FISH and FISHERIES

Aquatic food security: insights into challenges and solutions from an analysis of interactions between fisheries, aquaculture, food safety, human health, fish and human welfare, economy and environment

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Abstract

Fisheries and aquaculture production, imports, exports and equitability of distribution determine the supply of aquatic food to people. Aquatic food security is achieved when a food supply is sufficient, safe, sustainable, shockproof and sound: sufficient, to meet needs and preferences of people; safe, to provide nutritional benefit while posing minimal health risks; sustainable, to provide food now and for future generations; shock-proof, to provide resilience to shocks in production systems and supply chains; and sound, to meet legal and ethical standards for welfare of animals, people and environment. Here, we present an integrated assessment of these elements of the aquatic food system in the United Kingdom, a system linked to dynamic global networks of producers, processors and markets. Our assessment addresses sufficiency of supply from aquaculture, fisheries and trade; safety of supply given biological, chemical and radiation hazards; social, economic and environmental sustainability of production systems and supply chains; system resilience to social, economic and environmental shocks; welfare of fish, people and environment; and the authenticity of food. Conventionally, these aspects of the food system are not assessed collectively, so information supporting our assessment is widely dispersed. Our assessment reveals trade-offs and challenges in the food system that are easily overlooked in sectoral analyses of fisheries, aquaculture, health, medicine, human and fish welfare, safety and environment. We highlight potential benefits of an integrated, systematic and ongoing process to assess security of the aquatic food system and to predict impacts of social, economic and environmental change on food supply and demand.

Keywords Ethics, food safety, food security, food system, health, sustainability

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Introduction

Food from aquatic environments makes an important contribution to human nutrition and health and is also sought and enjoyed by people for cultural and gastronomic reasons. Maintaining the long-term production and supply of such food, from both wild-capture fisheries and aquaculture, is a significant and ongoing challenge for society. Production has to be sufficient, safe and nutritious to meet immediate needs and preferences, but it also has to be environmentally, socially and economically sustainable to provide for the long term. Environmentally sustainable production is needed to maintain the productivity and diversity of the food resource and the ecosystems that support it and to ensure that the impacts of food production do not compromise other ecosystem services. Socially and economically sustainable production is needed to ensure that the communities, industries and supply chains that generate food continue to function and provide socially and ethically acceptable working conditions for the people involved.

Global demands for food from aquatic environments are expected to increase in future decades, because these foods will help to meet the needs and preferences of a growing human population. Median projections suggest global population growth of 2.4 billion, to over 9.7 billion, by 2050 (United Nations 2015). Food demand is expected to rise even faster than population growth, owing to the emergence of a larger proportion of 'middle-class' people who have greater spending power and typically consume more animal protein than people with lower incomes (Kharas 2010).

Globally, regionally, nationally and locally, the societal importance of aquatic food varies widely and methods of food production are diverse. Aquatic food may play a pivotal role in daily nutrition, or provide variety and a few essential nutrients in an already healthy and ample diet. Motivations for fishing and aquaculture may range from meeting immediate subsistence needs to generating substantial income for multinational companies trading in export markets. Consequently, the effects of increased food demands at global scales will vary among countries and among people within those countries, contingent on their dependence on, and access to, aquatic food. Some countries will likely come close to achieving food security, with all people, at all times, having physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and preferences for an active and healthy life (FAO 1996), but others will not. Prospects for individual countries depend on the relative importance of aquatic food in current or future diets; the sustainability, type, safety and adequacy of national production; capacity to import and export; the function of supply chains; and the equitability of food distribution.

In relation to their overall contribution to global food security, fish, treated here as fish and invertebrates from marine and freshwater environments, provided 16.7% of animal protein eaten by people in 2010. For 2.9 billion people, fish protein accounted for 20% of their required per capita intake of animal protein. The proportion of global fish production eaten by people has increased to 86% in recent decades. The remaining 14% is used for other purposes such as fish meal and oil production, which contribute indirectly to human food production when used in fish and animal feeds (FAO 2014).

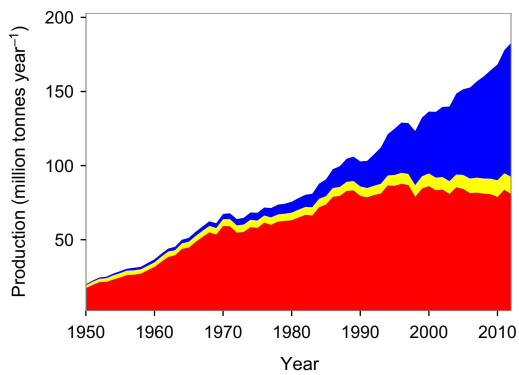

Figure 1 Trends in global production from marine (red)- and freshwater (yellow)-capture fisheries and aquaculture (blue). Data from FAO FishStatJ (FAO 2015).

In the last two decades, global aquaculture production has increased rapidly and now surpasses beef production (Fig. 1). While aquaculture production is rising, wild-capture production has more or less stabilized, because there are few opportunities to develop new sustainable fisheries or to increase catch rates in existing fisheries. Thus, in 2011, 61% of fished stocks assessed by the FAO globally were estimated to be fully but sustainably fished, 29% were overfished and only 10% under fished (FAO 2014). Global wild-capture fisheries production reported by FAO has fluctuated around 90 million tonnes (t) since 2000, while aquaculture production is currently 64 million tonnes and increasing (FAO 2014) (Fig. 1). Aquaculture production is predicted to substantially exceed capture fisheries production in the next few years (World Bank 2013).

Global trends in aquaculture and capture fisheries production belie large regional differences. In Europe, for example, capture production has fallen, but reductions have not been fully compensated by the rise in aquaculture (Fig. 2). Conversely, in Asia, a slow increase in capture production is supplemented by a dramatic rise in aquaculture production (Fig. 2). By far, the largest proportion of global aquaculture production is currently generated in Asia (Fig. 3). The mismatch between areas of fisheries and aquaculture production and areas of demand contributes to the very high levels of trade in fish and fish products (Watson *et al.* 2015).

The UK has the fifth highest GDP in the world, albeit around one-quarter of China's GDP and less

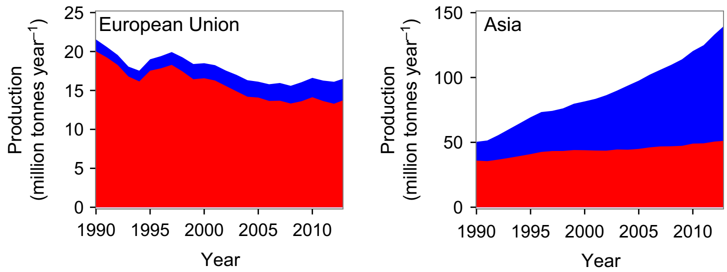

Figure 2 Trends in fisheries (red) and aquaculture (blue) production in the European Union countries and Asia. Data from FAO (2015).

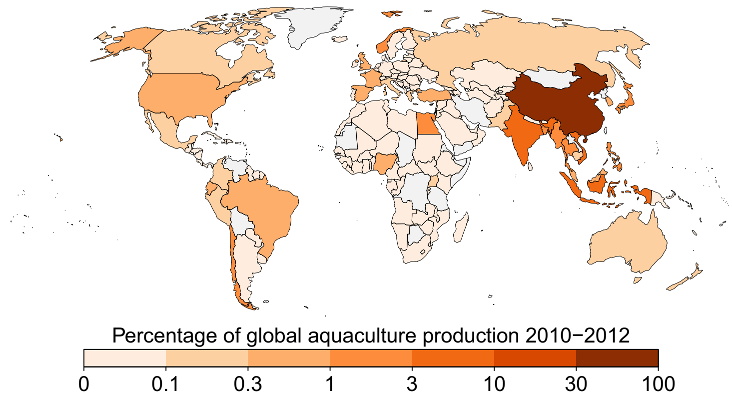

Figure 3 Proportion of global aquaculture production by volume by country. Data from FAO (2015).

than one-sixth of US GDP, and ranks 23rd in terms of GDP per capita (IMF 2015). For relatively wealthy nations such as the UK, the main food security issues relate to meeting the needs and preferences (wants and expectations) of consumers and ensuring that food is affordable for all. These extend to ensuring food variety, quantity, safety and nutritional benefits and ensuring that low incomes or benefit payments do not restrict access to adequate nutrition. Many consumers also expect, or require, that food is produced, processed and supplied in ethically acceptable ways.

UK wild-capture fisheries landed 624 kt of fish in 2013, of which 405 kt came through British ports. Total annual landings have decreased by 29% in the last 20 years, but annual aquaculture production now exceeds 200 kt, largely driven by growth of the Scottish Atlantic salmon (*Salmo salar*, Salmonidae) farming industry. The UK is also a significant importer of fish and fish products, ranking 8th among all countries for the value of fish imports. Net imports to the UK were 286 kt in 2013 and imports grew by 6% in value from 2002 to 2012 (FAO 2014). High fish imports are also recorded in other European Union (EU) Member States (MS). Even when trade between MS is excluded, EU fishery imports of US$25 billion in 2012 were 23% of the global total (FAO 2014).

For consumers in the UK, fish are just one of many sources of animal protein available. Dependency on fish protein is low, and consumption of meat is relatively high (Fig. 4a). However, to improve health and nutrition, the UK Government has recommended that people eat two 140-g portions of fish per week, one of which should be oily (PHE-FSA 2014). Mean fish consumption rates are just 100 g per person per week at present (Fig. 4a). Consumption is dominated by tinned and pre-prepared products rather than fresh fish (Fig. 4b).

Even for relatively wealthy nations such as the UK, there has long been a focus on the extent to which national food production can meet the population's needs. The UK tracks a food production to supply ratio for indigenous foods; a measure of the proportion of food consumed that could be produced nationally. This ratio has decreased by 10% since the early 1990s to 76% today (UK Government 2014a). The ratio is calculated from agricultural rather than fisheries and aquaculture production, but we can infer from UK import and

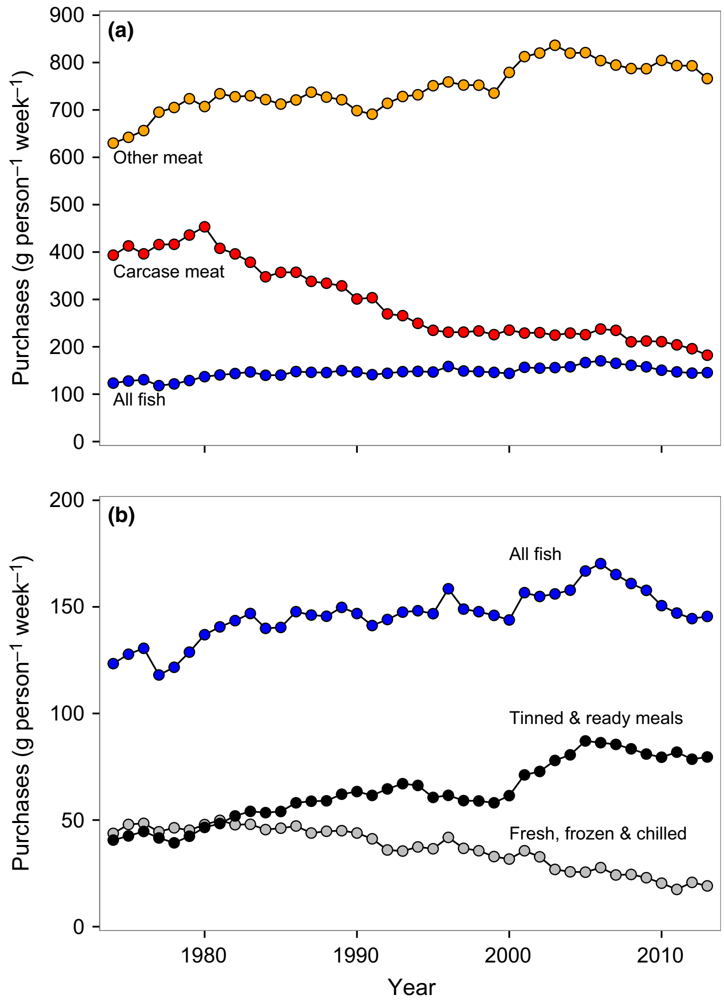

Figure 4 Consumption rates of fish by people in the UK, as estimated from purchases (a) fish (blue), carcass meat (red) non-carcass meat (yellow) and (b) all fish (blue), tinned and ready meal fish (black), frozen-chilled (grey). Data from UK Office of National Statistics (UK Government 2015).

export statistics, coupled with the potential yields of wild fish stocks caught by UK fleets, that the figure for aquatic food production is lower. Neither observation challenges the expectation that the UK can be self-sufficient in terms of food production, albeit with a diet that would be focused on crop production and very restricted by current standards. For example, around 10 million t year^{-1} of UK-grown crops are used for animal feed and a proportion of this production could be consumed directly by people if UK capacity to import foods was curtailed (UK Government 2010). This capacity for substitution may be one reason why far less attention is given to food balance for aquatic food than for agricultural crops. For crops, there have been frequent analyses of the consequences of increases in imports at the expense of national production (UK Government 2010, 2014a). The UK National Farmers Union, the UK farming trade association, also flags the day of the year on which British food supplies would run out if everything produced in a year was stored and eaten from January 1.

Here, we review the aquatic food system in the UK, the challenges to achieving food security and, when needed, potential solutions to ensure access to sufficient and safe aquatic food while sustaining the environment, production systems and supply chains. Our analysis of the food system spans fisheries, aquaculture, health, medicine, human and fish welfare, safety and environment. We take this integrated approach to reveal interactions and trade-offs that may be overlooked in sectoral analyses. As aquatic food is one of the world's most highly traded commodities, the UK is embedded in a dynamic global web of producers, processors and traders. Consequently, access to aquatic food in the UK can be strongly influenced by international as well as national supply and demand. Given these influences, our analyses highlight aquatic food security issues that are also relevant for other relatively wealthy countries, in Europe and elsewhere, where imports sustain a large proportion of national consumption.

The aquatic food system

Aquatic food production in the UK currently comprises fisheries landings (40% by volume), aquaculture production (13%) and imports (47%). Realized exports are 29% of this total, but imports and exports cannot be treated as entirely separate trade flows when a proportion of production is exported for processing and then imported. Measuring the trade balance accurately is also a challenge when weights may be whole or processed. Most fisheries landings, aquaculture production and imported product pass through and support the processing sector. In 2014, the processing sector employed 19 511 people in 403 processing units (Seafish 2014a). The value of seafood purchased in the UK in 2012 was estimated to be £ 6.2 billion (Seafish 2014a).

Wild-capture fisheries

Production from UK wild-capture fisheries has fallen steadily for several decades, although the UK is still a leading producer among EU MS (4th by value, 3rd by volume) because there has been an overall decline in EU wild-capture production (Fig. 2).

The UK fishing fleet comprises 5036 vessels of 10 m or less (overall length) and 1363 vessels >10 m (UK Government 2014b). Forty-nine percent of the UK fleet comprises English vessels, but these are generally smaller as Scottish vessels account for 58% of total vessel capacity in tonnes and 47% of total vessel power in kW. Recent estimates suggest there are 12 150 fishers, including 5600 in England and 5000 in Scotland. Both the numbers of vessels and fishers have declined slowly but steadily in the last decade, following steeper declines in the 1990s (UK Government 2014b). Declines were driven by increased mechanization and technology, the increased fishing power of smaller boats and by the loss or sale of fishing opportunities. UK fishing effort, measured as kW days at sea, has fallen since 2002 as a result of vessel decommissioning schemes and effort restrictions.

Landings by UK vessels into UK ports were 405 kt in 2013, comprising 30% bottom-dwelling (demersal) species, 33% pelagic species and 37% shellfish. These landings had a first sale value of £548 million. Almost half of the total value comes from shellfish (47%) with 16 and 37% from pelagic and demersal fishes, respectively. By species, landings weights were dominated by mackerel (*Scomber scombrus*, Scombridae) (78 kt), scallops (*Pecten maximus* and *Aequipecten opercularis*, Pectinidae) (49 kt) and Atlantic haddock (*Melanogrammus aeglefinus*, Gadidae) (39 kt). Landings value was dominated by *Nephrops* (£86 million), mackerel (£70 million) and haddock (£44 million). Landings of UK vessels into ports outside the UK accounted for a further 219 kt worth £169 million, of which 157 kt were pelagic species, predominantly mackerel and herring (*Clupea harengus*, Clupeidae). Shellfish are almost exclusively landed into the UK, but many are subsequently exported for sale or processing. The 241 vessels of length >24 m account for 68% of all landings volume and 54% of all landings value by UK vessels. In 2013, landings into the three Scottish ports of Peterhead, Lerwick and Fraserburgh accounted for 46% by volume and 35% by value of all landings by UK vessels into the UK (UK Government 2014b).

The total volume and species composition of UK fisheries landings is strongly influenced by regulation, principally the Common Fisheries Policy (CFP), the EU instrument for the management of fisheries (EC 2013a). The CFP applies to MS that have collective access to EU waters of 8.1 million km^{-2} around the continent of Europe (plus additional areas internationally around overseas territories), usually excluding coastal waters <12 nautical miles from the coastline of each MS (some access to other MS may be allowed from 6 to 12 nautical miles with historical precedent, and even closer access is permitted in occasional circumstances). The EC proposes an annual total allowable catch (TAC) for each stock based on scientific analysis of fishing mortality rates that produce the maximum sustainable yield. The TAC are then further considered and agreed among MS agriculture and fisheries ministers at the European Agriculture and Fisheries Council. The national shares of the TAC for each stock (quota) are based on records of historical fishing activity. Ultimately, it is the share of the TAC for stocks, which are received by the UK as quota and further divided to Devolved Administrations and then to vessels, which places a ceiling on wild-capture production for stocks covered by the CFP.

