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The mass balance of production and consumption: Supporting policy-makers for aquatic food security

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ABSTRACT

This work addresses divergences between data on consumption and availability for wild-caught and farmed fish, and normalisation of reported production data, to support integrated fisheries and aquaculture management. The methodologies developed, centred on improved parameterisation and on mass balance closure, were tested in two case studies: (i) the cod fishery in Europe, with particular emphasis on Iceland and the United Kingdom; and (ii) the overall balance of aquatic products for Portugal, the ICES member with the most diverse range of landed marine species. Data for consumption, Illegal, Unreported, or Unregulated (IUU) catch, and official availability statistics were used to identify discrepancies between consumption and official availability data. The identification of discrepancies between supply and demand, when coupled with source-discriminated data, showed a pattern where products with no unmet demand tend to display a considerable IUU percentage—above 9% in three cases (hake, sardine, and horse mackerel).

By contrast with fished products with an over-met demand such as cod (144%) and sardine (124%), farmed species display low Optimal Consumption Level (OCL) satisfaction. Atlantic salmon, gilthead seabream, and European seabass register 45%, 58% and 44% respectively; this suggests a considerable unmet demand for these products and/or a high volume of undeclared fish reaching consumers, which may be due to the lack of landings control that exists for wild-caught fish.

Improvements to production estimates using live-weight coefficients illustrate the impacts of seafood processing. Different processing methods can generate variations in live-weight estimates, leading to errors in officially reported data, and expose the limitations of the current statistical methods. As an example, the corrected *per capita* consumption for Portugal for 2014 (the latest FAO data) increases from 57 to 66 kg ind^{-1} y^{-1}, which places the country as the second-greatest consumer in the world, well above both Malaysia and South Korea (each with 58 kg ind^{-1} y^{-1}). The corrected data show that Portugal had the highest consumption rate in the world until the mid-1970's, when it was overtaken by Iceland for reasons discussed herein.

The lack of detailed per-species consumption data, as well as the grouping of species by commodities, hinders a more detailed seafood consumption analysis, required by policy makers and stakeholders to effectively develop management measures to reduce illegal fishing or bycatch, and to correctly formulate strategic options for development of aquaculture and fisheries, necessary for ensuring food security over the next decades.

1. Introduction

Seafood production worldwide primarily originates from shelf and coastal areas, including bays and estuaries. Demand for finfish and other aquatic products generates employment and supports livelihoods in coastal regions and nations, but may also be a significant environmental stressor (FAO, 2016a; Newton et al., 2014; Robins et al., 2016; Wilson, 2002), for instance by perturbing ecosystem equilibria (Rocchi et al., 2016; Smith et al., 2011) or impacting benthic habitat (Aguado-Giménez et al., 2011; Grigorakis

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and Rigos, 2011; Puig et al., 2012; Roberts, 2006).

Global consumption of aquatic products has increased from 9.9 kg per *capita* in the 1960's to an all-time high of 20 kg *per capita* in 2014 (Carlucci et al., 2015; FAO, 2016a). The most significant planetary challenge for the next three decades will be the supply of safe and adequate nutrition to a population of nearly 10 billion by 2050 (Cressey, 2009; FAO, 2016a; Godfray et al., 2012); worldwide seafood consumption *per capita* is expected to reach 21.8 kg in 2025, generating an additional annual requirement of 31 million tonnes of aquatic products (FAO, 2016a).

Many wild fish stocks around the globe are currently over-exploited (Halpern et al., 2012; Jayasinghe et al., 2016) and capture fisheries will be unable to address this shortfall (Cressey, 2009; Naylor et al., 2000; Pauly et al., 2002). Since the late 1970's, the decline of world fisheries has been accompanied by strong growth in aquaculture. In 2014, farmed finfish and shellfish production reached 73.8 million tonnes, representing 44% of total seafood production (FAO, 2016a; Merino et al., 2012; Naylor et al., 2000), and in May 2013, world aquaculture production overtook capture fisheries for human consumption (Fig. 1).

This 'blue revolution' has been led by China, which accounts for 60% of global production, and countries in SE Asia. In the European Union, by contrast, farmed finfish and shellfish production has grown modestly at 1% per year, and the high demand for aquatic products, accompanied by recent stagnation and even decrease of autochthonous production (European Commission, 2014a, 2012, 2008), has increased dependency on external sources of seafood (Esteban and Crilly, 2012; Little et al., 2012). Over the coming decades, the increase in *per capita* GDP in China and SE Asia will drive up the price of seafood, as domestic consumption increases in Asian nations (Ferreira et al., 2014; Nunes et al., 2011). Total seafood consumption in India and China alone has increased by approximately 20 million tonnes in less than 10 years (FAO, 2014, 2008), and the expected additional consumption by 2025 should increase this number by a further 14 million tonnes (FAO, 2016a).

The rapid increase in worldwide seafood demand, fuelled by the twin factors of increased population and *per capita* GDP, poses a major challenge for food security and makes it compelling to better understand demand, the key driver for this sector (Carlucci et al., 2015). Consumption is estimated based on a mass balance (Eq. (1))

$$C = P + I - E \quad (1)$$

where C is apparent consumption; P is production; I is imports and E: is exports.

Although this approach is useful for dealing with large time periods, and multi-country data that require normalization, the output represents availability and not real consumption, despite

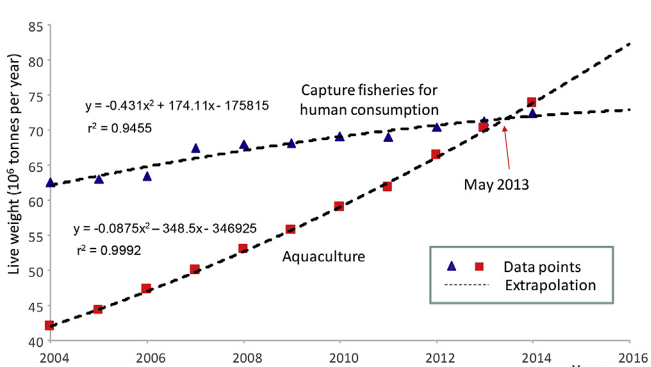

Fig. 1. Worldwide production of capture fisheries for direct human use and of aquaculture over the period 2004–2014.

