer scrutiny. Firstly, maintaining the status quo is simply not an option for global fisheries as tolerable limits have already been reached for 58% of stocks and exceeded for 31%, the latter being classified as overfished. In addition, there is currently no fair distribution mechanism for fish that is geared towards real needs. Secondly, the WHO's recommended intake of fish primarily focuses on the valuable micronutrients rather than on the protein. In many countries, the current demand for fish is well above the average WHO recommendation because the affected areas actually rely on fish for their basic protein supply and very few alternatives are available. In Senegal, 24 kg of fish are consumed per capita per year and fish provides almost half of the animal protein consumed. In Germany and France, per capita consumption of 14 and 32 kg respectively also exceeds the WHO's recommended 11.7 kg. However, in these countries, fish provides just 7% of the animal protein consumed. Even if we were to abstain completely from fish in northern Europe, we would not suffer from protein deficiency. The situation is very different in poorer regions with high levels of fish consumption.

3 We can assume that developed countries will use the option of importing fish at higher prices when they are confronted with a shortage in fish supply in 2050. Developing countries with abundant fish stocks will then export their fish rather than eat it themselves. Rich countries would thus still be able to afford 'their' fish in the future while poorer nations would not. For poor coastal countries, the probability that poverty and hunger will become more widespread within their borders increases.

In 2050, LMEs in Africa and in Latin America (with the exception of northwest Africa and Peru) and those along the Asian coast will not be able to meet the local demand for wild-caught fish. Neighbouring countries of LMEs in East Asia, West Africa and in western South America could export their fish due to high fish prices and low prices for substitute goods. On the other hand, developed countries with high purchasing power such as Australia and the USA would probably increase their fish imports. Germany, France or South Africa could import fish from other marine regions to offset the major shortfalls that will sometimes occur in their own supply.

I Can Have Your Fish and Eat it

Today, Europe imports about a quarter of the world's total fish catch and represents the largest market for fish and fish products globally. More than half of the fish imported into the EU originates in developing countries. In statistical terms, we in Europe have already eaten all of the fish from our own waters by the middle of any given year. For the remainder of the time, we eat imported fish which is then missing elsewhere as a source of nutrition and/or as the cornerstone of local economic structures. The high demand for imported fish would almost certainly decrease if fish stocks in the European Union's own waters were once again at healthy levels.

We must assume that fish consumption in the Northern hemisphere will have an even more serious impact in the future on the living conditions of those who depend on fish in various ways. Moreover, our analysis of distribution flows clearly suggests that any additional catches will not be used to meet the growing demand in fish-dependent countries. However, the increasing scarcity of resources and unequal distribution of marine fish must not be borne by the poorest countries. This would fuel conflicts and exacerbate instability particularly if the fishing sector is not better regulated.

WWF Conclusion

Our report 'Fishing for Proteins – Impacts of marine fisheries on global food security to 2050' identifies the key factors driving a sustainable future fish supply. It also highlights that consistent changes are required in the fishing industry and in its administration to ensure that the worldwide problems of hunger and poverty do not continue well into the future. That would be contrary to the commitments set out in the United Nations plan of action for the future: ending hunger and poverty by 2030 are two of the 17 Sustainable Development Goals (SDGs). To achieve these goals, fishery management, amongst other things, must be improved significantly everywhere. Apart from bad management, fish stocks also suffer from the effects of climate change as well as the pollution and destruction of their habitats. Investment in improved fishery management, in sustainable aquaculture, in the protection of vital marine habitats and in fair trade policies would restore the productivity of our seas and pay off for billions of people in developing countries. Our results clearly show that the world's growing population must not serve as an excuse for even more reckless exploitation of our seas. In fact, the solution to these problems can be achieved by implementing and enforcing ecosystem-based and sustainable fishery management. In addition, fair access rights and prices must be guaranteed. An increasing supply of sustainably produced, fair trade fish is not merely intended to ease the conscience of European consumers; it must also benefit fishermen and fish farmers in developing countries with measurable effects.

The responsibility for this rests with us – not only politically but also as consumers.

FISHING FOR PROTEINS
Impacts of Marine Fisheries on Global Food Security to 2050. A Global Prognosis

1. Structure of the Report

We begin by describing developments in recent years, current fish consumption, and explain facts about fish, food security and the fish supply using a newly developed index of fish dependency. Alongside a global perspective, we also consider individual regions and selected representative countries.

Next, we calculate the quantity of wild-caught fish on a global as well as selected regional basis that will be available in 2050. For modelling, we consider various economic scenarios and levels of management quality, and compare the results with the future demand for fish. In this comparison as well, we consider both the global and the regional persepctive at the level of large marine ecosystems.

We calculate future demand based on shared socioeconomic pathways, (SSPs[3]) and the regional supply of alternative protein sources – and thereby generate an entirely novel approach for forecasting demand. For calculating potential fish production, we adopt a global predator-prey model. This means that we additionally take into consideration the biological interactions and amplify the current model with an element of 'ecological realism'.

Finally, we combine regional fish production in the large marine ecosystems (LMEs) with the regional and global demand for fish. In the last section we present the findings from our model on the future of the ocean fishery and its effects on fish consumption, and discuss issues related to the distribution of resources and the challenges for trade.

All calculations and models are based on data from
» Sea Around Us (http://www.seaaroundus.org/) for global fish landings and prices in the large marine ecosystems (LMEs);
» FAO (http://faostat3.fao.org/home/E) for consumption levels and import-and-export prices for protein-rich foods:
» scientific literature on estimates for preference parameters;
» Shared Socioeconomic Pathways' (SSPs) for income and population scenarios.

Climate Change

This study focuses on the biological and economic effects and on the effects of fishery management quality on future fish catches and consumption levels. However, climate change is also likely to play an important role in the future of fishing (Cheung et al. 2010; Lam et al. 2012; Merino et al. 2012). While ocean warming may increase productivity for some stocks (Kjesbu et al. 2014; Voss et al. 2011), ocean acidification and warming (Voss et al. 2015; Blanchard et al. 2012) generally decrease the productivity of stocks. Against this background of mostly adverse climate change effects on fisheries, estimates for future fish catches may be regarded as somewhat optimistic.
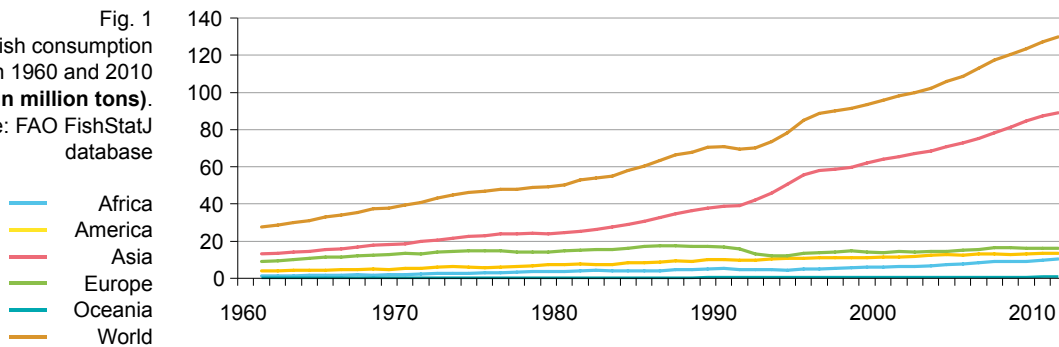
2. Fish Consumption

The term fish consumption is defined here as the amount of fish that is available for consumption in a specific country: production (excl. non-food uses) plus imports minus exports plus or minus changes in stocks.[4]

Fish consumption considered here includes pelagic, demersal and other marine fish, freshwater fish, molluscs, crustaceans and cephalopods from marine and aquaculture production. The data covers the 50 years from 1961 to 2011. Figure 1 shows the increase in global fish consumption, which totalled 130 million tons in 2011. While Africa, America, Europe and Oceania only show slight increases in consumption over 50 years, fish consumption in Asia strongly increased from the 1980s on. This increase is mainly driven by China and its expanding fish production (mainly aquaculture).

Fig. 1
World fish consumption between 1960 and 2010 **(in million tons)**. Source: FAO FishStatJ database

Legend: Africa, America, Asia, Europe, Oceania, World

The development of the world's per capita fish consumption in the same period is shown in Figure 2. Within 50 years it more than doubled and reached more than 19 kg per capita in 2013. Per capita fish consumption increased in every continent. However, the absolute amount of fish eaten by one person differs between regions. Africa has the lowest value of fish consumption per person, with 4.5 kg in 1961 increasing to 10.8 kg in 2011. Up to 1990, Europe had the highest level of per capita fish consumption (21.3 kg); since then, Oceania has led the field (26.5 kg in 2011). The steepest increase in fish consumption per person can be observed for Asia, obviously also driven by the strong increase in Chinese aquaculture production (see Fig. 2).

Figure 3 shows differences in current fish consumption levels at country level. Developed countries show the highest (a mean of 26.8 kg in 2013) while low-income food-deficit countries (LIFDCs) have the lowest per capita consumption (a mean of 7.6 kg in 2013). These differences in consumption depend on fish prices

Fig. 2
Per capita world fish consumption between 1960 and 2010. **(kg/per capita/year)**. Source: FAO FishStatJ database

Legend: Africa, America, Asia, Europe, Oceania, World
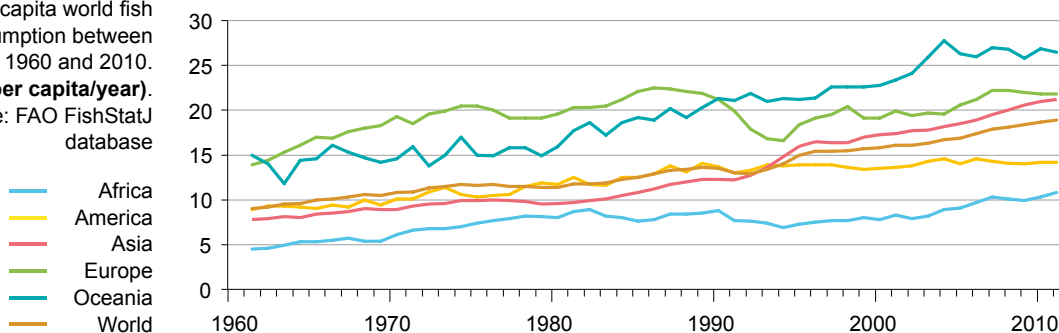
and availability of fish as well as substitutes, income and socioeconomic factors (FAO 2016).

In terms of world consumption patterns, the share of demersal, pelagic and other marine fish decreased over time while the share of freshwater fish increased (see Figure 4). Again, the strong growth in aquaculture production, especially in China, accounts for this shift and has led to increased consumption of species such as catfish, tilapia, pangasius (a freshwater fish), shrimps and bivalves (shellfish such as molluscs, crustaceans and cephalopods). The consumption of freshwater species grew from 1.5 kg per capita to 6.5 kg per capita in the period studied.

The consumption pattern at continental level reflects the global trend (see Fig. 5). However, the share of consumption of demersal and pelagic fish decreased in Asia, America and Europe. One reason for this decrease might be that aquaculture products serve as a cheap alternative to wild catches. The picture in Africa looks different. Here, the consumption pattern is relatively constant over time with only a slight increase in the consumption of pelagic species.

Northern Europe and North America favour demersal fish while the Mediterranean and East Asian countries prefer cephalopods. Overall, 74% of the 19.7 kg global per capita fish consumption in 2010 were finfish, 25% or 4.9 kg per capita were shellfish (FAO 2016).

Fig. 3
Global per capita
fish consumption
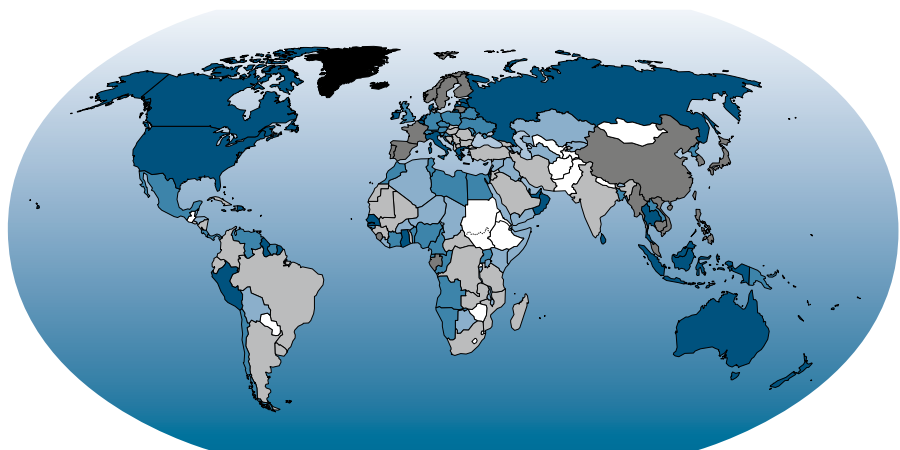(average 2008 to 2010)
(in kg/year).
Source: FAO 2014

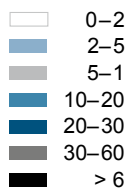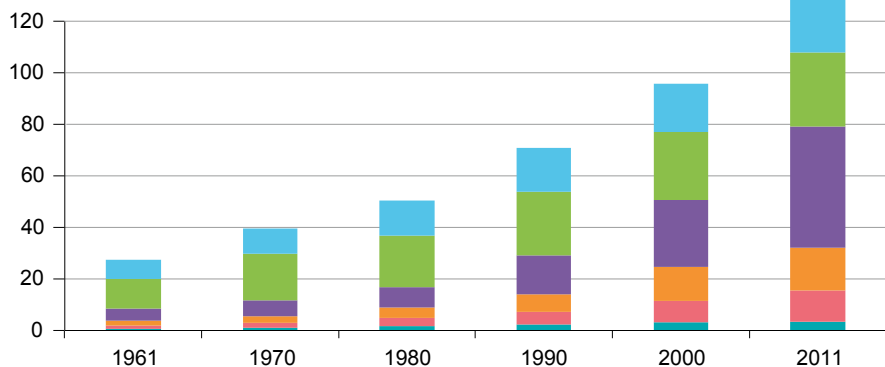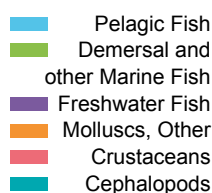| | 0–2 |
	2–5
	5–1
	10–20
	20–30
	30–60
	> 6

Fig. 4
Global fish consumption
pattern **(in million tons)**.
Source: FAO FishStatJ
database

Pelagic Fish
Demersal and
other Marine Fish
Freshwater Fish
Molluscs, Other
Crustaceans
Cephalopods

Africa

12
10
8
6
4
2
0

1961 1970 1980 1990 2000 2011

America

16
14
12
10
8
6
4
2
0

1961 1970 1980 1990 2000 2011

Asia

100
80
60
40
20
0

1961 1970 1980 1990 2000 2011

Europe

18
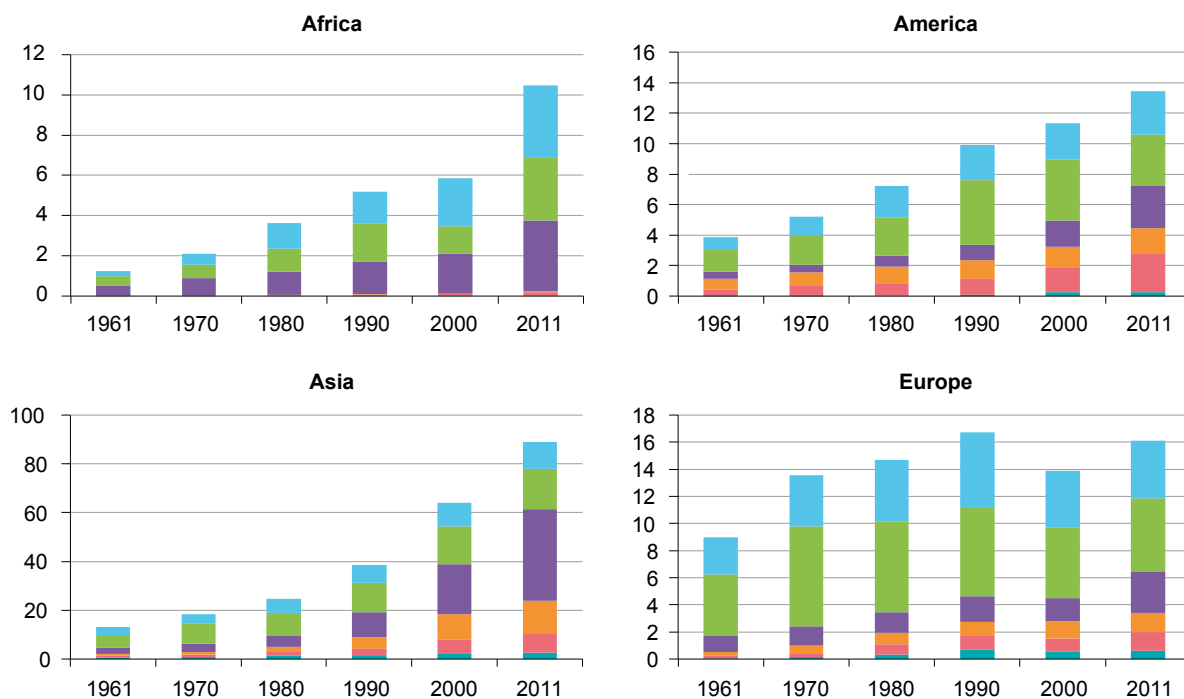16
14
12
10
8
6
4
2
0

1961 1970 1980 1990 2000 2011

Fig. 5
Fish consumption pattern in the case study continents **(in million tons)**. Source: FAO FishStatJ database 2016

Pelagic Fish
Demersal and other Marine Fish
Freshwater Fish
Molluscs, Other
Crustaceans
Cephalopods

2.1 Fish Consumption in Selected Case Study Countries

In addition to the broad overview provided above, we focused on eight countries in order to provide further and more detailed insights. The case study countries were:

» France and Germany (Europe),

» Peru and the United States of America (America),

» China and Indonesia (Asia),

» Senegal and South Africa (Africa).

The choice was based on the following criteria: (1) each continent (except Oceania) should be represented, (2) developed as well as developing countries should be included, (3) fish and fisheries should play an important role for those countries.