England and the Devolved Administrations (Scottish Parliament, National Assembly for Wales, Northern Ireland Assembly) have agreed a Concordat to deliver UK obligations to implement the CFP. The Concordat defines an approach for distributing annually agreed shares of UK fish stock quotas to national fleets, where vessel nationality depends on port of registration. The Concordat does not define a permanent split of UK quota, however, and fishing vessels can justify moving their registration to another part of the UK.

Aquaculture production

Aquaculture production in the UK has been rising steadily since the late 1980s, and the UK is one of the largest producers in the EU (1st by value, 3rd by volume) (Ellis *et al.* 2015). In 2012, there were approximately 645 active fish and shellfish farming businesses in the UK, operating over 1160 sites and employing 3231 people with an estimated turnover of £590 million (Table 1). The aquaculture industry is much larger in Scotland than in the other countries of the UK and Scottish aquaculture accounts for the majority of UK production (Fig. 5). Consolidation of businesses, increased automation and increasing site size have led to decreasing employment and increased productivity in UK aquaculture (OECD 2015).

Total finfish production was 178 kt in 2012, dominated by 162 kt of farmed Atlantic salmon and 15 kt of rainbow trout (*Oncorhynchus mykiss*, Salmonidae). There was a limited production of other species on a niche or emerging basis, such as tilapia (Cichlidae), sea bass (*Dicentrarchus labrax*, Moronidae) and halibut (*Hippoglossus hippoglossus*, Pleuronectidae), totalling <1 kt. Other freshwater fish species were produced for recreational angling (restocking) or ornamental markets, but are not considered here. Farmed shellfish production was just over 27 kt in 2012. Mussels (*Mytilus edulis*, Mytilidae) accounted for 95 and 82% of total shellfish production by volume and value, respectively.

Aquaculture in the UK is a responsibility that rests with the Devolved Administrations and the Department of Environment, Food and Rural Affairs in England. The devolution of responsibility likely contributes to different rates and scale of aquaculture development across countries in the UK. Regulation in this sector addresses registration of aquaculture production businesses (APB), aquatic animal health, managing the environmental impact of discharges, and planning and managing interactions with other users (e.g. navigation).

The EU intends to boost aquaculture growth across Europe as part of the implementation of the 2013 revision of the CFP (EC 2013a) and linked Blue Growth agenda (EC 2012a) and has published Strategic Guidelines presenting common priorities and general objectives which MS are encouraged to follow (EC 2013b). This includes tasking MS to produce Multiannual National Plans for the development of aquaculture, to outline how they intend to respond to these of aquaculture growth challenges (EC 2013b). The small-scale of aquaculture in countries other than Scotland suggests there is a considerable potential to produce more aquatic food in this way, but whether the potential is realized largely depends on the risks that investors are willing to take and

Table 1 Aquaculture sites, production and direct employment in the UK in 2012 (Ellis *et al.* 2015).

	Production (volume)		Production (value)		Employment	
Country	Tonnes	%	£m	%	Number	%
England	15 624	7.6	31.6	5.3	1081	33.5
Wales	9452	4.6	10.4	1.8	134	4.1
Scotland	174 531	85.1	541.7	91.7	1898	58.7
Northern Ireland	5528	2.7	6.7	1.1	118	3.7
UK (total)	205 134	100	590.5	100	3231	100

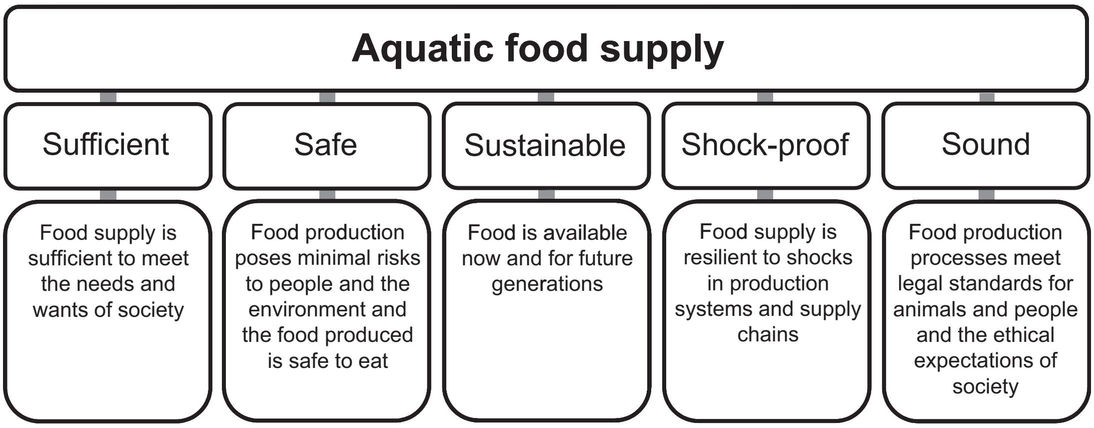

Figure 5 Five elements of a food supply which contribute to food security.

the commitment of the Devolved Administrations to such development.

Critical elements of food security

In general terms, an aquatic food supply contributes to food security when the food supply is sufficient, safe, sustainable, shockproof and sound (Fig. 5).

A sufficient food supply meets the needs and wants of consumers, in terms of quantity and nutritional benefits. We emphasize 'wants' as well as 'needs' because the current drivers of demand in the UK are choices about diet as much as people striving to meet basic nutritional needs. However, this situation may change rapidly if supply became limiting in terms of volume as well as choice, or if there were constraints on production in other parts of the food system. Here, we focus on sufficiency at the national scale, but for people and families, sufficiency will be contingent on equitability of distribution and on people's physical, social and economic access to food.

A sustainable food supply provides food now and for future generations. Sustainability of supply is predicated on the environmental sustainability of production, the state and function of ecosystems that support production, and the economic and social sustainability of production and processing methods and supply chains. Risks to environmental sustainability come from the direct and indirect impacts of production systems and supply chains on the environment, including those linked to energy demands. Risks to social and economic sustainability result from low financial viability of production systems and low resilience to shocks.

A safe food supply provides nutritional benefit while posing minimal health risks to consumers. Risk is minimal when any contamination with human pathogens, chemicals or radionuclides is within safe limits and when fish and fish products are harvested, handled, processed, stored, sold and prepared in ways that do not increase risks to human health. Traceability of products in supply chains is essential to ensure that contaminated products, or those with a high risk of contamination, do not mix with those that are identified as posing low risk.

A sound food supply is based on production processes, supply chains and markets that meet legal standards for welfare of animals and people as well as the ethical expectations of society. Ethical concerns about the capture and culling of aquatic animals are increasingly highlighted in some societies and access to some potential sources of aquatic production, such as marine reptiles or mammals, are legally restricted or prohibited in many countries. There are also ethical concerns about the welfare of people involved in aquatic food production, as a large proportion of aquatic food production relies on industries where workers can be, and/or are, exposed to higher risk of injury, death and human rights abuses than in many other jobs. A sound food supply is also authentic, so that buyers, processers and consumers know the type and origin of food they buy and/or consume.

A shockproof food supply is resilient to shocks in production systems, supply chains and markets. These may be caused by weather, climate, disease outbreaks, strikes, political unrest, failure of food to meet safety standards, breakdown of production or storage facilities or transport networks, economic factors (e.g. cost increases, reductions in purchasing power), health scares, consumer or supplier boycotts, campaign groups and trade restrictions or embargoes. Resilience at the national level may be maintained by sourcing food from diverse sources and supply chains (the portfolio effect) and by legislating for, and/or putting in place, structures, measures and support to ensure sustainability, safety and sufficiency of production.

While it may be argued that the 'sufficient', 'safe', 'shock-proof' and 'sound' elements of the food system are components of 'sustainable', we chose to highlight them as separate elements to emphasise their importance to society. In the following sections we describe all these elements of the food system and interactions between them.

Sufficient food supply

In countries such as low-income food-deficit countries (LIFDC), where fish are one of few available sources of many micronutrients and protein, the overwhelming focus of management agencies is on providing a supply that is sufficient to meet nutritional needs. In wealthier nations, many other sources of nutrition are often available, and 'sufficient' is usually treated as sufficient to meet demand. Markets and supply chains are largely responsible for taking care of sufficiency in the UK, and for a country with a relatively large and strong economy, inadequate supplies of aquatic food on global scales may not have national consequences. Thus, there is a limited Government involvement in defining or promoting specific rates of aquatic food supply, aside from the indirect effects of guidance and legislation which are intended to ensure sustainability and food safety.

Sufficiency of UK supply: production and consumption

Capture fisheries production by UK vessels landed into the UK is now at the lowest levels since the years during the two World Wars (Fig. 6). Despite the growth in aquaculture, UK fish production per capita is falling steadily as the UK population continues to increase (Fig. 6). Per capita consumption of fish and fish products in the UK, however, has remained relatively stable over the last two decades (Fig. 4), because UK production is supplemented by imports.

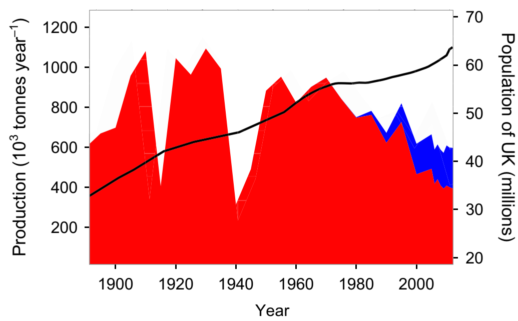

Figure 6 Trends in UK capture fisheries landings (red), aquaculture production (blue) and population (black line) since 1887. Data from UK Sea Fisheries Statistics (UK Government 2014b) and Office for National Statistics (UK Government 2015). Fisheries landings are landings by UK vessels into UK ports only.

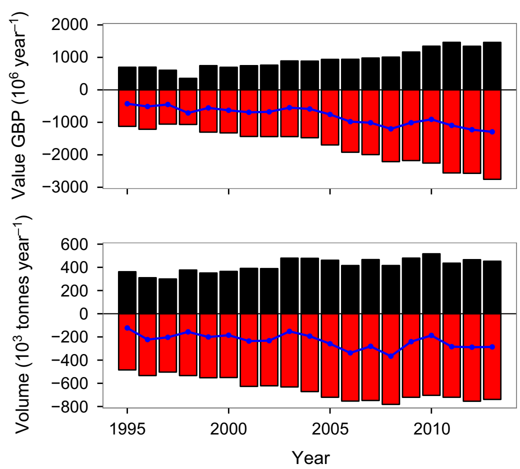

Figure 7 Imports (red) and exports (black) of fish and fish products into/from the UK by value and volume since 1995. Blue line indicates trade balance by year. Data from UK trade statistics (UK Government 2014b, 2015).

The proportion of UK aquatic food consumption that comes from imports has risen steadily in recent years, with the UK consistently importing more fish than it exports (Fig. 7). The composition of traded fish and fish products shows that trade by volume and value is dominated by relatively few groups (Fig. 8). Import volume is dominated by salmon, cod and tunas (species in family Scombridae) and export volume by salmon, mackerel and herring. Interestingly, herring and mackerel are caught in large volumes from ecologically and economically sustainable fisheries, are relatively cheap and would contribute to the consumption of 140 g of oily fish per person per week as recom-

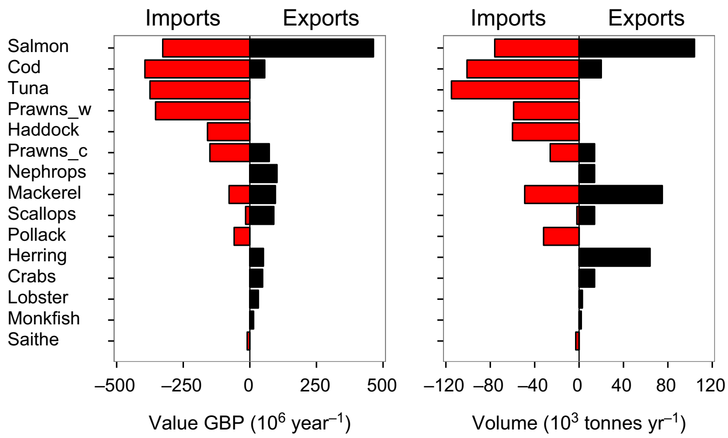

Figure 8 Imports (red) and exports (black) of fish to and from the UK in 2014, for the top 16 species and groups and ranked by total value of flows. Data from UK trade statistics (UK Government 2014b, 2015). The names salmon, tuna, prawns_w and prawns_c (warm- and cold-water prawns), scallops, pollack, crabs, lobster and monkfish used in import and export statistics each refer to multiple species. The other single-species not referred to in the text is *Nephrops* (*Nephrops norvegicus*, Nephropidae).

mended by UK Government. However, these species are almost exclusively exported rather than consumed in UK markets. These patterns of import and export suggest that consumer preferences and their effects on demand and price, rather than limits to supply, determine current patterns and rates of consumption of UK production.

For the UK consumer, sufficiency of supply is currently interpreted as sufficient to meet demands, and the volume of supply is governed by markets that supply a mix of UK-produced and imported fish and fish products. The capacity of production systems, importers and suppliers to meet existing demand is good, given that consumption is rising relatively slowly. Consumers have not eaten substantially more fish and fish products in recent years despite aforementioned Government recommendations to do so, to improve nutrition and health (PHE-FSA 2014). These recommendations to eat more fish stem from widespread acceptance that the Omega-3 fatty acids eicosapentaenoic acid (EPA; C20:5 n-3) and docosahexaenoic acid (DHA; C22:6 n-3) in fish oils are beneficial for human health and reduce the risks of cerebrovascular and other diseases (Chowdhury *et al.* 2012; Gil 2012).

Current mean consumption of oily fish in the UK is 54 g week^{-1} by those aged 19–64 and 90 g week^{-1} for those aged over 65, with both values well below the 140 g target. But, even at these low rates of consumption, fish still account for 17–23% of adult vitamin D intake and 17–22% of selenium intake. Some consumers are boosting their intake of EPA and DHA by consuming fish oils rather than eating more whole fish, with 24% of adults aged 65 years and over taking cod liver oil and other fish oils (PHE-FSA 2014). If the target for oily fish consumption alone were met by the entire UK population, this would require 464 kt of fillet, equivalent to approximately 650 kt of whole fish. One prediction, however, based on analysis of consumer preferences, suggests that consumption is unlikely to rise to this level, with total UK adult fish consumption predicted to increase from 410 kt today to around 480 kt in 2030. Most of this small projected increase is attributed to the growing proportion of people aged over 65 (21% in 2012 to 27% in 2030) who are expected to eat more fish (Sainsbury's Supermarkets 2012).

Access to aquatic food also depends on price and hence equitability of distribution. Even the current costs of staple foods make them inaccessible to parts of UK society. When individuals (or households) cannot obtain enough food to meet their nutritional and health needs, they are said to be in food poverty. Data collected by the Trussell Trust, the largest operator of food banks in the UK, suggested that approximately one million person-visits, each providing 3 days food, were made to their food banks in 2014 (Trussell Trust 2014). There are assumed to be more people in food poverty than the number using food banks, as research shows that most people treat food banks as a strategy of last resort. Some estimates suggest 4 to 5 million people are in food poverty in the UK (UK Government 2010). Despite increasing choice and affordability of food overall, many people are eating what they can afford, and consequently not the food with the highest nutritional value or the food they prefer (Lambie-Mumford *et al.* 2014).

If poorer consumers are motivated to eat fish, then the price of fish is expected to limit consumption. This is because most fish and fish products are relatively expensive. Relationships between income and oily fish consumption were identified in an analysis of data from the UK National Diet and Nutrition Survey (Maguire and Monsivais 2015). After adjusting for age, sex, ethnicity, total energy intake and survey year, all income groups with incomes higher than those in the lowest group (earning $<$ £14999 year^{-1}) were more likely to eat oily fish. Oily fish consumption also increased with education level; degree-educated people were three times more likely to consume oily fish than people with no qualifications (Maguire and Monsivais 2015). These recent results were broadly consistent with previous observations of links between income or social role and fish consumption (Akbaraly and Brunner 2008).

Other drivers and inhibitors of fish consumption were assessed in research conducted for supermarkets in the UK (Sainsbury's Supermarkets 2012). Fifty-one percent of consumers who already ate fish cited health as a driver for eating more fish, but this was countered by 33% who felt that rising prices encouraged them to eat less. Consumers tended to respond to rises in fish prices by 'trading down' or reducing the amount they buy. Other barriers to eating fish included lack of knowledge about how to prepare them, lack of availability of fresh fish locally, preparation time, dislike of fishy smells and the need for meal planning. Results for the UK were similar to those in Belgium, another relatively wealthy EU nation with relatively low fish consumption. In Belgium, taste and health were the biggest drivers for eating fish, but bones and price constituted negative factors (Verbeke and Vackier 2005).