being expressed in mass *per capita* (Almeida et al., 2015; FAO, 2007; Girard et al., 1998). These highly aggregated data are subject to the following potential limitations: (i) presentation as grouped commodities; (ii) application of normalization factors; (iii) unaccounted differences between net and live weight; and (iv) lack of illegal, unregulated, unreported (IUU) and subsistence fishing volumes. These factors condition seafood consumption estimates and are absent from official statistics (Fabinyi et al., 2016; FAO, 2007; Leitão et al., 2014; Pauly et al., 2002; Pramod et al., 2014; Rodgers et al., 2008). The importance of IUU data transcends fisheries, since aquaculture growth is considered to be partially driven by wild fisheries, either through bycatch or trash fish (Cao et al., 2015; Nunoo et al., 2009; Pauly et al., 2002), and due to the lack of a landings control on fish farms similar to what exists for wild fisheries. In addition to production factors, consumers are demanding better information and greater traceability of seafood (Pieniak et al., 2013), which begs a more detailed analysis of seafood sectors, from fishers to consumers.

In the context of the worldwide seafood market, the dried and processed aquatic goods trade has considerable importance in both value and volume. Cod is considered to be one of the key products in the dried goods industry; its importance in southern European countries, as well as in South America, is considerable, and cod trade plays an important role in determining prices both in vessels in Norway and in retailers in Portugal (Gudjónsdóttir et al., 2011; Lorentzen et al., 2016; Martínez-Alvarez and Gómez-Guillén, 2013; Pettersen and Myrland, 2016). Atlantic cod—the most commonly targeted and traded of the cod species—has in the past been used as an example of failed stock management, particularly the Newfoundland cod stock (Rose and Rowe, 2015; Schrank, 2007, 2005). This species has also been at the centre of fishing rights disputes among European countries, particularly the UK, Iceland, and Norway, since the XVth century (Thorsteinsson, 1976); the most recent disputes, from a documented series of ten so-called 'cod wars' or *þorskastríð* (Thorsteinsson, 1976), occurred between the mid-1950s and 1970s (Lescrauwaet et al., 2013; Stewart, 2016; The National Archives, 2016).

This study develops a methodology based on the compilation of both official statistics (imports, exports, aquaculture, and catch), and non-official reports (IUU and consumption surveys), in order to address seafood consumption and availability. This approach allowed a comparison between estimated consumption and total availability weights. To address availability estimates, the differences between net and live weight of a processed aquatic product were illustrated by means of a case study. The key objectives of this work are to:

1. Address the discrepancy between net and live weight of processed seafood products, and its impact on reported data;
2. Estimate seafood consumption at species level, discriminating among internal/external origin, and between regulated/unregulated fisheries and aquaculture sources;
3. Analyse the mass balance of availability calculated through a supply-side approach, and consumption estimated through demand. The null hypothesis is that this mass balance can be adequately closed for individual species and in aggregate;
4. Apply the results to improve decision-support for planning the sustainable development of aquaculture and fisheries in coastal and shelf seas.

2. Methodology

Two approaches were developed to test the hypothesis that the mass balance of supply and demand can be successfully closed. The first deals with improvements to production estimates, and the second addresses the mass balance through an analysis of supply and demand. The methodology was applied to two European case studies. The first estimates discrepancies in reported data for cod, and changes brought about by the 1970's fishery dispute between the UK and Iceland, following the creation of exclusive economic zones (EEZ); the second identifies potential inconsistencies in supply and demand data based on data for Portugal—a country with a one of the highest demand levels on a global basis (FAO, 2016a).

2.1. Data sources

The net supply (S) for human consumption is commonly determined using Eq. (2).

$$S = F + A + I - E - N + V \tag{2}$$

where S equals the sum of production through capture fisheries (F) and aquaculture (A), foreign trade, i.e. imports (I) − exports (E). Non-food uses (N) are excluded from the direct supply (Failler, 2007), and in some cases, the (positive or negative) stock variation (V) of commodities is included. The taxonomic resolution of seafood availability data is often reduced by the highly aggregated nature of fishery statistics (Rodgers et al., 2008). Furthermore, the differences between net and live weight (Failler, 2007), the application of normalization factors (Rodgers et al., 2008), and a lack of accurate discards and IUU statistics (Coll et al., 2014; Leitão et al., 2014; Pauly et al., 2002), all add to the uncertainty surrounding the amount of available seafood. Official seafood consumption estimates are also based on these statistics—net supply divided by the population, and thus reflects similar issues. Since consumption statistics are derived from net supply, the output represents availability rather than actual consumption, even if it is displayed as mass *per capita* (Almeida et al., 2015; Girard et al., 1998).

To increase the accuracy of these estimates, the data sources to be used in this analysis needed to meet the following conditions:

- Production (catch + aquaculture) and foreign trade (imports − exports) at species level should be discriminated;
- IUU data at species level are required;
- Seafood consumption data must stipulate the species or product consumed.

Data sources that meet the criteria above were used for the selected case studies.

2.2. Improvements to production estimates

Cod is sold in various forms, and the lower water content of salted and dried cod makes these products particularly appealing to retailers (Gudjónsdóttir et al., 2011; Lorentzen et al., 2016), and consumers (Cardoso et al., 2013; Martínez-Alvarez and Gómez-Guillén, 2013). This lower water percentage can have an impact on the reported volumes of the traded commodities and the captured fish—due to the differences between net and live weight—which in turn has an impact on consumption weights.

2.2.1. Weight normalisation

Data for cod production in the U.K. and Iceland were obtained from FAO (FAO, 2016b). For each group of cod products, coefficients were applied to normalize the different processing methods from net to live weight, to differentiate among product categories (Table 1).

2.3. Mass balance estimates for supply and demand

Due to the lack of species-level data for demand and for IUU catch in official databases (Almeida et al., 2015; Cardoso et al., 2013; Coll et al., 2014; Leitão et al., 2014; Pauly et al., 2002), a range of data sources and methodologies was employed. The use of different data sources has both advantages and disadvantages: Different time windows for supply (availability) data, demand (consumption) values, and IUU statistics reduced temporal overlap. Although this is not usually positive, the negative impact was reduced due to the greater importance of average rather than annual values for each product. The detailed implementation of the methodology, together with the assumptions considered, is provided below.