The African countries **Senegal** and **South Africa** have the lowest fish consumption overall, starting with 0.06 million tons (Senegal) and 0.1 million tons (South Africa) increasing to roughly 0.3 million tons in both countries. **Peru's** fish consumption slightly exceeds African values with 0.14 million tons in 1961 and 0.65 million tons in 2011. In contrast, fish consumption in the **USA** started much higher in 1961 with 2.5 million tons and increased to 6.8 million tons in 2011. Although **Indonesia's** fish consumption was less than 1 million tons in the early 1960s, it has reached values similar to the USA in recent years with a maximum of 6.9 million tons in 2011. The leader in fish consumption is **China**. It doubled its fish consumption from 3.4 million tons in 1961 to 6.9 million tons in 1984. From the 1980s until today, China's fish consumption grew at very high rates, leading to 46 million tons in 2011. In comparison, the development of fish consumption was quite moderate in the two European countries **Germany** and **France**. Fish consumption levels in Germany stayed relatively constant over time at 0.7 million tons in 1961 and 1.2 million tons in 2011. France experienced a stronger increase, rising from 0.7 million tons in 1961 to 2.2 million tons in 2011.
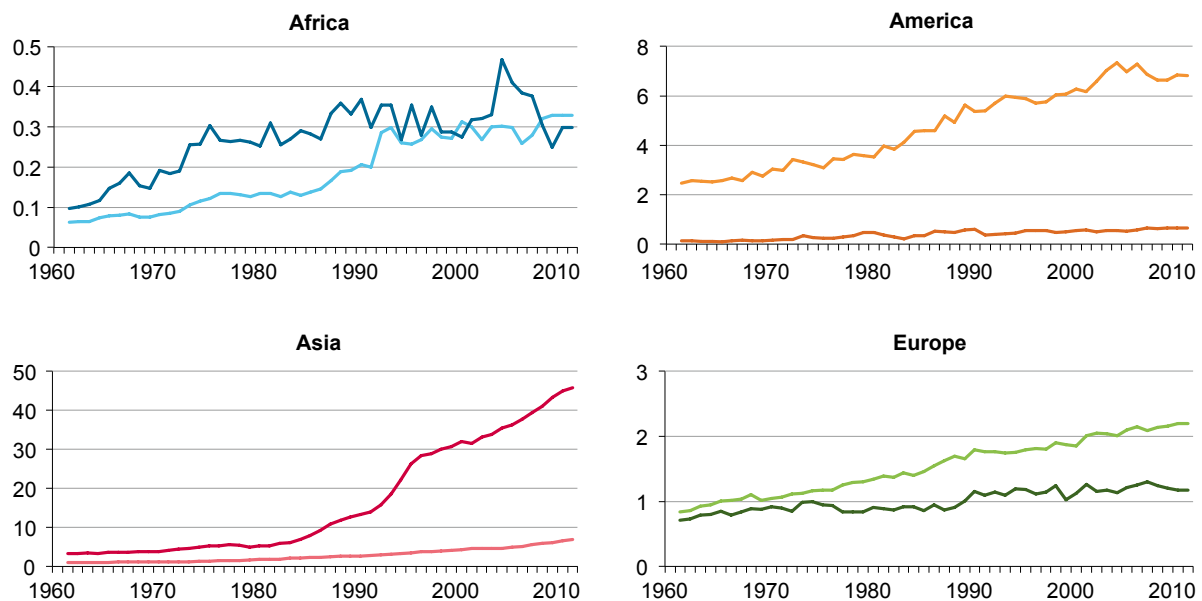
Africa

America

Asia

Europe

Fig. 6
Fish consumption in the
eight case study countries.
(in million tons).
Source: FAO FishStatJ
database

Senegal
South Africa

Peru
USA

Indonesia
China

France
Germany

Differences between the case study countries can again be found in the per capita fish consumption over time (see Fig. 7). While South Africa's per capita consumption is similar to the African average, Senegalese people consume four to five times more fish than people in South Africa. Peru and the USA both exceed their continent's average. Also, these two countries show a similar development in per capita fish consumption over time. However, Peru shows a high fluctuation. This variability is mainly driven by the strong dependence (up to 80%) of the Peruvian fishery on anchoveta (Engraulis ringens). For example, in the early 1980s, anchoveta stocks west of South America drastically decreased – mainly because of an El Niño event (FAO 2016a). This decrease was reflected in the Peruvian per capita consumption.

China and Indonesia experienced a strong increase in per capita consumption, similar to the overall Asian development. Per capita consumption in Germany and Europe is relatively steady over time. Germany lies below the European average. In contrast, France exceeds the European average in terms of fish intake per person and experienced a relatively strong increase over time from 18 kg per person to 35 kg per person.

When comparing consumption patterns at country level, differences between the developing countries (South Africa, Senegal, Indonesia and Peru) and the developed countries (China, France, Germany and the USA) can be noticed (see Fig. 8). In the developing countries, marine fish form the biggest share of consumed fish with pelagic fish clearly dominating. Also, except for Indonesia, the share of freshwater fish consumption is very small. Indonesia is one of the biggest aquaculture producers in the world. The main freshwater species produced are carp, tilapia and gourami; shrimp are also cultivated (FAO 2016b). A similar argument might hold true for Peru, which shows increased consumption of freshwater species and molluscs from 1990 on. Towards the end of the 1980s, Peru initiated aquaculture production of trout, tilapia, shrimps and scallops which developed successfully in subsequent years (FAO 2016c).

Among the developed countries considered in this report, Germany and France
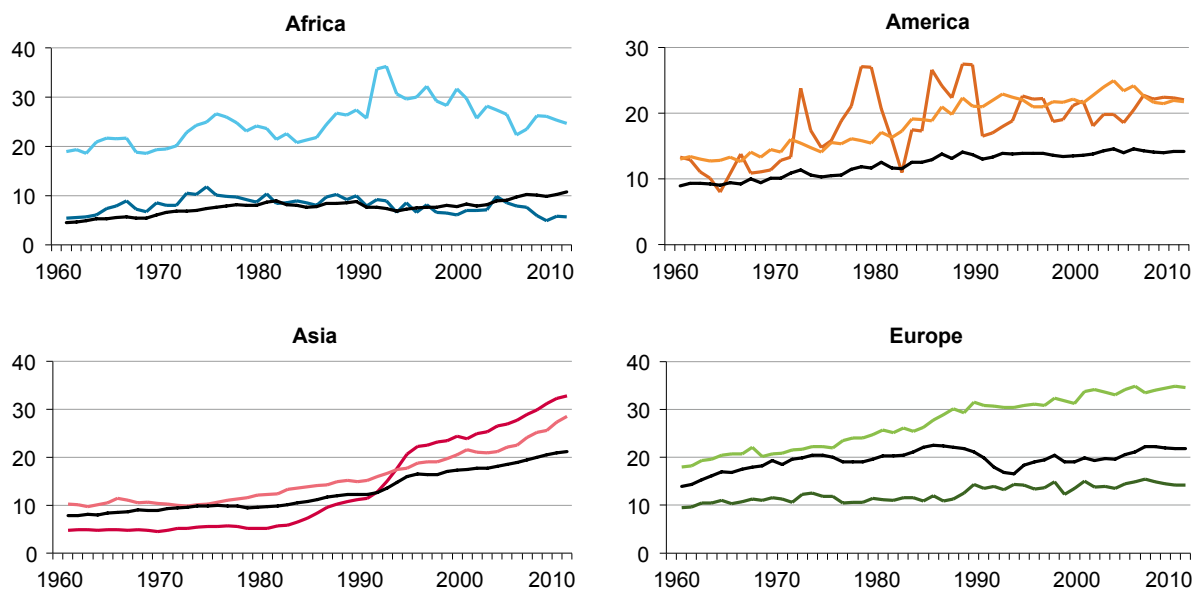
Africa

America

Asia

Europe

Fig. 7
Per capita fish consumption
in the eight case study
countries and the
corresponding continent
(black line)
(in kg/year).
Source: FAO FishStatJ
database

Senegal
South Africa

Peru
USA

Indonesia
China

France
Germany

have the highest intake of marine fish. However, over time this share has decreased in France in favour of molluscs and crustaceans. In Germany freshwater fish consumption has increased. In the USA, overall consumption has stayed relatively stable, while, as in France and Germany, the share of marine fish has decreased while the share of freshwater fish and crustaceans has increased. The increase in the consumption of freshwater species, crustaceans and molluscs may be driven by imports of aquaculture products, which are cheaper compared to wild catches.

China is the world´s leading country in aquaculture production and shows the highest share of freshwater fish and molluscs consumption in recent decades. In contrast, its consumption of pelagic and demersal fish is the smallest of all the eight case study countries.

The rapid increase in fish consumption in the developing economies in Asia can be explained by the correlation between increasing fish consumption and increasing wealth: per capita intake of fish increases fastest where wealth and urbanisation are combined and where domestic supply is increasing as well (HLPE 2014).

Overall, the share of marine fish and seafood in world consumption has declined over time, while the share of freshwater fish has shown an increase. However, marine fish still forms the majority of the world´s fish consumption, and some countries, for example South Africa, rely almost entirely on wild catches. Nevertheless, although Sub-Saharan Africa currently contributes less than 1% of global aquaculture production, it registers as the fastest-growing aquaculture industry measured by its growth rate (World Resources Institute 2013). African aquaculture production is still very low. There are a number of reasons for this, including difficult market conditions and a focus on smallholder aquaculture, which is very important for local food security but cannot meet the goal of increased fish production at national level (Beveridge et al. 2010).

Monoculture of fish is increasingly replacing the traditional consumption of small fish species in some low-income countries (FAO COFI 2014). Small pelagic

Fig. 8
Fish consumption pattern
in the eight case study
countries **(in million tons)**.
Source: FAO FishStatJ
database

Pelagic Fish
Demersal and
other Marine Fish
Freshwater Fish
Molluscs, Other
Crustaceans
Cephalopods
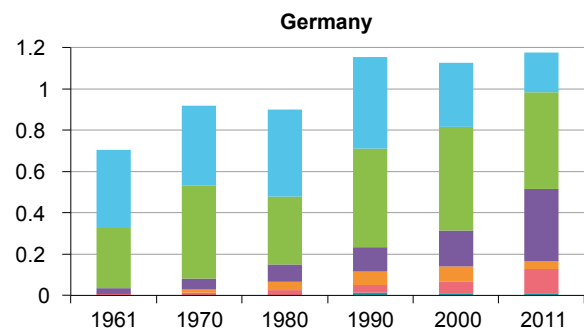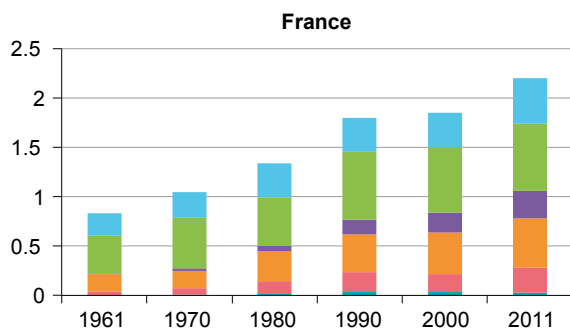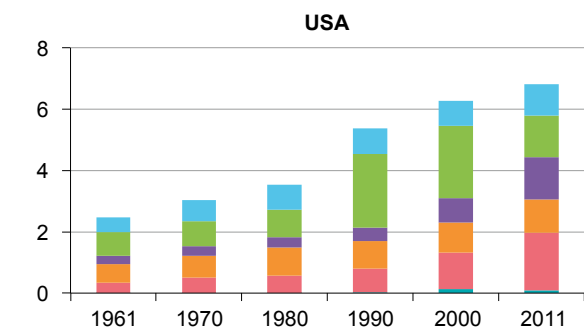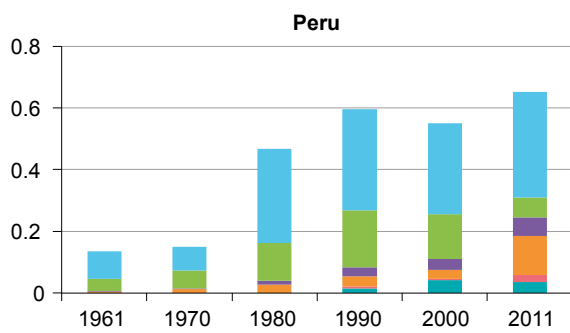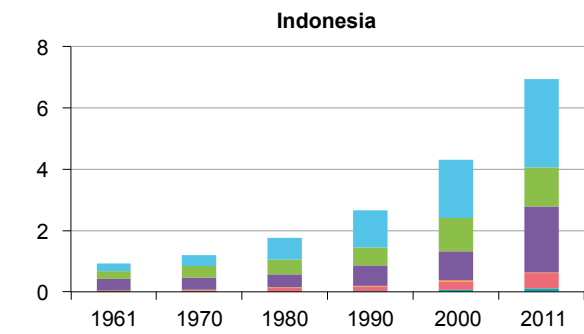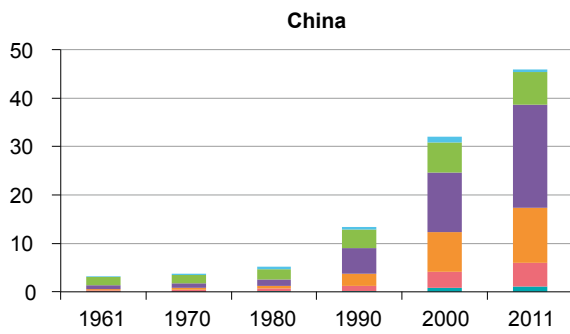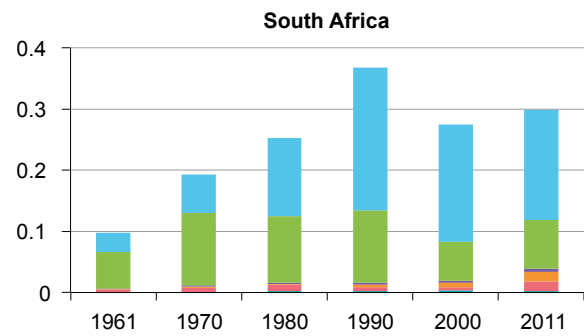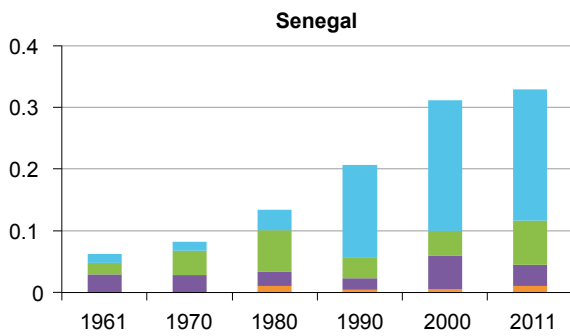
fish in particular have a unique nutritional composition and are hence of great nutritional importance. Moreover, small fish are more affordable and more easily accessible than larger fish or other animal-based foods and vegetables (Kawarazuka and Bené 2011). Consumption of these should be encouraged and promoted, while the use of small pelagic fish for fish meal and fish oil should be reconsidered (Tacon and Metian 2013). In addition to Germany, pelagic fish play an important role in consumption for all developing countries in the case studies (see Fig. 8). The availability of marine fish in the future is very important, especially for those countries with low aquaculture production.

Conclusion

» Total fish consumption has increased over time, but the share of marine fish and seafood has declined.

» Marine catches still play an important role in fish consumption, some countries rely on wild catches at 100%.

» Increasing fish consumption is driven mainly by Chinese aquaculture.

» Aquaculture products are not a substitution option for all countries.

2.2 Global Importance of Fish as a Protein Source

A unique combination of high-quality protein and vital nutrients make fish an invaluable food. Fish is not only a source of animal protein – 150 g of fish provides about 50 to 60% of an adult's daily protein requirements – but also of fatty acids, vitamins and other essential elements such as iodine and selenium, which do not occur in such quantity and diversity in cereals, other crops or meat (Beveridge et al. 2013; Kawarazuka and Béné 2011; WOR2 2013). Dietary diversity and dietary adequacy are high on the agenda in the fight against hunger and malnutrition. Severe poverty is highly correlated with the intake of 'too many' staples and too little protein, fat and micronutrients.

In coastal regions of developing countries fish is often the only affordable and relatively easily available source of animal protein. In countries like Sierra Leone, which has a very low overall food security, the share of fish in animal protein is over 50%. Marked differences exist between and within countries and regions in terms of the quantity and variety consumed per capita and the subsequent contribution to nutritional intake. In a global comparison, Africa and Latin America consume relatively little fish (around 10 kg per person per year), whereas per capita consumption in Asia, North America and Europe is above the global average (20 kg) at around 22 kg per year.[5] This reflects the factors that affect fish consumption: how available fish is, how expensive it is, whether there are dietary traditions in relation to fish and how developed the country is. Generally speaking, the lower the income the lower the fish consumption. Dietary tradition relates to the fact that countries with a strong fishing tradition due to a long coastline, many fish-rich rivers or islands tend to still consume more fish (FAO 2016).

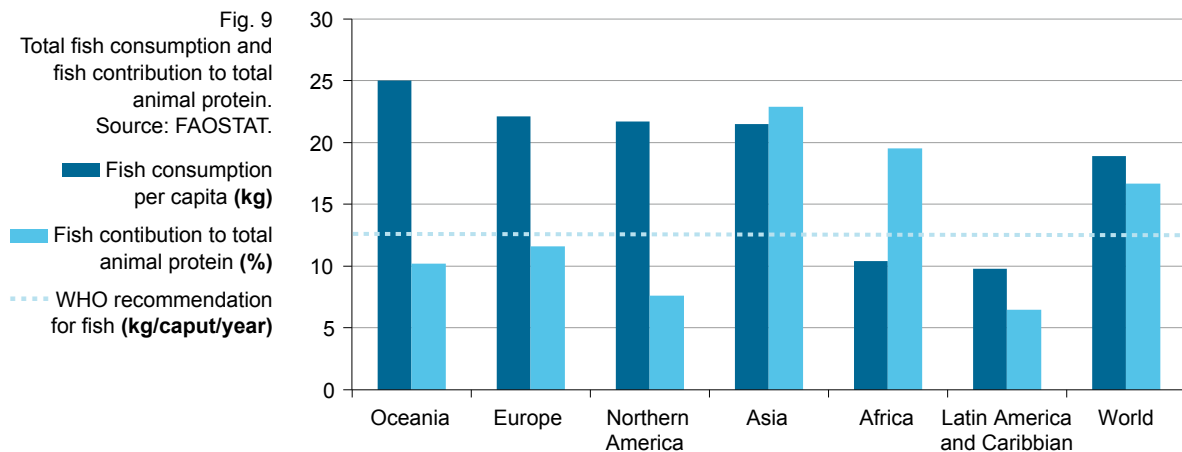The WHO recommends on average an annual intake of 11.7 kg fish per person (about 32 g per day or 225 g per week). Averaged over world regions, only Africa and Latin America come close to meeting this reference value. Globally speaking, however, there is an unequal distribution of fish and Northern hemisphere consumes too much fish per capita.

In 2013, fish accounted for 6.7% of all protein consumed and for 17% of the global

population's intake of animal protein. In developing countries, this share was 19.6% and 24.7% in low-income food-deficit countries (LIFDCs) (see Fig. 9). For 3.1 billion people, fish accounts for 20% of their animal protein; for 4.3 billion people, this share is 15% (FAO 2016). Some small island states such as Kiribati, Micronesia and the Maldives depend almost exclusively on fish as a protein source (FAO 2016). The average daily dietary contribution of fish in terms of calories is about 34 calories per capita. In countries where there is a lack of alternative protein food and where there is a traditional preference for fish (e.g. Senegal), as well as in several small island states such as the ones named above, the daily fish calorie intake reaches 130 calories per capita or more (FAO 2016).

However, based on this data, we may underestimate the importance of fish as a protein and nutrient provider, in particular for countries with low food security and/or poor populations. There are a number of reasons for this.

» There is a huge variation between and within countries, in particular coastal regions within small island countries depending to a much higher extent on fish as a source of animal protein. When these coastal regions are remote, i.e. far away from major markets and not easily accessible, and have a high prevalence of poverty, substitution possibilities are limited in the short run. Consumption in this case is supply driven.

