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Viewpoint

The past and future of fish consumption: Can supplies meet healthy eating recommendations?

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ABSTRACT

In many developed countries fish and shellfish are increasingly promoted as healthy alternatives to other animal protein. We analysed how much fish was available to UK and global populations after accounting for processing losses, and compared this to recommended levels of fish consumption. In 2012, UK domestic fish landings per capita fell 81% below the recommended intake, although declines were masked by increased imports and aquaculture from the 1970s onwards. Global wild fish supply per capita declined by 32% from its peak in 1970. However, overall fish supplies per capita increased by 10% over the same period due to rapidly expanding aquaculture production. Whilst aquaculture has so far prevented a downturn in global fish supplies, many developed nations continue to aspire to consume more fish than they produce. Until demand is balanced with sustainable methods of production governments should consider carefully the social and environmental implications of greater fish consumption.

1. Introduction

Fish constitute a major source of animal protein in many nations, with some countries, for example Bangladesh, the Solomon Islands and Indonesia, relying on fish for over half their animal protein intake (Kawarazuka, 2010). However, in recent years a crisis has developed in global fish supply (Watson et al., 2013). Commercial fish stocks are experiencing widespread collapses and the rate is accelerating (Worm et al., 2006). Predator species are particularly vulnerable to the effects of fishing, with estimates of more than 90% decline in predator biomass in coastal areas of the North Atlantic and North Pacific in the last 50 years (Tremblay-Boyer et al., 2011). The last 50 years have also seen expansion of fisheries across the Southern Hemisphere and further offshore (Swartz et al., 2010), whilst demersal fisheries have expanded to targeting species at greater depths, for example, deep water species such as orange roughy (*Hoplostethus atlanticus*) and blue ling (*Molva dypterygia*) (Morato et al., 2006). These patterns demonstrate that current exploitation rates are unsustainable. In addition, as marine biodiversity declines the quality of ecosystem services we receive are reduced and future recovery of marine communities becomes less likely (Sala and Knowlton, 2006).

In recent decades the health benefits of eating fish have also become better appreciated. Fish protein (including shellfish) is typically lower in saturated fats than red meat, whilst oily fish is high in essential fatty acids (Calder, 2004). Research suggests that a diet rich in fish protein lowers the risk of cardiovascular disease, whilst omega-3 fatty acids are critical for neurological development and health (Daviglus et al., 2002). Fish is also high in dietary nutrients such as calcium, selenium and zinc (Sheeshka and Murkin, 2002). These properties have led to recommendations by various national and international bodies on how much fish we should eat to benefit health, with examples we found ranging from 97 to 550 g capita^{-1} week^{-1} (Table 1).

In this paper we explore historical patterns of fish supply to ask whether there are enough fish to go around to meet health aspirations, both now and into the future. In the United Kingdom, records of domestic fish landings and imports were recorded annually from 1888, presenting a useful case study to illustrate broader patterns in developed nations' fish consumption. These records allow us to determine patterns in fish availability (i.e. quantity of fish per capita) over a period of 124 years as national landings have declined and the UK's population has increased. We examine these patterns in the context of national recommendations on how much fish people should consume for good health. We then use fish production data published by the World Food and Agriculture Organisation and other literature to quantify global fish supply from 1950 to 2012. Using these global data alongside detailed historical

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records from the UK, we consider the global implications of fish-importing nations recommending higher levels of fish consumption than they can meet from domestic supplies.

2. Methods

2.1. UK fisheries supply

To quantify UK (including Ireland until 1921, and Northern Ireland thereafter) fish supplies for the period 1888 to 2012, we obtained figures for domestic landings of finfish and shellfish by UK vessels from annual fisheries statistical tables (Table 2). Landings of finfish were reported as the weight of head on, gutted fish. Prior to 1965 many shellfish landings were provided in numbers of individuals rather than weight. We converted these to metric tonnes either using guidelines present in the statistical tables or by estimating the average weight per specimen based on the results of literature searches. We gathered figures on UK aquaculture production from the FAO FishStat Plus database (FishStat, 2013); these included marine, freshwater and brackish aquaculture production. To adjust UK fish supply for imports and exports, we gathered import and export data for the whole of the UK from the Ministry of Agriculture, Fisheries and Food (MAFF) statistical tables. We did not include fish products such as fish meals and oils as the vast majority are used for livestock and aquaculture feeds rather than direct human consumption (Naylor et al., 2009).