2.3.1. Supply

In some cases, consumers do not provide species-level information on the composition of a seafood meal (Pieniak et al., 2013). For that reason, certain species were grouped into products, reflecting the resolution of available consumption data (Table 2). This approach was used when dealing with availability estimates, and in the subsequent analysis of inconsistencies between supply and demand data.

Seafood supply data for 2015 were obtained from the FAO dataset, which discriminates between farmed and wild-caught fish, and respective import and export volumes, while retaining taxonomic resolution. For IUU catch at species level, no official statistics were available, and data were obtained by means of a literature review.

A tonnage between 1% and 10% for illegal fishing of tuna worldwide has been proposed (Agnew et al., 2009), based on the annual tuna catch; the average (5.5%) was therefore applied to tuna production values. Leitão et al. (2014) analysed IUU fishing for other internally fished key products, captured with different gear types over an extended period (1938–2009). The total IUU for the period between 2009 and 2013 was estimated based on pre-2009 data, since these were not available in the work by Leitão et al. (2014). The IUU weight for each key species was estimated, and supply (S) was calculated using internal production—fisheries (F) and aquaculture (A)—and international trade volumes—import (I) and export (E)— as well as illegal and subsistence fishing volumes (IUU) (Eq. (3)).

$$S = F + A + I + IUU - E \tag{3}$$

2.3.2. Demand

Surveys have been acknowledged as a valid method to obtain consumption data (Cardoso et al., 2013; Carlucci et al., 2015), although with some limitations since they are focused mostly on demand rather than supply (FAO, 2007). The consumption frequency of 23 selected seafood products (Cardoso et al., 2013) for specific time periods is given in Table 3.

The raw data on consumption frequency for each product (in meals per week/month/year) were converted to the annual weight consumed D. The amount of seafood consumed per meal was estimated for the period between 2005 and 2013 from *per capita* consumption data (Eq. (4)), assuming two daily seafood meals (Table 4).

$$D = \frac{0.002M}{365} \tag{4}$$

where:

D: demand (kg ind^{-1} y^{-1})

Table 1
Conversion coefficients from net to live weight for cod products (FAO, 2016c; INE, 2014b; Johansen, pers. com., 2016).

Processing method	Products designation in FAO data	Conversion factor used (in % of live weight)
Frozen	Fillets; whole fish; roes	70
Salted[3]	Fillets; sugar salted; in brine; whole fish; roes	40
Dried	Klipfish; stockfish; whole fish; roes	20
Other (fresh or chilled)	Fillets; whole fish	100
Smoked	Fillets; whole fish	62

Table 2
Grouping of species as products for estimation of OCL.

Product	Species included			
Cod	*Gadus morhua*			
Sardine	*Sardina pilchardus*			
Horse mackerel	*Trachurus trachurus*	*Trachurus picturatus*	*Trachurus mediterraneus*	
Tuna	*Katsuwonus pelamis*	*Thunnus* spp.	*Auxis* spp.	*Sarda sarda*
Gilthead seabream	*Sparus aurata*	*Diplodus* spp.	*Other Sparidae*	
European seabass	*Dicentrarchus labrax*			
Hake	*Merluccius merluccius*	*Urophycis tenius*	*Other Merlucciadae*	
Salmon	*Salmo salar*			

Table 3
Consumption frequency of the 23 selected products (Cardoso et al., 2013).

Consumption frequency (%)					
Product/species	Annual	Monthly (number of meals)		Weekly (number of meals)	
	0	<1	$1 \le 4$	$2 \le 4$	$5 \le 7$
Octopus	10.0	55.9	31.8	1.8	0.5
Cod (soaked)	2.8	13.8	62.6	18.8	2.0
Gilthead seabream	7.9	37.1	44.2	10.2	0.6
Salmon	12.4	30.3	45.7	10.2	1.4
Hake	9.9	25.4	45.0	18.1	1.6
Sardine	16.7	42.4	32.0	7.4	1.5
Horse mackerel	14.1	42.6	32.9	9.0	1.4
Chub mackerel	58.5	29.5	9.3	2.4	0.3
Canned tuna	5.5	27.9	45.8	17.5	3.3
Canned sardine	43.9	33.4	17.1	4.5	1.1
Black scabbard fish	32.9	43.9	19.6	3.1	0.5
Squid	9.0	53.5	35.3	1.8	0.4
Cuttlefish	20.8	54.9	22.7	1.1	0.5
Shrimp	7.9	57.7	30.5	3.6	0.3
Edible crab	34.6	59.5	4.9	0.5	0.5
Common mussel	40.0	52.1	6.7	0.9	0.3
Grooved carpet shell	21.7	63.4	13.4	0.9	0.6
Seabass	13.9	42.0	36.8	6.6	0.7
Panga	74.4	16.3	7.3	1.4	0.6
Pink cusk-eel	37.0	35.1	22.8	4.9	0.2
Redfish	44.0	36.5	15.7	3.5	0.3
Perch	54.6	30.5	12.7	1.6	0.6
Sole	35.2	47.3	14.5	2.6	0.4

M: consumption per meal (g ind^{-1} y^{-1})

D was then used to estimate *per capita* consumption for each product, based on the consumption frequencies (meals per year/month/week) from Table 3, considering three different scenarios: minimum (C_{min}), medium (C_{med}), and maximum (C_{max}) consumption weights. Average values were used to estimate the medium consumption level. For the minimum and maximum tiers, the lowest and highest number of meals was considered (Table 5).

These were upscaled to determine the total consumption for the 23 products using population data (Table 4 and Eq. (5)). This process was repeated for each consumption tier.

Table 4
Consumption *per capita*, population, estimated daily and per meal consumption of seafood, based on yearly consumption weights and population for each year of the selected time period (estimated based on data from FAO, 2014; INE, 2014a,b; 2013, 2012, 2011, 2010, 2009, 2008, 2007, 2006).