» Consumption data is likely to be underestimated in view of the under-recorded contribution of subsistence fisheries and small-scale fisheries in official statistics (FAO 2014; Pauly 2016). Hence, actual fish consumption in developing countries is probably higher than official data reports.

» Economic dependence on fish as a source of income plays an important role in coastal areas in developing countries with repercussions on food security.

Fig. 9
Total fish consumption and fish contribution to total animal protein. Source: FAOSTAT.

■ Fish consumption per capita (kg)

■ Fish contibution to total animal protein (%)

···· WHO recommendation for fish (kg/caput/year)

The dietary pattern of poor people typically has a very strong component of staple food (in particular maize, rice and other cereals), with fish consumption an important factor in helping to correct an imbalanced calorie/protein ratio. Fish often represents an affordable source of animal protein that may not only be cheaper than other animal protein sources, but also part of local and/or traditional recipes. In countries with a long coastline such as Senegal and islands such as Indonesia, fish accounts for, or exceeds, 40% of total animal protein intake (see Tab. 1 next page).

	Prevalence of undernourishment (% of population)	Fish consumption (kg per capita per year)	Fish contribution to total animal protein (%)
	2013 – 2015	2011	2011
China	9.3	33.5	20.56
Indonesia	7.6	28.9	54.82
Senegal	10.0	23.5	43.73
South Africa	< 5	5.7	5.2
Peru	7.5	22.7	22.28
France	< 5	34.8	13.3
Germany	< 5	14.2	7.28
USA	< 5	21.7	7.37

In Figure 10 we provide a graphical representation of 'the role of fish in the diet in relation to economic development'. While very low income tends to be associated with hunger, rising income first leads to adequate availability of calories and subsequently to adequate nutritional quality. At low income levels (bottom left) fish contributes to an unbalanced diet: fish tends to be consumed in very small or very large quantities depending on availability. At very high income levels (top right), fish also tends to contribute to an unbalanced, overly protein-rich diet. Economic development is associated with structural change in which the share of people involved in fishing declines in line with increasing development.

Fig. 10
Importance of fish in the
diet in relation to economic
development of a country
or population.
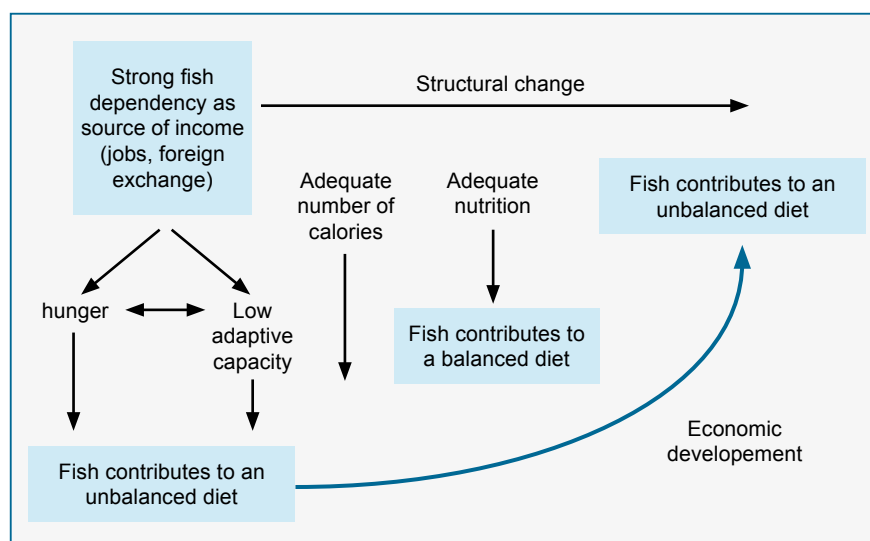
While in absolute numbers animal protein intake is lower in developing countries than in developed countries, the growing share of animal protein worldwide is driven mainly by developing countries catching up, particularly in Africa and Asia. Splitting up animal protein intake into fish and meat, the contribution of fish to total animal protein intake has been declining slightly since 1990 at the expense of other animal proteins.

In poor countries where fish is a traditional food, increasing income leads to increased meat consumption and greater consumption of more valuable fish

species, e.g. demersal instead of pelagic fish. Not surprisingly, consumption of fish from aquaculture is growing fast. Between 1990 and 2012, fish consumption from wild sources remained almost the same, but consumption of fish from aquaculture has multiplied by five. Half of fish produced for human consumption came from aquaculture in 2012, compared to just 5% in 1962 and 37% in 2002 (FAO 2015).

Just as there is enough food on average to feed everyone on the planet and hunger is a question of distribution, there is also no protein gap considering current world average protein supply.

Fig. 11
Total protein consumption in the eight case study countries subdivided into total protein (excluding fish, light blue) and fish protein (dark blue).
Source: FAOSTAT

■ Fish protein (2009-11). **(in g/caput/day)**

■ Non-Fish protein (2011) **(in g/caput/day)**

···· Nutrition recommendation for total protein intake **(in g/caput/day)**

── Global average protein consumption **(g/caput/day)**
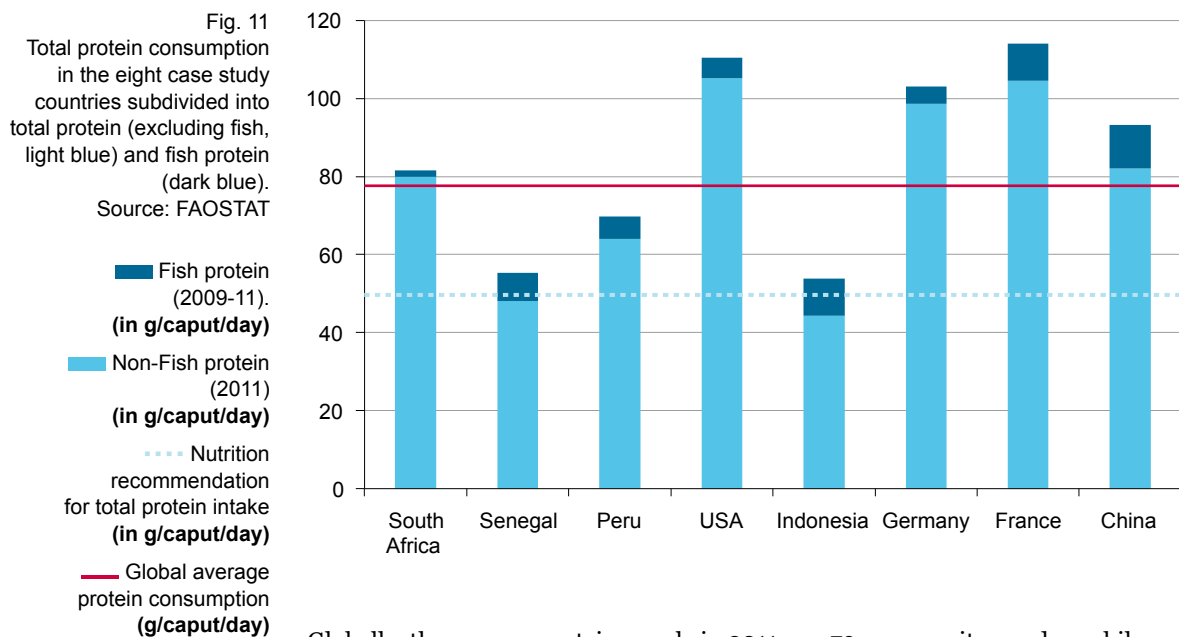
Globally, the average protein supply in 2011 was 79 g per capita per day, while the average protein need was 49.6 g per capita per day. The latter was calculated from the recommended 0.8 g per kg of body weight and the average weight of a person (62 kg) in 2011. Figure 11 shows protein consumption in the eight case study countries. The height of each column represents total protein consumption: the darker blue parts represent fish and the lighter blue parts represent all other protein. Based on this data, all countries except Liberia, Guinea-Bissau, Mozambique, Haiti and Madagascar had enough protein available in 2011. Nevertheless, the distribution within and between countries is highly unequal.

2.3 Food Security and Fish

Undernourishment is a major problem worldwide, with one in seven people undernourished and more than one-third of infant mortality attributable to undernutrition. This is especially the case in many developing countries, with the bulk of undernourished people living in rural areas (see Tab. 1). Most of the world's undernourished people live in South Asia, closely followed by Sub-Saharan Africa and East Asia.

In addition to the prevalence of undernourishment, researchers often use several other indicators in order to assess the food security level of a country such as stunting, measured by height-for-age, and wasting, measured by weight-for-age.

A common multidimensional index used is the Global Hunger Index (GHI, see Tab. 2). To reflect the multidimensional nature of hunger, the GHI combines the following four component indicators into one index:

» 1/3 for undernourishment: the proportion of undernourished people as a percentage of the population, reflecting the share of the population with insufficient caloric intake

» 1/6 for child wasting: the proportion of children under the age of five who suffer from wasting, i.e. low weight for their height, reflecting acute undernutrition

» 1/6 for child stunting: the proportion of children under the age of five who suffer from stunting, i.e. low height for their age, reflecting chronic undernutrition

» 1/3 for child mortality: the mortality rate of children under the age of five, partially reflecting the fatal synergy of inadequate nutrition and unhealthy environments (all standardised based on thresholds set slightly above the highest country-level values observed worldwide for that indicator between 1988 and 2013.[6]

This indicator emphasises the nutrition situation of children – a vulnerable subset of the population for whom a lack of dietary energy, protein or micronutrients (i.e. essential vitamins and minerals) leads to a high risk of illness, poor physical and cognitive development or death. It also combines independently measured indicators to reduce the effects of random measurement errors (GHI 2015).

The GHI categorises countries according to hunger severity into low (values <10), moderate (scores of 10 – 20), serious (20 – 35), alarming (35 – 50) and extremely alarming (>50). In our target countries, **Senegal** and **Indonesia** fall into the serious category, South Africa has moderate levels, and all others are in the low category. The index is not calculated for Germany, France and the USA, which are considered to be generally food secure.

Tab.2
(Multidimensional) Global
Hunger Index 1995 to 2015
for case study countries.
Source: Welthungerhilfe
(WHH); International Food
Policy Research Institute
(IFPRI); and Concern
Worldwide 2015

	1995	2005	2015
	With data from		
	1993–1997	2003–2007	2010–2016
China	23.2	13.2	8.6
Indonesia	32.5	26.5	22.1
Senegal	36.9	28.5	23.2
South Africa	16.5	21.0	12.4
Peru	25.0	18.8	9.1

Conclusion:

» The relevance of fish for food and nutrition security manifests itself in its value as a protein and micronutrient source.

» Poor people generally consume too few micronutrients and too little protein.

» Globally speaking, there is no protein gap.

2.4 Dependence on Fish

In this section we combine the country-specific situation of food (in)security and general health/hunger situations with the socioeconomic value of fish and fisheries to the livelihoods in these countries in order to describe the countries´ dependence on fish.

The following factors determine dependence on fish for food and nutrition:

» **Fish as a food source, i.e. as a source of calories.** This is particularly relevant in countries such as Senegal with food insecurity and a high fish intake.

» **Fish as a protein and micronutrient source.** This is particularly relevant in countries where the protein share of fish in the diet is high or low. It is also particularly relevant in almost all poor countries that have an imbalanced diet, where people eat too much staple food and not enough micronutrients (e.g. Senegal, Indonesia). The fisheries and aquaculture sector plays, and can continue to play, a particularly prominent role in diversified and healthy diets. While average per capita fish consumption may be low, even small quantities of fish can have a significant positive nutritional impact, given that it is a concentrated source of essential dietary components. Micronutrient deficiencies[7] affect hundreds of millions of people, particularly women and children in the developing world. More than 250 million children worldwide are at risk of vitamin A deficiency (leading to blindness), more than 30% of the world's population are iron deficient, 200 million people have goitre with 20 million suffering from learning difficulties as a result of iodine deficiency and 800,000 child deaths per year are attributable to zinc deficiency.

» **Economic dependence on fish as an income source to buy (healthy) food.** This is particularly relevant in countries with high poverty rates and in countries where people working in fisheries are comparably poor. When they lose their jobs in the fish industry, poverty rises and this affects diets in two ways: hunger and quality of the diet. A lack of money to buy food leads first to a less balanced diet, with a tendency to eat less fish and meat, hence less protein and micronutrients and in even more severe cases to a lower intake of calories overall. The severity of this effect depends on the strength of the formal or informal social security systems in place. As an example, if Senegal stopped fishing completely, this would have adverse impacts on the livelihoods of fishermen with widespread hunger as a likely consequence, at least in the short run. This is a typical distribution problem: globally speaking, enough is available, but it is distributed highly unequally.[8]

Hence, fish contributes to the nutritional security of poor households in developing countries in various ways. These include a consumption pathway where the direct consumption of fish increases intakes of not only calories, but more importantly protein, micronutrients and omega-3 oils, and a cash-income pathway, whereby the fish industry contributes to employment and higher overall food consumption in poor countries (see Fig. 12). Commercialisation, fish processing and small-scale aquaculture offer important livelihood opportunities, particularly for women in developing countries, through their direct involvement in the production, processing and sale of fish. In particular, countries where a large share of the population is dependent on fishing (e.g. Senegal) may suffer from higher hunger rates and political instability if the fishing sector declines. According to estimates by the FAO, a total of 660 to 820 million people are directly or indi-

rectly dependent on fisheries and aquaculture. The FAO estimates the number of fishermen alone at 54 million, of which 87% live in Asia. In developing countries, the majority of them work in small-scale fisheries with low fish production per person: on average 1.5 tons per year compared to 25 tons per fisherman and year in Europe (FAO 2014).

2.5 Fish Dependence Index

Our fish dependence indicator measures the degree of dependence on fish as a source of income and food, in particular as a source of protein. It is based on a composite ranking of the following factors:

» food security: prevalence of undernourishment for the period from 2011 to 2013 in %, data from the FAO;

» fish consumption: fish share of total animal protein intake in % for 2011, data from the FAO;

» capture production per capita for 2011, data from FAOfishstat;

» gross domestic product (GDP) per capita as a proxy for substitution capacity for 2011, data from the World Bank.[9]

The indicator measures the short-run dependence. In the long run, the possibilities for compensating through new industries (e.g. building up an aquaculture industry) and new sources of protein (e.g. plant-based sources) have to be considered.
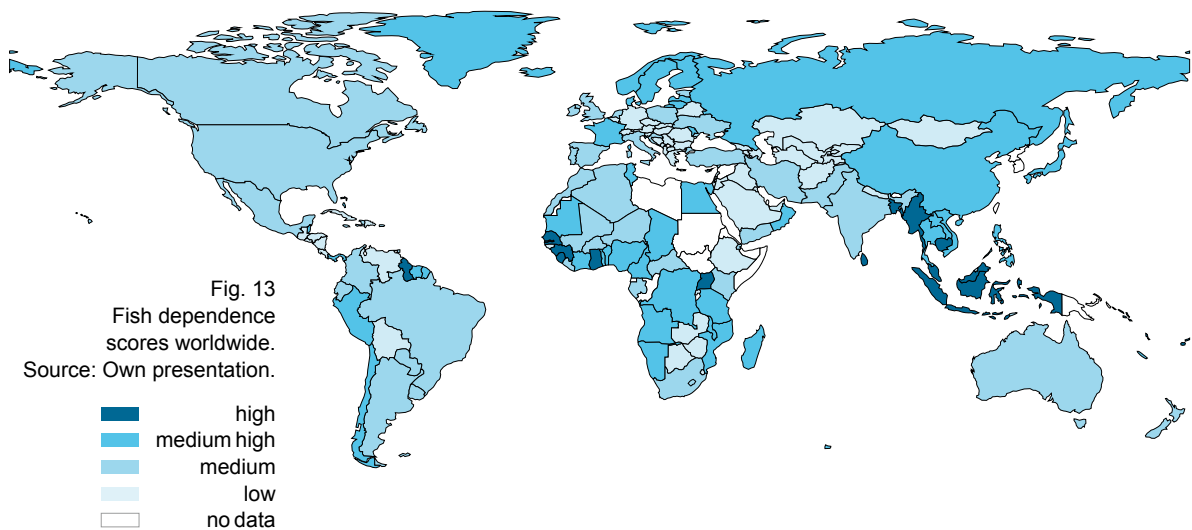
The indicator is similar in some ways to the indicator developed by Allison et al. (2009a, 2009b) and used in Badjeck et al. (2013). The main difference is the more recent data used in this index and the stronger focus on fish as food. Using more recent data (from 2011) is only possible because this index is composed of fewer components. The results of the two indices are in most cases very similar.