Some retailers and campaign groups are making direct efforts to encourage increased consumption of a wider range of fish, with a focus on those that can be obtained from sustainable sources. For example, from 2011 the Sainsbury's supermarket 'switch the fish' campaign offered anyone purchasing tuna, cod, salmon, haddock and prawns (refers generically to several wild-caught and cultured species in suborder Dendrobranchiata) at their fish counters, a sustainable, but lesser known or popular, alternative for free. This was one of a number of initiatives and led to some changes in buying patterns at the supermarket, but the overall types and volumes of fish consumed have changed little since that time. The choices made by the average consumer are usually quite conservative, although this belies strongly positive responses to consuming a few products, such as warm-water prawns, that have gained widespread acceptance in UK markets in recent years.

The UK food system is embedded in a global market. Nationally, the UK can currently meet average consumer demand and buffer any shortfall or reduction in UK production by importing. For example, as UK cod landings have declined, in response to loss of fishing grounds and overall reductions in TAC for stocks still accessible to the UK fleet, consumption of cod has been maintained by importing cod and cod products from other countries. Today, cod imports exceed cod landings to the UK by >10-fold (UK Government 2014b).

Global production and consumption

Globally, reported wild-capture production has stabilized at around 80 million t year^{-1} (Fig. 1). This global stability belies differences in regional capture production trends that result from reaching or surpassing of limits to sustainability, but also from managers who have increasingly achieved sustainable exploitation rates in the waters of some countries (Worm *et al.* 2009; Hilborn and Ovando 2014).

Given current management objectives, fishing technology and approaches to management, it is unlikely that global capture production will increase much further without risk to future sustainability, economic performance or commitments to biodiversity conservation. Although some model results suggest that a shift to targeting smaller individuals from species with smaller maximum body size or spreading mortality more evenly among species (Garcia *et al.* 2015) could increase global yields, substantial additional yield is unlikely to be realized in practice. Reasons include societal and political barriers to exploiting some abundant resources (e.g. krill, family Euphausiidae), technical and economic barriers to targeting sparsely distributed but collectively abundant resources (e.g. mesopelagic fishes) and barriers to achieving independent control of fishing mortality on individuals of different sizes and species (Jennings and Collingridge 2015). However, for a given landings volume, there may be opportunities to make more food available for human consumption, by reducing waste in production, processing and supply chains, and also, for often highly perishable products, among retailers and consumers.

In contrast to capture fisheries production, aquaculture production has been accelerating globally and is showing further potential for growth, not least because the current increase in production is largely attributed to Asia, while other continents have barely begun to develop their aquaculture industries by comparison (Figs 2 and 3). It is most likely that future increases in global fish production will be driven by aquaculture. Increases in the efficiency of aquaculture are also helping to support growth in production. For instance, trimmings from fish and meat processing plants are starting to substitute wild fish meal and oil in aquafeeds, although risks to cultured stock from disease or contaminant transmission will require consideration. In addition, the proportion of wild-caught fish in aquaculture feeds is decreasing as cheaper and more plentiful vegetable proteins are increasingly incorporated (Tacon *et al.* 2011).

Safe food supply

A safe food supply is one that poses minimal health risk to consumers. A food supply is safe when contamination with human pathogens, chemicals or radionuclides is within safe limits based on scientific evidence, and when aquatic products are harvested, handled, treated, processed, stored and prepared in ways that do not promote contamination or growth of microorganisms. Biological, chemical and radiation hazards are highly regulated in the UK and other countries. Such regulation, alongside risk-based surveillance and control measures and associated monitoring, has been shown to be critical for the protection of public health. Aquatic food in general is highly perishable and deteriorates quickly if not handled, stored and prepared appropriately. Spoilage is preventable through good storage and food hygiene practices which are not reviewed here.

Biological hazards

The main biological hazards affecting consumers of aquatic foods are pathogens and biotoxins that, when consumed in excess of threshold quantities, can lead to illness.

Pathogens of human concern

Bivalve molluscs, such as mussels and oysters, are filter feeders and can greatly concentrate protists, bacteria and viruses from their surrounding environments. Human-pathogenic protists such as *Cryptosporidium* spp. and the microsporidian *Enterocytozoon bieneusi* are commonly found as contaminants of shellfish. Human-pathogenic bacteria and viruses are also a concern owing to their presence in both wild-caught and cultured filter feeders. As bivalve molluscs are often eaten raw, consumption poses a direct threat to human health. Recent reports of human infections caused by established and emerging waterborne pathogens in Europe, such as members of the bacterial genus *Vibrio*, and viruses such as hepatitis A and E, and norovirus underline the need for greater understanding and preparedness for these threats, particularly under a changing climate system (Baker-Austin *et al.* 2013). Such threats can impact the commercial viability of bivalve shellfish production.

A wide range of human pathogens, including bacteria and viruses, have been responsible for shellfish-associated human illnesses in the EU. Enteric viruses are likely to be the most common pathogens transmitted via the consumption of bivalve shellfish (Potasman *et al.* 2002). In particular, the contamination of bivalve shellfish with norovirus from human faecal sources is recognized as an important human health risk (Lees 2000; Lowther *et al.* 2012). This single-stranded RNA virus can infect people of all ages, causing outbreaks of acute gastroenteritis with symptoms of fever, nausea, vomiting, cramping and diarrhoea that may persist for 12–60 h after an incubation period of 24–48 h (CDC 2009). Norovirus represents the largest aetiologically linked pathogen group found in bivalve molluscs in Europe, and each year numerous norovirus outbreaks are linked to the consumption of bivalve shellfish. Several characteristics of norovirus explain why they are formidable and significant shellfish-associated human pathogens; they are shed in high quantities by infected individuals, are present in high copy number in sewage waste, have a relatively low infectious dose, are environmentally stable and can mutate rapidly. Current estimates for the UK population indicate that 1 person in 219 is infected with norovirus each year, suggesting gross under-reporting of clinical cases (Tam *et al.* 2012). Several recent studies suggest that bivalve shellfish are widely and frequently contaminated with norovirus, particularly during the winter period. A systematic analysis of norovirus contamination in commercial oyster production sites in the UK indicated that 76.2% of 844 samples were norovirus positive, with all sites returning at least one positive result (Lowther *et al.* 2012).

In addition to norovirus, there is evidence of increasing risk of other emerging viral pathogens linked to bivalve shellfish, for example hepatitis E virus (HEV) (Crossan *et al.* 2012). This single-stranded RNA virus causes human infections via the faecal–oral route. Available epidemiological evidence on the prevalence of Hepatitis E in Western Europe indicates that the virus is responsible for around 5% of cases of acute hepatitis. However, since 2000, a number of clusters not associated with travel to areas where the virus is considered endemic were recorded, particularly affecting elderly persons and men (World Health Organization 2010). In the UK, there is also evidence of a large increase in reported cases in the last decade. There is now growing concern that commercially important livestock species, such as pigs, represent a significant environmental reservoir for HEV. Recent studies have shown high titres of HEV in swine wastewater and manure (McCreary *et al.* 2008), highlighting the potential for these pathogens to enter watercourses and then to bioaccumulate in bivalve shellfish species, such as oysters (family Ostreidae) and mussels. A recent study demonstrated the presence of HEV in mussels collected locally in Scotland for human consumption and raised concern as to whether these shellfish species are a potential source of infection. However, another systematic study conducted in France, which analysed almost 300 shellfish samples from a range of sites, did not identify HEV, despite evidence that this virus is circulating in some French areas (Grodzki *et al.* 2014).

Hepatitis A (HAV), unlike hepatitis E, is an established human pathogen. Its transmission route to humans has been linked to bivalve shellfish consumption. HAV infects the liver and is also transmitted via the faecal–oral route. It is responsible for approximately 1.5 million cases annually and as such is a serious infection particularly in individuals with underlying conditions and the elderly. HAV was responsible for the largest ever shellfish-associated food-borne outbreak in history, affecting almost 300 000 people in the late 1980s (Potasman *et al.* 2002). Several characteristics of HAV make it a particularly serious pathogen with regard to consumption of shellfish; it is relatively stable in the environment and can remain in shellfish matrices for long periods. Like norovirus, HAV is only slowly removed from shellfish by commercial depuration practices. This creates a significant technical barrier to reducing risk of infection from shellfish.

Bacteria of the genus *Vibrio* are among the most common Gram-negative bacteria that inhabit surface waters throughout the world. They are commonly found in tropical, subtropical and temperate coastal and estuarine waters and are responsible for a number of severe infections both in humans and animals (Vezzulli *et al.* 2013). Approximately a dozen *Vibrio* species are known to cause disease in humans, and infection is usually initiated from exposure to seawater or consumption of raw or undercooked seafood (Altekruse *et al.* 2000; Dechet *et al.* 2008; Baker-Austin *et al.* 2009, 2010). Two *Vibrio* species in particular, *Vibrio vulnificus* and *Vibrio parahaemolyticus*, are significant human pathogens that can occur in food from aquatic environments. *Vibrio cholerae* is also a foodborne pathogen, but is rarely implicated in human infections associated with seafood when compared to *V. vulnificus* and *V. parahaemolyticus* (Baker-Austin *et al.* 2009). However, *V. cholerae* may create a greater risk if more aquatic food is imported to the UK from areas where it is endemic.

Vibrio spp. grow preferentially in warm (>15 °C), low-salinity (<25 ppt NaCl) seawater (Baker-Austin *et al.* 2010, 2013). Warming of low-salinity marine environments can lead to larger *Vibrio* populations and consequently an increased risk of *Vibrio* infection. The number of *V. vulnificus* and *V. parahaemolyticus* infections is steadily increasing relative to that of other food-borne pathogens (Martinez-Urtaza *et al.* 2010). As some of the marine ecosystems in Western Europe are among the fastest warming marine ecosystems globally (Burrows *et al.* 2011), we are likely to see more infections with these pathogens. Surveillance and monitoring of these infections are poor, and so we likely underestimate the disease burden linked to *Vibrios* from shellfish consumption. In Europe, a recent review of infectious disease agents places non-cholera *Vibrios*, such as *V. vulnificus* and *V. parahaemolyticus* as among the most serious threats in the regions linked to climate change (Lindgren *et al.* 2012). In all cases where shellfish can be contaminated with pathogens of human origin (protists, bacteria and viruses), risk mitigation requires that shellfish production sites are located away from point sources of sewage pollution.

Marine biotoxins

Consumption of fishery products containing natural marine toxins can cause serious human illness. The risk from natural toxins in marine foods has long been recognized and incidents recorded for several hundred years (Bagnis *et al.* 1970). Toxins are produced by naturally occurring phytoplankton and accumulate in shellfish, particularly filter-feeding bivalve molluscs, as they feed (FAO 2004). Within the EU, maximum permitted levels have been established for toxins that cause Paralytic Shellfish Poisoning (PSP) and Amnesic Shellfish Poisoning (ASP), and for Lipophilic Toxins (LT) including those responsible for Diarrhetic Shellfish Poisoning (DSP) and Azaspiracid Shellfish Poisoning (AZP). Testing of water samples for microscopic identification of toxin-producing phytoplankton genera, along with the quantification of toxicity in molluscs, is conducted to help mitigate risk, with shellfish harvesting areas closed when toxin levels are above the specified limits in shellfish tissues (EC 2004). The impacts from consumption of contaminated products can be severe and even fatal (European Food Safety Agency 2009). Unlike marine pathogens, shellfish toxins cannot be eliminated through food processing techniques such as heating, and depuration is also inefficient.

Harmful algal blooms (HAB) that produce toxins of concern are recognized as having increased in distribution, intensity and frequency over the past 40 years (Hallegraef 2003). Locations of HAB are difficult to predict accurately. The occurrence and toxin content associated with PSP in bivalves also exhibits high spatial and temporal variability around the UK (Turner *et al.* 2014). While some success has been achieved with developing models for phytoplankton growth and shellfish toxin accumulation, these, along with other predictive tools such as satellite imagery, are not sufficient to manage risks, and direct testing of shellfish remains essential. While offshore siting of shellfish farms will reduce risks from accumulation of terrestrial contaminants, including both human pathogens and chemical pollutants, pelagic toxic phytoplankton are can still form extensive blooms in the open sea and are challenging to avoid. However, some risk of toxin accumulation may be ameliorated if shellfish farms are located in deeper areas away from benthic cyst beds (Kirn *et al.* 2005).

Changes in sea temperature and other environmental parameters over recent years have affected trends and distributions of toxins (Baker-Austin *et al.* 2013). Potential impacts of environmental change include the introduction of new or emerging toxins into UK marine waters. This can include the detection of new analogues of toxin groups currently present in UK waters, the introduction of new species of toxin-producing phytoplankton as a result of environmental change or ballast water transfer, or even the presence of new toxin threats such as the pufferfish (family Tetraodontidae) poison Tetrodotoxin which were previously not known in UK shellfish (Turner *et al.* 2015). The risk of accumulation of new toxin threats in UK shellfishery products not currently covered by EU legislation but is regarded as high. New methods and diagnostics are still needed to detect toxin threats (Higman *et al.* 2014).

Chemical hazards

Contaminants and veterinary residues

Chemicals in the environment, including pesticides, heavy metals and persistent organic pollutants, can accumulate in fish and shellfish and can pose a public health issue. Risks are linked to chronic (long-term) exposure and to a lesser extent to acute (short-term) exposure (Knowles *et al.* 2003). Fish can take up chemicals in three ways: dietary exposure through food or feed in wild and cultured fishes; veterinary products used to treat fish diseases in aquaculture; and uptake from the water column in wild and cultured fishes. Concentrations of environmental chemicals detected in fish and shellfish tend to vary in a single location as uptake is affected by many factors including host type, fat content, size, age, growth rate, gender and other physical, chemical and biological factors.

Human dietary exposure to bioaccumulative pollutants including methylmercury, polychlorinated biphenyls and emerging contaminants can pose risks to health; as many of these chemicals act as neurotoxicants (Nesheim and Yaktine 2007; Sunderland 2007; Grandjean and Landrigan 2014). Groups of people consuming high quantities of some fish species in some areas may be at risk from these bioaccumulative pollutants (Nesheim and Yaktine 2007; Oken *et al.* 2012) and lower levels of exposure may also pose risks to vulnerable individuals including children and pregnant women (Mahaffey *et al.* 2011; Grandjean and Landrigan 2014). Consequently, many countries, including the UK, run monitoring programmes to assess contamination in fish and fish products, and to advise on safe levels of consumption (Scientific Advisory Committee on Nutrition and Committee on Toxicity, 2004; Evers *et al.* 2008). In general, the health benefits from eating fish and fishery products (Saravanan *et al.* 2010; Swanson *et al.* 2012) are believed to outweigh the potential risks (Sidhu 2003; Scientific Advisory Committee on Nutrition and Committee on Toxicity 2004; Nesheim and Yaktine 2007) and recommended limits on consumption relate to a few species of fish or specific groups of consumers (e.g. people consuming fish during pregnancy).

In the UK, the Food Standards Agency (FSA; Food Standards Agency 2015) advises that no more than two tuna steaks a week (about 140 g cooked or 170 g raw each), or four medium-sized cans of tuna a week (about 140 g when drained), should be eaten during pregnancy because tuna typically contains more methylmercury than other types of fish. The FSA also recommends that children, pregnant women and women who are trying to get pregnant should not eat shark (class Elasmobranchii), swordfish (*Xiphias gladius*, Xiphiidae) or marlin (family Istiophoridae), which typically have higher methylmercury levels than tuna. Other adults are advised to eat no more than one portion of shark, swordfish or marlin per week. Given the poor status of some stocks of these species, any reductions in demand for health reasons would benefit stock conservation.

The European Food Safety Authority (EFSA) (EFSA 2015) recently produced a quantitative assessment of the balance of benefits and risks of eating fish. They estimated how many servings of fish people would have to consume each week to reach the dietary reference value (DRV) for $\omega 3$ long-chain PUFA as well as the tolerable weekly intake for methylmercury. When eating species with high methylmercury content, only one or two servings could be consumed before reaching the weekly intake limit, and this was often reached before the DRV. To protect against the neurodevelopmental toxicity of methylmercury, while receiving the benefits of fish consumption, which are typically associated with 1–4 fish servings per week, the EFSA recommends that species with high mercury content should be avoided. However, owing to differences in methylmercury content between species and regions, the identification of these species would ideally be progressed nationally and regionally to avoid measures that would be too precautionary in regions where methylmercury content was acceptable.

In the case of molluscs (oysters, mussels, scallops and other bivalves), local control authorities usually consider the degree of chemical contamination as part of their classification of harvesting areas and this determines whether shellfish harvesting is allowed or not.

The flesh of aquatic animals farmed in the EU can potentially be contaminated with a range of chemicals during production via licensed veterinary pharmaceuticals (antibiotics, parasitical treatments, anaesthetics), disinfectants (used to decontaminate equipment and eggs), other biocidal chemicals used to control diseases (e.g. formalin), feed additives (e.g. flesh pigments), contaminated feed ingredients (e.g. persistent organic pollutants, metals) and antifoulants applied to farm structures (e.g. copper oxide). The use of antibiotics in aquaculture has declined greatly since the 1980s due to introduction of vaccines against bacterial diseases (Shepherd and Little 2014). Authorized veterinary products have a prescribed withdrawal period (the minimum period between use and harvest for consumption), and regulations are in place to control the use of products of concern to consumer health; for example, malachite green was banned as a fungal treatment in the EU in 2002 (Anon 2002). Aquatic animals farmed outside the EU are exposed to a similar range of potential contaminant sources, although regulatory regimes may be different (Rico *et al.* 2013).