Year	Consumption (kg *per capita*)	Population	Consumption (g)	
			Daily	per meal
2005	53.5	10 570 000	146.6	73.3
2006	56.2	10 599 095	154.0	77.0
2007	61.4	10 617 575	168.2	84.1
2008	61.2	10 627 250	167.7	83.8
2009	61.1	10 637 713	167.4	83.7
2010	56.7	10 636 979	155.3	77.7
2011	56.8	10 541 840	155.6	77.8
2012	55.9	10 487 289	153.2	76.6
2013	55.0	10 427 301	150.6	75.3

$$T_c = \frac{CP}{1000} \tag{5}$$

where:

C: consumption level (C_{min}, C_{med} or C_{max}) (kg *per capita*)
P: population for each year
T_c: total yearly consumption of each product (T_{Cmin}, T_{Cmed} or T_{Cmax}) (t y^{-1})

The resulting data were used to determine the most important seafood products in terms of demand. Products such as fresh and canned sardines, which belong to the same species, were grouped, and the final 22 products were ranked by consumption weight to identify key products (Table 6), which correspond to a consumption of at least 5% of the total for each of the three levels. The 5% limit represents a yearly consumption of at least 10 000 tonnes and an annual consumption of 1 kg *per capita*. Below this threshold, calculated weights show a marked decrease (Table 6).

2.3.3. *Inconsistencies between supply and demand data*

Calculated consumption for each of the 3 tiers was compared with availability data to determine the Optimal Consumption Level (OCL) of key products, and to address discrepancies between supply and demand data. OCL was determined using the smallest difference between the calculated consumption level (C_{min}, C_{med}, or

Table 5
Equations to estimate consumption weights based on seafood consumption frequencies from Table 3.

Consumption *per capita* for each product					
Minimum consumption level (C_{min})					
Number of yearly meals (Y)	0	0	12	104	260
$C_{min} = X_{min} + M_{min1} + M_{min2} + W_{min1} + W_{min2}$	$X_{min} = \frac{(Y \times A \times f)}{\Phi}$	$M_{min1} = \frac{(Y \times A \times f)}{\Phi}$	$M_{min2} = \frac{(Y \times A \times f)}{\Phi}$	$W_{min1} = \frac{(Y \times A \times f)}{\Phi}$	$W_{min2} = \frac{(Y \times A \times f)}{\Phi}$
Medium consumption level (C_{med})					
Number of yearly meals (Y)	0	6	30	156	312
$C_{med} = X_{med} + M_{med1} + M_{med2} + W_{med1} + W_{med2}$	$X_{med} = \frac{(Y \times A \times f)}{\Phi}$	$M_{med1} = \frac{(Y \times A \times f)}{\Phi}$	$M_{med2} = \frac{(Y \times A \times f)}{\Phi}$	$W_{med1} = \frac{(Y \times A \times f)}{\Phi}$	$W_{med2} = \frac{(Y \times A \times f)}{\Phi}$
Maximum consumption level (C_{max})					
Number of yearly meals (Y)	0	12	48	208	364
$C_{max} = X_{max} + M_{max1} + M_{max2} + W_{max1} + W_{max2}$	$X_{max} = \frac{(Y \times A \times f)}{\Phi}$	$M_{max1} = \frac{(Y \times A \times f)}{\Phi}$	$M_{max2} = \frac{(Y \times A \times f)}{\Phi}$	$W_{max1} = \frac{(Y \times A \times f)}{\Phi}$	$W_{max2} = \frac{(Y \times A \times f)}{\Phi}$

Where:
A - Seafood consumption per meal (g/meal) (Table 4).
f – Frequency of consumption for each product (%), as available in Cardoso et al. (2013) (Table 3).
φ: unit conversion factor (g to kg).

Table 6
Average annual estimated consumption weights for the 2005–2013 period for the three calculated tiers (case study for Portugal).

Product	Minimum consumption			Medium consumption			Maximum consumption		
	Tonnes/year	Kg *per capita*	%	Tonnes/year	Kg *per capita*	%	Tonnes/year	Kg *per capita*	%
Total	218 139	20.67	100.0	421 947	39.99	100.0	625 755	59.30	100.0
Cod (soaked)	26 886	2.55	12.3	45 979	4.36	10.9	65 072	6.17	10.4
Canned tuna	26 896	2.55	12.3	44 174	4.19	10.5	61 452	5.82	9.8
Hake	23 653	2.24	10.8	40 209	3.81	9.5	56 766	5.38	9.1
Salmon	16 443	1.56	7.5	29 839	2.83	7.1	43 236	4.10	6.9
Gilthead seabream	14 560	1.38	6.7	27 725	2.63	6.6	40 889	3.88	6.5
Horse mackerel	14 123	1.34	6.5	25 695	2.44	6.1	37 266	3.53	6.0
Sardine	12 863	1.22	5.9	23 640	2.24	5.6	34 416	3.26	5.5
Seabass	10 916	1.03	5.0	21 700	2.06	5.1	32 483	3.08	5.2
Shrimp	6820	0.65	3.1	15 970	1.51	3.8	25 120	2.38	4.0
Squid	5957	0.56	2.7	14 880	1.41	3.5	23 803	2.26	3.8
Octopus	5823	0.55	2.7	14 385	1.36	3.4	22 946	2.17	3.7
Pink cusk-eel	6960	0.66	3.2	14 345	1.36	3.4	21 730	2.06	3.5
Canned sardine	7993	0.76	3.7	14 655	1.39	3.5	21 316	2.02	3.4
Black scabbard fish	5730	0.54	2.6	12 425	1.18	2.9	19 120	1.81	3.1
Cuttlefish	4307	0.41	2.0	11 150	1.06	2.6	17 993	1.71	2.9
Redfish	5253	0.50	2.4	11 080	1.05	2.6	16 906	1.60	2.7
Sole	4570	0.43	2.1	10 410	0.99	2.5	16 250	1.54	2.6
Grooved carpet shell	3420	0.32	1.6	9250	0.88	2.2	15 080	1.43	2.4
Perch	3957	0.37	1.8	8340	0.79	2.0	12 723	1.21	2.0
Chub mackerel	3660	0.35	1.7	7700	0.73	1.8	11 740	1.11	1.9
Common mussel	2100	0.20	1.0	6230	0.59	1.5	10 360	0.98	1.7
Edible crab	2007	0.19	0.9	6150	0.58	1.5	10 293	0.98	1.6
Pangasius (Vietnamese catfish)	3243	0.31	1.5	6020	0.57	1.4	8797	0.83	1.4

C_{max}) and the availability of each key product, for the period between 2005 and 2013. A classification system based on average values was developed (Table 7) to score each product according to: (i) demand satisfaction (OCL); and (ii) seafood origin—domestic or external production.