Fish as a share of animal protein in food and capture production as a proxy for economic relevance are the main factors and weighted equally. GDP per capita (in USD) and food security (prevalence of undernourishment) are the moderating factors. A high income reduces the dependence created by a high level of the two main factors due to compensation effects. This means that a high income increases possibilities for compensating for a loss of jobs or the loss of fish as a source of food, e.g. through imports and social security. A high level of food security reduces the potentially harmful effects of losing fish as a food source.
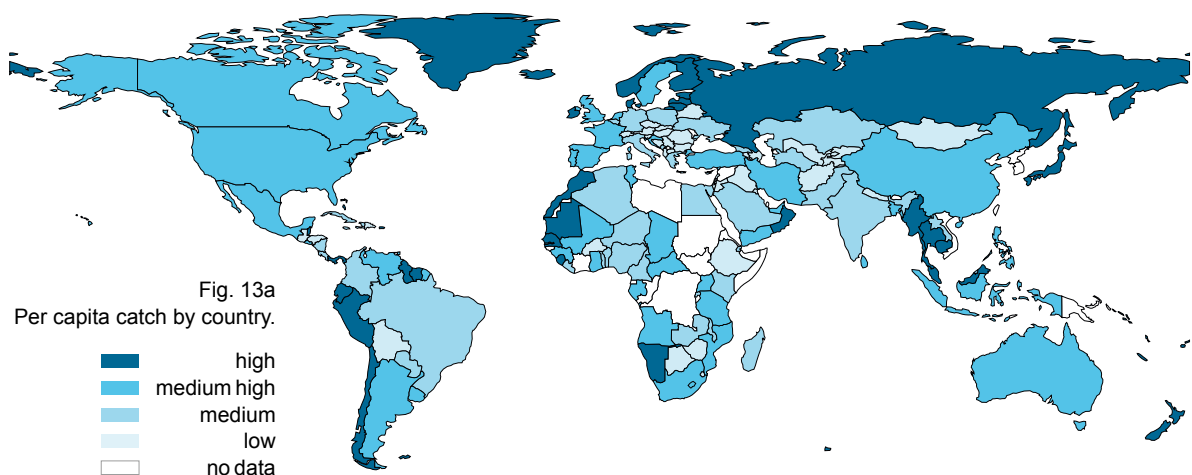
Figure 13 shows the worldwide distribution of fish dependence. Asian island states and West African coastal countries are most dependent on fish, whereas dependence in Europe is comparably low. Figures 13a to 13d show the effects of the application of one of the four factors: a) catch per capita, b) share of fish in total consumption of animal protein, c) per capita GDP, d) share of undernourishment.
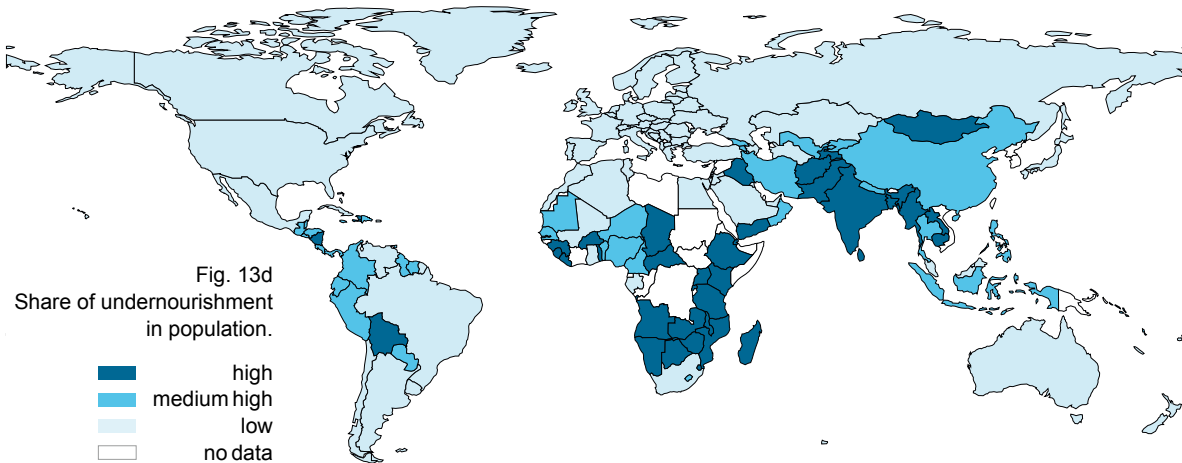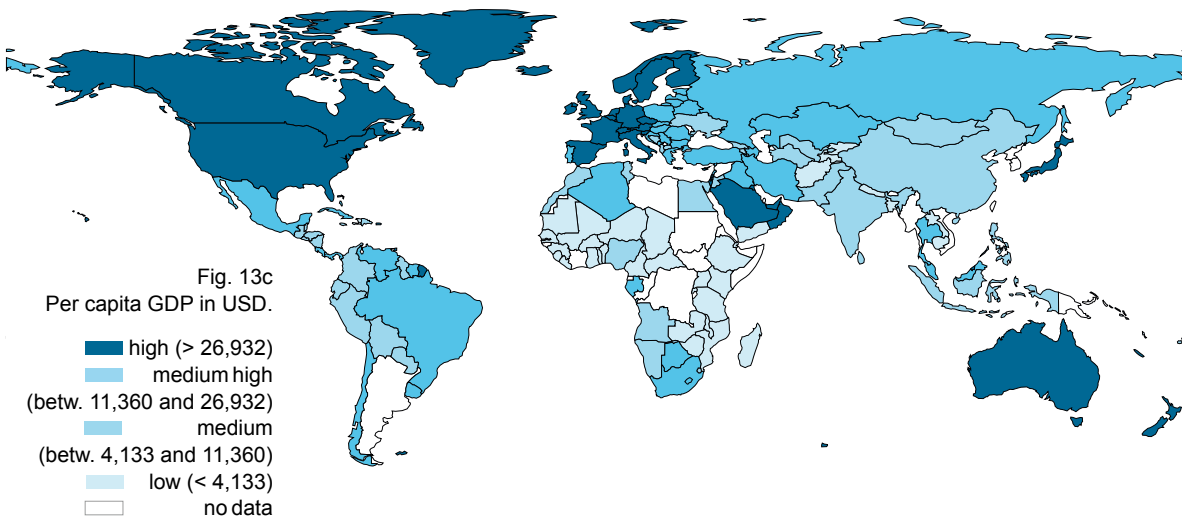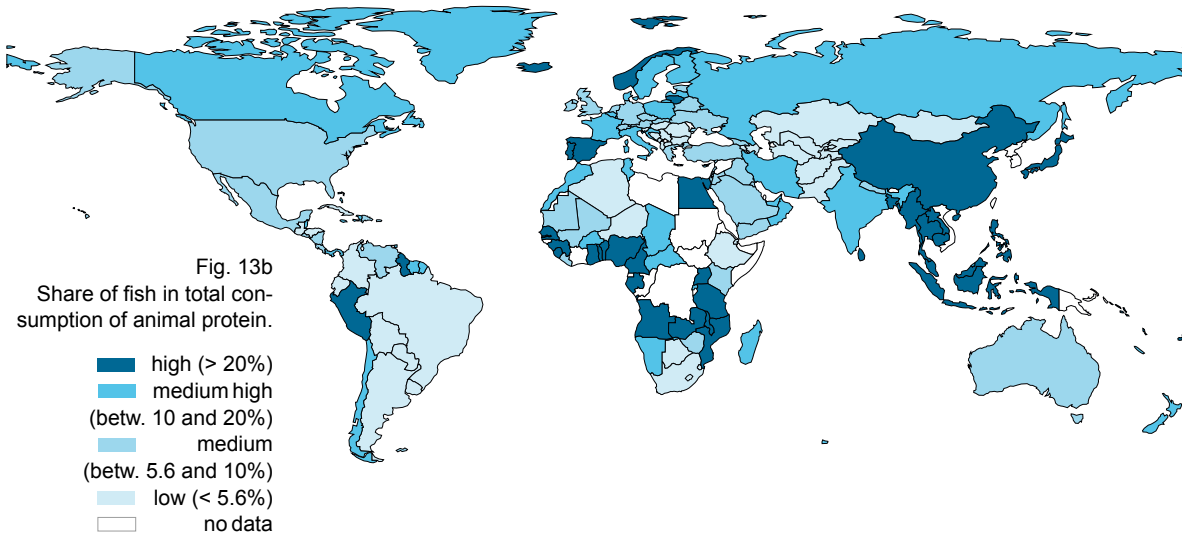
The index reveals that, not surprisingly, countries with a very high share of fish in the diet are highly dependent on fish (see Tab. 3, page 31). One important aspect is that these countries usually also have a comparably large fish industry and are not wealthy or particularly food secure countries. At the same time, the fish protein in high-income food-secure countries is, on average, relatively lower. Nevertheless, poverty and fish dependence do not necessarily go hand in hand (see Tab. 3, left). Among the poorest countries are countries with no access to the ocean (e.g. Ethiopia, Central African Republic).

Germany – with a low catch per person, a low share of fish protein, high income and high food security – has very little dependence on fish. South Africa and United States are also not particularly dependent on fish, even though they have

Fig. 13
Fish dependence
scores worldwide.
Source: Own presentation.

high
medium high
medium
low
no data

This world map is a composite ranking of the following factors:

Fig. 13a
Per capita catch by country.

high
medium high
medium
low
no data

Fig. 13b
Share of fish in total con-
sumption of animal protein.

high (> 20%)
medium high
(betw. 10 and 20%)
medium
(betw. 5.6 and 10%)
low (< 5.6%)
no data

Fig. 13c
Per capita GDP in USD.

high (> 26,932)
medium high
(betw. 11,360 and 26,932)
medium
(betw. 4,133 and 11,360)
low (< 4,133)
no data

Fig. 13d
Share of undernourishment
in population.

high
medium high
low
no data

8 poorest countries	Fish depend-ence
Liberia	medium
Malawi	high
Niger	low
Central African Republic	medium
Mozambique	high
Ethiopia	low
Guinea	very high
Togo	high

8 countries with the highest share of fish in total animal protein intake	Fish depend-ence
Sri Lanka	very high
Bangladesh	very high
Solomon Islands	very high
Kiribati	very high
Micronesia	very high
Cambodia	very high
Sierra Leone	very high
Maldives	very high

	Per capita GDP (USD)	Prevalence of undernourish-ment (%)	Fish share in animal protein	Catch per person (tons)	Dependence score
	2011	2011-13	2011	2011	
South Africa	12,291	5.0	5.02	0.01	medium
Senegal	2,163	12.3	43.73	0.03	very high
Peru	10,429	9.6	22.28	0.28	high
United States of America	49,804	5.0	7.37	0.02	medium
Indonesia	8,438	9.3	54.82	0.02	very high
Germany	42,080	5.0	7.28	0.00	low
France	37,325	5.0	13.30	0.01	high
China	10,286	11.0	20.56	0.01	high

a very large absolute catch and low consumption (see Tab. 4, page 31). The target countries also include Senegal and Indonesia, where many people are involved in the fishing industry, fish is an essential part of the diet and there is a relatively low level of food security.

As an example showing the complexity of fish dependence, Senegal is considered highly dependent on fish.[10] According to FAO figures, an estimated one million people are directly or indirectly dependent on fish. Fish accounts for 44% of animal protein intake, but only 12% of total protein. With a consumption of, on average, 24 kg of fish per year per head, Senegal 'over-consumes' fish if the WHO recommendation of 11.7 kg is taken as a reference. At 60 g per head per day, protein availability is also above the level needed (the recommended level is 49 g). So, even with a moderate decline in fish intake, there would be no protein gap in Senegal. Nevertheless, 10% of the population is undernourished. In coastal rural areas, the fishery sector is the main source of income (Thiao et al. 2012). However, despite an adequate protein supply, a decline in the fishing sector would likely result in increasing poverty and hunger in Senegal (Lam et al. 2012).

Conclusion:

» Poverty and fish dependence do not necessarily coincide.

» However, poor countries with a comparably large fishing sector have a very high risk of becoming food insecure if fish is lost as an income source.

2.6 Current Fish Consumption and Fish Supply

Since fish consumption and fish supply differ between regions it is interesting to see which regions are able to meet their demand with their own production and which regions depend on imports to meet their demand for fish. Using population and catch data for 64 LMEs, we first calculate to what extent fish landings from the LMEs meet local fish consumption in 2010 for the population living in the respective neighbouring countries.[11] Up to 95% of the annual global fish catch originates from these 64 areas (Sherman et al. 2009). They pose particular challenges for regional, and in some cases, multinational management. We used data from the University of Vancouver's Sea Around Us project for these calculations (Sea Around Us-database).
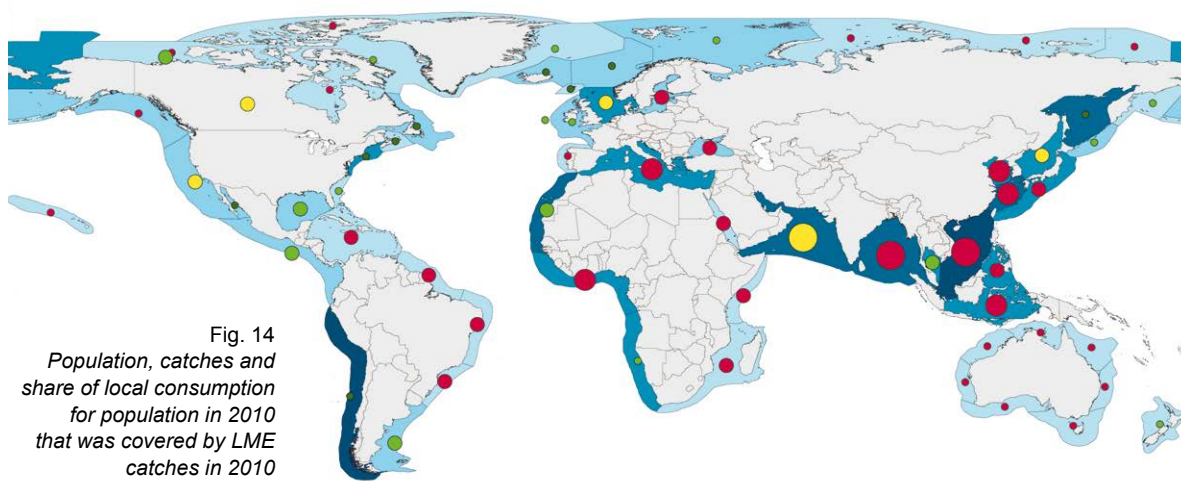

Fig. 14
Population, catches and share of local consumption for population in 2010 that was covered by LME catches in 2010
Source: Sea Around Us database/own mapping.

Pop. 2010 Scenario (mn)

- ● > 50
- ● 50–150
- ● 150–500
- ● 500–1,000

Fraction
- ■ 0–80%
- ■ 80–100%
- ■ 100–500%
- ■ > 500%

Catches (mn tons)
- □ Keine Daten
- ■ 0.01 – 0.60
- ■ 0.61 – 1.50
- ■ 1.51 – 4.00
- ■ 4.01 – 8.00
- ■ 8.01 – 12.86

The regions depicted in Figure 14 refer to LMEs. Data on catches per LME in 2010 is taken from the Sea Around Us database. Data on population per country in 2010 is taken from the IPCC Shared Socioeconomic Pathways Scenario 1. Fish consumption per capita and country in 2010 is taken from the FAOStat database. (Important: According to the FAO, fish consumption includes all kinds of fish and seafood products including aquaculture and inland fisheries products while, according to Sea Around Us, the catches only cover marine fish and seafood in the LMEs. High seas catches are not included in our model. Land-locked countries are not included.)

Figure 14 shows how LMEs differ in the extent to which local landings are sufficient to meet local needs in terms of fish consumption. LMEs in which landings are not sufficient to meet local fish demand are indicated in red (coverage 0 to 80%) or yellow (coverage of 80 to 100%). LMEs in which landings are more than sufficient to meet local fish demand are indicated in light green (coverage between 100% and 500%). Extremely over-supplied LMEs are able to meet much more than local demand and are indicated in dark green (coverage greater than 500%).

There is a substantial variation: in very Arctic waters, e.g. the Canadian High Arctic, North Greenland, the Beaufort Sea or the Insular Pacific Hawaiian LME, fish production covers less than 1% of local consumption while the Scotian Shelf, Newfoundland-Labrador Shelf, Icelandic Shelf and Sea and the Faroe Plateau stand out with their massive production, which exceeds local needs and leads to coverage of more than 1,000%.

Landings in 9 of the 64 LMEs are much higher than local needs. The north east coast of North America and the northwest coast of Europe, including Iceland and the Faroe Plateau, are characterised by very high catches relative to consumption in the local population. In the remaining 16 LMEs, landings are sufficient to cover local consumption of fish.

Thirty-nine LMEs have landings that are not sufficient to cover local consumption; of these 34 have a fraction of less than 80% and 21 have a fraction below 50%. The weakest LMEs are the areas in the High Arctic, north of Canada and Russia. LMEs around Australia struggle to meet at least half of the local demand.

The ratio of landings to local needs for all LMEs considered is 82%. This means that 82% of the aggregated fish consumption in all LMEs is covered by marine catches from LMEs. So, obviously those catches are not sufficient to satisfy consumption. As mentioned earlier, the catches do not include aquaculture, inland or high seas production. Catches from these sectors probably account for the 18% of fish demand that is not covered by LMEs.

A similar calculation using the WHO recommendation for fish consumption of 11.7 kg per capita per year, instead of the actual fish consumption levels of 2010, lead to a ratio of landings to local needs of 144% for all LMEs considered. This indicates that in 2010 LME catches were sufficient to satisfy the basic needs in terms of fish consumption according to the WHO. However, a redistribution of the resource is required. In this scenario, 39 LMEs are in the under-supplied category while 9 LMEs are in the extremely over-supplied category.

Overall, it seems that LMEs with many bordering countries tend to have a lower potential to meet demand. Examples include the Mediterranean, the Caribbean Sea and the Baltic Sea. In contrast, LMEs with only one or a few coastal countries perform better. Also, LMEs located in the North Atlantic and the East Pacific seem to have a stronger potential to meet local demand. This also holds true for Europe, the east and west coast of the USA and the west coast of Latin and South America. In contrast, LMEs around Africa (North West Africa being the exception) and along the Asian coasts as well as in Australia show a deficit in marine fish production compared to local demand.

In our case studies, only Indonesia and China are facing a clear under-supply in terms of marine catches. However, both countries might find suitable substitutes through their aquaculture production.

Conclusion:

» Catches vary strongly at LME level.

» In approximately two-thirds of all LMEs, the total demand for fish
   in 2010 could not be covered by local marine catches.

» Marine catches can cover 82% of global demand for fish.

» Excess catches are mainly reported for LMEs in the North Atlantic
   and East Pacific.

3.   The Bio-economic Model

We are interested in future global marine catches and effects on consumption levels, specifically focusing on the year 2050. Fish markets are globalised to a very large extent (Smith et al. 2010; Asche et al. 2015). Global markets allocate worldwide catches so that they equal total demand for both human consumption and animal feed. Global catches are determined by the fishing effort applied and the productivity of the fish stocks. Thus, an assessment of potential future catches requires a bio-economic modelling approach that combines the ecological approach describing productivity of fish stocks with the economic part describing the economic incentives to exerting fishing effort and markets that allocate fish catches to different consumers. The literature suggests that the efficiency of fishery management plays a central role in this respect (Costello et al. 2008; Quaas et al. 2016).

The model is designed to tell us how the overall size of the fish catches changes under different economic and fishery management scenarios and how the total global catch is allocated in terms of regional catches and regional consumption quantities. To address these questions, we use a nested modelling approach. Here we briefly sketch the modelling approach; details are given in the technical appendix.[12]

3.1 The Model Approach

Questions 1 and 2 are addressed in a global model that separates predatory and prey fisheries using Lotka-Volterra stock dynamics. With this model approach we take biological interaction into account. The model assumes that the change in biomass over time depends on the natural growth of a stock, the interaction between predator and prey and fishing activities. The predator has a negative impact on the prey biomass, meaning that if the predator stock increases, the prey stock will decrease because the predator feeds on prey. On the other hand, if the prey stock increases, the predator stock will also increase. Hence, the prey stock has a positive impact on the predator's biomass. Fishing activities are influenced by the demand parameter and reduce the change of a stock over time. Available studies investigating a similar research question at the global level have so far not taken into account such ecological interactions and lumped all fish into one aggregate surplus production model (World Bank 2009), or considered several biologically independent stocks (Quaas et al. 2016; Costello et al. 2016).

Furthermore, we look into the interactions of predatory and prey fisheries on the global fish markets, as well as into the interaction between fish and non-fish protein food, by means of a stylised consumer demand system, where different types of fish and non-fish protein food are imperfect substitutes (Anderson 1985; Quaas and Requate 2013). Besides predatory fish and forage fish, we consider protein-rich non-fish food, including beans, dairy products, eggs, lentils, peas, maize, meat, nuts and rice.

Questions 1 and 3 are addressed in a regionalised model where each large marine ecosystem hosts one individual fish stock. In this model we abstract from ecological interactions between the stocks and consider a generalised Schaefer surplus production model for each LME, but include economic interactions that are mediated by the global fish market. Thus, we do not differentiate between predator and prey but assume that all fish in one LME can be seen as one stock.

The change of biomass over time is determined by the natural growth of a stock and the fishing activity. Again, fish production is affected by the LME-specific demand parameters for fish goods. As fish is a traded commodity on a worldwide market, demand in one region of the world will affect the production in another region: a higher world-market price makes it more attractive to exert fishing effort. In our regional demand model we consider regional consumption of three commodities at the LME level: domestically produced fish, imported fish and protein-rich non-fish substitution goods, again including beans, dairy products, eggs, lentils, peas, maize, meat, nuts and rice.