Fish supply is usually quoted as gross tonnage (FAO, 2012), but such figures overstate what is available for consumption. To determine the overall weight of fish actually available for human consumption, we converted landed weight of fish to processed weight using conversion weight ratios produced by HM Revenue and Customs (2010) (HMRC) in consultation with the National Federation of Fishmongers. We used HMRC estimations of the proportion of usable whitefish (cod, codling, haddock, hake, ling, whiting, lemon sole and plaice) and herring after conversion to fillets as a proxy conversion factor for all finfish. The conversion factor from whole fish (head on, gutted except for herring which is usually landed whole) to fillets with skin averaged 0.49 (S.E. 0.02) edible proportion by weight. Shellfish conversion weights were an average of the different conversion rates for all shellfish provided (lobster, prawn, langoustine, shrimp, cockle, mussel, oyster, scallop, whelk and winkle). The average conversion factor for shellfish was 0.28 (S.E. 0.05) edible proportion by weight. Whilst some imports include whole fish, many are already prepared in some measure (e.g. frozen fish fillets, processed fish cakes, shelled prawns, etc.), so no conversions were applied to imported weight (Agriculture and Agri-Food Canada, 2011; Seafish Industry Authority, 1991; United Nations, 2010).

To calculate UK annual fish supply per capita we acquired British human population data from censuses produced by Histpop (2010) and the Office of National Statistics (2014) for the period 1881–2011. Histpop provided census data every 10 years from 1881 to 1931 and the Office of National Statistics provided census data every 10 years from 1971 onwards. We interpolated between data points to provide yearly population estimates of adults and numbers of children under 15 years old. The Central Statistics Office (2014) provided annual Irish and Northern Irish population data for the period 1891–2008 (until 1921 the population of the UK included all of Ireland, from 1922 just Northern Ireland).

2.2. Global fish supply

To quantify global fish supplies, we obtained data on global capture fisheries and aquaculture (freshwater, brackish and marine) production from the United Nations Food and Agriculture Organisation (FAO, 2009, 2012) and FAO FishStat Plus (FishStat, 2013). We disregarded landings of aquatic plants, marine mammals and inedible species (e.g. corals, sponges) from the analysis, as these are not sources of fish protein and thus were assumed not to contribute to fish intake recommendations. Fish production was separated into finfish and invertebrates and corrected for processing losses using the formula from HMRC. Whilst we recognise that processing losses will vary around the world as a result of the different species landed, cultures, markets and processing techniques, we used these conversion rates to account for the fact that some degree (however variable) of processing loss will occur. To calculate fish supply per capita we obtained annual world population estimates from 1950 to 2012 from the Population Reference Bureau (PRB, 2013). The global population was also adjusted to account for the assumption that children under 15 need to consume half the quantity of fish.

2.3. Quantifying fish production needs based on health recommendations

The UK Food Standards Agency recommends that people eat 280 g of fish/shellfish per week (Food Standards Agency, 2010). To determine whether the UK's fish supplies are sufficient to meet

Table 1
National dietary guidelines for fish consumption.

Country	National guidelines	Recommended amount (g wk^{-1})	Source
United Kingdom	2 portions (140 g each) per week, one of which should be oily	280	Food Standards Agency (2010)
United States	2 average meals (6 oz each) per week, not including species high in mercury	340	U.S. Food and Drug Administration (2014)
Australia	2–3 servings per week (150 g each) not including species high in mercury	375	Food Standards Australia New Zealand (2013)
New Zealand	2–3 servings per week (150 g each) not including species high in mercury	375	Food Standards Australia New Zealand (2013)
Canada	At least 150 g each week	150	Health Canada (2011)
Denmark	200–300 g fish per week	250	WHO (2003)
Iceland	300 g fish per week	300	Gunnarsdottir et al. (2009)
Austria	1–2 portions per week (total 150 g)	150	WHO (2003)
Germany[a]	1 portion of seafood per week	100	WHO (2003)
Greece[a]	5–6 servings per week	550	WHO (2003)
Georgia	12.8–15 g fish per day	97	WHO (2003)
Ukraine	20 g fish per day	140	WHO (2003)
Estonia	2–3 servings per week (50 g each)	125	WHO (2003)
Armenia	30 g fish per day	210	WHO (2003)

[a] Specific portion size not provided, assumed that one portion equals 100 g.