The development of a classification system has advantages, not only in the analysis of data, but also when reporting results to stakeholders, in particular to policy-makers and managers (Vale, C., pers. com.; Elliott, 2002; Girard et al., 1998). OCL data were analysed to determine the growth potential of the seafood production sector,

Table 7
Species classified by its most important origin (letters from A to E). Key product classification regarding the satisfaction of calculated consumption weights (OCL) (roman numerals) (Classification systems developed by the authors).

Type (According to origin)	Classification (description)	Conditions
A	Exclusively imported	100% external origin
B	Mainly imported	≥75% external origin
C	Mixed	25% > 75% of internal origin
D	Mainly internal production	≥75% internal origin
E	Exclusively internal production	100% internal origin
Type (According to OCL satisfied)	**Conditions/description**	
V	≥ 100%	Of OCL satisfied
IV	75% < 100%	
III	50 ≤ 75%	
II	25% < 50%	
I	≤25%	

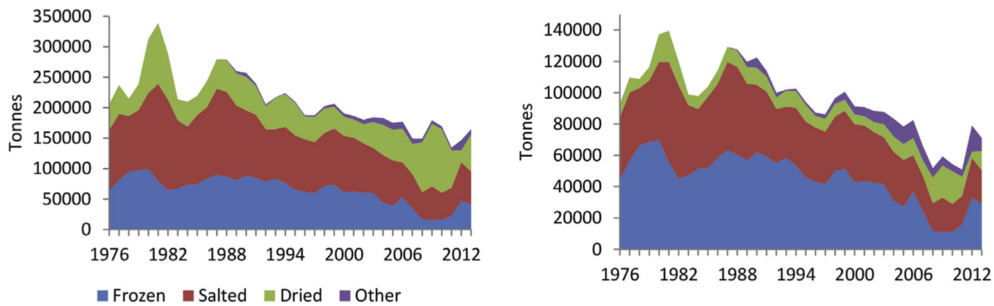

Fig. 2. Cod production (in tonnes) in the UK and Iceland from 1976 to 2013, showing the various cod processing methods (frozen, salted, dried, smoked, and other). Tonnage was estimated based on FAO data and using the coefficients of conversion to live weight in Table 1. UK cod production is shown in the top panes: corrected to live weight (left), and untreated (right). Icelandic production is shown in the bottom panes, corrected to live weight (left) and untreated (right).

and to identify potential outliers. The differences between the three estimated OCL tiers and availability were used to estimate growth potential.

3. Results and discussion

3.1. Improvements to production estimates

Data from the UK shows a 43% increase in average landings from uncorrected to corrected weights between 1976 and 2013 (Fig. 2). The most important segment is frozen cod, representing 99% of production. Icelandic cod production is more diversified, with salted, frozen, and dried cod representing the bulk of the production weight with 38%, 47%, and 11% respectively of the total uncorrected tonnage. When the weights are corrected to live weight, salted cod becomes the most important product (43%), followed by frozen (30%), and dried cod (24%). Average total annual cod production for Iceland between 1976 and 2013, using the corrected tonnage, increased by 120%, from 96 190 to 211 794 tonnes. The largest discrepancies between reported data and corrected weights were identified in the data for Iceland, especially for dried cod, where the highest differences in water content are observed (Gudjónsdóttir et al., 2011; Lorentzen et al., 2016). The discrepancy is also noticeable in frozen cod, with a 17% reduction (47%–30% of total production) when using the live-weight coefficients.

The main impact of the 'cod wars' on the UK was the loss of free fishing rights in Iceland's 200 mile EEZ, especially during the third and final dispute in 1975–76 (Stewart, 2016; The National Archives, 2016). Between 1976 and 1980, after the third (historically the tenth) dispute (Thorsteinsson, 1976), production in the UK dropped 70% from 190 971 tonnes to 112 377 tonnes (corrected to live-weight tonnage). Over the same period, Icelandic production increased by a similar amount, from 206 038 tonnes to 312 528 tonnes (Fig. 2), and was also accompanied by an increase in exported weight—from 192 000 tonnes to 328 000 tonnes—and value, while UK imports doubled (FAO, 2016b).

In 1975–1976, Iceland's cod catch overtook UK landings, and has remained higher ever since (Fig. 3); although the lack of detailed species-level consumption data does not permit a more detailed analysis, the last 'cod war' may also have impacted total *per capita* consumption on both countries.

The discrepancies between supply and demand are also clear in Portuguese cod supply data (Fig. 4). In Portugal, the political revolution of 1974—allied to the loss of fishing rights in the ex-colonies, and in Newfoundland due to the EEZ regime and the 'cod moratorium' (Bjørndal et al., 2015; Coelho and Stobberup, 2000; Cole, 1990; Davies and Rangeley, 2010)—brought to an end the 'cod campaign'[1] (Coelho et al., 2011a; Garrido, 2005), with impacts over the source and availability of cod products. In 1978, availability dropped below 100 000 tonnes, recovering in 1983 to over 200 000 tonnes, and in this period the most important source of cod shifted from internal production to imports, with impacts on trade balance (Bjørndal et al., 2015).

The processing of aquatic products also has an impact on *per capita* consumption, and since official production and trade statistics do not account for these differences, the resulting data can present significant discrepancies (Fig. 5). Portugal's seafood consumption is considerably influenced by the role of cod products (Almeida et al., 2015; Coelho et al., 2011b), particularly salted and dried cod. This is also the case, albeit to a lesser extent, in other Southern European nations such as Spain and Italy, and in countries like Brazil and Angola.

For the Portuguese case, the differences between net and live weight of these commodities influence the total availability and *per capita* consumption, resulting in a 16% increase from 57 kg (FAO, 2016b) to 66 kg *per capita* using corrected weights.

3.2. Mass balance for supply and demand

3.2.1. Discrepancies between supply and demand

Five of the eight key species have over 100% of their demand satisfied (Table 8), thus being categorized as class V, while the remaining three species have less than 75% of consumption satisfied. The overall OCL satisfaction values reflect the higher impact of certain species. Cod and sardine represent 52% of consumption; hake, tuna, and horse mackerel are responsible for 41%. Together they represent over 90% of key species consumption. The remaining three products, farmed species both nationally and from external sources (European Commission, 2014a), are responsible for 7%. The bulk of consumption is satisfied via imports (60%) and regulated fisheries (40%). Aquaculture presents a smaller percentage (1%) than unregulated fisheries (7%).