For most of the cultured species sold in the EU, stocks destined for consumption are not hormone treated. However, overseas tilapia production systems may use a small quantity of 17α-methyltestosterone at the very early life stages to sex-reverse female fry. Male tilapia grow faster, and the absence of females prevents breeding and stunting in culture systems. Methyl testosterone does not persist in the fry and does not pose a risk to human consumers (Megbowon and Mojekwu 2014). The impacts of regular 17α-methyltestosterone use on workers and the environment can be mitigated by good practice.

Consumer health in the EU is protected by setting maximum acceptable residue levels of authorized and other chemicals, and samples of both domestic and imported fish are monitored. In 2012, over 8000 samples of aquaculture products were analysed across 14 MS and <1% were found to be non-compliant (EC 2012b). Within the UK, the Veterinary Medicines Directorate analyses samples collected directly from fish farms by the Centre for Environment, Fisheries and Aquaculture Science and Marine Scotland Science Fish Health Inspectorates. Such monitoring illustrates that the vast majority of domestically produced fish are free from residues, although the incidence in imported fish may be higher (Anon 2006). Over the period 2012–2014, residues (of PCBs, malachite green and emamectin) were detected in 7 of the 4587 samples of UK farmed fish (<0.2%). Cases of identified residues are investigated and action taken to protect consumer health.

In 2004, concerns were raised about persistent organic pollutants (dioxins and polychlorinated biphenyls) accumulating in farmed fish, originating from the dietary fish oil derived from wild fish (Hites *et al.* 2004). However, subsequent studies have suggested that the health benefits of consumption outweigh the health risks (Shepherd and Little 2014), and prompted the UK Food Standards Agency recommendations on fish consumption. Further, dietary fish oil is routinely monitored for contaminants (Shepherd and Little 2014), partial substitution with vegetable oils dilutes contaminants (Berntssen *et al.* 2005), and methods are being developed to remove contaminants (Kawashima *et al.* 2009). However, vegetable oils are usually rich in ω6 fatty acids that are incorporated in the tissues of farmed fish and can reduce the health benefits of the farmed fish for people (Nichols *et al.* 2014). Ways to increase health benefits are being developed, including the use of 'finishing' diets with higher fish oil content, and therefore richer in ω3 long-chain PUFA, for a short period immediately before slaughter. There are also emerging feed products that will need to be assessed in future. For example, there are few existing studies of contaminants in insect protein, even though this is increasingly proposed as an addition to feed. One screening of insect-based feeds for 1000 chemical risks found few contaminants, but cadmium levels were higher than permissible EU limits in some instances (Charlton *et al.* 2015).

Radiation hazards

Nuclear licensed sites in the UK release controlled amounts of radioactive waste into the sea during their normal operations, and the public can be exposed to these artificial sources of radioactivity via the food chain. The nuclear industry is highly regulated, and the FSA is responsible for food safety throughout the UK. In England and Wales, the Centre for Environment, Fisheries and Aquaculture Science undertakes monitoring of radioactivity in the marine environment as well as surveys of people's diet to identify the people who are likely to be the most exposed to radioactivity, such as, fishermen working in the vicinity of nuclear sites who eat their own catch. This information is used to estimate the doses to the population in the vicinity of nuclear sites and thus assess the safety of the aquatic food chain. The monitoring programmes have demonstrated that radioactivity in aquatic food is currently within safe levels and that exposure to members of the public from authorized discharges is well below the UK national and European limit of 1 mSv year^{-1}. For comparison, the average exposure of a person in the UK to natural sources of radiation is approximately 2.2 mSv year^{-1} (EA *et al.* 2013; Papworth and Garrod 2013). With continued use and replacement of nuclear sites in the UK, however, ongoing assessment of risk remains necessary.

Sustainable food supply

Production of aquatic food has to be ecologically sustainable to maintain the ecosystems and resources on which production depends. It also has to be socially and economically sustainable, so that the industries and supply chains that produce and process the food and make it available to consumers continue to function.

For capture fisheries, sustainable rates of production are determined by the natural abundance of stocks, as shaped by evolution, competition, predation and the environment. Access to potential production depends on location and concentration of the fish, time of year, weather and in some cases quota availability, catches of other fishermen and quota and abundance of other species. Production can vary markedly across seasons and years as a result of uncontrollable changes in the physical and biological environment and thus the abundance and dynamics of stocks. Many age and size-classes of fish will often mix on fishing grounds. As most fishing gears are rather unselective, individuals are not consistently caught at sizes and ages that maximize potential yield.

In aquaculture, sustainable rates of production are controlled by the number and size of facilities, choice of cultured species and densities, inputs of food, capacity to remove waste and prevent disease, rates of escape and the carrying capacity of the local environment. The physical, chemical and biological environment may be fully controlled (e.g. intensive enclosed systems), partially controlled (e.g. semi-intensive systems) or managed indirectly (e.g. by choice of location and seasons of stocking and harvest in extensive systems). There is considerable control of the timing and volume of production and of the size and age of individuals harvested. Control of size and age at harvest can be used to maximize the ratio of production to inputs and to maximize income by meeting the needs of specific markets. There is also some control of the ratio of inputs to outputs, based on the trophic levels and efficiencies of species cultured, the diet provided and control of feeding rates.

The main environmental impacts of capture fisheries and aquaculture are different and thus pose different risks to sustainability of production. Differences in pressure on the environment largely result from differences in the direct footprints of capture fisheries and aquaculture that follow from differences in the concentration of production. For UK bottom trawl fisheries, for example, the most productive areas that account for 70% of total production extend to more than 137 000 km^{-2} (Fig. 9) and currently yield 0.83 t km^2 $year^{-1}$ (fresh ungutted weight) worth £1280 km^2 $year^{-1}$ (first sale value). Fisheries benefits and impacts are therefore widely distributed reflecting the dispersed natural resource base that supports them (e.g. plankton and benthic production). Aquaculture production, conversely, comes from highly productive sites that cover a small area. Most forms of aquaculture in the UK, except extensive shellfish farming, are supported by an artificially concentrated resource base. Aquaculture sites are found across the UK (Fig. 10) but are estimated to occupy <100 km^{-2} in total. Some semi-intensive and intensive facilities may produce 1500–20 000 t km^{-2} $year^{-1}$ depending on inputs and stocking densities. This rate of production is at least one thousand times higher per unit area than the production of bottom trawl fisheries. Direct environmental impacts of aquaculture tend to be localized around production sites, but aquaculture has wider indirect effects on the environment when drawing on feed production from larger areas of land or sea, often internationally.

Spatial differences in the scale of capture fisheries and aquaculture production account for differences in the main costs to the two industries. In wild-capture fisheries, the main costs are fuel, vessel maintenance, labour and quota leasing. In aquaculture, the main costs are feed, labour and facilities. Capture fisheries and aquaculture both support processing industries where the main costs are the purchase of fish and labour (Seafish 2014b).

Wild-capture fisheries

Fisheries have long contributed to the UK food supply. Fisheries for many of the species that dominate catches today were important and active before 1000 AD (Enghoff 2000; Barrett *et al.* 2011). During the latter half of the 20th century, UK fish catches generally declined, initially owing to the collapse of some of the larger stocks following overfishing and then to the loss of traditional fishing grounds as more countries claimed extended jurisdiction (Kerby *et al.* 2012). In the last three decades, landings have been increasingly restricted by regulation, which sought to reduce fishing mortality rates to sustainable levels to meet the objectives of the CFP. Landings also fell because quota (the share of the TAC for each stock that was ultimately allocated to UK vessels) was sold or leased to other countries.

As almost all the fish stocks targeted by the UK fleet are fished by other EU MS in EU waters, and, in some cases, by countries with rights to adjacent waters (e.g. Norway), the quantities of landings and stock status depend on the collective decisions

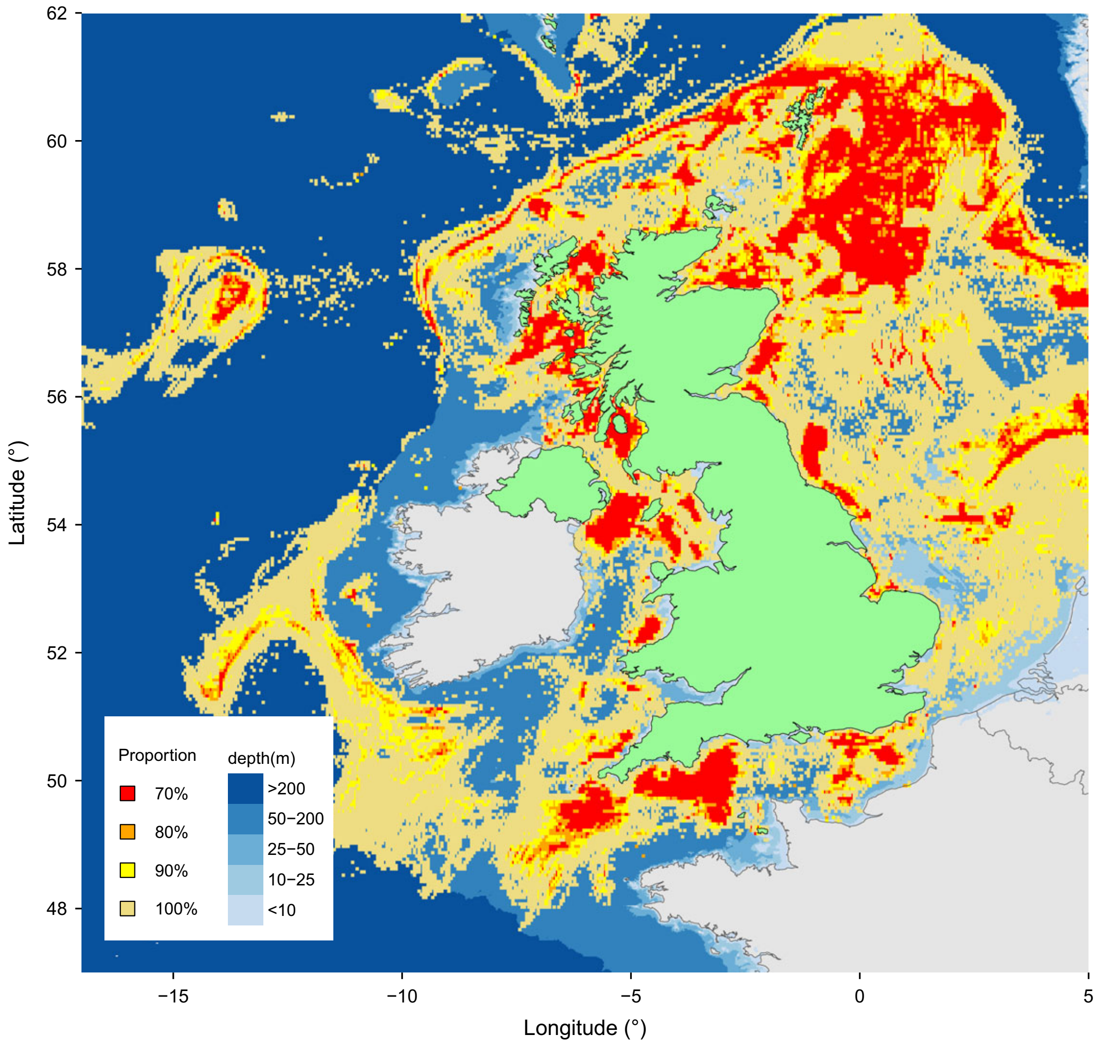

Figure 9 Areas fished with bottom trawls by UK vessels that account for 70–100% of landings weight in the period 2006 to 2009. From analysis of VMS and logbook data (Lee *et al.* 2010; Jennings and Lee 2012). Mean annual landings successfully linked to VMS position data were 165 thousand tonnes.

and actions of managers internationally. In recent years, fishing mortality rates have reached sustainable targets for an increasing proportion of the stocks supporting UK fisheries, and the spawning stock biomass of a number of these stocks has also increased to sustainable levels (Fig. 11). Despite past overfishing and ongoing management efforts to reduce fishing mortality, the larger UK stocks have made a long-standing contribution to food supply. The cumulative international landings of five of the main North Sea demersal species of importance to the UK show that cod, saithe (*Pollachius virens*, Gadidae) and plaice (*Pleuronectes platessa*, Pleuronectidae) have each produced more than 6 million tonnes over the relatively short period during which their status has been assessed, several times their mean standing biomass (Fig. 12a). For the largest pelagic stocks of interest to the UK, the cumulative landings since status assessments began have been 23–35 million t per stock, and fishing rates are predominantly sustainable today (Fig. 12b).

Wild-capture fisheries have impacts on the ecosystem as well as the target species. These result from the differential sensitivity of species and size-classes to fishing mortality and the impacts of fishing gears on seabed habitat. The direct effects of fishing have knock-on consequences for other species, communities, food webs and ecosystem functions and processes. Fisheries

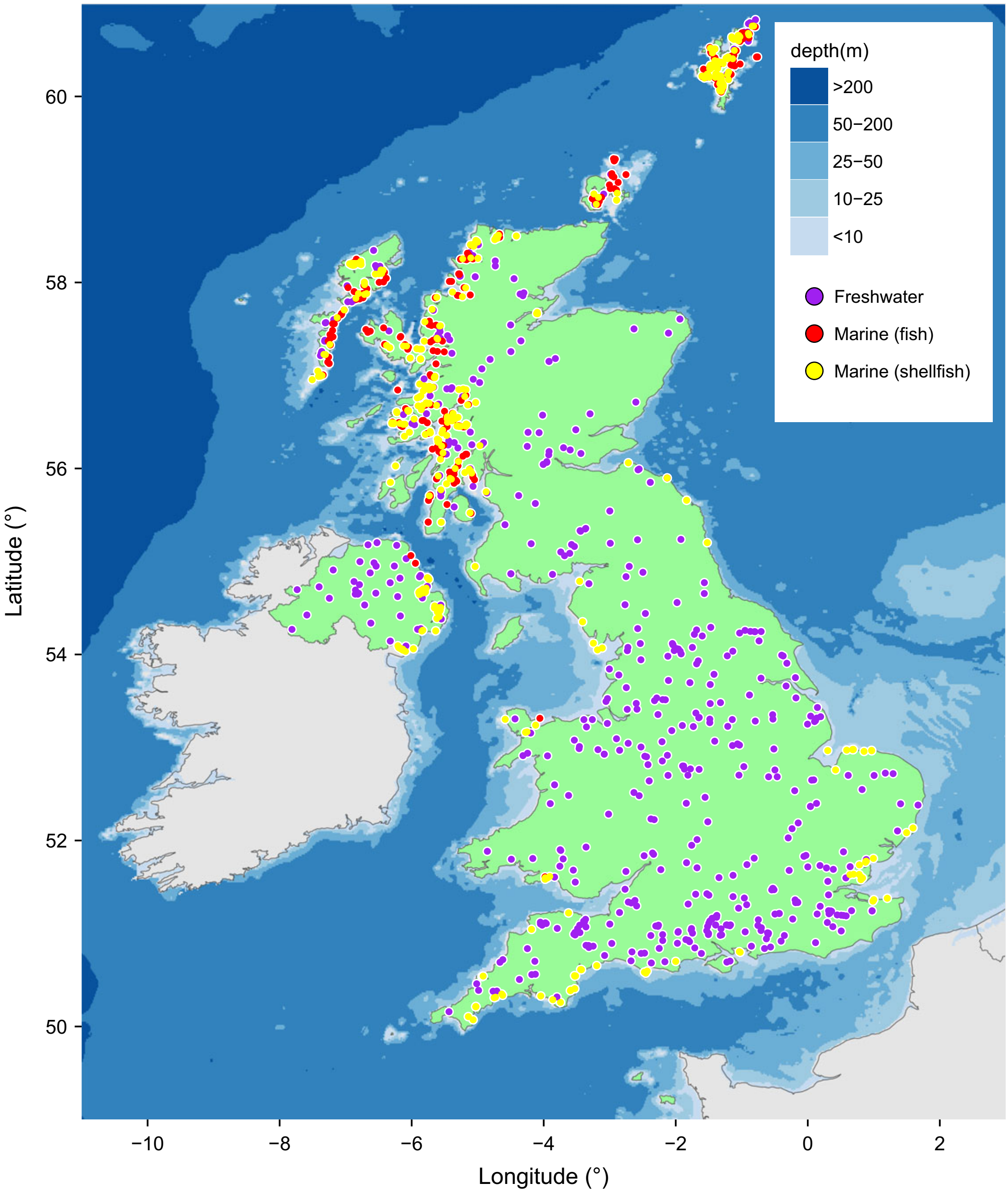

Figure 10 Location of aquaculture sites in the UK. Location and farm-type data from information compiled in the UK Multiannual plan for the development of sustainable aquaculture (Morgan 2014).

may also remove low trophic level forage species that support populations of fish predators, marine mammals and birds (Smith *et al.* 2011). Bottom fishing gears can modify seabed habitats and change the composition of seabed communities (Kaiser *et al.* 2002, 2006). As fishing is necessarily selective, it can also have genetic effects, by selecting for faster life histories or depleting substocks. Impacts of fishing vary widely among fisheries. The wider effects of fishing are usually exacerbated by fishing intensities that are unsustainable for target species, while sustainable rates of mortality for target species usually result in a limited number of wider effects that compromise sustainability (Jennings and Le Quesne 2012). These are usually impacts on sensitive species or habitats. For instance, larger and slower growing species taken as by-catch (e.g. large elasmobranchs) may not be able to withstand rates of mortality that are sustainable for smaller and more productive species and can be substantially depleted or extirpated by fishing (Dulvy *et al.* 2000).