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Table 2
UK fish landings data statistical table sources.

Years published	Source	Country the records relate to
1888–1902	Board of Agriculture and Fisheries	United Kingdom and Ireland
1903–1919	Board of Agriculture and Fisheries	England and Wales
1920–1954	Ministry of Agriculture and Fisheries (MAF)	England and Wales
1955–1964	Ministry of Agriculture, Fisheries and Food (MAFF)	England and Wales
1903–1964	Fishery Board for Scotland	Scotland
1903–1921	Department of Agriculture and Technical Instruction for Ireland	Ireland
1922–1962	Department of Commerce: Report on Sea and Inland Fisheries	Northern Ireland
1965–1998	MAFF	United Kingdom
1999–2008	Department for Environment, Food and Rural Affairs (DEFRA)	United Kingdom
2009–2012	Marine Management Organisation	United Kingdom

this recommendation for the UK population as a whole, available fish from all sources (i.e. capture and aquaculture production after correction for processing losses, plus imports but minus exports) was converted to g capita^{-1} week^{-1}. The UK shortfall was then calculated assuming that children under 15 require half the recommended amount. To calculate shortfalls in global fisheries production, we used current health advice on levels of fish consumption from all the countries that we could find information for (a total of 14 countries, Table 1). This produced an average recommendation of 246 g capita^{-1} week^{-1} for fish consumption. Whilst we acknowledge that this figure will differ between nations (some countries are very dependent upon fish protein whilst others consume very little fish), we used it as a benchmark to explore how much fish are theoretically required to provide the global population with a healthy quantity of fish protein. Global capture and aquaculture production (freshwater and marine) after correction for processing losses was converted to g capita^{-1} week^{-1} based on the adjusted global population. Recognising that a significant proportion of global fisheries landings are not recorded in FAO statistics, we also reviewed the scientific literature (using keyword searches in Google Scholar and Thomson Reuters Web of Science) to determine how much extra fish are potentially available from other sources.

3. Results

3.1. Historical trends in UK fish supplies

The quantity of fish landed by UK vessels peaked in 1913 and then declined throughout the remainder of the 20th century to the present, although large declines in landings also occurred during the two World Wars when boats were put to other uses and it became dangerous to fish (Fig. 1a). Our time series ran until 2012; during the last 5 years of our time series, landings were the lowest at any point in the last 120 years except during the Second World War, with domestic landings in 2012 falling 69% below their 1913 peak. Although invertebrate landings have increased since the 1960s these have not compensated for the decline in finfish (Fig. S1, supplementary figures).

Significant proportions of fish landed by UK vessels are landed abroad and are thus classed as exports. In 2012, the quantity of wet fish and shellfish landed abroad by UK vessels came to 234,100 t, equivalent to 60% of the domestic landings by UK vessels that same year (Fig. S1, supplementary figures). These exports are mostly made up of pelagic species such as herring and mackerel (in 2012 pelagic species comprised 73% of UK landings abroad), for which historically there has been little UK market but for which human consumption and fish reduction markets exist in northern Europe (Marine Management Organisation, 2013). If these quantities are included in UK domestic production, landings fell 51% below their peak in 1913.