More than half of availability is met by imports (56%). Fisheries are the next origin of key species availability, followed by IUU (7%) and aquaculture (1%). Four species have a predominant external origin (type A or B, Table 8). Despite this, three (cod, hake, and gilthead bream) have internal production. Cod is the second highest import, with 94% of availability from foreign sources, and is also the most important in Portugal in terms of tonnage, consumption and value (Almeida et al., 2015; Cardoso et al., 2013; Coelho et al., 2011b). For the remaining A or B type products, i.e. hake and gilthead seabream, different sources are responsible for the majority of domestically produced fish. The second-highest source of hake is

[1] The 'Cod Campaign', or *Campanha do Bacalhau*, was a national initiative of dictator Salazar's *Estado Novo*; the campaign started in 1934 and continued until the late 1960's, with the objectives of providing self-sufficiency in supply and protecting the internal market (see e.g. Villiers, 1952).

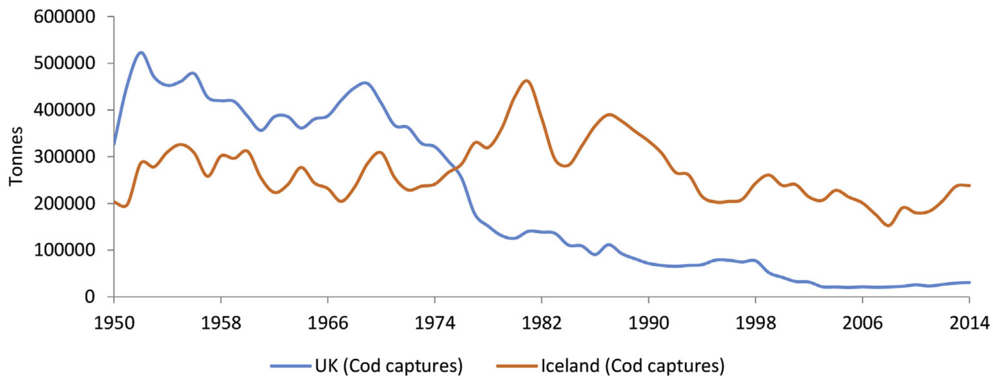

Fig. 3. Wild Atlantic cod captures (1950–2014) for Iceland and UK (data adapted from FAO, 2016b).

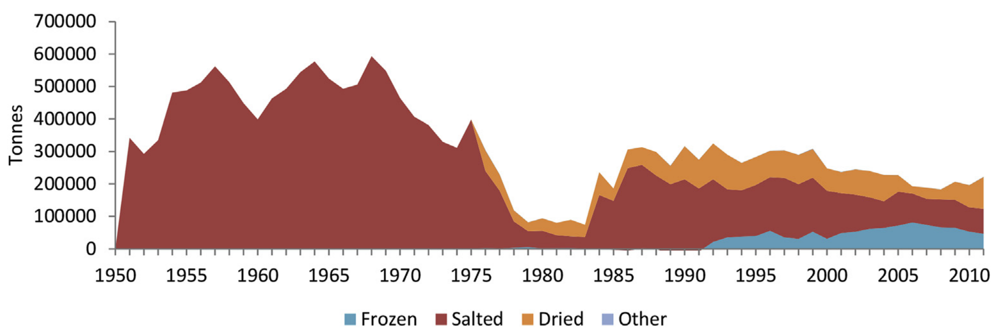

Fig. 4. Historical cod availability in Portugal from 1950 to 2011 (corrected tonnage using coefficients from Table 1).

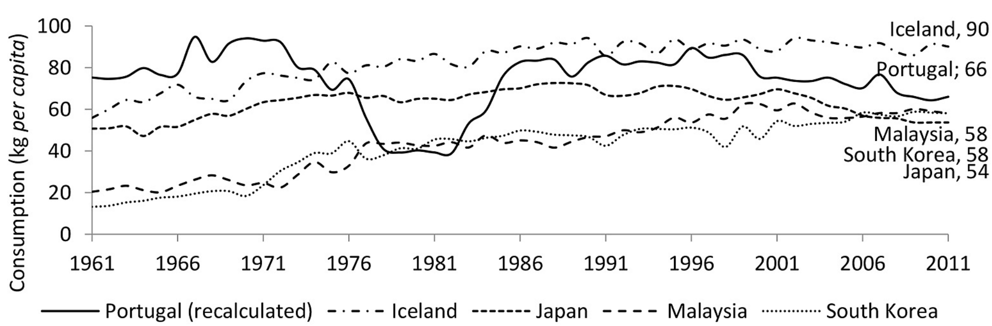

Fig. 5. Countries with highest *per capita* consumption of aquatic foodstuffs. Weight for Portugal is displayed using corrected weight for cod products.

IUU catch (14%) and the smallest part of availability is due to regulated fisheries (6%). Gilthead seabream is different from other A or B type products, mainly because its second-highest source is aquaculture, responsible for 15% of availability. Of the three products—European seabass, tuna, and horse mackerel—with mixed origin, seabass presented the highest values of external trade (70%). As in the case of gilthead seabream, seabass availability includes a significant proportion of domestically farmed fish (18%).

Tuna is the product most equally divided between external and internal origins, with 55% being imported and 43% fished by the national fleet. Horse mackerel is also classified as a Type C product with external origins of 35%, 45% from regulated fisheries while illegal sources amount to almost 20% of total availability. Sardine is the only key product with more than 75% of internal origin, since 100% of this species is supplied by the Portuguese fleet, which is dominated by regulated fishing (91%), with 9% of illegally caught fish.

Calculated consumption estimates (Table 8) show that the highest discrepancies between supply and demand occur in farmed fish species—salmon, seabass, and seabream—and in the most consumed product—cod. For the latter, this might be explained due to the considerable importance of this species in national culture and traditions (Almeida et al., 2015; Cardoso et al., 2013), leading to an underestimation of consumption, but may also be due to undeclared export.