For target species, the stated management objectives for the UK, and other MS fishing these species, are clear: to fish stocks at rates yielding the maximum sustainable yield. For other fishing effects, the objectives are more varied or may not exist, and largely come from legislation linked to environmental protection [e.g. Marine and Coastal Access Act of 2009 (UK Government 2009a), Wildlife and Countryside Act of 1981 (UK Government 1981) and European legislation (Habitats and Birds Directives of 1992 and 2009, respectively (EC 1992, 2009a), Marine Strategy Framework Directive of 2008 (EC 2008)].

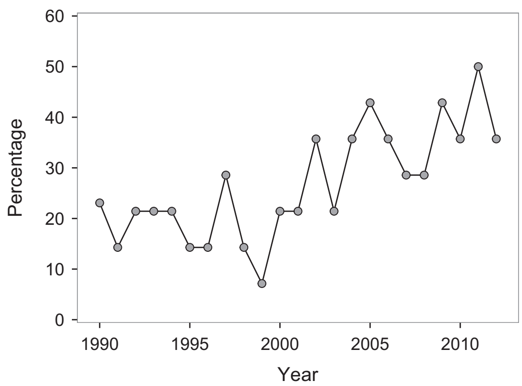

Figure 11 Proportion of UK stocks fished at or below maximum sustainable yield and with biomass at or above the biomass associated with maximum sustainable yield. Data from the International Council for the Exploration of the Sea (ICES 2014).

There are trade-offs between fisheries yields and fisheries impacts on the environment. Broadly, as yields from all species rise to a maximum, there will be more biomass depletion of fished and other species as well as changes in properties of the community such as size and trophic structure (Fig. 13). While a range of exploitation rates can lead to relatively high and sustainable fisheries yields (e.g. 90% of theoretical maximum, Fig. 13), the implications of fishing at the lower and upper end of this range are very different, with much higher target species' biomass and lower fishing impacts associated with lower rates of exploitation. Links between exploitation rates on target species and impacts on the environment can be decoupled

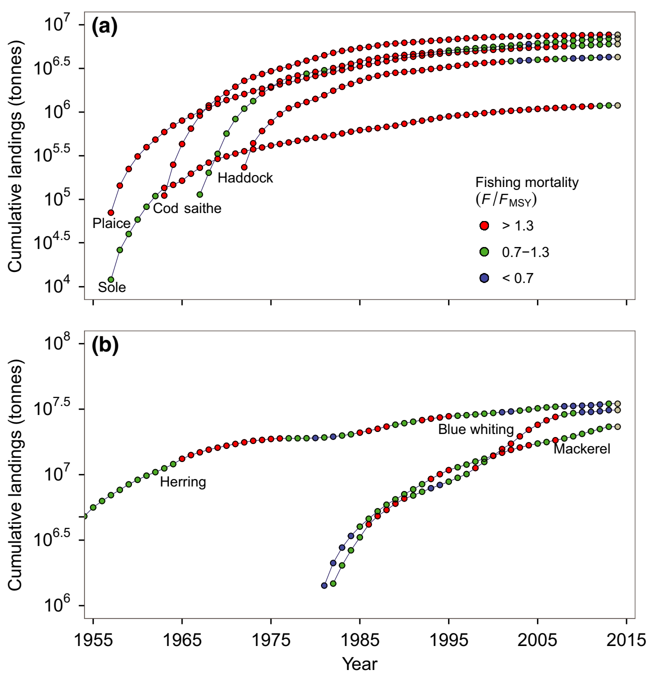

Figure 12 Cumulative landings from (a) selected North Sea demersal stocks and (b) the most abundant pelagic stocks fished by UK vessels, for the period of assessment. Stock status is shown in relation to the fishing mortality reference point (F_{MSY}) or a proxy for F_{MSY}. Data from ICES (2014).

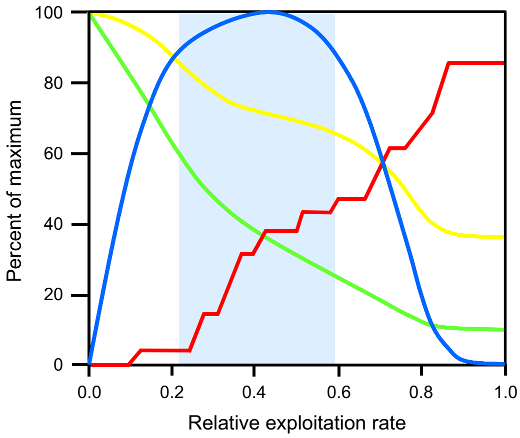

Figure 13 An example of modelled trade-offs between fish production (blue), number of collapsed species (red; species with biomass <10% of unexploited), biomass (green) and mean maximum size (yellow; a measure of the life history composition of the community) as the rate of exploitation on a fish community rises. The pale blue band indicates the range of exploitation rates producing 90% of the maximum multispecies sustainable yield (MMSY). After Worm *et al.* (2009), based on predictions from a size-based fish community model (Hall *et al.* 2006).

to some extent, by measures such as gear modifications and spatial and temporal controls on fishing activity, and the development of such measures has become a strong focus of management systems that are seeking to meet objectives for high and sustainable yields as well as biodiversity conservation.

More widely, many management tools are available and used to achieve sustainability of wild-capture fisheries and the resource base that supports them, including catch (TAC, quota) and effort controls and technical measures such as seasonal, real-time and permanent closed areas and gear restrictions. These are typically used in combination to meet objectives for target stocks, and increasingly for biodiversity and ecosystems. EU, national, regional and local governance, as well as enforcement and compliance, all contribute to the effectiveness of management measures. Monitoring wild-capture fisheries, levels of impact and levels of compliance with regulations is challenging when activity is diverse and dispersed.

The sustainability of the aquatic food supply will also depend on the economic and social viability of the fishing industry. First sale prices for UK fish have only risen slowly in recent years and have not compensated for increased costs, especially for fuel, in most fishery sectors (e.g. Abernethy *et al.* 2010). Prices appear to be rather static because UK prices are strongly linked to global markets when much of the catch is exported and much UK consumption is imported. Further, if production can be increased in an effort to maintain margin, prices may fall owing to oversupply relative to consumption. Some sectors of the UK industry have relatively high profit as a proportion of turnover, such as the large pelagic vessels, but others such as the beam trawlers and demersal otter trawlers do not (Seafish 2014b). The UK fleet was estimated to use 268–298 million litres of fuel per year from 2008 to 2012. For the fleet as whole, fuel use per landed tonne of fish decreased by 100 L from 533 L (2008) to 433 L (2012). Landings value per litre was £2.57 in 2008 increasing to £3.50 in 2012 (STECF 2014). Fuel cost as a proportion of turnover for the UK fleet was estimated to be 19.3% in 2012 (Seafish 2014b). The high fuel use of bottom trawlers can also create a challenge to financial viability during oil price spikes (Abernethy *et al.* 2010) and has also been highlighted internationally because it leads to high greenhouse gas emissions (Tyedmers *et al.* 2005).

The total net profit of the UK fishing fleet in 2012 was estimated to be £98 million, equivalent to 12% of income, with average net profit margins ranging from 26% for drift and fixed nets under 10 m to −19% for longliners (Seafish 2014b). From these net profits, many vessel owners need to make capital repayments on loans as well as making necessary investments in the business to maintain operations. Preliminary analyses by Seafish (2014b) have suggested a high debt to asset ratio for the fleet, ranging from 15 to 65% depending on the sector. But, if the general decline in the size of fishing industry continues and catches stabilize close to current levels, there may be greater financial sustainability for remaining players. Although there are increasingly few fishermen, there is some evidence for long-term roles in fishing within viable sectors. One analysis in 2013 (Scottish Government 2014) showed that more than half the British fishermen in the Scottish Industry had worked in the industry >6 years although there was considerable reliance on non-UK labour to work as deckhands (44% non British compared with 27% of all surveyed). A relatively high rate of interchange between employment in fishing and aquaculture was also recorded, with

21% of fishermen having previously worked in aquaculture.

Many small-scale fishers rely on diversification of activity to maintain the overall profitability fish production, targeting different types of fish or shellfish through the year as well as using their boats for pleasure and fishing charters when opportunities are available. Maintaining livelihoods of these fishers and their communities is challenging when centralized approaches to management tend to reduce flexibility and increase resource dependency (Allison 2005). Emergence of a more widespread coastal aquaculture industry would provide other opportunities for diversification and potentially relieve some of the local pressures on access to wild resources although, as we will see, recent economic pressures have tended to result in fewer but larger aquaculture businesses.

Aquaculture production

Since production of cultured species is managed at a site level, threats to sustainability of production are controlled locally through controls on feed, water quality and disease. In contrast to wild-capture fisheries, many of the environmental impacts of aquaculture are localized rather than diffuse and lead to rapid and direct feedbacks on the sustainability of production (e.g. deoxygenation), so the producer may directly bear the costs of the impact. The scale of impact is usually considered in aquaculture licensing. For example, the Scottish Environment Protection Agency identifies an allowable zone of effect (AZE) for nutrient releases from salmon farms beyond which environmental quality standards must be adhered to. The AZE is predicted from models that account for depth, current speed and other variables that predict nutrient emission patterns.

Impacts of aquaculture vary widely among production systems. Local environmental impacts of aquaculture result from the presence of structures, the physical impacts of harvesting (some shellfish cultivation facilities), organic enrichment and contaminants (Black 2000). Structures may directly change habitats and hydrodynamics, with direct effects on the status of habitats in the areas affected and indirect effects on rates of water flow and mixing. Organic enrichment can lead to eutrophication, changes in the depth of the redox potential discontinuity in sediments and changes in benthic communities to favour bacteria and deoxygenation. Contamination may be linked to releases of heavy metals (from anti-fouling compounds), antibiotics and pesticides. Aquaculture effects with larger-scale implications include the impacts of fishing or farming used to provide feeds, introduction of non-indigenous species, transfer and introduction of pathogens, interbreeding of wild stocks with escapees from aquaculture, increased densities of pathogens and the removal of primary production that would otherwise support natural food chains. Aquaculture may also have effects on predator and competitor species, with predators potentially benefiting from additional food but also subject to depletion by culling. The environmental impacts of UK aquaculture are managed by the Devolved Administrations and associated regulatory bodies through the consenting system. Progress towards sustainability also relies on adoption of best practice by the industry.

Sustainable aquaculture feed supplies will be necessary for continued and sustainable growth of aquaculture. Fish meals and oils are still an essential part of many feeds because the $\omega3$ long-chain PUFA α-linolenic acid (LNA, 18:3ω3) and linoleic acid (LA, 18:2ω6) are required in the diet of fish (there are also varying requirements for EPA and DHA depending on species) and are most easily and cost-effectively obtained from marine sources at present (Hixson 2014).

Nearly half of the current global aquaculture production volume is estimated to rely on feed inputs, and global feed demand is likely to exceed 70 million tonnes in 2020 (Tacon *et al.* 2011). Fish meals and oils are still an essential part of many feeds, but the proportion used in feeds is falling. Even for intensively farmed species such as salmon, aquaculture systems can now be net producers of fish (Crampton *et al.* 2010). In coming decades, total fish meal use is expected to decline further owing to cost pressures and the ongoing emerge of alternatives (Tacon *et al.* 2011; Olsen and Hasan 2012), but total fish oil use may have to increase to contribute to overall growth in feed use (Crampton *et al.* 2010), unless alternate ways of providing $\omega3$ long-chain PUFA are developed or existing methods effectively commercialized (Usher *et al.* 2015).

Feed composition influences the efficiency of consumption, utilization and conversion of that feed and has a large effect on the environmental impact and sustainability of aquaculture (Hixson 2014). As well as affecting fish production, feed composition affects the amount of waste material entering the water or excreted by fish (Schneider *et al.* 2004).

The economic sustainability of aquaculture in the UK and Europe is currently improving. Across Europe, the economic crisis of 2008–09 led to the collapse of many of the economically inefficient aquaculture businesses and led to mergers and acquisitions that resulted in a more efficient industry which is now showing strong recovery and increased profitability (STECF 2013). EU-wide, the major costs are feed (31%), stock (18%), other operational costs (18%) and labour costs (15%), but there is a considerable variation across sectors and countries. In the UK, the industry has also shifted towards fewer larger producers as competition from other larger producers and cheaper imported fish are reducing profit margins.

Relative impacts of fishing and aquaculture

Capture fisheries and aquaculture production methods and their impacts are incredibly diverse, so methods such as life cycle assessment (LCA) have been used to compare systematically their sustainability and to support comparisons between fisheries, aquaculture, agriculture and livestock production. LCA is a standardized and structured method that was developed to assess the life cycle impacts of manufactured products, but has been modified and adopted to assess the life cycle impacts of food production on the environment (Mattsson and Sonesson 2003). Categories used for common accounting of impact in LCA include contributions to greenhouse gas emissions or eutrophication.

Fisheries LCA have shown that fishing operations are the main contributor to environmental impacts from wild-capture fisheries (Avadí and Fréon 2013). Fuel use by fishing vessels typically accounts for the majority of the life cycle greenhouse gas emissions of seafood and as such, it is a relatively reliable indicator of the carbon footprint of landed, unprocessed fish (Parker and Tyedmers 2014). Generally, demersal fisheries use more fuel and emit more refrigerants, per unit volume of fish landed, partly due to the greater dispersion and challenges of locating demersal species (Ziegler and Hornborg 2014). Purse seine fisheries use little fuel compared with trawling (Vásquez-Rowe *et al.* 2010). For example, one study shows that 80% less fuel is needed to catch herring with purse seines rather than trawls (Driscoll and Tyedmers 2010). Most fishery LCA studies do not yet take account of impacts on the ecosystem, which is seen as a deficiency when ecosystem impacts have become a significant focus of environmental concern (Vásquez-Rowe *et al.* 2012).

Given the diversity of production systems within fishing and aquaculture, it is more logical to compare these production systems than the overall performance of fishing and aquaculture. For example, within aquaculture, bivalve culture has a very small impact compared with semi-intensive and intensive aquaculture (Hall *et al.* 2011). The methods of aquaculture with the highest environmental impact are intensive forms of eel, salmon and shrimp farming (Hall *et al.* 2011). For semi-intensive aquaculture, the environmental footprints are comparable with those of fisheries and chicken farms producing similar amounts of protein, but lower than those for pork and beef farming (Ellingsen and Aanondsen 2006; Hall *et al.* 2011). Most aquaculture operations contribute less per unit volume of production to global emissions of nitrogen, phosphorus and greenhouse gas emissions than most pork and beef production systems. Fish fed on well-formulated diets also convert a higher percentage of the food they eat into consumable protein than most farm animals (Hall *et al.* 2011). The major contributor to the footprint of salmon aquaculture, the largest sector in the UK, is feed (Pelletier *et al.* 2009). The domestic (UK) production of fish meal destined for aquaculture feed, includes herring and mackerel, blue whiting (*Micromesistius poutassou*, Gadidae) sandeel (family Ammodytidae) and whitefish trimmings. Therefore, the footprint includes the fuel needed to catch wild fish.

When impacts of both production and supply chains are included in analyses of environmental footprints, it is usually the differences between production systems that dominate the differences between footprints and not the costs of transport to market. So, focusing on local supply will only reduce impact if the production systems are comparable. In many cases, imported fish and fish products from low-intensity fisheries or aquaculture will have smaller environmental footprints than fish caught locally by demersal trawls or cultured locally in semi-intensive and intensive systems.

Processing

A sustainable supply of aquatic food will also depend on the sustainability and viability of the fish processing sector. The gross value added (GVA) of the UK processing industry was an estimated £766 million in 2012. GVA per employee (full-time equivalent) in this industry has increased between 2008 and 2012 reflecting growth in output. From 2008 to 2012, industry turnover increased by 16%, while operating costs increased by 20%, resulting in a 24% drop in operating profit. The industry operating profit margin was an estimated 7% in 2012 (Seafish 2014b), a nominal increase of 2% from 2008 to 2012. The processing industry is viable and supported by inputs from UK fisheries and aquaculture as well as imports. However, the industry continues to face challenges from rising costs because these cannot be passed on to consumers in full owing to competition, including competition from producers and processors of cheaper sources of animal protein such as chicken. Further, with a few exceptions, UK landings comprise relatively small volumes. Thus, apart from basic filleting and freezing services, the value added by UK primary processors may not meet the format, quantity and species demands of large-scale food manufacturers.

Drivers of sustainability

While a range of European and national legislation seeks to ensure that fisheries and aquaculture production is sustainable, there are other drivers influencing sustainability. Foremost among these are certification schemes. These seek to define the provenance of aquatic food in relation to environmental (and in some cases animal and social welfare) standards; an increasingly important consideration for producers, buyers and sellers in societies where many people can make choices about how they produce and source food (Ward and Phillips 2008). The certification scheme run by the Marine Stewardship Council (MSC), for example, now certifies approximately 10% of the global catch by weight. The MSC was created by the World Wide Fund for Nature and Unilever in 1997 to drive improvements in the management of the world's fisheries, but since 1999 the MSC has operated as in independent body. The MSC does not certify fisheries directly but sets standards that independently accredited certifiers use to perform assessments of fisheries. Assessments are based on three principles relating to the state of the targeted fish stock, the impact of the fishery on the environment and the effectiveness of management. The fishery must be deemed sustainable in relation to these standards to be certified. One aspect of the MSC approach is that it seeks to drive improvements in management of fisheries by certifying fisheries for 5 years if they are very close to achieving the standard (Agnew *et al.* 2014a,b). All handling and transfer of MSC-certified seafood is also covered by a Chain of Custody Standard that aims to ensure traceability and segregation of products throughout the supply chain. Certified products tend to be more expensive, but suit buyers and consumers who want assurances and can afford to make a choice. The logos used on certified product and seen by consumers are intended to inform them about the environmental sustainability and provenance of the product they are purchasing. Certification schemes work on the basis that sustainability matters enough to add value or reduce risk for producers and buyers, but different schemes have different sustainability standards and there is inevitably ongoing debate about appropriate benchmarks for sustainability and the relationship between selected benchmarks and societal expectations.