3.2 Data and Estimation of Model Parameters

We use data from three main sources for the estimating parameters of the bio-economic fishery models:

» Sea Around Us (www.seaaroundus.org),

» FAO database FAOStat (http://faostat3.fao.org/home/E) and

» FAO Fisheries and Aquaculture Department's database FishStatJ (http://www.fao.org/fishery/statistics/software/fishstatj/en).

Fig. 15
Large marine ecosystems considered in this study.

Data on catches and landed values of fish is taken from the Sea Around Us database. From this database we use time series of catches and landed values from 1950 to 2010 for 64 LMEs (see Figure 15).
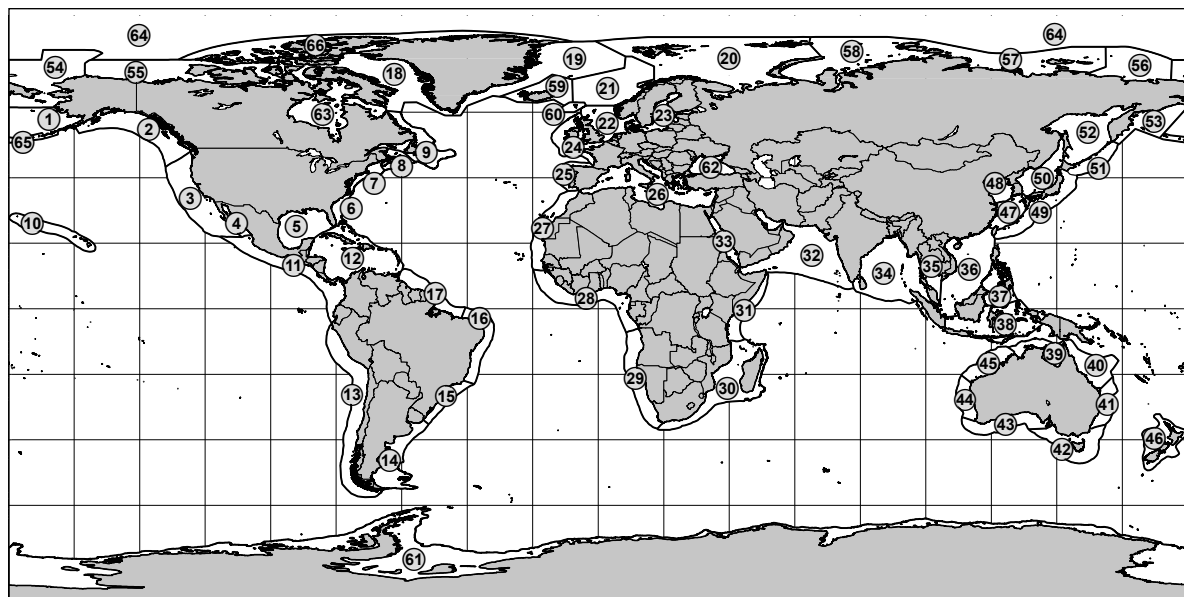
1. East Bering Sea	15. South Brazil Shelf	28. Guinea Current	42. Southeast Australian Shelf	55. Beaufort Sea
2. Gulf of Alaska	16. East Brazil Shelf	29. Benguela Current	43. Southwest Australian Shelf	56. East Siberian Sea
3. California Current	17. North Brazil Shelf	30. Agulhas Current	44. West-Central Australian Shelf	57. Laptev Sea
4. Gulf of California	18. Canadian Eastern Arctic -	31. Somali Coastal Current	45. Northwest Australian Shelf	58. Kara Sea
5. Gulf of Mexico	West Greenland	32. Arabian Sea	46. New Zealand Shelf	59. Iceland Shelf and Sea
6. Southeast U.S. Continental Shelf	19. Greenland Sea	33. Red Sea	47. East China Sea	60. Faroe Plateau
7. Northeast U.S. Continental Shelf	20. Barents Sea	34. Bay of Bengal	48. Yellow Sea	61. Antarctic
8. Scotian Shelf	21. Norwegian Sea	35. Gulf of Thailand	49. Kuroshio Current	62. Black Sea
9. Newfoundland-Labrador Shelf	22. North Sea	36. South China Sea	50. Sea of Japan/East Sea	63. Hudson Bay Complex
10. Insular Pacific-Hawaiian	23. Baltic Sea	37. Sulu-Celebes Sea	51. Oyashio Current	64. Central Arctic Ocean
11. Pacific Central-American	24. Celtic-Biscay Shelf	38. Indonesian Sea	52. Sea of Okhotsk	65. Aleutian Islands
12. Caribbean Sea	25. Iberian Coastal	39. North Australian Shelf	53. West Bering Sea	66. Canadian High Arctic-
13. Humboldt Current	26. Mediterranean	40. Northeast Australian Shelf	54. Northern Bering-	North Greenland
14. Patagonian Shelf	27. Canary Current	41. East-Central Australian Shelf	Chukchi Seas	

The Sea Around Us database includes differentiated data on catches, landings and estimated discards of large-scale, small-scale, subsistence and recreational fishery. The data in the Sea Around Us database combines reported values from the FAO and additional unreported data estimated by Sea Around Us. Additional information on missing data was collected for this estimate (Pauly and Zeller 2015). The main sources were governmental websites and publications, statistical agencies responsible for the fishing industry, international research organisations such as the FAO, the International Council for the Exploration of the Seas (ICES) or regional fisheries management organisations such as the Northwest Atlantic Fisheries Organization (NAFO) as well as academic literature. Based on this information, anchor-points in time are derived and used for interpolation. A linear interpolation between anchor-points is used to reconstruct commercial catches. Either population trends or trends in the number of fishers over time are used to interpolate between anchor points for non-commercial catches from subsistence and recreational fisheries. The reconstructed catches are then combined with the reported FAO data.

The Sea Around Us catch data is disaggregated into catches by species, functional groups and size groups of 0-30, 30-89 and >89 cm average length. We use this information to group the catches into predator and prey categories. We take a size-based approach and consider large fish to be most likely predatory and small fish to be most likely forage fish. Specifically, we consider all fish greater than 90 cm to be predatory while fish smaller than 90 cm and invertebrates are considered to be prey. In the global predator-prey model and the global demand model, the data is aggregated per year over all 64 LMEs, leading to 61 observations each (= number of years from 1950 to 2010) for predator and prey catches. In the fish supply model at LME-level we use total catches per year aggregated over size groups. In this model the data has been aggregated by LME and year. In total, we use a dataset with 3,904 observations.

Figure 16 shows the development in total catches and catches from 1950 to 2010. The amount of total catches peaks in 1996 at 123 million tons. Since then, catches are decreasing. This is in line with Pauly and Zeller (2016) who also calculated the global peak in catches in 1996 at a level of 129 million tons. In contrast to the global data of Pauly and Zeller (2016), we do not include high seas catches, which results in the difference of 6 million tons. In addition, some small island states, such as Wallis and Futuna Islands (France), Saint Helena (UK) or Nauru, are not included because their geographical position does not lie within the area of an LME.

The biological parameters are estimated using the Catch-MSY method developed by Martell and Froese (Martell and Froese 2013). This method allows biological parameters, such as biomass based on catch data, to be estimated. It requires time series of catch data and prior ranges for the parameter values as well as possible ranges of stock sizes from the initial and the final period.

After specifying initial stock sizes and limits for the final stock size, a parameter set is randomly drawn from the prior parameter distribution. Then, the underlying fish supply model is used to calculate the biomass corresponding to the level of harvest given the parameter set. If this biomass is in a reasonable range, the parameter set is stored. In our analysis, we repeat this procedure 10,000,000 times for each LME. We use samples of 1,000 randomly picked accepted parameter values in our model computations to compute mean estimates and confidence intervals. Thus, all results reported below are based on averages and standard deviations obtained from 1,000 separate model runs.

Fig. 16
Development of global total
catches and predatory/prey
catches from 1950 to 2010.
(in million tons)
Source: SeaAroundUs

— Total
— Prey
— Predator
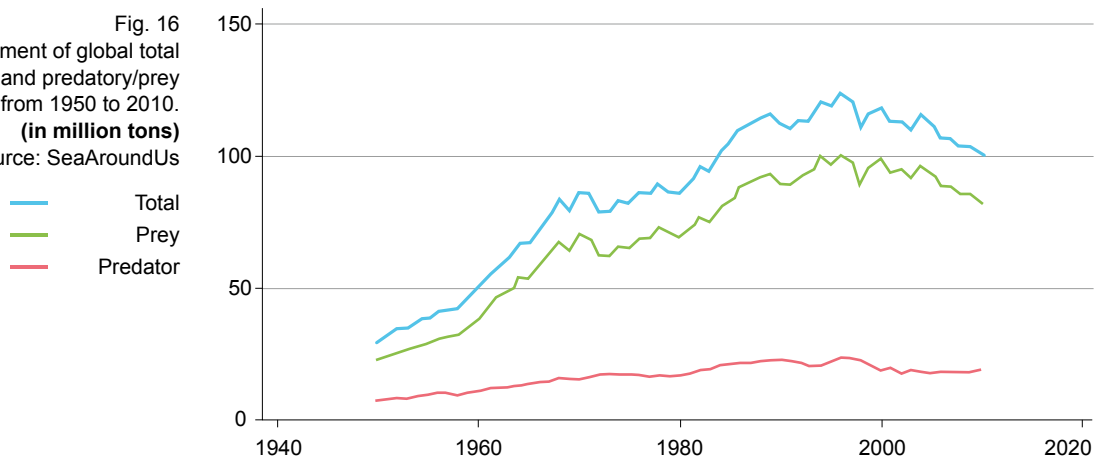
We use the above-mentioned approach by Martell and Froese with a Schaefer
surplus production model for each LME and for one global stock of aggregated
fish. In the global predator-prey model we extend the approach by Martell and
Froese and determine parameter values for a Lotka-Volterra predator-prey
model (Hannesson 1983). In each case, initial parameter sets are randomly
drawn from a uniform distribution to be tested. Economic theory predicts a
positive relationship between fish stock biomass and market supply of fish (or
no relationship at all in the case of a pure schooling fishery), and thus a negative
relationship between stock biomass and the fish price. We use price data in
each run for a tested parameter[13] set to check whether this requirement is met.
Biological parameters that do not pass this test are rejected. Otherwise, we use
the resulting information on the relationship between price and stock biomass to
obtain an estimate for economic parameter values.

3.3 Global and Regional Demand Systems

To quantify the demand systems, we use data on fish prices from Sea Around Us.
The data on landed values is used to derive prices. The ex-vessel fish prices, used
to calculate the landed values, are derived using two approaches. Local ex-vessel
prices, converted to US dollars, form the starting point. These are combined with
ex-vessel prices calculated from reported landed values and catches.

Real prices are determined by deflation using the consumer price index of 2005
(Sumaila et al. 2015). We use this price data for the calculation of production
values in the global demand model. Figure 17 shows the development of ex-vessel
prices over time for predator and prey fish. Since prey also include valuable in-
vertebrates such as shrimp, lobster or sea urchins, the prey price does not deviate
much from the predator price.

In addition to fish production quantities and fish prices, the global demand model
also requires data on total expenditures and consumption levels for the three
commodities: predatory fish, prey fish and non-fish protein-rich substitution
goods. Total national expenditures are calculated from production, export and
import values, while national consumption is calculated from production, export
and import quantities (see Fig. 19).

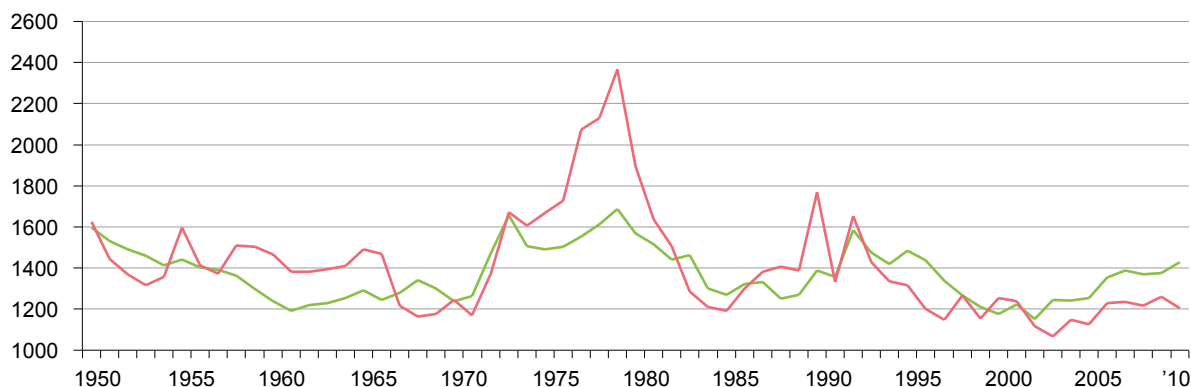Data on substitution goods is taken from the FAO Statistics division, with a

Fig. 17
Global real ex-vessel price
per year in 2005
(in USD per ton).
Source: Sea Around Us/
Own graphic

——— Prey
——— Predator

time series running from 1961 to 2013. Collection of the data is restricted by the availability of both trade and production data and the length of the corresponding time series. Considering all these limitations, the following commodities are included in the group of substitution goods: beans, dairy products, eggs, lentils, peas, maize, meat, nuts and rice.[14]

The global demand model reflects total global production (quantity in tons), global export price (per ton in current USD) and global export value (in current USD) for the above-mentioned commodities. In contrast to this, the demand model at LME-level does not require data on predatory fish and prey fish, but on domestically produced fish and imported fish.

We use the FAO database to provide data on total national domestic production (quantity in tons), exports (quantity in tons, value in current USD) and imports (quantity in tons, value in current USD) from 1976 to 2010. The FAO FishstatJ database does not contain information on production values for fish goods hence we calculate the production value as the product of production quantities and export prices. Export (import) prices for fish as well as for substitution goods are calculated by dividing export (import) values by the corresponding quantities.

Sea Around Us only provides deflated landed values (real prices) of predatory and forage fish and is hence not comparable to the nominal FAO price data for non-fish substitution goods. For this reason, data on global export values and global export quantities of fish is also taken from the FAO FishStatJ database for the period from 1976 to 2010. Global nominal export prices per ton are calculated using this data. The FAO FishstatJ database does not differentiate between forage and predatory fish. For this reason, we were not able to calculate the price for these two types of fish separately. Instead, a common global export price per year for

Fig. 18
Global expenditure per
year **(in billion USD
from 1976 to 2010)**.
*Source: FAO FishstatJ/
Own graphic*
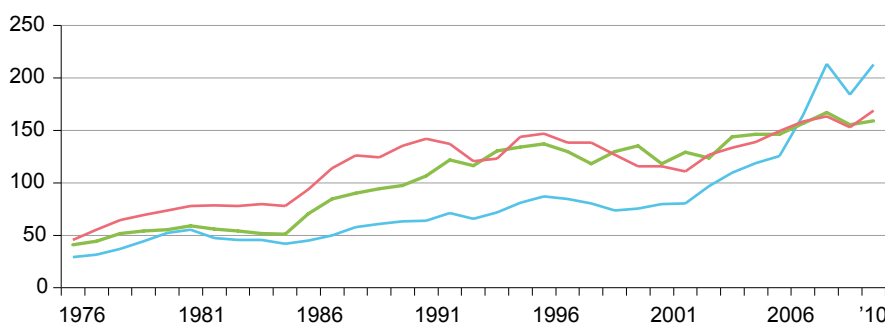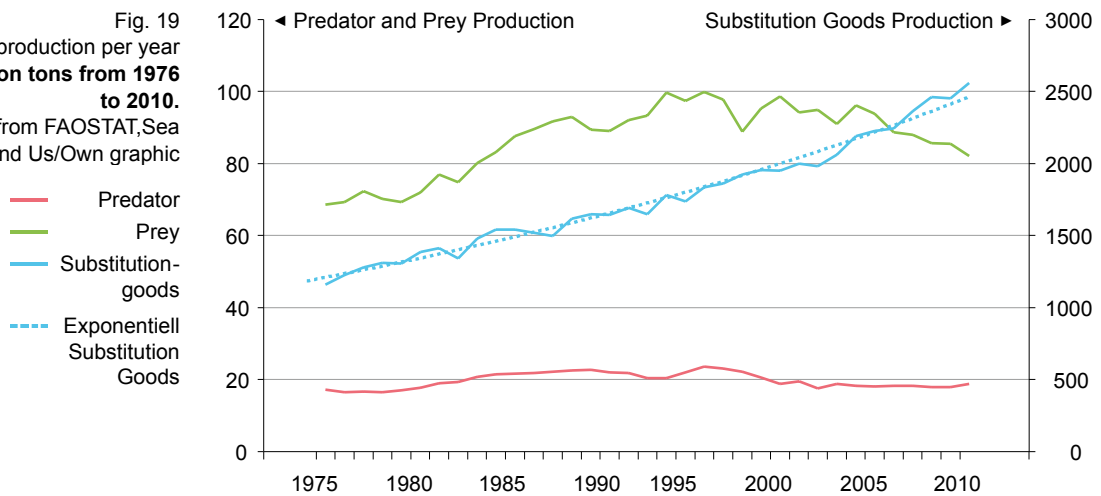
——— Predator
——— Prey
——— Substitution-
goods

both types of fish is calculated. Furthermore, both wild-caught fish and fish from aquaculture are included in the FishstatJ database. Since we calculate a global price for all fish commodities in this database, this price does not differ between wild-caught fish and fish from aquaculture either. Hence, the information entered into our database from these two sources relates to:

» total global marine catches of predatory and forage fish (in tons),

» the global export value of predatory and forage fish (in current USD),

» the global export price for fish (per ton in current USD).

Finally, total national expenditures are calculated as the sum of production and import values minus export value.

National consumption is calculated as the sum of domestic production and imports minus exports. For some observations, the resulting value for consumption is negative. In these cases, we set the negative values equal to zero.

We assume one global consumer who has preferences regarding the quantities of each commodity she consumes. We further assume that the consumer prefers to substitute fish with another species of fish rather than with non-fish substitute goods.

To calculate global demand for a) predatory fish, b) forage fish and c) protein-rich non-fish substitute goods, we use the following yearly input data at global level: export prices, production quantities, total expenditures for all three commodities and a parameter that expresses the above-mentioned preferences of our consumer. With the given information on predatory and forage fish and substitute goods, we estimate the demand parameters for each commodity for each year from 1976 to 2010. The demand parameters indicate the estimated share each commodity has in the consumption of protein-rich food.

For the projections of global fish demand in 2050, we then calculate the mean of these demand parameters over time per LME and commodity. To match catch data from Sea Around Us at LME level with FAO country data, we estimated each country's share in a particular LME based on the spatial overlap of the country's coastal waters with the LME. Some countries included in the FAO data do not

have coastal waters in any LME, either because they are landlocked or because there is no LME defined in their coastal waters. We remove countries without access from our dataset.[15]

Some countries have coastal waters in more than one LME. For these countries we assumed that the fraction of trade and production associated with an LME is equal to the fraction of the country's area of coastal waters in the corresponding LME. The shares are calculated using GIS software and information on the area of exclusive economic zones (EEZs) and LMEs.

Estimating regional consumption requires the aggregation of all input data (domestic production quantities, etc.) at LME level. With regard to the regions, we group input data by the 64 LMEs provided by Sea Around Us. In each LME, the consumer has preferences regarding the quantities of each commodity she consumes. We assume that each LME's consumer prefers to substitute fish with another species of fish rather than with a non-fish substitute good and that she differentiates between imported and domestically produced fish.