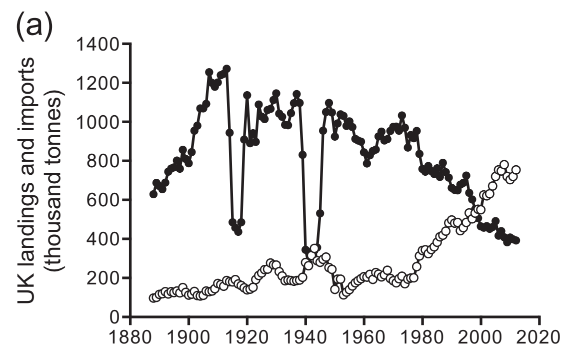

Fig. 1a. UK fish landings and imports. Domestic landings of finfish and shellfish (closed circles) by UK vessels and imports of fish and fish preparations (open circles) into the UK (these include direct landings of fish by foreign vessels, but exclude fish meals and oils), 1888–2012.

UK capture fisheries only represent one source of fish for UK consumers, the others being imports and aquaculture. Imports have increased dramatically since the 19th century, whilst exports (which include UK vessel landings abroad) have fluctuated (Fig. S2, supplementary figures). There was a sharp upward trend in imports from the 1970s onwards when domestic landings began to fall steeply (Fig. 1a). Hence, imports made up some of the expanding deficit left by declining landings. Domestic aquaculture production (marine and freshwater) has also increased in importance in the last fifty years, rising from 30 t in 1950 to 203,000 t in 2012 (Fig. S2, supplementary figures).

Taking all sources (but excluding landings abroad and exports), the quantity of fish available (before processing) to UK consumers increased from 621,000 t yr^{-1} in 1888, peaking shortly after the Second World War at 1.29 mt yr^{-1} (Fig. 1b). Fish supply gradually declined after this period before dropping swiftly in the 1970s, after which increasing imports stabilised overall fish supply at around 900,000 t yr^{-1} before processing (Fig. 1b).

After correcting for the increasing human population, UK domestic fish supply has been in decline since prior to World War I (Fig. 1c), although high exports during the early 20th century meant that many of these fish were not, in fact, available to UK consumers. Since 1970, imports have filled some of the growing gap between supplies and the Food Standards Agency recommended intake of 280 g capita^{-1} week^{-1} (dashed line in Fig. 1c). Total supplies today meet only 64% of the recommended intake; if UK landings abroad are included this figure is increased to 77%. UK citizens have only had sufficient supplies of fish to meet the recommended level of intake twice since 1889, once in the early 20th century and again after World War II, covering just 10 years out of 120. These figures also likely overestimate the supply of fish to UK consumers, as they do not distinguish fish that is landed but is destined for non-human consumption (i.e. fish meals and oils).

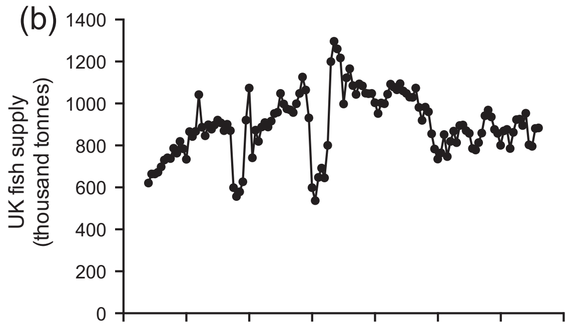

Fig. 1b. UK fish supply prior to processing losses. Supply of fish to UK consumers prior to processing losses (domestic landings plus imports and aquaculture, minus exports), 1888–2012.

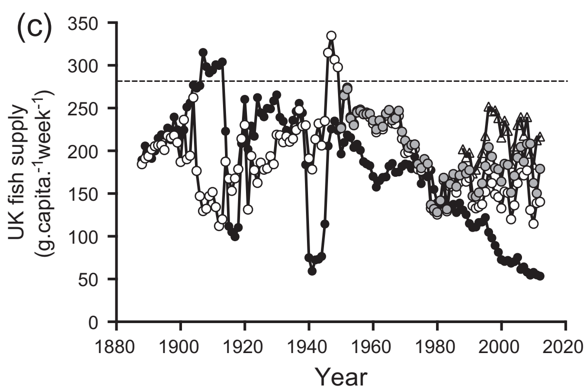

Fig. 1c. UK fish supply per capita. Fish supply per capita (g capita^{-1} week^{-1}) on an annual basis in the UK after adjustment for proportion of children in the population. The closed circles show fish supply from capture fisheries alone after processing. Open circles show fish supply when imports minus exports are included, the grey circles when aquaculture is added to the latter. Open triangles show available quantities if landings abroad by UK vessels are included. The dashed line shows the amount of fish UK citizens should eat according to the UK Food Standards Agency (280 g capita^{-1} week^{-1}).