The greatest proportion of certified wild-caught seafood in the UK is certified by the MSC. Over 1000 fish products are now certified, including annual sales of >25 000 t of cod, haddock, tuna and prawns. The Seafish Risk Assessment for Sourcing Seafood and other initiatives are also helping buyers and consumers to make judgements about sustainability when sourcing seafood. These inform consumer choice and may apply to smaller fisheries and niche fish products because the costs of certification by larger schemes are relatively high. A large proportion of aquaculture production is also certified, by a range of schemes, but no single player has yet achieved the same dominance as the MSC in the wild-capture sector.

There is also a trend towards addressing other aspects of sustainability in certification and related schemes, with a number of groups addressing the treatment of people working in fisheries, processing and supply chains. One emerging UK example is the Seafish Responsible Fishing Scheme, an independently audited scheme which aims to demonstrate that a vessel and its skipper are operating to best practice in relation to: safety, health and welfare; training and professional development; the vessel and its mission; care of the catch; and care of the environment. The scheme is intended to allow skippers of certified vessels to demonstrate compliance with industry best practice and enable the supply chain to demonstrate its commitment to responsible sourcing by buying from such vessels (Seafish 2015).

As well as the ethical issues raised by the well-being of people contributing to aquatic food production (see section 'sound food supply'), there is a significant commercial risk for companies when it is highlighted in the media and elsewhere that they are producing or trading aquatic foods that do not meet expectations of consumers and society.

Shockproof food supply

A shockproof food supply is resilient to shocks in production systems and supply chains. Shocks may be driven by environmental, political, technical, demographic and economic forces. The UK Food security assessment conducted by the UK Government Department of Environment, Food and Rural Affairs (UK Government 2009b) detailed potential threats to resilience of the UK food system as a whole (Table 2) and these threats are all relevant to the aquatic food system.

Risks to wild-capture production

In many ways, wild-capture fisheries are well adapted to changing fishing opportunities as these are the norm given the variable dynamics and distribution of wild fishes and changes in quota. The industry is relatively shockproof because vessels may be able to operate over large areas to pursue fish as their distribution changes and may deliberately target a range of species, often with a range of gears, to maintain fishing opportunities despite changes in relative abundance, fishing opportunities and weather. However, there are other risks to production that are harder to mitigate. Shellfish fisheries may be temporarily closed at short notice and without prior warning owing to the presence of biological and chemical hazards. In shellfish fisheries, such as the Burry Inlet in South Wales, there have also been unexplained mass mortality events that dramatically reduced production over several years. Prolonged periods of extreme weather can block access to fishing grounds and spikes in fuel prices can limit fishing effort and profitability. Further, in mixed fisheries, so-called choke species that limit fishing opportunities for other species because the quota has been reached, may limit overall catches.

Environmental effects on fish recruitment mean that variations in TAC and catches of non-quota species are expected. These variations are exacerbated by fishing (Planque *et al.* 2010). There are many examples of stocks of small pelagic fishes fluctuating in abundance by over 100-fold on decadal timescales (Beverton 1990) and sustained periods of low abundance impact the fishing and processing industries. For instance, collapse of the 'Downs' herring stock in the southern North Sea saw spawning stock biomass of almost 1 million tonnes in the early 20th century fall to <10 000 t when the fishery was closed in 1977 (Cushing 1992). The absence of herring from UK markets following the collapse of the Downs herring and other stocks also appeared to change consumer's attitudes to this fish. When stock recovery led to herring fisheries being reopened in the 1980s, most herring landings were exported and only a very small proportion consumed in the UK.

The effects of climate variation and change on stock distributions can also shock the production and supply chain when stocks are shared among jurisdictions. For example, the north-east Atlantic mackerel is one of the largest and most mobile stocks fished by UK vessels, but in recent years its migrations and centres of distributions, especially of the western stock component, have shifted north. This has led to increasing numbers of fish spending increasing amounts of time in Icelandic and Faroese waters (ICES 2011, 2013). The mackerel fishery is one of the most important to the UK by value and volume (Figs 8 and 12b). From 2007, Iceland wanted, and started, to catch this species in quantity as it was now using Icelandic waters, when 90% of the TAC was already allocated to the EU and Norway. From 2008, Iceland set a unilateral quota for mackerel, with the net result that the total landings from the stock could significantly exceed the TAC. Overshoot of the TAC led to suspension of MSC certification for fisheries targeting this stock in 2012. In March 2014, a new political agreement was reached that allocated 49% of the TAC to the EU, 22.8% to Norway and 12.6% to the Faroes. The agreement set aside 15.6% of the TAC for Icelandic and Russian catches, but Iceland remained outside the agreement and continued to set a unilateral quota. Although the UK has maintained catches from the stock, because it remained relatively productive

Table 2 Potential threats to the UK food system. Based on an analysis by the UK Government Department of Environment, Food and Rural Affairs with small modifications (UK Government, 2009b).

	Types of threat to resilience			
Issue	Political	Technical	Demographic and economic	Environmental
Global availability of food	Wars, export restrictions, bilateral land deals, biofuel policies	Reduced yield growth, investment and skills	World population growth, income growth	Climate, weather, disease, pests
Global sustainability of food production	Wars, institutional and policy failures	Unsustainable fishing, farming and aquaculture practices	World population growth, intensification of farming and aquaculture	Ecosystem breakdown, water scarcity, soil erosion, climate, desertification
UK access to food	Trade embargoes, breakdown in EU or international trade, regulations	Energy security, port and airport closures, transport failures	Importance of imports, decline in UK economic competitiveness	Climate, weather, disease, biodiversity risks
UK food chain resilience	Strikes, protest, regulation	Radioactive fallout, IT systems corruption, contingency planning, just-in-time provision	Energy price shocks, pandemic flu, financial crisis, production and supply-chain concentration	Weather
Household affordability and access	Planning restrictions	Lack of transport	Poverty, food price inflation, currency devaluation, unemployment	Weather
Safety and confidence	Malicious activity, regulatory failures	Contamination	Demand for complex processed products, longer supply chains	Pests, diseases

even when the TAC was exceeded, an unresolved division of the TAC coupled with uncertainty about further changes in the distribution of the mackerel places ongoing pressure on the industry, exporters and processors.

Imports have buffered shocks to the processing industry that resulted from rapid decreases in landings by UK vessels during the latter half of the 20th century, although direct shocks to the UK 'distant water' catching sector resulted in the demise of this sector of the fishing industry and several ports and businesses that supported it. Landings in this sector were impacted by the loss of traditional fishing grounds and reduced productivity of UK cod stocks. Thus, extension of Icelandic jurisdictional claims to 4 miles in 1950, 12 miles in 1958, 50 miles in 1972 and then 200 miles in 1975 led to three 'cod wars' and effectively removed UK access to these fisheries. As UK cod catches from Icelandic waters fell, they were to some extent buffered by UK landings from the North Sea. Here, there was a so-called gadoid outburst from the mid-1960s to mid-1970s, characterized by high recruitment of cod and haddock that allowed high landings to persist despite increasingly heavy fishing. However, this period was followed by a rapid fall in productivity and landings once recruitment fell (Pope and Macer 1996). Landings have remained relatively low since then, owing to lower recruitment and hence lower productivity of the stocks (O'Brien *et al.* 2000) and implementation of more conservative management measures. The loss of access to Icelandic waters and the lower cod landings from UK waters mean that 90% of the cod currently consumed in the UK is imported. The importing of cod has buffered shocks for the supply chain and consumers. Imports are now sustaining processing industries that were originally developed to process UK landings. In 2010, Iceland alone supplied 40% of the whole cod and 80% of cod fillets imported by the UK (European Market Observatory for Fisheries and Aquaculture Products 2013). In general, this is indicative of a pattern where most of the countries fishing in the northern north-east Atlantic now produce more fish than they consume while those fishing in the southern and central areas are net consumers (Fig. 14).

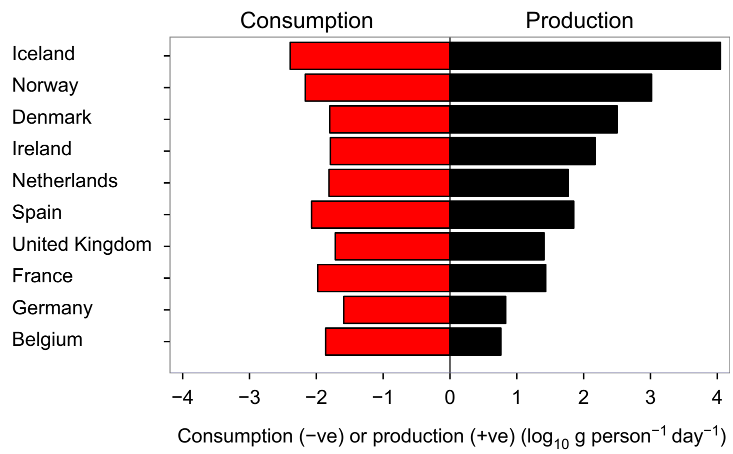

Figure 14 Fish production and consumption by selected nations bordering the north-east Atlantic. Fisheries data from FAO FishStatJ (FAO 2015) and population data from the United Nations (2015).

Extended periods of bad weather affect supply and lead to short-term increases in fish prices (Graddy 2006). These predictable price spikes have led to risk taking among fishing vessels that seek to be the first to land catches after protracted periods of bad weather. Prolonged periods of stormy weather in 2014 increased short-term prices of fresh fish by 10% or more, but equally, prolonged periods of good weather can maintain lower prices (Fishing News 2014).

In the longer term, pressure on marine space, especially in the inshore zone, may significantly constrain the activities of small-scale fishers because vessel types and access rights may not allow them to rove widely when local opportunities are constrained (e.g. Hart and Johnson 2005; Caveen *et al.* 2014). Given the contribution of small-scale fisheries to total UK landings, such changes are unlikely to influence overall food security. But they could have significant impacts on the availability of fresh fish in rural communities and on the associated businesses that benefit from fishing and fish.

Risks to aquaculture production

The single biggest risk to the maintenance and growth of aquaculture production is disease, often as a consequence of diverse indirect factors such as hypoxia and climatic events (e.g. El Niño). The FAO estimate that at least \$6 bn is lost from annual aquaculture yield with certain diseases playing a particularly dominant role [e.g. white spot disease in shrimp has continued to cause losses exceeding \$1 bn per annum since emergence in the early 1990s (Stentiford *et al.* 2012)]. Other risks come from storm events and the changing prices and availability of feed. Disease reduces the volume and stability of aquaculture production. Atlantic salmon dominates aquaculture production in the UK, and three commonly imported groups are *Pangasius* spp. from Asia and sea bass and sea bream (family Sparidae), mainly from Greece and Turkey. Stability and growth of production of all these species are at risk owing to pathogens. Emergent issues, such as microsporidiosis in farmed bream, have the ability to stunt fish development, with very little current scope for treatment (Palenzuela *et al.* 2014).

Sealice infections are arguably the most important disease issue for Atlantic salmon production in Scotland. The cost to the UK industry, in terms of treatment and lost production, is estimated to be £33 million year^{-1} (> £300 million year^{-1} globally) (Costello 2009). Sealice counts have to be monitored and treatment is mandatory above a fixed threshold, which is set to minimize transmission from farmed to wild salmon. Failure to control sealice abundance is largely attributed to the development of resistance to treatments (e.g. organophosphates, pyrethroids and avermectins). In Norway, the authorities have ordered the destruction of infected farmed salmon to protect wild migrating salmon. Failures to develop and/or register new treatments or approaches (e.g. cleaner fish) that reduce rates of lice infection are a major threat to maintenance of current rates of production as well as expansion of the industry.

Selective breeding for resistance of salmon to sea lice infection and disease has recently been proposed and would reduce the need for chemical and physical interventions (Gharbi *et al.* 2015). Other approaches to reduce risks that are being pursued including the use of cleaner fishes, salmon diets that deter lice, reducing the time that salmon are in the sea and siting cages at depths where lice are less abundant. Despite the current importance of sealice issues to the aquaculture sector, a major outbreak of a disease listed in Annex IV Part 2 of the Aquatic Animal Health Directive (EC 2006), such as Infectious Salmon Anaemia (ISA; Murray *et al.* 2010), would represent a highly significant threat to production, with movement restrictions and stock destruction orders potentially closing down large farming areas, disrupting supply chains and impacting national production volumes.

Despite high levels of disease-related mortality, *Pangasius bocourti* production in Asia, particularly Vietnam, has expanded rapidly in recent years. However, the production systems are highly susceptible to disease emergence due to contact with wild species, high density and continuous production, physical linkage between ponds and some high-risk production practices (e.g. use of mortalities as feed) (Bridges *et al.* 2007). In general, levels of biosecurity are poor and surveillance systems are not well developed. The large majority of *Pangasius* production takes place in the Mekong delta that is effectively as a single epidemiological zone. Also, farms are densely clustered (distance between farms is often only a few metres). Thus, a newly emerged and highly infectious disease would spread rapidly between farms. In addition, management of any emerging disease is likely to be inadequate given weak regulation, little management infrastructure and poor access to aquatic animal health services. These factors combine to make emergence of new diseases a major threat to *Pangasius* production in Asia. Parallels can be drawn to intensive shrimp production in Asia where a series of emergent pathogens over the past 2 decades (Stentiford *et al.* 2012) have most recently culminated in 'early mortality syndrome', a multifactorial disease causing huge production losses in nations such as Thailand (Lee *et al.* 2015).

Sea bass and gilthead sea bream (*Sparus aurata*, Sparidae) production in the Mediterranean has grown rapidly in recent years, despite considerable disease problems, notably viral nervous necrosis (Le Breton *et al.* 1997). However, a major threat to future culture of these and other species comes from the potential withdrawal of formalin from use in aquaculture. Although the environmental risks from formalin are considered to be limited (FDA 1995), a number of studies have raised concerns about the risks it poses to workers (National Toxicology Program 2014). It is likely, therefore, to be banned in the EU within the next few years due to human (operator) health risks. Formalin is the cheapest and most commonly used treatment for protozoan (e.g. *Trichodina* and *Ichthyophthirius multifiliis*), oomycete (e.g. *Saprolegnia parasitica*) and monogean (e.g. *Gyrodacytlus* spp.) ectoparasites of range of freshwater and marine aquaculture species, including Atlantic salmon, rainbow trout, sea bass and sea bream (Verner-Jeffreys and Taylor 2015). It is also used as a general disinfectant and to treat eggs. There is often no obvious, proven, alternative to formalin. Currently, it is not clear what impact the withdrawal of formalin may have on the productivity and profitability of aquaculture, but if alternatives cannot be rapidly identified, then it is possible that costs of production will rise and production may fall.

Risks to supply chains

Supply chains may be impacted by changes or fluctuations in the rate and types of production by fisheries and aquaculture, strikes, political unrest, failure of food to meet safety standards, breakdown of production or storage facilities or transport networks, economic factors (e.g. cost increases, reductions in purchasing power), health scares, consumer or supplier boycotts, campaign groups and trade restrictions or embargoes. Risks are exacerbated by just-in-time approaches that effectively reduce costs for industry but risk continuity of supply for consumers when supply chains are disrupted.

The volume and types of products entering supply chains will depend on the management of fisheries and aquaculture and the effects of the threats to production we have already discussed, such as weather, disease and changes in management. For wild-capture fisheries changes in volume and types of fish entering supply chains are an inevitable consequence of changes in TAC and its effect on quota, and other factors such as the size of fish in landed catches will vary with the success of recruitment and the numbers of fish in different year- and size-classes. In coming years, the introduction of the so-called landing obligation in the CFP (EC 2013) will change the sizes and relative numbers of landed fish that are entering supply chains because discarding will be reduced. Broadly, the landing obligation requires that catches of all species with a TAC must be landed, subject to some exemptions linked to high survivability of returned fish, disproportionate costs of handling and technical challenges associated with reducing selectivity. While the magnitude of impact is still uncertain pending decisions on exemptions, it is likely that a higher ratio of landings to catches for TAC species will 'choke' mixed fisheries in which different species and stocks are caught with the same gears at the same time. Choke species are those that stop all fishing in mixed fisheries because their quota has been used. As the landings obligation will also reduce or stop 'high grading' (the retention and landing of only the highest-quality and highest-value fish to maximize the value of quota), the size, quality and seasonality of supply from fisheries may also change. As well as affecting the size and value of fish and fish products in the supply chain, the landings obligation is also expected to affect the seasonality and stability of supply. One recent analysis of the potential effects of the landings obligation on UK supply chains (Tegen Mor Consultants, 2015) concluded that effects would be greatest in ports when fish first entered the supply chain, but would dissipate downstream. Small ports would likely be most affected as they had least capacity to make profitable investments in additional handling; given volumes of material would be variable but small. Further along the supply chain, changes in the volume and types of products derived from UK fisheries may have a small influence on patterns of importing and thus the balance between imports and UK production.