To calculate regional demand for a) imported fish, b) domestically produced fish and c) protein-rich non-fish substitute goods, we use the following yearly regional level input data: export prices, import prices, domestic production quantities, imported production quantities, total expenditures for all three commodities and two parameters that express the above-mentioned preferences per LME.

Using this information, we estimate the demand parameters for each good and each year from 1976 to 2010. The demand parameters specify the estimated share of each of the three goods in the total consumption of protein-rich foods. To project the demand for fish in 2050, we calculate the average value per LME and per good from the time series of the demand parameters.

## 3.4 Scenarios: Socioeconomic Pathways and Fishery Management

Fish consumption crucially depends on income that consumers in different parts of the world spend on fish and non-fish protein-rich food. It also depends on population numbers.

With regard to income and population numbers, we base our scenarios on GDP development data from the International Institute for Applied Systems Analysis (IIASA) quantification of the Intergovernmental Panel on Climate Change (IPCC): so called 'shared socioeconomic pathways' (SSPs) describing world futures in the 21st century.[16] Five SSPs describe five scenarios of global future societal development. These SSPs are one component of the IPCC scenarios integrating future changes in climate and society to investigate climate impacts and options for mitigation and adaptation (O'Neill et al. 2015). Among those, SSP1 is deemed to describe sustainable development. We use SSP1 for our baseline scenario.

Figure 20 shows the projection of GDP in each of the scenarios. In order to cover the range of future GDP we also used scenarios SSP3 (minimum GDP scenario) and SSP5 (maximum GDP scenario).

For the base case of the SSP1 scenario, global GDP increases by a factor of 3.757. The income elasticity of demand for food is the parameter that determines what

Fig. 20
Development of global
GDP from 2010 to 2050
for IPCC scenarios SSP1,
SSP3 and SSP5.
(in trillion USD)

— SSP1
— SSP3
— SSP5
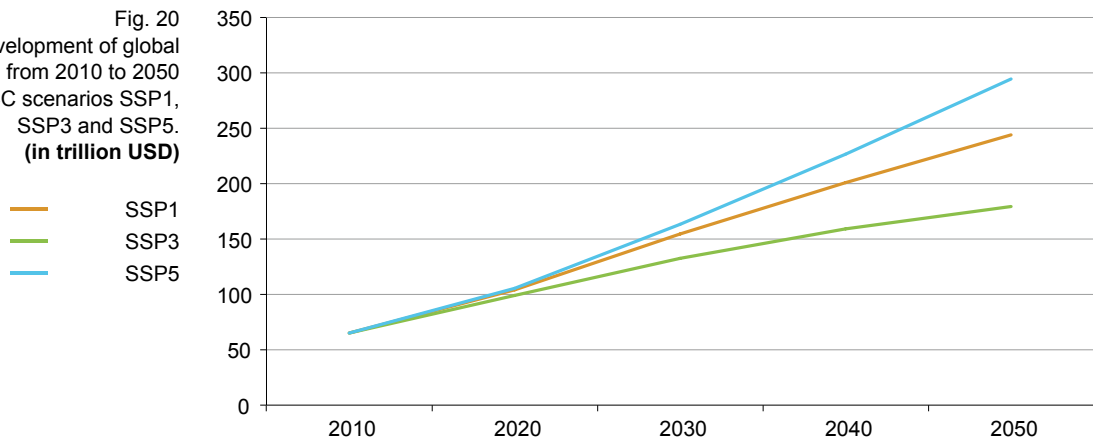
fraction of additional income will be spent on food by 2050. The review by Cireira and Masset (2010) indicates that, while the income elasticity of fish demand is close to 1, the best global estimate for the income elasticity of food demand is 0.48.

For the base case, we assume that global expenditures for fish and non-fish protein-rich food increase by a factor of 0.48 x 3.757. In addition, we consider a very conservative scenario (SSP3) where food expenditures increase by a factor of 0.48 x 2.758 and no further technical progress is made in fishing technology; and a high-pressure scenario (SSP5) where global food demand increases by a factor of 4.534 and income elasticity is 1, which may be adequate for fish as well (Cireira and Masset 2010).

The corresponding population development is depicted in Figure 21. To calculate future fish demand, we will use the scenarios SSP1 and SSP3 in order to cover the range of possible population numbers in 2050. While SSP1 assumes the smallest population level in 2050 (8.5 billion) with a population increase factor of 1.23, SPP3 refers to the biggest population level in 2050, namely 9.95 billion with a population increase factor of 1.45.

With regard to the supply of non-fish protein-rich food, we estimate the trend between 1976 and 2010, which was characterised by an annual growth rate of 2.09%. In all scenarios we assume that this growth rate can be sustained until

Fig. 21
Development of the global
population from 2010 to
2050 in the IPCC scenarios
SSP1, SSP3 and SSP5.
(in billion people)

— SSP1
— SSP3
— SSP5
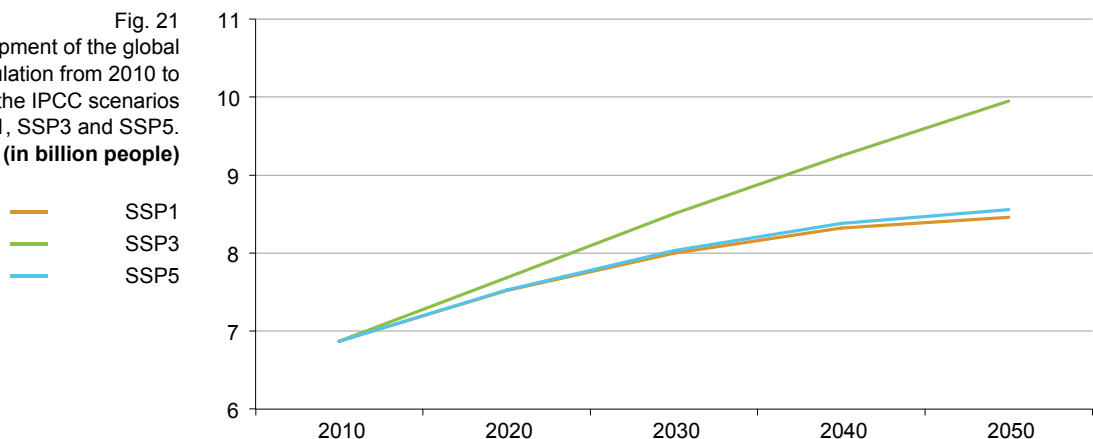
2050. The economic parameters estimate gives an estimate of the improvement in fishing technology and corresponding reduction in fishing cost by 2.4% per year for predator fisheries and 1.1% per year for prey fisheries on average. This is in line with previous findings in the literature (Squires and Vestergaard 2013). We also assume that this trend will persist until 2050, except in our most conservative scenario in which we assume that there will be no further technical progress.
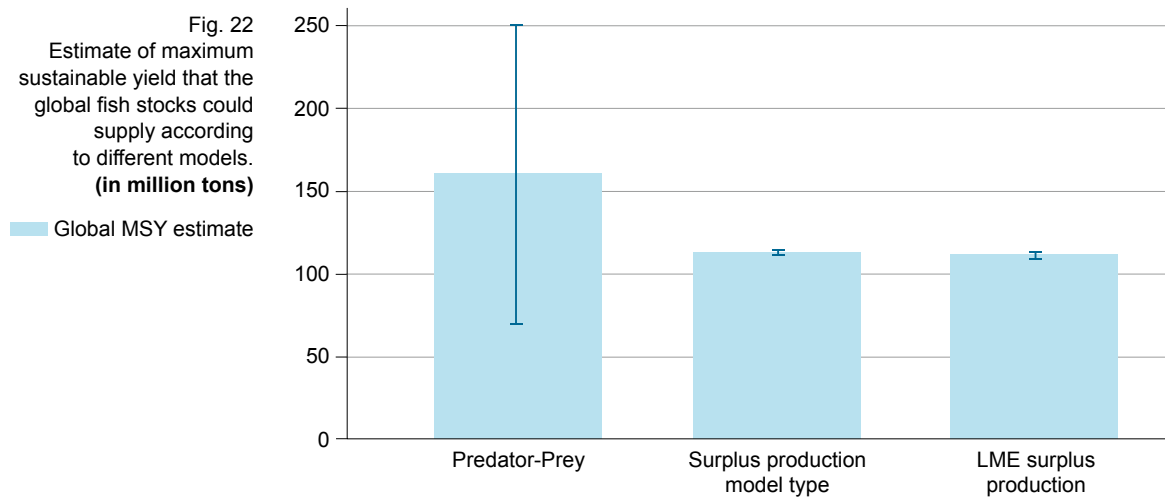
Fishery management may have a very important effect on future stock development and catches (Froese and Proelß 2010; Quaas et al. 2016; Costello et al. 2016). We consider different scenarios with respect to management effectiveness. One such scenario is that all fisheries will be managed according to the maximum sustainable yield, i.e. in such a way that the long-term catches in tons are maximised (Froese and Proelß 2010).

Furthermore, we consider different scenarios where fishing effort is managed by means of total allowable catches and effort regulations (Grafton et al. 2005). In our modelling approach, we follow Quaas et al. (2016) and conceptualise management effectiveness as the fraction of external costs of fishing that are internalised in the fishermen's decisions with regard to their catch effort. Such external costs arise if individual fishermen do not fully take into account the effects of fishing on future fishing opportunities. Economically optimal management would set the total allowable catch (TAC) so that 100% of external costs of fishing are taken into account and fisheries are regulated. No management at all would correspond to open access conditions and 0% of the external costs of fishing would be taken into account. We quantify management effectiveness based on Mora et al. (2009). We consider the case of perfect management (management effectiveness at 100%) and eight cases of imperfect management (management effectiveness from 20% to 90%, respectively). We neglect costs of management, e.g. for monitoring and enforcement, throughout the analysis.

4. Results and Discussion

The following section presents model output regarding fish supply and fish demand in 2050 based on the global demand model and the global predator-prey model.

We assume maximum sustainable yield management for all fisheries. This allows us to answer the question of the extent to which the fish stocks in the global oceans could contribute to the supply of protein for the world population in 2050. Based on the global predator-prey model, the global surplus production model and aggregated results from the regional model, we present estimates of the maximum sustainable yield (MSY) that the global fish stocks could supply. Figure 22 shows the estimates for the three models; Table 5 shows the corresponding figures:

Fig. 22
Estimate of maximum sustainable yield that the global fish stocks could supply according to different models.
(in million tons)

Global MSY estimate

The first bar shows the global catch quantity for a predator-prey model; the second and third bars show the maximum catch for Schaefer surplus models. In the second model, one global stock is assumed for the entire sea; the third model represents the total maximum sustainable yields from 64 LMEs each of which has one stock. In this third model, we analyse the potential contribution of the LMEs to meet global and regional needs for fish protein.

The diagram indicates that the global MSY is 112 million tons in the Schaefer surplus model. We calculate that total global catches reached 101 million tons in 2010.[17] This means that marine resources are already almost fully exploited, which does not leave much space for an increase in catches in the future.

Tab. 5
Mean catches in 2050 according to three model specifications.

	Mean catch (million tons)	Standard deviation (million tons)
Yield-oriented, global predator-prey	160	91
Global surplus production (global Schaefer model)	112	1
Aggregate of regional surplus production model (64 LMEs)	111	3

The global MSY estimate for the predatory-prey model is much larger – almost 160 million tons. If the management strategy focuses exclusively on yield, the total global catch could therefore be substantially higher. A growing global population coupled with a rising demand for protein-rich food like fish could justify a management strategy that is focused on maximising biomass. However, in doing this, all other conservations objectives of a sustainable fishing industry (ecological effects, ecosystem-related effects, socioeconomic consequences) would have to be disregarded. A high maximum catch also comes with much higher uncertainty. This is in line with studies showing that the stability of ecosystems declines sharply if predatory populations are disproportionately reduced (Britten et al. 2014; Essington et al. 2015).

Next, we analyse how global catches depend on the management effectiveness for the three scenarios in the global bio-economic predator-prey model. Figure 23 shows the global catches in 2050 for the demand scenario based on the reference scenario with GDP increase from SSP1 and an income elasticity of food demand of 0.48.

In a scenario where there is perfect management (100% effectiveness), global catches of predatory fish and prey fish reach levels of 21 and 116 million tons, re-spectively. Together, this totals 137 million tons, significantly above current yields (Figure 23). The current level of fishery management effectiveness, however, averages out at about 50-60% (Mora et al. 2009; Watson et al. 2009; Quaas et al. 2016). If it remains at this level, global catch yields in 2050 would be only slightly above the current level. Current management does not sufficiently reflect on the species´ interactions. Thus, predatory fish would be heavily fished, which would alleviate predatory pressure on forage fish, enabling slightly higher total catches. Compared to a scenario of perfect management, fish consumption would gradual-ly shift towards smaller and smaller species.

A decrease in management effectiveness to levels below the current status leads to a strong decrease in catches for both predatory and forage fish. Thus, in line with the finding of Quaas et al. (2016), achieving a sufficiently high degree of management effectiveness is essential for sustaining fish catches while global fish demand continues to increase.

For the sake of comparison, we consider the high-pressure scenario with GDP growth based on SSP5 and a unit income elasticity of fish demand. Results are shown in Figure 24. If management was perfect, global catches of predatory fish

Fig. 23
Global fish catches accord-ing to global bio-economic predator-prey model based on varying degrees of management effectiveness (reference scenario, income growth from SSP1). **(in million tons)**

Global catches of predatory fish
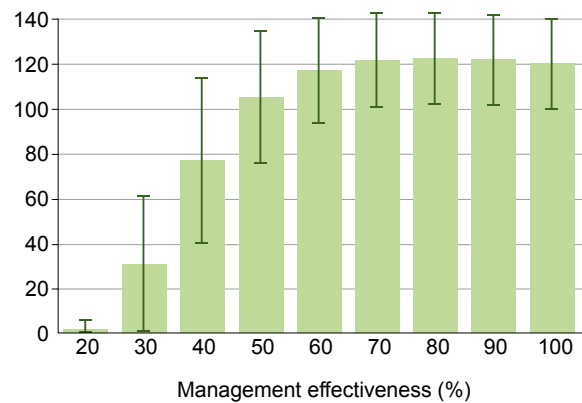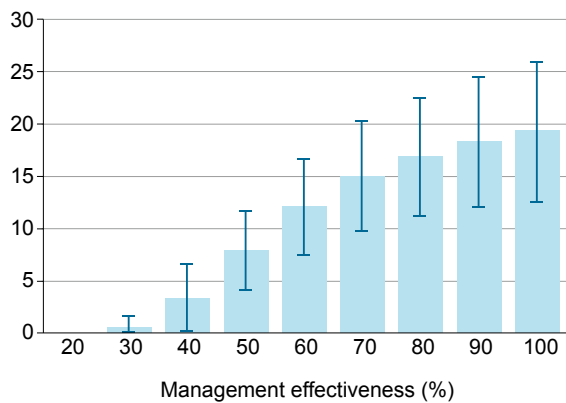
Global catches of prey fish
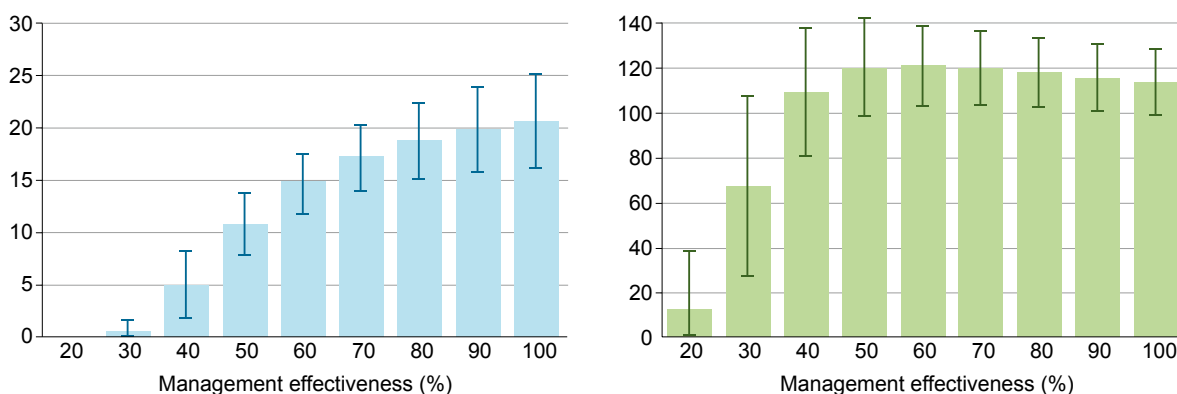
Fig. 24
Global fish catches according to global bio-economic predator-prey model based on varying degrees of management effectiveness (high-pressure scenario, income growth from SSP5, unit income elasticity of food demand).
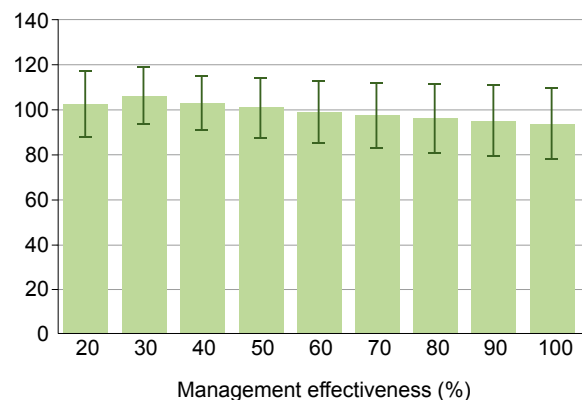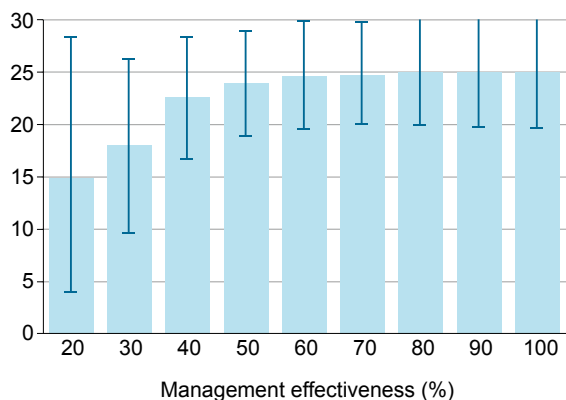**(in million tons)**

Fig. 25
Expected global fish catches according to a global bio-economic predator-prey model based on varying degrees of management effectiveness (low-pressure scenario, income growth from SSP3, no technical progress in fishing).
(in million tons)

■ Global catches
of predatory fish

■ Global catches
of prey fish

and prey fish could be sustained at similar levels as in the reference scenario. However, with decreasing management effectiveness, the catches decrease much more strongly than in the baseline scenario.

Results for the most conservative scenario with demand growth derived from SSP3, and assuming that there will be no further technical progress in fishing, are shown in Figure 25. In this case, fish catches could be sustained even if management did not improve compared to current levels. However, the assumptions made here are not very realistic: in particular, the trend of improving fishing technology is likely to continue in the coming decades, which would lead to strongly increased fishing pressure. Nevertheless, this scenario shows that economic driving forces, in particular increasing demand and technical progress in fishing technology, are central factors influencing the future fate of fisheries.