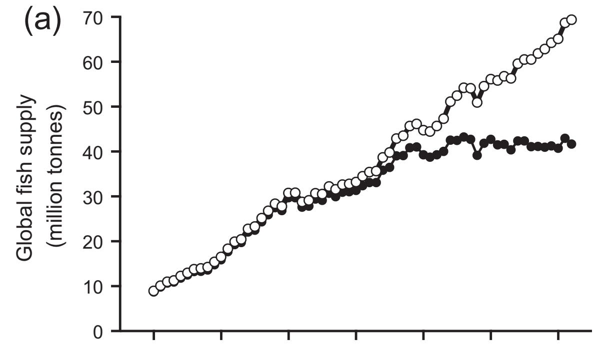

Fig. 2a. Global supplies of fish after processing. Global supply of finfish and invertebrates 1950–2012 after applying processing conversions. Closed circles show wild capture fisheries supply, and open circles show total fish supply when aquaculture is included. *Source:* FishStat (2013)

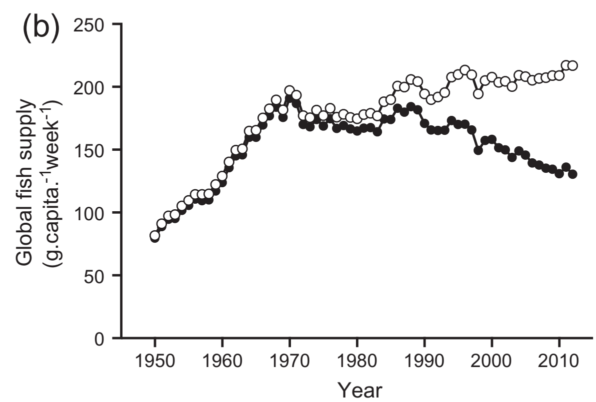

Fig. 2b. Global fish supply per capita. Fish supply per capita (g capita^{-1} week^{-1}) on an annual basis after adjustment for proportion of children in the population. Closed circles show fish supplies from capture fisheries alone after processing. Open circles show fish supplies when aquaculture is added to the latter.

3.2. Patterns in global fish supply

On a global scale, available wild capture fish supply (i.e. finfish and invertebrate quantities after correction for processing losses) has stabilised since the late 1980s after a period of rapid growth during the 1950s and 1960s, that slowed through the 1970s and 1980s (Fig. 2a). Continued increases in overall fish supply are the result of expanded aquaculture production, which increased from 604,000 t in 1950 to 65.8 mt in 2012 (FishStat (2013) before processing). When human population growth is taken into account (Fig. 2b) per capita wild capture fish supply declined by 32% since 1970. An overall decline in fish supply has been checked by the rapid growth in aquaculture over the last three decades. This rise resulted in a 10% increase in per capita global fish supply over the same period because aquaculture growth has outpaced human population increase (Fig. 2b). However, these patterns do not distinguish between fish destined for food and fish destined for processing into fish meal and oils. Whilst the quantity of fish sourced for non-human use is significant, since the 1980s the proportion of global fish supply directed towards human use has increased: in 2011, 15% of fish was destined for non-human uses, down from about 32% in the 1980s (FAO, 2012).

3.3. Fish supply versus health aspirations

FAO (2012) provided data on global landings and consumption in 2011. Total world fisheries production (including inland and marine capture fisheries and aquaculture) was estimated at 154 mt (FAO, 2012): this included 131 mt for direct human consumption and 23 mt for other uses, such as manufacture of fish meals and oils. Fish available for human consumption converts to 359 g capita^{-1} week^{-1} landed weight equivalent per year (i.e. unprocessed) for a human population of 7.0 billion in 2011 (FAO, 2012). When processed weight conversions were applied and the percentage of children in the world population corrected for (who require only half portions), this converts to 181 g capita^{-1} week^{-1}, 65 g less than the average amount of 246 g capita^{-1} week^{-1} recommended by the 14 countries for which we could find dietary recommendations (Table 1).

