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Illustrating the hidden economic, social and ecological values of global forage fish resources

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ABSTRACT

People benefit from the existence of forage fish through a wide range of uses, both direct and indirect. However, due to lack of data and gaps in existing research, the commercial importance of these species tends to get prioritized over the wider benefits they provide to society and the environment. This paper aims to identify all the multiple beneficiaries of forage fish and present their global value that encompasses different categories of benefits using both quantitative and qualitative methods. By adopting the Millennium Ecosystem Assessment framework, we estimated the global economic benefit provided by forage fish to be $18.7 billion per annum, over three times of their direct catch value. This is a partial estimate due to data limitation. We demonstrated the importance of forage fish to the livelihoods of coastal communities by providing direct employment to 5.6 million fishermen globally. The analysis also explored the important role forage fish plays by addressing the nutritional needs of indigenous and coastal communities, and their role in shaping the culture and customs - the significance of all of which cannot be captured by money values alone. We concluded that attempts to capture the economic values of forage fish are likely to be underestimates of the true value that forage fish hold for humans and other interlinked ecosystems. Understanding the true value of forage fish is important to avoid inadvertently making undesirable tradeoffs or management decisions that are environmentally and economically unsustainable.

1. Introduction

Forage fish is a category used to define highly productive, small and medium sized low trophic pelagic fish, such as anchovy, herring, sardine, and krill, which are preyed upon by higher trophic level species such as marine fish, mammals and birds. Most of forage fish are critically important in marine food webs, feeding upon phytoplankton, zooplankton, and in some cases, the early life stages of their predators (Pikitch et al., 2012). They provide the main pathway for energy and nutrients to flow from lower trophic level to higher trophic level, and few other species in this trophic level can serve channeling the energy flow as much as forage fish do (Pikitch et al., 2012; Essington et al., 2015). Forage fish also hold a direct value to marine capture fisheries, as they are caught for direct human consumption or support high-value fisheries for roe (such as herring) destined for the Japanese market. A significant portion of the catch is “reduced” to fishmeal and fish oil, which are used primarily as feed ingredients for aquaculture and terrestrial animals (Alder et al., 2008). Like many other products of natural systems, forage fish are effectively produced by the oceans at no charge. They are caught at low cost because they usually aggregate in large schools. The low harvesting cost, along with price increases of fishmeal and fish oil driven by changes in the feed industry (Asche et al., 2013; Tai et al., 2017), makes them extremely attractive to fishers to meet short-term commercial gains.

Whether forage species are more susceptible to collapses from fishing compared with other longer-lived species has been long debated (Mullon et al., 2005; Pinsky et al., 2011; Pikitch et al., 2012; Hilborn et al., 2017). These stocks are short-lived and more vulnerable to environmental fluctuations than fishing (Hilborn et al., 2017), and exhibit strong natural variability (Christensen et al., 2014). Global landings of

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major forage fish have been estimated to be close to the average maximum sustainable yield (MSY) (FAO, 2018; Froehlich et al., 2018) (See Supplemental Figure S1). However, fishing forage fish at conventional MSY level in low yield years may lead to overfishing (Smith et al., 2011). The continuous high fishing rates can also amplify the risk of population collapses when productivity and abundance is in rapid decline (Essington et al., 2015). Because of the uncertainty and inherent complexity of these highly dynamic species, the relationship between forage fish and their dependent predators is quite complicated. Evidence does not universally show that the abundance of predators is affected by the decline of forage fish at a global scale (Hilborn et al., 2017). Yet the local and regional impact of forage fish on the reproduction, survival rate, and population density of predators should not be ignored (Jahncke et al., 2004; Frederiksen et al., 2005; Crawford et al., 2007; Cury et al., 2011; Robinson et al., 2015; Koehn et al., 2017). Even from this narrow perspective, and especially given their supporting role for dependent predators, collapses of forage fish can clearly pose a risk that would lead to longer-term ecological and economic loss.

This risk of stock collapses may intensify as aquaculture production increases with increasing human population. The aquaculture industry has doubled its size in the past decade and is expected to keep increasing at an annual growth rate of 2.3% until 2026 (OECD/FAO, 2017). In response to the growth of aquaculture there is a growing demand for fishmeal (World Bank, 2013; Cao et al., 2015). Fishmeal is traded globally with the largest volumes exported from Latin America (i.e. Peru) and imported to Asia (i.e. China) (FAO, 2018). While technological improvements have already allowed for significant reductions in fishmeal inclusion in aquaculture feeds, forage fish continue to serve as a critically important feed ingredient and are still vital to the growth and commercial viability of the aquaculture industry. If the adoption of sustainable and nutritionally equivalent substitutes by aquaculture is not quicker, the demand for fishmeal from production of aquaculture will outstrip the supply of forage fish and there is some evidence that the ecological limits of forage fisheries could be reached as early as 2037 under ‘business as usual’ scenarios (Froehlich et al., 2018) and ultimately push the overexploitation of major commercial forage fish species.