In the last step we analyse how the LMEs within the global ocean can contribute to meeting the needs of fish protein intake around the globe. To do this, we use the MSY estimates for the different LMEs and compare them with regional fish consumption, based on FAO data for fish consumption in 2010 and the population in 2050 assumed from the two scenarios used (SSP1 and SSP3). These scenarios refer to the extremes in population development with SSP1 referring to the smallest projected population in 2050 and SSP3 referring to the largest projected population among the five scenarios.

The results are depicted in Figure 26 and Figure 27. The LMEs are again colour-coded according to their potential to meet local needs. The red and yellow
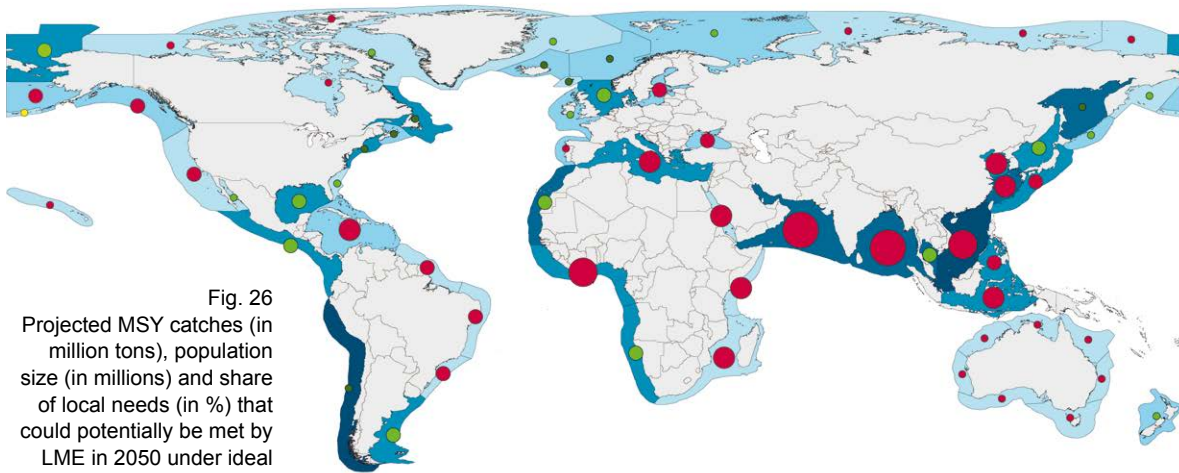
Fig. 26
Projected MSY catches (in million tons), population size (in millions) and share of local needs (in %) that could potentially be met by LME in 2050 under ideal conditions and population development according to SSP1 scenario.
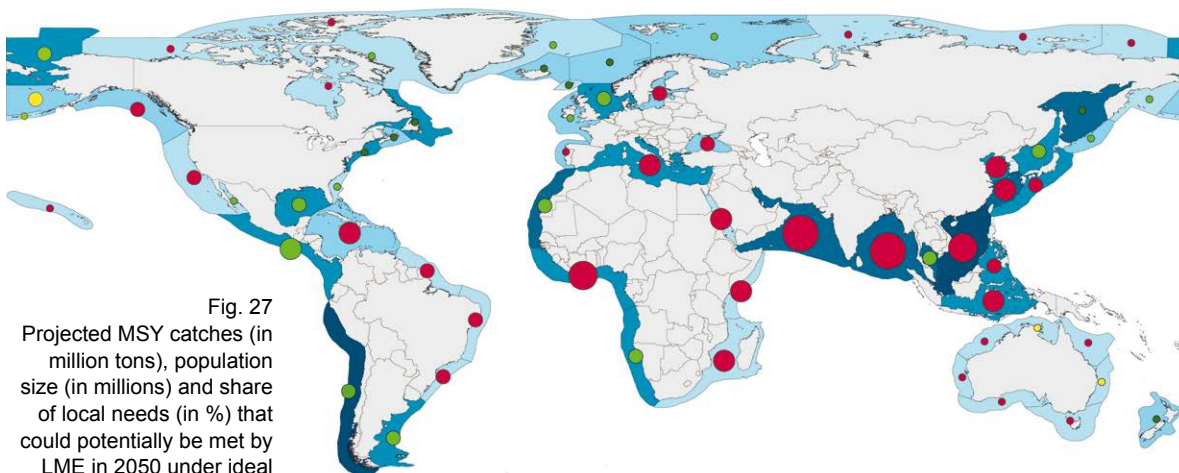

Fig. 27
Projected MSY catches (in million tons), population size (in millions) and share of local needs (in %) that could potentially be met by LME in 2050 under ideal conditions and population development according to SSP3 scenario.

Pop. 2010 Scenario (mn)
- > 50
- 50−150
- 150−500
- 500−1,000
- > 1,000

Fraction
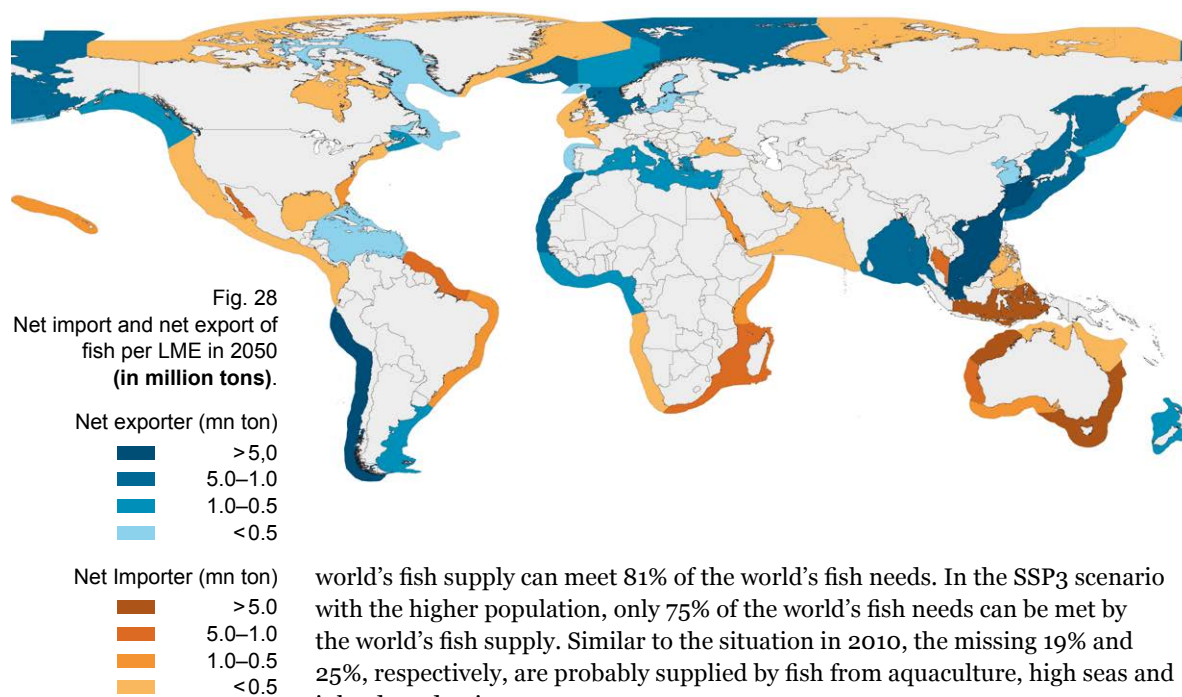- 0−80%
- 80−100%
- 100−500%
- > 500%

Catches (mn tons)
- No Data
- 0.01 − 0.60
- 0.61 − 1.50
- 1.51 − 4.00
- 4.01 − 8.00
- 8.01 −13.15

dots indicate that the LME is not able to meet local needs – not even according to the MSY management scenario assumed here. The green dots indicate that the LME is able to meet more than local needs with MSY management.

Compared to 2010, the results are quite similar. In 2050, 38 LMEs in the SPP1 scenario and 37 LMEs in the SSP3 scenario are not able to meet the needs of the local population. The extremes of 2010 can also be found in the 2050 scenarios. In very Arctic waters, e.g. the Canadian High Arctic, North Greenland or Beaufort Sea or the Insular Pacific Hawaiian LME, fish production meets less than 1% of their demand while the Scotian Shelf, Newfoundland-Labrador Shelf, Icelandic Shelf and Sea and the Faroe Plateau stand out with their massive overproduction, which leads to coverage of more than 1,000%.

However, a few LMEs change their category. The North Sea and the Sea of Japan will probably be able to meet local needs in 2050. In contrast, the Arabian Sea and the California Current are likely to not be able to meet local needs in 2050.

Regarding the world's potential to meet population needs in terms of fish, the scenarios differ. In the SSP1 scenario with the lower population in 2050, the

Fig. 28
Net import and net export of
fish per LME in 2050
(in million tons).

Net exporter (mn ton)
>5,0
5.0–1.0
1.0–0.5
<0.5

Net Importer (mn ton)
>5.0
5.0–1.0
1.0–0.5
<0.5

world's fish supply can meet 81% of the world's fish needs. In the SSP3 scenario
with the higher population, only 75% of the world's fish needs can be met by
the world's fish supply. Similar to the situation in 2010, the missing 19% and
25%, respectively, are probably supplied by fish from aquaculture, high seas and
inland production.

In the SSP1 scenario with the slow population development, 28 LMEs experience
a decrease of more than 10% in their share of MSY catches and local needs. The
average decrease in these LMEs is 25%. In 20 LMEs the share increases by more
than 10% with an average increase of 37%. Overall, decreases and increases seem
to level out since the world's share only decreases by 1%.

In the SSP3 scenario with the strong population development, the share reduces
by more than 10% in 19 LMEs. The average decrease in these 19 LMEs is 35%.
In contrast, 28 LMEs experience an increase in their share by more than 10%.
On average, the increase is 43%. However, since the world's share shows a clear
decrease from 82% in 2010 to 75% in 2050, it seems that although more LMEs
will probably face a stronger deficit in fish supply in the SSP1 scenario, this total
deficit will be bigger in the scenario with the higher population.

Overall, Figure 26 and Figure 27 clearly show that the world's future fish needs
will probably not be met by marine catches alone. Aquaculture will be required as
well, with the caveat that some aquaculture production uses wild captured fish as
well (Essington et al. 2015).

In order to find out which LMEs are likely to export fish products and which
LMEs are likely to depend on imports in the future, we calculate net import
and export quantities per LME in 2050 from estimates of the demand model at
LME-level. The distribution is shown in Figure 28.

Figure 29 and Figure 30 show the absolute deviation of fish consumption between
2010 and 2050 for all LMEs. The LMEs in Figure 29 experience a decrease in fish
consumption in 2050 compared to 2010 while Figure shows the LMEs where fish
consumption will increase.

According to Figure 29, waters along the East Asian coast will experience the
biggest decrease in fish consumption by 2050 although these areas struggle to

meet local demand with local supply (see Figure 26 and Figure 27). Since LMEs interact on a global market, price levels for fish and substitution goods will influence people´s decision on whether they will consume fish or turn to a substitute instead. If fish prices are sufficiently high, fish will become an unaffordable good for a substantial share of the population in the LMEs along the East Asian coast. These people will turn to the more affordable substitution goods and fish is going to be exported for the higher export price. This might explain the leading position of East Asian LMEs among the net exporters.

Fig. 29
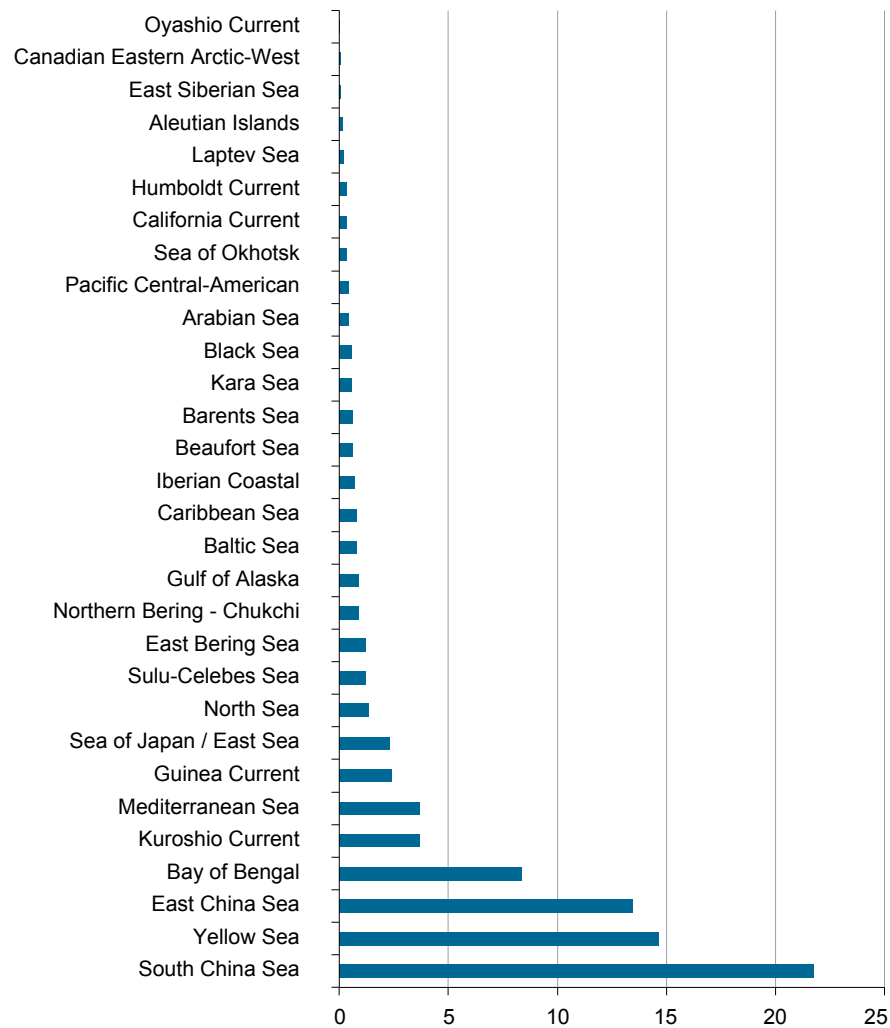LMEs with decreasing fish consumption between 2010 and 2050
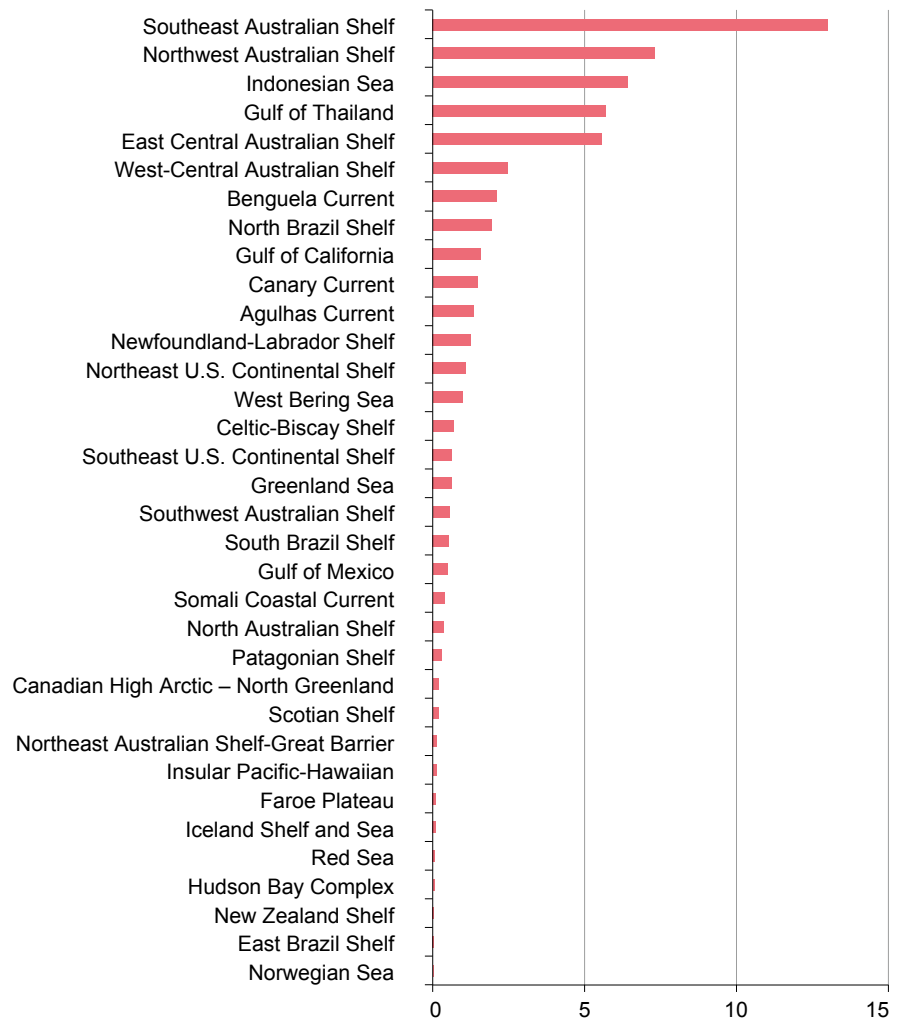**(in million tons)**.

Fig. 30
LMEs with increasing
fish consumption between
2010 and 2050
(in million tons).

LME	Value
Southeast Australian Shelf	13
Northwest Australian Shelf	7.3
Indonesian Sea	6.5
Gulf of Thailand	5.7
East Central Australian Shelf	5.6
West-Central Australian Shelf	2.4
Benguela Current	2.0
North Brazil Shelf	1.9
Gulf of California	1.5
Canary Current	1.4
Agulhas Current	1.3
Newfoundland-Labrador Shelf	1.2
Northeast U.S. Continental Shelf	1.0
West Bering Sea	0.9
Celtic-Biscay Shelf	0.6
Southeast U.S. Continental Shelf	0.6
Greenland Sea	0.6
Southwest Australian Shelf	0.5
South Brazil Shelf	0.5
Gulf of Mexico	0.4
Somali Coastal Current	0.4
North Australian Shelf	0.3
Patagonian Shelf	0.2
Canadian High Arctic – North Greenland	0.2
Scotian Shelf	0.2
Northeast Australian Shelf-Great Barrier	0.1
Insular Pacific-Hawaiian	0.1
Faroe Plateau	0.1
Iceland Shelf and Sea	0.1
Red Sea	0.1
Hudson Bay Complex	0.1
New Zealand Shelf	0
East Brazil Shelf	0
Norwegian Sea	0

Appendix

Tab. 6
National recommended
intakes for fish
(based on the WHO's
recommended standards).