Whilst FAO statistics provide us with an overview of fishery production, they are unable to capture additional supplies of fish that remain unrecorded but which contribute to overall supply. For example, FAO statistics under-represent small-scale fisheries, many of which go unrecorded. Chuenpagdee et al. (2006) estimated that small-scale fisheries landed around 21 mt per year, although how much of that is included in FAO landings data is uncertain. If none are recorded in official statistics, this would provide an extra 21 mt of available fish.

Illegal fishing should also be factored into present global fish supplies in order to make a full account of landings. Agnew et al. (2009) estimated that the worldwide extent of illegal fishing was between 11 and 26 mt yr^{-1} (mean 18.5 mt) in recent years. Whilst not all illegally caught fish will become available for human consumption (some will be discarded, for example), the highest levels of illegal fishing are reported to be associated with high value demersal fish and invertebrates (Agnew et al., 2009). The majority of these catches likely end up being consumed directly by humans. Therefore, if we assume the mean value calculated by Agnew et al. (2009) is available for human consumption, it would provide 18.5 mt of additional fish. Together illegal and small-scale fisheries would provide an additional 61 g $capita^{-1}$ $week^{-1}$, a conservative estimate since we assumed no small-scale fisheries landings are included in official statistics. This is just 4 g $capita^{-1}$ $week^{-1}$ or 2% less than the average intake level recommended by the 14 countries in Table 1.

4. Discussion

UK fishery records dating from 1888 provide an opportunity to explore long-term patterns in fish availability at a national scale. Although fish was rarely a preferred source of protein for UK consumers, fish consumption initially increased prior to World War I as distant water fleets expanded, with a gradual decline in per capita consumption witnessed in the decades after World War II (Reid, 2003). The supply from domestic fleets dwindled throughout the 20th century. By the 1970s a decrease in fish supplies from distant water sources, competition from other food sources and an increase in retail price meant that fish consumption had nearly halved compared to pre-war consumption levels (Reid, 2003). Since the 1980s, fish consumption has increased, although the fish commodities most favoured by the UK public have altered greatly since the early 20th century. That current fish supplies only make up 64% of the present recommended intake indicates that the demand for fish from consumers is still lower than government recommendations. However, if demand were to increase, either from population growth, continued decline in domestic landings or an increase in per capita consumption, the bulk of this deficit would likely have to be sourced from imports. In recent years, scientific and nutrition bodies have increasingly emphasised the need to encourage fish consumption (Food Standards Agency, 2010), yet the UK already imports large quantities of fish. Whilst increasing amounts of imports are not necessarily an indication of unsustainability, also reflecting shifts in consumer preference and an increasingly globalised trade in fish and fish products, it clearly shows the potential for developed countries to mask domestic shortfalls through increased imports and aquaculture.

After a steep downturn in the fortunes of the domestic fleet in the 1970s the UK stepped up imports, which rose 305% between 1970 and 2012, whilst domestic aquaculture became more significant from the 1980s (FishStat, 2013). The largest categories of these imports comprised demersal species such as cod and haddock (21% by weight in 2012 (Marine Management Organisation, 2013)), caught in the waters of Northern Europe, or shrimp and prawns (11% of imports by weight in 2012) imported from countries like Thailand (Marine Management Organisation, 2013). Whilst late 20th century domestic fishery declines can be partly attributed to the loss of traditional fishing grounds as countries extended their national waters (Kerby et al., 2012), similar declines in landings have also occurred throughout Europe. For example, capture fishery (finfish and invertebrates) landings by European and Russian fleets declined from 22.7 mt in 1988 to just 13.3 mt in 2009 (FishStat, 2013). The situation facing the UK is emblematic of wider trends in developed nations: the European Union as a whole now imports an estimated 60% of the fish it consumes (European Commission, 2008), while the United States imported 86% of its fish in 2011 (NOAA, 2012).