Although the surveys used to calculate consumption only addressed soaked cod (Cardoso et al., 2013),[2] the data revealed the highest consumption weights, comprising over 10% of the total average weight, and a *per capita* consumption between 2.53 kg and 6.11 kg. Cod available in Portugal is almost exclusively imported; despite this, the importance of the cod processing industry, and the history linking this species to Portuguese traditions (Coelho et al., 2011b; Garrido, 2005; Villiers, 1952), still places it as one of the

[2] A particular culinary treatment in which dried cod is soaked for approximately 60 h (Rodrigues et al., 2003).

[3] Coefficient includes added salt, so the actual fish weight will be lower.

Table 8
OCL satisfied per species and source in weight (tonnes) and percentage. Total weight displayed corresponds to the estimated OCL for each species. Weights displayed in each category of each product correspond to the availability. Availability discriminated by external or internal source included. Classification of species type according to satisfaction of OCL (roman numerals) and origin (letters) (see Table 7 for details) included. Average values for the 2005–2013 period.

	Classification according to Optimal Consumption Level satisfied (% and tonnes)										
	External		Internal						Type	Total	
	Foreign trade		IUU		Production						
					Aquaculture		Fisheries				
Cod	134	87 424	0	0	0	0	9	5981	V	143	65 072
Hake	84	33 594	14	5666	0	0	6	2610	V	104	40 209
Tuna	56	17 134	2	744	0	0	44	13 528	V	102	30 679
Sardine	0	(-13 793)	10	4795	0	0	114	61 488	V	124	46 141
Horse mackerel	40	15 073	22	8364	0	0	51	19 146	V	114	37 266
Salmon	45	7368	0	0	0	0	0	0	II	45	16 443
Gilthead seabream	47	6778	0	52	9	1293	2	284	III	58	14 560
European seabass	31	3340	0	53	8	853	5	522	II	44	10 916
Key species	60	156 919	7	19 675	1	2146	40	103 557	V	108	261 287

	Classification according to source (% of availability)						
	External	Internal			Type	External	Internal
	Foreign trade	IUU	Production				
			Aquaculture	Fisheries			
Cod	94	0	0	6	B	94	6
Hake	80	14	0	6	B	80	20
Tuna	55	2	0	43	C	55	45
Sardine	0	9	0	91	E	0	100
Horse mackerel	35	20	0	45	C	35	65
Salmon	100	0	0	0	A	100	0
Gilthead seabream	81	1	15	3	B	81	19
European seabass	70	1	18	11	C	70	30
Key species	56	7	1	36	C	56	44

main exports, mainly to former colonies such as Brazil (Almeida et al., 2015; Cardoso et al., 2013; Martínez-Alvarez and Gómez-Guillén, 2013), particularly in value of dried and salted fish (Dias et al., 2001).

Conversely, farmed species—salmon, European seabass, and gilthead seabream—are the only key products with an unsatisfied demand, exceeding 40% in all three cases, i.e. a remarkable shortfall. Gilthead seabream and European seabass are both native species (Abecasis and Erzini, 2008; Ribeiro et al., 2008) and are sourced from both capture fisheries and aquaculture. They are also popular in subsistence and recreational fisheries, and can be sold illegally or kept by fishermen (Leitão et al., 2014). Seabream and seabass are appreciated by consumers and farmed product is sold at lower prices than wild-caught fish of the same species (Cardoso et al., 2013; INE, 2014a). Salmon is an exclusively imported product. Despite this, estimated consumption places this species as the sixth most consumed in Portugal, averaging above 16 000 tonnes. As seen for cod, it is possible that consumption was overestimated for this species. The difference between OCL and availability could also mean an underestimation of IUU values, both in subsistence and recreational fishing and from aquaculture operations, in the seabass and seabream cases.

The remaining key products present smaller discrepancies between supply and demand. Sardine, horse mackerel and hake have a moderate degree of over met demand. Illegal and unregulated sources also play an important role in the availability of hake and horse mackerel, which could mean that traditionally employed methods to prevent IUU fishing, such as monitoring of fishing activities (PCEU, 2013), are not succeeding in avoiding these practices on board of fishing vessels. This leads to an influx of illegal products to consumers, which presents a challenge for both taxation and conservation objectives. These apparent inconsistencies in the mass balance of supply and demand, both in species such as cod, where there appears to be an oversupply, and in cultivated species, where the reverse is true, present a significant problem for policymakers in setting aquaculture and fisheries growth targets.

3.2.2. Unmet demand and growth potential

Difficulties in obtaining accurate growth potential estimates for both fisheries and aquaculture are an issue, due to factors such as data accuracy, production practices, or competition for marine space (Campbell and Pauly, 2013; Gjedrem et al., 2012; Natale et al., 2013). These issues are apparent when setting growth targets and defining policy changes. Despite this, it was possible to obtain an approximation based on the seafood supply and demand estimates (Table 9). Gilthead seabream and seabass present the best opportunities for internal industry growth regarding the OCL evaluation, mainly due to unmet demand. Salmon, despite presenting a similar OCL satisfaction to the other farmed species, is not a viable option regarding internal growth potential due to environmental limitations. The remaining species, for which over 100% of consumption is satisfied, are not classified the same way, mainly due to consumption being overly met.

OCL levels that exceed availability suggest an unmet demand, indicating an economic opportunity for suppliers, or may simply correspond to undeclared supply. Despite this, in other species where OCL weights are below availability, there is still opportunity for improvement of biological stock status or mitigation of illegal fishing and discards, which in turn can lead to improvements in production weights and value chains.

Some of the key species have high IUU values. Hake and sardine present high quantities of illegal fishing and both have low biomass levels (ICES, 2015, 2013), therefore a mitigation of the causes for IUU can also aid in fish stock recovery. The recent Common

Table 9
Interpretation of discrepancies as growth potential estimates for aquaculture and fisheries of key species identified for the selected case study. Growth potential is considered, according to source and OCL satisfaction. The best areas of intervention are identified for each product. Products are classified according to potential from lowest (− −) to highest (+ +). Weight in tonnes.