	National recommended intake	Recommended quantity (g/week)	Source
United Kingdom	2 portions (140 g each) per week, one of which should be oily	280	Food Standards Agency (2010)[18]
Australia/New Zealand	2-3 servings (150g each)	375	Food Standards Australia New Zealand (2013)[20]
Canada	At least 150g each week	150	Health Canada (2011)[21]
Austria	1-2 portions per week (total 150g)	150	WHO (2003)[22]
Germany	1-2 portions per week	150	
Georgia	12,8-15g fish per day	97	WHO (2003)[23]
Ukraine	20g fish per day	140	WHO (2003)[24]
Estonia	2-3 servings per week (50g each)	150	WHO (2003)[25]
United States of America	8 oz per week	226	http://bit.ly/1nhRps6
Italy	100-240g per week	170	http://bit.ly/294BDQm
France	100-200g per week	150	http://bit.ly/29AcfCm
Ireland	2x per week	200	http://bit.ly/29Anq8D
Norway	2-3x per week	250	http://bit.ly/29KT48J
Denmark	2-3x per week	350 (explicit)	http://bit.ly/29xPV69
Sweden	2-3x per week	250	http://bit.ly/29AVhkg
Iceland	2-3x per week	250	http://bit.ly/29T6jU8
Eastern Mediterranean (Cyprus, Lebanon, Turkey, Greece, Jordan, Syria, Israel, Palestine, Egypt, Libya)	2x per week	180	http://bit.ly/29t25Cn
Malaysia	2-3x per week (200-300g/week)	250	http://bit.ly/29T6leL
Sri Lanka	2-3x per week (fatty fish)	250	http://bit.ly/29t2F30
Barbados	2-3x per week	250	http://bit.ly/1TbViHR
Mexico	2x per week	200	http://bit.ly/29M12LC
Argentina	2-3x per week (75-100 g each)	244	http://bit.ly/1OLY18D

Total:

31 national recommendations		Ø = 204,25	204.25 x 52 = 10.6 kg/capita x year

19) to 25): from Thurstan et al. (2013)

Fish Supply Model

a. Global Predator-Prey Model

We assume a Lotka-Volterra type of predator-prey model (Hannesson 1983) where x refers to the biomass of the predatory species and y to the biomass of the prey species. Changes in biomass over time ($\dot{x}_t$ and $\dot{y}_t$) are defined as

$$\dot{x}_t = r_x x_t - k_x x_t^2 + a x_t y_t - H_t$$
$$\dot{y}_t = r_y y_t - k_y y_t^2 - b x_t y_t - L_t$$

Here, x_t and y_t describe the stock size in year t, r_x and r_y denote the intrinsic growth rates, k_x and k_y capture density-dependence for predator and prey species, respectively, and a and b denote the interaction parameters. An increase in the biomass of prey has a positive impact on the development of the predator's biomass which is why the interaction term $a x_t y_t$ is positive. However, an increase in the biomass of the predator has a negative impact on the development of the prey's biomass which is why the prey's interaction term $b x_t y_t$ is negative. H_t and L_t denote harvest levels for predator and prey species respectively. Thus, the change in biomass is determined by the biological growth of the stock, minus catches, plus or minus the interaction term.

We assume generalised Schaefer harvest production functions,

$$H_t = q x_t^{X_x} E_{xt}$$
$$L_t = d y_t^{X_y} E_{yt}$$

for predator and prey species respectively. Here, c and d denote catchability coefficients and χ_x and χ_y denote the stock elasticities of output, which are allowed to differ from one. E_{xt} and E_{yt} are effort levels directed at predatory and prey fish respectively.

Assuming that the marginal effort costs are constant for both fisheries, and allowing for a trend of declining costs due to technical progress (at rates v_x and v_y) , fishing costs can be written as

$$C_x(H_t, x_t) = exp(c_x - v_x t) x_t^{-X_x} H_t$$
$$C_y(L_t, y_t) = exp(c_y - v_y t) y_t^{-X_x} L_t$$

As discussed in the main text, the biological parameters are estimated using the Catch-MSY method developed by Martell and Froese (Martell and Froese 2013). This method allows biological parameters based on catch data to be estimated. It requires time series of catch data and prior ranges for the parameter values as well as possible ranges of stock sizes from the initial and final period. After specifying initial stock sizes and limits for the final stock size, a parameter set is randomly drawn from the prior parameter distribution. Then, the underlying fish supply model is used to calculate the biomass corresponding to the level of harvest given the parameter set. If this biomass is in a reasonable range, the parameter set is stored. In our analysis, we repeat this procedure 10,000,000 times for each LME. We use samples of 1,000 randomly picked accepted parameter values in our model computations to compute mean estimates and confidence intervals. Thus, all results reported below are based on averages and standard deviations obtained from 1,000 separate model runs each. In the global predator-prey model, we extend the approach by Martell and Froese (2013) and determine parameter values for the Lotka-Volterra predator-prey model. In each case, initial parameter sets to be tested are randomly drawn from a uniform distribution. Biological parameters are accepted if final biomasses fall between a minimum and two-thirds of their equilibrium value without fishing.

Economic theory predicts a positive relationship between fish stock biomass and market supply of fish (or no relationship at all in the case of a pure schooling fishery), and thus a negative relationship between stock biomass and the fish price. We use price data in each run for a tested parameter set to check whether this requirement is met. Specifically, we assume that the open access conditions $p_{Ht} = C_x(H_t, x_t)$ and $p_{Lt} = C_y(L_t, y_t)$ should hold for the period between 1976 and 2000 (Quaas et al. 2012). We use observed prices from Sea Around Us and the stock estimates from the test runs in the Martell/Froese procedure to estimate a log-linearised OLS regression of the open access conditions using the cost functions and including the time trends below. We accept a parameter set if it gives non-negative estimates for both X_x and X_y. Parameter sets that do not pass this test are rejected. Otherwise, we use the resulting information on the relationship between price and stock biomass to obtain an estimate for economic parameter values.

The means and standard deviations for the 1,000 parameter sets used in the computations are given in the table below.

	r_x	r_y	k_x	k_y	a	b	c_x	c_y	v_x	v_y	χ_x	χ_y
Mean	1.44	2.24	0.044	0.0096	0.0046	0.014	49.14	24.27	0.024	0.011	0.24	0.32
Std	0.56	0.74	0.023	0.0062	0.0020	0.0077	10.45	7.82	0.005	0.003	0.20	0.20

	r_x	r_y	k_x	k_y	a	b	c_x	c_y	v_x	v_y	χ_x	χ_y
Mean	1.44	2.24	0.044	0.0096	0.0046	0.014	49.14	24.27	0.024	0.011	0.24	0.32
Std	0.56	0.74	0.023	0.0062	0.0020	0.0077	10.45	7.82	0.005	0.003	0.20	0.20

b. Fish Supply Model at LME-Level

In the total fish supply model, the change of biomass over time is defined as

$$\dot{x}_{lme,t} = r_{lme}x_t - k_{lme}x_{lme,t}^2 - H_{lme,t}$$

$x_{lme,t}$ describes the stock size in the large marine ecosystem *lme* in year t, r_{lme} describes the intrinsic growth rate of the stock, k_{lme} is a measure of density dependence and $H_{lmt,t}$ describes the catches from the LME in year t (Clark 1991). Thus, the change of biomass is the biological growth of a stock minus the catches taken by the fishing industry. In a similar way as for the global predator-prey model, we assume a fishing cost function

$$C_{lme}\left(H_{lme,t}, x_{lme,t}\right) = exp(c_{lme} - v_{lme}t)x_{lme,t}^{-\chi_{lme}}H_{lme,t}$$

All parameter values differ for the 64 LMEs. We use the same approach as for the global predator-prey model for the regionalised model, which yields 64,000 parameter sets for r_{lme}, k_{lme}, c_{lme}, v_{lme}, and χ_{lme}.

Demand Model

a. Global Demand Model

In our global demand model, we consider one representative consumer who has preferences over consumption of three types of protein-rich food, namely non-fish, protein-rich food items (quantity C_t), high-trophic-level predatory fish (quantity H_t), and low-trophic-level forage fish (quantity L_t).

Preferences over these goods as well as numeraire consumption X_t is described by the utility function:

$$U_t = N_t + \frac{E_t\sigma}{\sigma - 1} ln(V_t)$$

with E_t being total expenditures of w for protein-rich food in year t, N_t being numeraire consumption, and V_t being a sub-utility index for protein food consumption, given by (Quaas and Requate 2013; Quaas et al. 2016).

$$V_t = \left[(1 - \eta_H - \eta_L)C_t^{\frac{\sigma-1}{\sigma}} + \eta_H H_t^{\frac{\sigma-1}{\sigma}} + \eta_L L_t^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}$$

Here, σ reflects the elasticity of substitution between different types of food. Following Quaas et al. (2016), we assume $\sigma = 1.7$. The further preference parameters η_H and η_L are estimated using price and quantity data from Sea Around Us and the FAO. Using the yearly prices of non-fish protein-rich food, P_{Ct}, predatory fish, P_{Ht} and forage fish, P_{Lt}, maximisation of the utility with respect to consumption of protein-rich food leads to the following inverse demand functions

$$P_{Ct} = \frac{E_t}{V_t}(1 - \eta_H - \eta_L)C_t^{-\frac{1}{\sigma}}$$

$$P_{Ht} = \frac{E_t}{V_t}\eta_H H_t^{-\frac{1}{\sigma}}$$

$$P_{Lt} = \frac{E_t}{V_t}\eta_L L_t^{-\frac{1}{\sigma}}$$

from which we estimate the demand parameters η_{Ht}, η_{Lt}, using data on H_t, L_t, C_t, P_{Ct}, P_{Ht}, and P_{Lt} for the period 1976 to 2010. This leads to

η_H	0.1554
η_L	0.3675

For expenditures E_t we use the scenarios described in section 2.3. For the consumption of non-fish protein-rich food, we assume that the past trend over the period 1976 to 2010 will continue, with an exponential growth rate of 2.09% per year.

b. Demand Model at LME Level

For the modelling of regional demand we grouped countries at large marine ecosystem (LME) level. We assume that there is a representative consumer for each large marine ecosystem who consumes protein-rich food in each year t, which is composed of a quantity $C_{lme,t}$ of non-fish, protein-rich food items, quantity $F_{lme,t}$ of fish food-items. Preferences are described by the utility function

$$U_{lme,t} = N_{lme,t} + \frac{E_{lme,t}\sigma}{\sigma - 1}\ln(V_{lme,t})$$

$$U_t = N_t + \frac{E_t \sigma}{\sigma - 1} \ln(V_t)$$

As in the global model, $E_{lme,t}$ describes the total expenditures for protein-rich food in year t, $N_{lme,t}$ is numeraire consumption, and $V_{lme,t}$ is a sub-utility index for protein food consumption:

$$V_{lme,t} = \left[\left(1 - \eta_{lme,t}^d - \eta_{lme,t}^i\right) C_{lme}^{\frac{\sigma-1}{\sigma}} + \eta_{lme,t}^d \left(F_{lme,t}^d\right)^{\frac{\sigma-1}{\sigma}} + \eta_{lme,t}^i \left(F_{lme,t}^i\right)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}$$

Here, σ reflects the elasticity of substitution between fish and non-fish protein-rich food. Using the Armington (1969) assumption[1] allows a distinction to be made between domestically produced and imported fish. Again we assume that the elasticity of demand is 1.7 according to Asche et al. (1996) and Quaas and Requate (2013). The demand parameters $\eta_{lme,F}^d$ and $\eta_{lme,F}^i$ measure relative preference for domestic and imported fish. Using the yearly prices of non-fish protein-rich food $P_{C,lme,t}$, domestically produced fish food items $P_{F,lme,t}^d$ and imported fish food items $P_{F,lme,t}^i$, utility maximisation leads to the following inverse demand functions:

$$P_{C,lme,t} = \frac{E_{lme,t}}{V_{lme,t}} \left(1 - \eta_{lme,t}^d - \eta_{lme,t}^i\right) C_{lme,t}^{-\frac{1}{\sigma}}$$

$$P_{F,lme,t}^d = \frac{E_{lme,t}}{V_{lme,t}} \left(F_{lme,t}^d\right)^{-\frac{1}{\sigma}} \eta_{lme,t}^d$$

$$P_{F,lme,t}^i = \frac{E_{lme,t}}{V_{lme,t}} \left(F_{lme,t}^i\right)^{-\frac{1}{\sigma}} \eta_{lme,t}^i$$

With the given information on prices and quantities of domestically produced and imported fish and substitution goods for the period 1976 to 2011, we estimate the preference parameters $\eta_{lme,F}^d$ and $\eta_{lme,F}^i$.

For food consumption expenditures, we use the SSP1 scenario on income growth and an income elasticity of food demand of 0.48 (Cireira and Masset 2010). For the consumption of non-fish protein-rich food, we determine linear trends for each LME based on past observations for the period 1976 to 2010 and assume that they will continue until 2050.

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[1] The Armington assumption is a standard assumption of computable equilibrium models and implies that consumers are assumed to differentiate between goods based on origin, that is whether the good is produced domestically or imported.

List of Large Marine Ecosystems (according to Sea Around Us)

Agulhas Current
Aleutian Islands
Antarctic
Arabian Sea
Baltic Sea
Barents Sea
Bay of Bengal
Beaufort Sea
Benguela Current
Black Sea
California Current
Canadian Eastern Arctic -West Greenland
Canadian High Arctic - North Greenland
Canary Current
Caribbean Sea
Celtic-Biscay Shelf
Central Arctic Ocean (no data available)
East Bering Sea
East Brazil Shelf
East China Sea
East Siberian Sea
East-Central Australian Shelf
Faroe Plateau

Greenland Sea
Guinea Current
Gulf of Alaska
Gulf of California
Gulf of Mexico
Gulf of Thailand
Hudson Bay Complex
Humboldt Current
Iberian Coastal
Iceland Shelf and Sea
Indonesian Sea
Insular Pacific-Hawaiian
Kara Sea
Kuroshio Current
Laptev Sea
Mediterranean Sea
New Zealand Shelf
Newfoundland-Labrador Shelf
North Australian Shelf
North Brazil Shelf
North Sea
Northeast Australian Shelf-Great Barrier Reef
Northeast U.S. Continental Shelf

Northern Bering - Chukchi Seas
Northwest Australian Shelf
Norwegian Sea
Oyashio Current
Pacific Central-American Coastal
Patagonian Shelf
Red Sea
Scotian Shelf
Sea of Japan / East Sea
Sea of Okhotsk
Somali Coastal Current
South Brazil Shelf
South China Sea
Southeast Australian Shelf
Southeast U.S. Continental Shelf
Southwest Australian Shelf
Sulu-Celebes Sea
West Bering Sea
West-Central Australian Shelf
Yellow Sea

List of Protein-Rich Non-Fish Food Substitute Goods (FAOstat Database 2016)

Almonds, shelled
Bambara beans
Beans, dry
Beans, green
Brazil nuts, shelled
Broad beans, horse beans, dry
Butter, cow's milk
Cashew nuts, shelled
Cashew nuts, with shell
Cheese, sheep's milk
Cheese, whole cow's milk
Chestnuts
Chick peas
Coconuts
Cream, fresh
Eggs, hen, in shell
Eggs, other bird, in shell
Ghee, buffalo milk

Groundnuts, shelled
Hazelnuts, shelled
Kola nuts
Lard
Lentils
Maize
Maize, green
Meat, cattle
Meat, chicken
Meat, duck
Meat, game
Meat, goat
Meat, goose and guinea fowl
Meat, horse
Meat, not elsewhere included
Meat, pig
Meat, rabbit
Meat, sheep

Meat, turkey
Milk, skimmed, cow
Milk, skimmed, dried
Milk, whole, condensed
Milk, whole, dried
Milk, whole, evaporated
Milk, whole, fresh, cow
Nuts, not elsewhere included
Nuts, prepared (exc. groundnuts)
Peas, dry
Peas, green
Rice – total (rice milled equivalent)
Soybeans
Walnuts, shelled
Walnuts, with shell
Whey, condensed
Whey, dry
Yoghurt, concentrated or not

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Footnotes

2) WHO technical report series 916: Diet, Nutrition and the Prevention of Chronic Diseases – Report of a Joint WHO/FAO Expert Consultation 2002.

2) Recommendation issued by the German Nutrition Society (DGE): 1 to 2 portions of fish per week. Recommended portion size is approx. 150 g = 225 g per week or 11.7 kg per capita per year. https://www.dge.de/ernaehrungspraxis/vollwertige-ernaehrung/10-regeln-der-dge/

3) SSPs were developed by the climate change research community (e.g. IPCC) in order to simplify the integrated analysis of the future effects of climate change. They lead to prognoses for population development and economic development, especially for the following elements: 1. population by age, gender and educational status; 2. urbanisation; and 3. Economic development (GDP). In addition to these basic elements, there are other hypothetical scenarios, among others, for 4. energy supply and use; 5. land use; 6. greenhouse gas emissions and air pollution; 7. average global radiative forcing and temperature changes; as well as 8. mitigation costs.

4) http://www.fao.org/fishery/cwp/search/en

5) See also section on fish consumption.

6) Standardised according to the limit values which, between 1988 and 2013, were slightly above the highest country values of the relevant indicator measured worldwide.

7) Among the most common micronutrient deficits, fish has the greatest potential to help alleviate vitamin A, iron and iodine deficits. This is particularly true for small species consumed whole with heads and bones, which can be an excellent source of many essential minerals such as iodine, selenium, zinc, iron, calcium, phosphorus and potassium, as well as vitamins such as A and D and several vitamins from the B group (Kawarazuka and Béné 2011). In addition, fish is usually low in saturated fats, carbohydrates and cholesterol with a few exceptions for selected species

8) A similar conclusion, albeit with a different intention, was reached by Thurstan and Roberts (2014).

9) Measured in USD purchasing power equivalent, i.e. correcting for exchange rate fluctuations using a hypothetical exchange rate to achieve equal purchasing power for a fixed basket of goods. This measure is often used in international comparisons in order to minimise the effects of (short-term) fluctuations in exchange rates when comparing the poverty status in several countries, for example.

10) As in the Allison et al. (2009a, 2009b) indicator.

11) For a full list of LMEs see appendix. The Antarctic and the Central Arctic Ocean are excluded due to a lack of data.

12) The full sets of parameter values, computation results and programming codes are available electronically as supplementary material. For the numerical calculation we employ the interior-point algorithm of the Knitro (version 9.1) optimisation software (Byrd et al. 1999; 2006). All programming codes were implemented in AMPL and are available as supporting material.

13) Details on the resulting accepted parameter values for the global predator-prey model are given in the technical appendix.

14) See appendix for a detailed list of substitution goods. Note: 'other' refers to the FAOstat specification 'not elsewhere included'.

15) The following countries have been removed: Armenia, Austria, Azerbaijan, Belarus, Bermuda, Bhutan, Bolivia (Plurinational State), Botswana, Burkina Faso, Burundi, Central African Republic, Chad, Cook Islands, Czech Republic, Czechoslovakia, Ethiopia, Ethiopia PDR, Republic of Fiji, French Polynesia, Guam, Hungary, Kazakhstan, Kiribati, Kyrgyzstan, Lao People's Democratic Republic, Lesotho, Luxembourg, Former Yugoslav Republic of Macedonia, Malawi, Mali, Marshall Islands, Mauritius, Federal States of Micronesia, Republic of Moldova, Mongolia, Nepal, Niger, Northern Mariana Islands, Palau, Palestine (Occupied Territories), Paraguay, Rwanda, Samoa, Serbia, Serbia and Montenegro, Slovakia, Swaziland, Switzerland, Tonga, Turkmenistan, Tuvalu, Uganda, Uzbekistan, Vanuatu, Yugoslavia SFR, Zambia, Zimbabwe.

16) https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=welcome

17) Note that the data underlying this study only considers marine catches in LMEs. High seas catches, aquaculture production and inland fisheries are not included.

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Why we are here
To stop the degradation of the planet's natural environment and to build
a future in which humans live in harmony with nature.

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