At the global scale, we found that per capita wild fish supply has been in decline since 1970. This predates by nearly two decades the much-reported inflexion in global fish landings of 1988 that signalled the transition from continuous increase in supply to decrease (Watson and Pauly, 2001). However, the rapid growth of aquaculture has so far shielded consumers from the consequences of overfishing and human population growth.

Whilst our metric of 'per capita fish supply' does not reflect the complexities of fisheries demand and supply (FAO, 2012; Garcia and Rosenberg, 2010), the reality is that many developed nations such as the UK continue to aspire to eat more fish in a world full of malnourished people. They increasingly source imports from places where many poor people rely upon fish protein, such as West Africa (Atta-Mills et al., 2004). Fish is currently a vital source of animal protein (almost 20% of intake) to 3 billion people (FAO, 2012) and as the human population continues to grow this number is likely to rise. In the next section we explore ways in which the gap between supply and demand can be reduced.

4.1. Closing the gap between supply and demand

(i) *Improved fisheries management*

Many fisheries around the world are exploited at intensities that have driven stocks far below maximum sustainable yield levels. Fishing less intensively is expected to lead to stock recovery, which would deliver higher catches sustainable over the long-term for less cost (Roberts, 2012). Watson et al. (2012) estimated that despite an average 10-fold increase in global fishing intensity since the 1950s, fishery landings had halved over the same period, whilst Sumaila et al. (2012) calculated that to rebuild global fisheries (i.e. maximise sustainable catch) fishing effort would need to be reduced by 40–60%. A different approach adopted by Costello et al. (2012) showed that rebuilding global fisheries could increase fishery yields by 8–40%.

(ii) *Reduced discards*

Discarded fish could be utilised more fully in a future in which discarding is prohibited, as has been a successful policy in Norway (Diamond and Beukers-Stewart, 2011). According to the Norwegian model, unsaleable fish are converted to fishmeal and oil rather than discarded. Global discards are estimated to be 7.3 mt (Kelleher, 2005), a substantial amount of which could potentially be made available for direct human consumption or indirectly through aquaculture.

(iii) *Consumption of animals from lower trophic levels*

As demand for fish grows, there is likely to be increasing demand for 'forage' fish (small pelagics like herring and anchoveta) for direct human consumption rather than as industrial feed for agriculture and aquaculture, for which the majority of such fish landings are currently destined (Tacon and Metian, 2009). Direct consumption could reduce feed supplies and thus aquaculture production. The alternative is to increase exploitation of forage fish. Although prey species naturally sustain higher levels of mortality than their larger, less abundant predators and hence may be considered more resilient to high levels of fishing, the complex biological systems these species support means that increased exploitation of forage fish may have substantial knock-on effects on the rest of the ecosystem, including other target species (Smith et al., 2011). Forage fish species already make up more than 30% of global capture fish landings (Smith et al., 2011) but are also subject to enormous fluctuations from year to year. Hence major increases in landings may result in both large-scale ecosystem alterations and greater uncertainty in annual fish production.

In some ecosystems consumption of lower trophic levels already occurs as a result of overfishing and even extirpation of

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predatory species, known as fishing down the foodweb (Pauly et al., 1998) or fishing through the foodweb (Essington et al., 2006). For example, Gulf of Maine lobsters (*Homarus americanus*) dramatically increased in abundance as their predators declined. Now, lobster landings produce over 80% of the total value of all fisheries in Maine (Steneck et al., 2011). However, many of these altered ecosystems are at increased risk of disease and environmental perturbations, making their long-term viability uncertain (Howarth et al., in press).

(iv) *Aquaculture*

Given human population growth, reformed fisheries management and increased efficiency may not be enough to ensure fish supplies meet future demand. Aquaculture will likely need to contribute substantially more than today. It has so far spared the world a downturn in fish supplies by outpacing human population growth since the 1950s, averaging a remarkable growth of 8.8% $year^{-1}$ since 1980 (FAO, 2012). At current rates of growth, keeping up with future demand looks achievable, but present practises are not always sustainable (Liu and Sumaila, 2008). Aquaculture operations must reduce impacts and transition to sustainable methods of production to be viable in the long term.