The reliance of the UK on trade in aquatic food means that the UK relies heavily on the function of supply chains that cross UK borders. Large volumes of fish and fish products are imported and exported via the Channel Tunnel and ferry routes from the UK to the European mainland and also by air. As perishable commodities, fish and fish products and the markets they support are rapidly affected by transport delays. In July 2015, for example, the Scottish Government raised concerns over the impact that delays and the threat of delays at the Channel Tunnel were having on Scottish seafood production and export businesses. Producers and exporters reported that supermarkets and wholesalers on the European mainland were cancelling orders and fish were being rejected due to deterioration, as a result of delays caused by the Channel Tunnel being closed owing to migrant incursions and industrial action in France. For UK-based aquaculture businesses, the resilience of the feed supply chains is also important. These are affected by fluctuations in forage fish stocks and changes in global prices and demand for feed.

Resilience to shocks at the national level may be maintained by sourcing food from a wide range of sources and supply chains (portfolio effect) and legislating and/or putting in place structures, measures and support to ensure sustainability, safety and sufficiency of production. Large shocks to aquatic food supply, while unlikely to affect overall UK food security, may still have significant social and economic impacts. For example, there are currently 10 500 fish and chip shops in the UK serving 382 million portions of fish and chips each year (National Federation of Fish Fryers 2015). In practice, however, the largest shocks to the aquatic food system owing to factors such as energy availability and price (Table 2) are likely to be linked to shocks to the food system as a whole.

Sound food supply

A sound food supply is based on production processes and supply chains that meet legal standards for welfare of animals and people as well as the ethical expectations of society. A sound food supply should also be authentic, so that buyers, processors and consumers can be confident about the identity (species, stock) and origin (region as well as sourcing from wild-capture fisheries or aquaculture) of the products they buy and sell. Legal standards may provide some assurances about welfare and authenticity, but parts of society continue to raise additional ethical concerns about the welfare of people involved in aquatic food production and supply, environmental sustainability of production systems, the use of genetically modified feed or fish, and animal welfare. Even if legal standards are not set, adhered to or being developed to address welfare and ethical issues, certification bodies have addressed or raised awareness of these issues and increasingly influence the choices made by a proportion of buyers and consumers.

Ethical concerns about fish production and supply have focused on well-being of people, fish and the environment. The FAO defines ethics as a 'systematic and critical analysis of the moral factors that guide human conduct in a particular society or practice'. Welfare and ethical issues in aquatic food production are diverse but may be broadly grouped into three categories: social, environmental and animal (Table 3). Welfare and ethical issues can emerge at many stages in the production process and supply chain (Table 4).

Many welfare and ethical issues are common to both aquatic and to land-based food production and processing. Some welfare and ethical issues are already addressed by legislation. Fish welfare in aquaculture is currently regulated, for example, but fish welfare in wild-capture fisheries is not. Access to some potential sources of aquatic production, such as marine reptiles or mammals, is legally restricted or prohibited in some countries but not in others. As a large proportion of aquatic food production relies on industries where workers can be, and/or are, exposed to higher risk of injury, death and rights abuses than in many other jobs, social welfare issues are an increasing focus of analysis and legislation.

Social welfare and ethics

The exploitation of people working in fisheries, aquaculture and fish processing has received considerable media coverage. Internationally the issue involves thousands of people and many issues including bonded labour, forced labour, child labour, other modern slavery and health and safety violations (Table 5; International Labour Organisation 2013; Ratner *et al.* 2014; Couper *et al.* 2015). We have highlighted the extensive global trade in fish and fish products, and some production and supply chains involving exploited workers are known to support UK consumption. The fishing industry, retailers, importers and certification bodies have increasingly reacted to concerns and reports about the use of forced and bonded labour and poor treatment of workers in fisheries and aquaculture. For example, Seafish are currently modifying their Responsible Fishing Scheme (RFS), which was introduced in 2006 to raise standards in the UK catching sector, into an International Organisation for Standardisation (ISO)-accredited standard that will also deal with social and ethical issues. Vessels in the RFS can therefore provide assurance to the supply chain that fish have been caught responsibly. The Marine Stewardship Council (MSC) has also stated that companies prosecuted for forced labour violations in the last 2 years will be out of scope of the MSC programme and will be ineligible for MSC certification. It applies to the fisheries and to the chain of custody, although the MSC standard does not require a direct assessment of the social and employment conditions in fisheries and supply chains.

Despite the focus on social welfare issues among countries exporting to the UK, bonded and forced labour, modern slavery and health and safety violations have also been reported in UK fisheries. In the most serious recent example, in February 2004, 38 illegal immigrants from China were collecting cockles (*Cerastoderma edule*, Cardiidae) in

Table 3 Welfare and ethical issues linked to the production and supply of aquatic food.

Category	Issues
Social welfare and ethics	Access to wild and 'free' food resources and environments: who has, and who should control, access and supply
	Safety and treatment of people: health, safety and human rights in the fishing and aquaculture industries and associated supply chains
Environmental welfare and ethics	Human impacts on the state of the aquatic environment that affect the capacity of the environment to produce food
	Sustainability of production systems: responsibility for paying and ameliorating environmental costs of production (including corporate responsibility)
	Impacts on biodiversity: welfare of impacted species and habitats, responsibility for bearing costs of impacts
Animal welfare and ethics	Fish welfare: in aquaculture and wild-capture fisheries, prior to and during death and during live transportation and storage

Table 4 Welfare and ethical issues during production and in the supply chain.

Supply-chain element	Description	Main ethical issues
Pre-production	Processes and industries that provide services supporting capture or aquaculture production	Safety and treatment of people
Fish capture	Process of catching and handling fish	Safety and treatment of people, state of the environment, impacts on biodiversity, sustainability of production systems, animal welfare
Aquaculture production	Process of farming and handling fish	Safety and treatment of people, state of the environment, impacts on biodiversity, sustainability of production systems, animal welfare
Purchase and collection	From farm, fisher or vessel, may involve transfer of live animals	Safety and treatment of people, state of the environment, animal welfare
Processing	Fish processing and packaging for sale to markets or consumer	Safety and treatment of people, state of the environment
Distribution	Transport of product between locations of collection, preparation and sale	Safety and treatment of people, state of the environment, animal welfare (if live distribution)
Storage	Handling of fish in freezing or dry storage (fish meal and oil) facilities, live storage facilities	Safety and treatment of people, state of the environment, animal welfare (if live storage)
Sales	Sale of product to consumers	Safety and treatment of people, animal welfare (live sales)
Preparation	Preparation for consumption in food outlets and homes	Safety and treatment of people, animal welfare (live cooking)
Support-services	Third-parties processes and industries that support post-capture components of the supply chain	Safety and treatment of people, state of the environment, fish welfare

Table 5 Social welfare issues. Definitions are based on more comprehensive definitions developed by the International Labour Organisation of the United Nations, the United Nations, and the Convention Concerning Forced and Compulsory Labour.

Issue	Description
Bonded labour	Forced work for an employer without being paid, often as a way of paying a debt
Forced labour	Work extracted from any person under menace of any penalty
Child labour	Work that deprives children of their childhood, their potential and their dignity, and is harmful to their physical and mental development
Other modern slavery	Issues of recruitment, transportation, transfer, harbouring or receipt of persons, by means of the threat or use of force or other forms of coercion to extract work that are not explicitly categorized as bonded labour, forced labour and child labour
Health and Safety violations	Work conducted for an employer who knowingly failed to comply with a national legal requirement or acted with indifference to employee safety, thus increasing risk of hazards leading to accidents or illness

Morecambe Bay when they were cut off by the rising tide, and 23 of these people died. When their gangmaster was sentenced to 14 years in prison for manslaughter, facilitation and perverting the course of justice (in practice he was released and deported to China in 2012), the judge at Preston Crown Court commented that he had been motivated by avarice and displayed little regard for the safety of the cocklers. This event catalysed a series of changes to legislation to regulate labour in fisheries, agriculture and food processing, from the Gangmasters (Licensing) Act 2004 that was intended to prevent exploitation and maintain working standards to the Modern Slavery Act of 2015 which consolidated existing human trafficking and slavery offences. Nonetheless, there are continued reports of illegal, bonded and forced labour in fisheries, and in 2012, the UK Serious and Organised Crime Agency (SOCA) reported 74 potential victims of exploitation in the fishing industry (SOCA 2013). Their exploiters were abusing an immigration concession (transit visas) for seamen to facilitate the potential victims' entry to the UK. A subsequent report noted that fishermen continue to find employment in the UK via agencies in the Philippines and Ghana, but then experience poor working conditions and are not paid the wages originally contracted once they arrive (National Crime Agency 2014). Raids by SOCA in both England and Scotland have led to least 50 exploited fishermen being freed from fishing boats.

Fishing, and to a lesser extent aquaculture, are inherently dangerous industries. There were 1039 fatalities from accidents involving UK fishing vessels from 1948 to 2008 (Roberts *et al.* 2010), most resulting from vessels that foundered. Risks are highest in the winter. From 1996 to 2005, fatal accidents among fishermen exceeded those among the general UK workforce by 100:1, and from 1992 to 2006, the average fatality rate was 126 per 100 000 fishermen year^{-1} with main causes being foundering vessels and fishermen falling or being pulled overboard (Maritime Accident Investigation Branch 2008). The highest fatality rates are recorded in the agriculture sector in the UK, and fishing is the most dangerous job within this sector (Health and Safety Executive 2014a). As fatalities in recent years have often been linked to fishing vessels that are unstable, overloaded and unseaworthy, there are strong ethical arguments to ensure that the industry is profitable and that regulations do not encourage more risk taking. Aquaculture is a safer occupation than working in wild-capture fisheries, but the relative fatality rates are still high. In the Scottish aquaculture industry, for example, there were 5 fatal accidents in the 11-year period 2003–13 (Health and Safety Executive 2014b). This equates to a rate of approximately 25 per 100 000 year^{-1}.

Environmental welfare and ethics

Environmental ethics concern the moral and ethical relationship between humans and their environment, focusing on non-human nature rights. A 'weak anthropocentric' environmental ethic assigns an instrumental value to nature (Turner 1998). Both fishing and aquaculture affect the current state of the environment and the state of environment inherited by future generations. Most regulation of the impacts of fishing and aquaculture on the state of the environment is intended to achieve sustainability. While the concept of sustainable development (World Commission on Environment and Development 1987) implicitly recognizes that future generations should inherit an environment that meets their needs, it has been variously interpreted in practice, and often in ways that heavily discount future environmental benefits. Further, approaches for assessing sustainability may be developed without understanding future trajectories and tipping points that may compromise ecosystem function and services in the longer term (Bishop 1978; Perrings and Pearce 1994).

Producers of aquatic food rarely pay the full costs of production because external costs (i.e. negative externalities) are borne by others. External costs include changes to the immediate environment and ecosystem services and costs that affect the future environment and will be paid by future generations. Approaches have been developed to convert these costs into a common monetary unit to assess the 'real' costs of production, but the methods to do this are often controversial when the wider costs of production do not have a clear market price (Smith *et al.* 2010). There are ongoing debates about the extent to which society should pay wider costs of food production (Godfray *et al.* 2010). For example, is it legitimate for deep-water fisheries to damage habitat-structuring cold-water corals or for salt marshes or mangrove forests to be removed to make space for aquaculture?

There remains significant interest in the idea that the costs of food production should better reflect future environmental impacts and that this would drive the development of more sustainable food systems. Owing to the high greenhouse gas emissions from the food system as a whole, the use of carbon markets to drive changes in practices and hence emissions in agriculture has been considered, but this has been little debated for fisheries. Creation of supranational governance structures and management of an equitable system would be challenging, as national activities as well as financial incentives can have transnational impacts and there will often be strong trade-offs between local and national or international objectives (Sandler 1998; Godfray *et al.* 2010; Smith *et al.* 2010). In comparison, market-based economic incentives based on the 'polluter pays' principle, such as emission permits trading schemes, have limited costs and may be used instead (Turner 1999). For example, carbon trading schemes could help mitigate negative externalities and as well as high level of consumption (Godfray *et al.* 2010).

Animal welfare and ethics

For wild-capture fisheries, welfare becomes an issue from the time that fish encounter fishing gear, after which point they may either escape or be caught. Fish that are caught will die and be processed, while others will be discarded. If not already dead, discarded fish may subsequently die from trauma or predation, while others may recover and survive. In aquaculture, welfare is an issue throughout the life cycle as well as at the point of slaughter. Stocking density, diet, feeding technique and management procedures all affect welfare prior to death. In part, welfare is a focus of aquaculture operations because it affects the health and flesh quality of fish (Ashley 2007).

In most commercial wild-capture fisheries, fish die as a consequence of the harvesting process and are not intentionally slaughtered (Metcalfe 2009). With some fishing methods, death may occur during, and as a direct consequence of, the catching process. But often, and including when high-value fish are targeted and where flesh quality is of primary concern, fish will be alive when brought aboard the fishing vessel. There is currently little, if any, welfare regulation that constrains how such fish are handled or killed. In the UK, and most other countries, no livestock farmer or aquaculture worker could legally treat animals in the way that commercial fishermen are legally allowed to.

Animal welfare (including farming and aquaculture) in the UK is currently regulated by the Animal Welfare Act of 2006 (UK Government 2006), but 'nothing in this Act applies in relation to anything which occurs in the normal course of fishing' (Section 59). At an international level, an FAO analysis of ethical issues in fisheries (FAO 2005) notes that 'Animal welfare, which will probably play a larger role in ethical discussion in the future, is not considered further in the study'. The major part of the FAO study deals with ethical concerns related to the well-being of humans and the ecosystem.

There are likely to be two reasons why comparatively little attention has been directed to welfare in wild-capture fisheries. First, fish welfare is regarded as a highly contentious issue that attracts vociferous comment from an inevitably polarized community: from animal rights activists who might wish to ban fishing altogether to a fishing industry that would largely defend current practices. In part, this defence would be based on the argument that there are few, if any, workable and economically viable alternatives to current fishing practices. Second, there is a widely held belief that fish cannot feel pain. This has been increasingly contested with evidence in recent years (Braithwaite 2010; Rose *et al.* 2014), and while it may be difficult ever to establish that fish suffer in the same way as mammals, including humans, these analyses suggest that fish have aversive experiences during capture and death that are reasonably described as painful.

Many types of fishing gears and fishing methods are used. Consequently, the time between first encounter with a gear and death can vary from minutes to hours or days. Once caught, fish may experience different types of gear-specific trauma. For example, fish caught with many other fish in the cod end of a large demersal trawl will have different experiences from those caught on individual hooks on a line. Different gears will have different loss rates and levels of specificity. Thus, some fish will encounter gear, possibly sustaining some level of damage or stress, but then escape and some gears will catch mostly the target species or size-classes, while others may catch many other species and size-classes that will later be discarded dead or dying. For fishes that escape, almost nothing is known about sub-lethal effects on growth, predation and reproduction.

Current trends in public attitudes to human and animal welfare suggest that issues relating to fish welfare in wild-capture fisheries are likely to become a more visible issue in the UK. For example, the organization 'Fishcount' has campaigned to increase understanding of fish sentience, raise awareness and promote solutions to the suffering of fishes in commercial fishing. It also aims to increase awareness of welfare issues in aquaculture (Mood 2010). Their campaigning activity has been paralleled by a growth in research on humane slaughter of animals in wild-capture fisheries, including feasibility testing of some systems in fisheries.

In UK aquaculture, slaughter has to meet the requirements of the Animal Welfare Act, but farmed fish are specifically excluded from the detailed provisions of the European Council Regulation on the protection of animals at the time of killing (EC 2009b). Automated percussive systems are widely used for killing fish in aquaculture, especially salmon in the UK. Electrical stunning systems have also been developed and used for humane slaughter of large numbers of fish (Robb and Kestin 2002). The fish are usually killed in the water by passing an electrical current. Voltage and duration of current can be set so that the fish are stunned immediately, and die without regaining consciousness (Lines *et al.* 2003). With advances in methods and understanding of impacts, there are ongoing efforts to provide effective guidance on the slaughter of fish in aquaculture (Farm Animal Welfare Committee 2014).

With the adoption of humane slaughter methods in aquaculture, there has been some focus on adapting these for use in wild-capture fisheries (Lambooija *et al.* 2010). This focus has also been motivated by the potential improvements in flesh quality that are achieved from rapid slaughter and bleeding of fish for human consumption (Olsen *et al.* 2013, 2014). However, developments in slaughter have yet to address commercially feasible methods for culling the very large numbers of fish that are caught and processed together in some fisheries.

As with fish, crustaceans are believed to have aversive experiences during capture and death, and commercial devices are available and used for electrical stunning prior to processing, although there is commonly live storage and transport before killing (Elwood *et al.* 2009; Neil 2010; Roth and Øines 2010).

If and when fish welfare becomes more of a societal issue and impacts purchasing decisions, the main questions for regulators to address will be what is acceptable in terms of welfare and ethics and what is acceptable and feasible commercially and economically. The ways in which regulators address and answer these questions and the ways in which society interacts with regulators and markets will inevitably impact access to aquatic food production.