	Source	OCL satisfied	Δ(Availability - OCL)	Δ(Availability - next consumption level)	Priority areas of intervention
Cod	+ −	− −	29 838	29 838	Product valorisation
Hake	+	− −	1928	−14 544	IUU control and mitigation; Biological stock status improvement
Sardine	+	− −	5974	5974	IUU control and mitigation; Biological stock status improvement
Salmon	− −	+	n.a.	n.a.	−
Tuna	+ −	− −	1112	−12 467	Product valorisation
Horse mackerel	+	− −	5465	5465	IUU control and mitigation
Gilthead seabream	+ +	+ −	−5973	−5973	Farmed fish production
European seabass	+ +	+	−6099	−6099	Farmed fish production
Aquaculture	+ +	+ +	−12 072	−12 072	
Fisheries	+ −	+ −	0	−27 011	
Key species total	+ −	− −	−12 072	−39 083	

Fisheries Policy (CPF) reform, which implements a gradual ban on discards (PCEU, 2013), is a notable innovation (European Commission, 2009; Salomon et al., 2014). Mandatory discard landing has the potential to greatly reduce the IUU catch, which would be a significant improvement on present conditions (Diogo et al., 2016; Veiga et al., 2016).

The improvement of the biological status of fish stocks can lead to an increase in fishing yields from rebuilt stocks, which can be translated into economic gains (Froese and Quaas, 2013) if fishing capacity is adequate, based on sound scientific knowledge, and provided limits are not exceeded (European Commission, 2014b). The conservation measures implemented to date by the EU have had little success in returning certain wild fish stocks to safe biological levels (ICES, 2014, 2013).

Of the key seafood products identified on the case study, farmed species —and cod— present the highest discrepancy level between supply and demand. Although suitability of coastal areas for aquaculture may vary (Kapetsky et al., 2013), technology continues to evolve, allowing exploration of harsher environments (Kaiser et al., 2010), and better management of marine space while reducing environmental impacts (Ferreira et al., 2012; Nobre et al., 2010).

National aquaculture plans and other strategies are important in order to identify and remove constraints when establishing objectives for increased production (DGRM, 2014), but other obstacles remain, such as delivering comprehensive and accurate data to managers on seafood consumption. This would allow the identification of discrepancies between supply and demand statistics providing a tool for mitigation of undeclared imports or sales from fish farms.

4. Conclusions

Accurate data for supply and demand of aquatic products are required for improved policy decisions. The challenge resides in providing managers with a synthesis of the detailed information produced by researchers, with the accepted risk of forfeiting some degree of detail (Elliott, 2002; Ferreira et al., 2006).

Discrepancies between supply and demand of aquatic products emphasize the need for improved statistical data on fish consumption, as well as illegal, recreational, and subsistence fisheries. The large differences identified for farmed fish products are of particular concern, given aquaculture's increasingly significant role as a source of aquatic food.

In the context of the CFP European Maritime and Fisheries Policy (EMFF, EC, 2016), European Union nations (EU27) have recently published their national aquaculture plans, setting production targets for 2023 (Fig. 6). EU aquaculture is planned to grow by 28% over the period 2013–2023, i.e. at an APR of 2.4% y^{-1}, but an analysis of the planning basis for the twenty-seven nations does not reassure the reader with respect to the underlying assumptions.

In particular, it is difficult to understand how spatial planning criteria, market factors, and social licence issues are taken into consideration. Projected growth rates are highest for small nations starting from a very low production base (e.g. the Baltic states, Ireland, Portugal, or Austria), but there is no breakdown of the

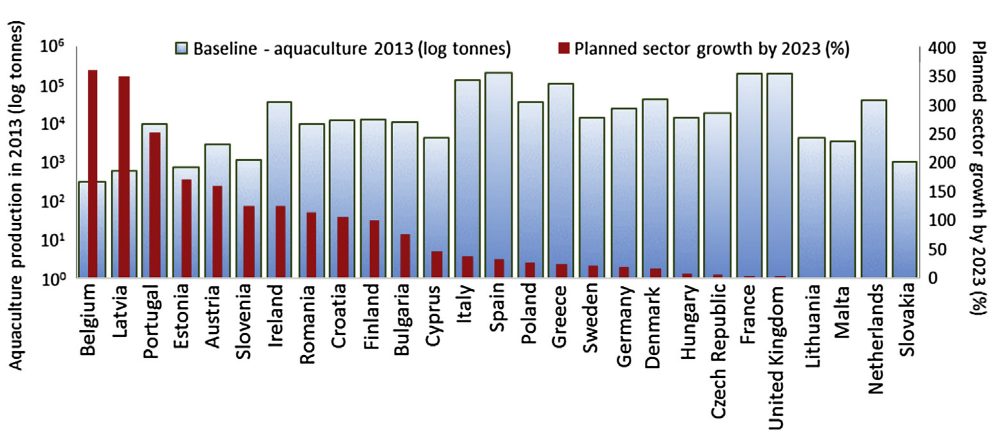

Fig. 6. Present status (2013) and planned expansion in EU aquaculture (2023), according to national plans for the EU27 submitted to the European Maritime and Fisheries Fund (EMFF). In 2023, the EU *plans* to produce an extra 330 kt y^{-1} of aquaculture products; the projected global requirement in 2050 is for an additional 31 million tonnes per year (FAO, 2016a).

species to be cultivated, or of the business, trade, regulatory, and environmental issues that must be overcome. Furthermore, an analysis of the 27 EU (Luxembourg did not report) Multiannual National Plans (MNP, EC, 2016), shows that taken collectively the MNP lead to an APR of 4.5% y^{-1}, in line with the figures proposed by Lane et al. (2014), but not easily reconciled with the EMFF predictions.

If the challenges in closing the mass balance of supply and demand are added to these concerns, then planning for improved food security in Western nations appears to require a new paradigm—fisheries and aquaculture must be analysed jointly, and production and consumption must be reconciled. With respect to the latter, the supply chain must be involved in the reporting of consumer data, particularly in nations where surveys will not yield reliable data. The inclusion of species-level demand will help provide a coherent picture for expansion, allowing investors to understand the opportunities and limitations of farming food from the sea.

Asian nations (where 90% of aquaculture takes place), and in particular China, are increasingly aware of the recreational potential of coastal zones, as *per capita* GDP and disposable income increases; fish farming, which has historically been focused on production, is now losing space to other uses. By contrast, developed nations are focused on *increasing* production, while preserving or increasing ecosystem services.

The types of issues identified in this study are not only relevant for Europe, but applicable on a global scale—the world balance of supply and demand for aquatic products undoubtedly reflects the discrepancies observed at a national scale, and an understanding of the underlying factors is critical to planning for the next decades, in order to reach an equilibrium that combines sustainable fisheries with eco-farming, to provide global food security for the next generations.

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