The environmental costs of aquaculture expansion to date are evident across the world. Around 30% of the world's mangrove forests have been cleared since the mid-20th century, much of it to make way for prawn and fish ponds (Alongi, 2002; Murray et al., 2014). Nearly a third of seagrass beds have gone since the late 19th century and the rate of decline has increased to 7% per year since 1990 (Waycott et al., 2009). Loss of these coastal habitats not only imperils wildlife, but may also bear some responsibility for wild fisheries decline as they constitute vital nurseries for commercial species (Aburto-Oropeza et al., 2008). Aquaculture also causes pollution from feeds, pesticides, prophylactic drugs and wastes (Azad et al., 2009; Biao and Kaijin, 2007), while wild fish may be threatened by parasites, disease and competition from escaped farmed species (Krkosek et al., 2006; Cottee and Petersan, 2009).

The use of wild fish for feed is well documented (FAO, 2009). If present growth rates continue, aquaculture production will require more wild fish for feed. Fish stocks that depend upon wild fish protein include piscivorous finfish and crustacean species. However, the feed of many omnivorous cultures is now being supplemented with wild fish protein in order to raise production, often from highly unsustainable sources such as 'trash' fisheries in India (Naylor et al., 2009; Lobo et al., 2010). If these practises continue, wild fish demand could increase still further. However, recent improvements in feed conversion ratios, substitution of wild fish for non-fish ingredients (such as genetically modified crops and feeds created from waste recycling (Kroekel et al., 2012)), as well as a shift to obtaining fish meal from fish processing waste have substantially reduced the ratio of wild fish input to farmed fish output (Naylor et al., 2009). These developments may help to counter increasing demand from the aquaculture sector.

Whilst some aquaculture operations exhibit a heavy environmental cost, there are more sustainable methods. For example, most mollusc culture requires no or little additional feed input, whilst many freshwater fish are fed on low-protein, grain-based diets (Bostock et al., 2010). Mollusc culture operations and bivalves in particular, have fewer of the environmental problems associated with carnivorous or intensively farmed finfish or crustacean species (Dumbauld et al., 2009). Such culture methods often also involve low impact techniques, for example, suspended culture, although these methods vary and some shellfish culture and harvesting methods can cause localised disturbance to the benthos (Dumbauld et al., 2009). Currently, the growth rate of mollusc culture is slower than overall aquaculture production. In 1988, molluscs made up 22% of recorded production, which dropped to 18.5% by 2009 (FishStat, 2013). Increasing the rate of bivalve culture or other low-impact aquaculture will require incentives to boost shellfish culture or a shift in consumer preferences towards lower trophic level aquaculture species (Bostock et al., 2010). Other possibilities include offshore pelagic cage culture, which would reduce coastal habitat loss and pollution (Holmer, 2010). However, the high costs of transport and management of offshore areas means that coastal space will likely be viewed as a more economic alternative for decades to come (Holmer, 2010).

5. Conclusions

Our historical analysis shows that global wild capture fish supply per capita has been in decline for over 40 years, and that supplies have only kept up with population growth as a result of rapid growth in aquaculture. Consumers in the UK have been partially protected from falling domestic production by increasing imports, a situation typical of many high-income countries. Such an approach is not sustainable, however, and demand from developed countries has been filled at a high social and environmental cost, encouraging overexploitation farther afield and undermining supply of fish protein to local communities (Kaczynski and Fluharty, 2002; Smith et al., 2010). Despite these trends, countries such as the UK aspire to consume still greater quantities of fish on health grounds. We have highlighted the need for governments of nations with limited domestic fish supplies to think carefully about the implications of promoting greater fish consumption in a world where many are already protein deficient.

Our findings also have interdisciplinary implications. Future trends in aquaculture practises hold the key as to whether we will be able to provide enough fish to meet aspirations for healthy nutrition. However, national policy measures must adopt a global outlook and strive to balance consumption with sustainable methods of production, while safeguarding marine biodiversity and ocean health. Closer collaborations between the fields of marine and medical research (e.g. joint conferences or special issues in medical journals on the conflicts between healthy eating and food security) would aid in this endeavour and promote the importance of considering how our national policy measures resonate at the global level.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.marpolbul.2014.09.016.

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