Food authenticity

Aquatic food is highly traded and wild-capture fisheries catch a very diverse range of species, often closely related. Several species are produced by aquaculture as well as caught in the wild. Given the visual similarity of fish white muscle from different stocks or species, as well as the processing of fish into products where appearance or flavour are modified by other ingredients, most consumers will not be able to identify what they are eating or where it comes from unless this information is provided. Sources of aquatic food need to be known to ensure food safety, to provide confidence in certification schemes, to protect stocks or species from overfishing, to meet legal requirements and to ensure fair competition among producers and processors (as the species identity and origin of fish can have a large impact on price).

With aquatic food often passing through complex production and supply chains (Table 4), there can be a high probability that products mix inadvertently. Further, if common names of fish and shellfish are used on sales notes and labels, several different species may be mixed as part of normal practice. There are also opportunities for deliberate misrepresentation and mislabelling of product in many supply chains (food fraud). If these are taken, they can increase income and meet demand for fish that cannot be met through legal routes.

Ensuring the authenticity of fish products is desirable because it ensures that consumers receive what they pay for and that the health benefits and risks of the products are known. Risks include the risks of contamination previously identified, but also general food safety concerns. For instance, the refreezing of fish that are purported to be fresh-chilled when they have already been in long-term cold storage, the use of undeclared chemical additives to increase the water carrying capacity of fish muscle, and thus the weight and value of product (e.g. Lampila 1993), and the addition of bulking agents. If authenticity is effectively monitored and largely assured, then fish caught or imported illegally are much harder to market, thus reducing the incentive for illegal, unreported and unregulated fishing (Helyar *et al.* 2014). Assuring authenticity also reduces the risk that species of conservation concern will be caught and marketed (Marko *et al.* 2004; Barbuto *et al.* 2010). Confidence in authenticity encourages consumers to pay higher prices for certified products and is essential if certification schemes are to incentivize intended changes in fishing and aquaculture practice. For the production, processing and retail sectors confidence in authenticity creates parity in markets and is more likely to incentivize legal activity.

Food fraud is the misrepresentation of foods at any point in the supply chain. Many visual, genetic, biochemical and stable isotope methods are employed to identify types and origins of aquatic food (Lees 2003; Rehbein and Oehlenschlager 2009; Martinsohn *et al.* 2011; Nielsen *et al.* 2012). Food fraud relating to aquatic-sourced foods is relatively common, even in nominally well-regulated supply chains. In the UK, traceability and labelling are regulated by laws (UK Government 2013) that include the transposition of several EU requirements for the traceability of labelling and food (e.g. EC 2001, 2002). Certification bodies also place considerable emphasis on chain of custody certification as an essential part of the process that ensures their labels are only used correctly, reassuring buyers and maintaining credibility of certification.

Mislabelling of fish is monitored and reported in the UK by the FSA, and also on an *ad hoc* basis by consumer groups and others. Although mislabelling is reported in some sectors, such as fish and chip shops and other catering outlets in the UK, the rates have been relatively low [e.g. 7.4% cod mislabelling in one recent study of catering outlets (Miller *et al.* 2012)]. Higher levels of mislabelling have been reported in other wealthy countries. In the USA, a study by Oceana (Warner *et al.* 2013) from 2010 to 2012 involved purchasing 1215 samples from 674 retail outlets in 21 states. When these were DNA tested, one-third were shown to be mislabelled according to the U.S. Food and Drug Administration (FDA) guidelines. Systematic mislabelling of fish and fish products has also been reported in Canada (Hanner *et al.* 2011), Australia (Lamendin *et al.* 2014), Italy (Filonzi *et al.* 2010) and other countries.

Conclusions

Aquatic food security depends on a food supply that is sufficient, safe, sustainable, shockproof and sound. The UK, as a single nation embedded in a dynamic global web of producers, processors and markets, relies heavily on trade to keep fisheries and aquaculture profitable and to meet the preferences of UK consumers. Aquatic food in the UK is sufficient in volume and affordability to meet the preferences of the most people, and the supply is relatively secure, at least in the short term, because alternative foods are available and consumer demand is fairly stable. Ongoing challenges to food security are expected, however. A growing global population and middle class, predominantly outside Europe, is likely to influence UK trading relationships and the cost and availability of fish and feed imports. With few opportunities to increase capture fisheries production, there may be greater economic incentives to develop UK aquaculture.

The UK aquatic food supply is sufficient to meet the current needs and preferences of most consumers, although equitability of access and distribution varies substantially with individual wealth. Imports and UK production combine to support fish consumption of <100 g person^{-1} week^{-1}, well below recommended consumption rates of 280 g person^{-1} week^{-1}. A lack of consumer demand rather than lack of access to production accounts for consumption falling below recommendations. As a relatively wealthy nation, the UK is likely to be able to import more fish or export less home production if consumer demand increased, but we have seen that price and other factors continue to limit any growth in demand (Sainsbury's Supermarkets 2012). Indeed, total per capita meat and fish consumption is now stable or falling in the UK (Fig. 4) and it is uncertain whether this is a short-term response to the economic factors or indicative of a persistent change in preferences.

As global fisheries and aquaculture production is dominated by output from relatively few regions and countries, aquatic food is a highly traded commodity and many countries rely on imports to support national consumption. Trade is an essential part of the current UK food system. The net volume of UK fish imports is equal to approximately 75% of fisheries landings by UK vessels into the UK. Consumers tend to eat small amounts of a fairly narrow range of species, often those which are not predominantly UK caught or farmed. Income received from exporting products of low interest to UK consumers and/or which fetch higher prices overseas maintains profitable fisheries and aquaculture businesses. Imports provide aquatic foods that meet consumer preferences for product type and price.

Many of the most valuable species that are caught and cultured are exported (e.g. shellfish, salmon), along with lower value high volume but nutritious species that are not favoured by UK consumers (e.g. mackerel, herring). As climate and changing fishing opportunities have led to greater prevalence and higher productivity of warm-water species in UK waters (Simpson *et al.* 2011), consumers have not consistently eaten more of these species. Rather, they have maintained their consumption of cold-water species, which are declining in productivity or prevalence in UK waters, by eating imports from countries to the north of the UK. Over 90% of UK cod consumption, for example, is now sustained by imports. Responses of this type have been dubbed 'maladaption' in the context of climate change (Barnett and O'Neill 2009). Current imports thus comprise fish that were traditionally consumed in the UK but can no longer be caught in sufficient numbers to meet demand and cultured species that have proved attractive to UK consumers. The low impacts of campaigns to encourage consumption of a wider range of fish suggest that the majority of UK consumers have rather conservative patterns of fish consumption.

At present, relatively low consumption and demand in the UK, coupled with a diversity of supply chains and high purchasing power, suggest that aquatic food security in the UK as a whole would not be seriously impacted by most shocks to the aquatic food supply chains. However, when specific sectors are highly dependent on a small selection of species or producers, they are exposed to greater risks of shocks. For example, the stability of supply of warm-water prawns has proved vulnerable to disease outbreaks in producer countries. If shocks affected food imports more widely (e.g. breakdown of transport networks) or affected terrestrial and aquatic production (e.g. weather), the effects on aquatic food could exacerbate overall impact. In future, the UK will be influenced by trends in capture fisheries and aquaculture production and changing demand internationally, as well as pressures on the overall food system. Indeed, the Government has highlighted the importance of global food security for the UK because global stability depends on there being enough food in the world to feed everyone and that this food is distributed in a way that is fair to all (UK Government 2010).

Globally there is little prospect of increased supply from wild-capture fisheries, but aquaculture production is likely to keep growing. Wild-capture fisheries are unlikely to expand owing to more vigorous and effective management to reduce the risks of future unsustainability, efforts to improve fisheries' economic performance and the impacts of biodiversity conservation. Further, climate effects on underlying productivity are likely to be neutral or slightly negative globally, although this may belie increased production in some temperate and polar regions (e.g. Cheung *et al.* 2010; Barange *et al.* 2014). Currently, the bulk of global aquaculture production comes from relatively few nations, but many other nations could further develop aquaculture. The balance between the global growth of aquaculture and trends in demand for aquatic food, outside and inside the UK, will likely influence the probability of investment in building a larger UK aquaculture industry.

If growth in global aquaculture production slows and the proportional contributions of existing countries to total production remain relatively stable, then increases in fish demand and consumption in the main producing countries may reduce the economic incentive to export. For example, growing national demands in many Asian countries, coupled with slower growth of Asian aquaculture, could limit or increase the costs of supply to the EU and UK. Growing domestic demand in Asian countries is expected owing to ongoing population growth, income growth and urbanization (Kharas 2010). Alternatively, rising global demands for aquatic food may fuel the growth of aquaculture in regions where current production is low, but production costs and regulation are lower, helping to meet demands in Asia as well as Europe and providing fewer incentives for further aquaculture growth in the UK.

The economic incentives to develop aquaculture in the UK and internationally will also be influenced by feed costs and availability, the main exception being for shellfish farms that rely on natural sources of production. Pressures on costs are already driving developments in the feed industry, including the substitution of fish meals, and to a lesser extent fish oils, with other products. However, most feed ingredients can also be used in animal feeds and are thus subject to wide-ranging price competition and the volatility of international markets. For example, a fivefold increase in consumption of farmed meat in China in the last 20 years has driven demand for grain and pushed up costs of production internationally. Indeed, imports of soya bean, soya bean meal and oil to China account for half the world trade in these commodities, and global prices are sensitive to Chinese demand. The United States Department of Agriculture (USDA) has predicted fairly stable volumes of soy imports to Europe through 2023, but expected increases in cost will affect margins or be passed to consumers (USDA 2014). The effects of increasing demand for animal feed in other parts of the world are well recognized as an issue for UK agriculture in general. The recent UK Government Food Security Enquiry highlighted risk to the UK from reliance on animal feed imports from outside the EU and recommended additional efforts to source from within the EU and to promote the farming of legumes that provided greater output per unit area (UK Government 2014a).

The increasing number of middle-class people globally may also drive other demands for fish meal and oil that compete with traditional feed markets. For example, the middle classes are expected to own more pets and often feed them with pet food containing fish products. One study that attempted to estimate fish use in pet food, based on the composition of Australian pet food, estimated that 14% of the wild catch not destined for human use was currently used in pet food, and this estimate excluded pets in China (De Silva and Turchini 2008).

The EU has highlighted potential risks to aquatic food imports that result from changes in global supply and has tasked MS to plan for growth in aquaculture. With aquaculture a devolved responsibility in the UK, it remains to be seen how support for aquaculture will be addressed around the UK and the differences in rates of development that will evolve. The UK Government is considering the role of aquaculture in achieving food security and the UK Food Security Assessment (UK Government 2010) concluded that 'The growth in consumption of fish and seafood against the backdrop of overfishing suggests a greater role for aquaculture in meeting future demand and ensuring the future security and sustainability of global fish stocks'. Technically, there is scope to increase aquaculture production in the UK. A doubling of current UK production with little change in current consumption would make UK more or less sufficient in terms of aquatic food volumes, although aquaculture would not be expected to replace imports given the preferences of consumers and limitations on the variety of species which could be farmed. Given consumer preferences and costs of producing large volumes of warm-water species, it is likely that imports of warm-water species, including prawns and generic low-cost whitefish for processed products, will be an enduring component of the UK aquatic food supply.

Further growth in aquaculture would also buffer volatility in fish supplies to processors and consumers. It may also provide more stable employment opportunities and bolster coastal communities, where much of the supporting and processing infrastructure can serve both aquaculture and fisheries. For example, analyses of the Scottish production sector demonstrated that interchange of people between fisheries and aquaculture jobs can be particularly important for sustaining rural coastal communities (e.g. Shetland) which have been heavily reliant on the fishing industry for employment (AB Associates 2008). Growth of UK aquaculture outside Scotland would increase the resilience of the UK aquatic food supply to external shocks (James and Slaski 2009) and, if consumer demands for fish persist, development of UK aquaculture would allow the UK to manage and account for the sustainability, safety and resilience of this production system rather than exporting risk and impacts to other regions.

Wild-capture fisheries accessible to the UK provide a significant and sustainable source of aquatic food, but it is unlikely that production volumes can be increased while ensuring sustainability. Seeking more production would increase long-term risks to stocks, the economic viability and safety of the industry and progress towards meeting environmental objectives. The extent to which the UK will depend on aquatic food imports in future will largely depend on changes in UK aquaculture production and the extent to which this production is consumed in the UK.

The EU currently imports >80% of all protein used in fish and livestock production, exposing the EU and UK industries to the volatility of global markets (EC 2011). Consequently, efforts are underway to identify and use alternate protein sources. One option, which is also being used and explored as a means for producing food for people directly (Van Huis 2013), is the rearing terrestrial invertebrates (e.g. fly larvae) for aquaculture feed (Makkar *et al.* 2014). As a natural component of the diets of some fish, fly larvae provide a rich source of protein and are much more digestible than vegetable-based protein alternatives. Many insects can be raised effectively on biological waste in small areas, up to 200-fold smaller than those required to produce the same volume of traditional protein crops (e.g. soya). Insect-based aquafeeds can also replace wild-caught fish protein in feeds and can be produced locally. Pilot production facilities are currently producing insect-based aquaculture feed alternatives at a comparable cost to traditional products. The crude protein content of dried housefly larvae, black soldier fly, mealworms, crickets and silkworm pupae is closely comparable to that of soya meal and only slightly lower than wild-caught fish meal (Makkar *et al.* 2014).

Technological developments will continue to influence the growth of aquaculture and also the demands for fish. There have been continued reductions in the use of fish meal and oil in feed (Tacon *et al.* 2011), but there is also the possibility of complete replacement. *Camelina sativa* plants, for example, have now been genetically engineered to augment endogenous fatty acid biosynthesis with the capacity to synthesize the otherwise non-native $\omega 3$ long-chain PUFA. The *Camelina sativa* seed oil produced is sufficiently rich in $\omega 3$ long-chain PUFA that it can likely be used as an alternative to fish oils in aquafeeds and recent field trails that showed genetically modified *Camelina sativa* could be grown as a routine crop (Usher *et al.* 2015). Many factors currently discourage consumers from eating recommended amounts of fish and, to obtain health benefits, $\omega 3$ fish oil supplements are already widely taken as an alternative to fresh fish. Given the technological developments described, there may be increased use of plant-based $\omega 3$ supplements or the direct use of plant-based $\omega 3$ in other food products, thus weakening the arguments to eat fish on health grounds.

Sustainable growth of the aquaculture sector worldwide would be improved by increased availability of cost-effective vaccines for control of the major disease threats, reducing reliance on chemical treatments (antibiotics and antiparacitica1s) and the environmental impacts that may result. For example, the rapid growth of aquaculture in the Mekong Delta, Vietnam relied on high levels of antibiotic use (Nguyen Dang Giang *et al.* 2015). There is the possibility that aquaculture systems relying heavily on antibiotic use may also contribute to human health risks by driving the development of antibiotic resistance in bacteria associated with these aquatic animals, some which may be human pathogens, such as certain *Vibrio* spp.

Clearly, the security of aquatic food production in the UK is heavily influenced by global production and markets and our review highlights how connections between environment, economy, society and health influence the sufficiency, sustainability, safety, shockproofing and soundness of the UK food system. Many interactions and potential interactions which need to be understood to improve predictions of the effects of alternate policy, management and investment options and the effects of social, economic and environmental change on the food system. For example (i), how do different combinations of aquaculture and fisheries production, by type and location, influence the sustainability of processing industries and rural communities? (ii) how do environmental impacts resulting from changes in fishing and aquaculture production in the UK compare with corresponding impacts from changes in imported production? (iii) how would changes in the balance of UK fisheries and aquaculture production, imports and exports affect the resilience of the aquatic food system, particularly in the light of recent changes in fish stocks and fishery management and the effects of climate change? (iv) how do changes in the balance of UK fisheries and aquaculture production, imports and exports affect the safety of people working in these industries in the UK and abroad? and (v) how might health advice on fish consumption be linked to information on the availability and sustainability of production?

Our assessment has addressed the sufficiency of supply from aquaculture, fisheries and trade; the safety of supply given biological, chemical and radiation hazards; the social, economic and environmental sustainability of production systems and supply chains; the resilience of the food system to social, economic and environmental shocks; the welfare of fish, people and environment; and the authenticity of aquatic food. Our assessment reveals trade-offs and challenges overlooked in sectoral analyses of fisheries, aquaculture, health, medicine, human and fish welfare, safety and environment. Information to support our assessment was highly dispersed and collected or collated by groups responsible for monitoring diet, human health, aquaculture, fisheries, the environment, maritime and human safety and poverty. There is no systematic process for assessing the extent to which the aquatic food system is secure. While there are some good examples of efforts to understand the interactions between parts of the food system, such as the trade-offs between the risks and health benefits of fish consumption (EFSA 2015) and the relative environmental impacts of different types of fish production (Hall *et al.* 2011), the generally disparate treatment of different parts of the food system makes it challenging to assess the future and wider implications of change in any part of the food system. For instance, how is current advice on fish consumption linked to the capacity of fisheries, aquaculture and import markets to provide for that consumption and what are the knock-on consequences for people and the environment? Further, the groups collecting relevant data spanned different parts of Government, non-Governmental organizations (including charities) and commercial organizations. To improve understanding and assessment of different parts of the aquatic food system, and to identify opportunities and trade-offs, an initial step might bring together a series of surveillance indicators to provide a broad analysis of progress and threats to achieving aquatic food security. This would require only a small investment as most of the underlying data or indicators are already reported in sectoral analyses, and many are highlighted here.

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