The interaction between aquaculture and fisheries is only one aspect of the trade-offs between the multiple benefits that forage fish provides to humans, marine ecosystems, national economies and industries. Given the challenges in non-market valuation and knowledge limitations in marine biodiversity, there is lack of a single study that identifies all the multiple beneficiaries of forage fish and presents a holistic value that attempts to include the different categories of benefits (social, economic and ecological) derived from the resource. Pikitch et al study (2012) addressed a key knowledge gap in this area, as it estimated the value of forage fish to be $16.9 billion, including a direct catch value ($5.6 billion) and value to dependent predators ($11.3 billion). It did not disaggregate the direct catch value by users (e.g., human consumption, and non-food uses by aquaculture and livestock sectors), nor does it quantify the contribution of these species towards coastal tourism. In addition, there are values that go beyond these monetary estimates, which are important for human health and societal well-being. These values include cultural and spiritual values of marine resources to indigenous communities (Jones et al., 2017), and amenity values arising from restored and healthy marine ecosystems (Berman and Sumaila, 2006). There are also ecological or intrinsic values which acknowledges marine ecosystems has the right to exist and create value, even if they are not directly beneficial to humans (Bayram, 2012; Selck et al., 2016; Rea and Munns, 2017). Understanding these multiple benefits that forage fish provide and their values can inform prioritization decisions when managing stocks and allow a better forage fish resource allocation, without sacrificing the long-term benefit forage fish provide to society.

This study builds on the Pikitch et al (2012) study and applies the UN Millennium Ecosystem Assessment’s (Millennium Ecosystem Assessment, 2005) approach which provides a basic framework for evaluating ecosystem services and paves the way for further assessments and integrating ecosystem service thinking into decision making (Millennium Ecosystem Assessment, 2005; Satz et al., 2013; Small et al., 2017). Ecosystem services are the direct and indirect contributions of ecosystems to human well-being (TEEB, 2010). Using the MEA framework, we examined the ecosystem services provided by forage fish, including provisional services (contribution to direct and indirect human consumption), supporting services (provision of nutrition to marine predators, indirect contribution to commercial fisheries and coastal tourism), regulating services (role in regulating ocean carbon cycle and the ‘biological pump’), and cultural services (shaping traditions of coastal and indigenous communities through traditions, religious customs and ceremonies). We also assessed the contribution of these marine resources towards economic (revenues generated, direct jobs created, and trade) and social development (help achieve the sustainable development goals and targets) that are not captured in the MEA framework but are important in influencing policymakers’ decision to sustainably manage these resources. In addition, we evaluated the ecological value provided by forage fish species by supporting a range of marine predators, and highlight the intrinsic value of all the species – including forage fish themselves – which rely on a healthy functioning ecosystem to survive. Using both quantitative and qualitative evidence, this paper aims to help illustrate the scale of the hidden non-market values of forage fish and identify gaps for further research.

2. Methods

In this paper, we assessed the values of forage fish resources in three ways (Fig. 1): (1) values associated with ecosystem service benefits which include the values of provisional, regulating, supporting, and cultural services; (2) values associated with measuring the contribution of forage fish towards economic development, which include revenues generated by industries that rely on forage fish as a key input (such as aquaculture and fishmeal production), gains from trading commodities derived from forage fish, and employment benefits; and social contribution in terms of the role forage fish plays in helping countries achieve their Sustainable Development Goals (SDGs) and targets in relation to ensuring food security, hunger and nutrition (SDG indicators for 2.1 and 2.2); (3) the wider ecological values which focus on the biodiversity benefits that forage fish encompasses by supporting a wide range of marine species and by maintaining the health of the marine environment. We described the methodology used under each section below.

2.1. *Ecosystem service value*

2.1.1. *Provisional services*

Provisioning services are the products obtained from ecosystems such as food, fresh water, wood, fiber, genetic resources and medicines (TEEB, 2010). The calculation of provisional services was divided into three parts – catch used for the production of feed for aquaculture and land-based livestock; and catch used directly for human consumption. It is important to note that to estimate the total amount of reduction fishery, we focus on fishmeal component of feed. This is because fish oil is a by-product of fishmeal, so in our model the same amount of whole forage fish and trimmings would produce both fishmeal and fish oil.

The model began with selecting eight key aquaculture species groups, which account for more than 70% of aquaculture species that feed on fishmeal. The eight groups of species are carp (filter feeding species excluded), tilapia, catfish, salmon, trout, freshwater crustaceans, marine shrimp, and milkfish. Low-trophic species such as carp and tilapia are still considered in spite of their low fishmeal inclusion rate as their market share is high. The total amount of fishmeal (FM_A) used by the eight species groups is calculated by the following equation:

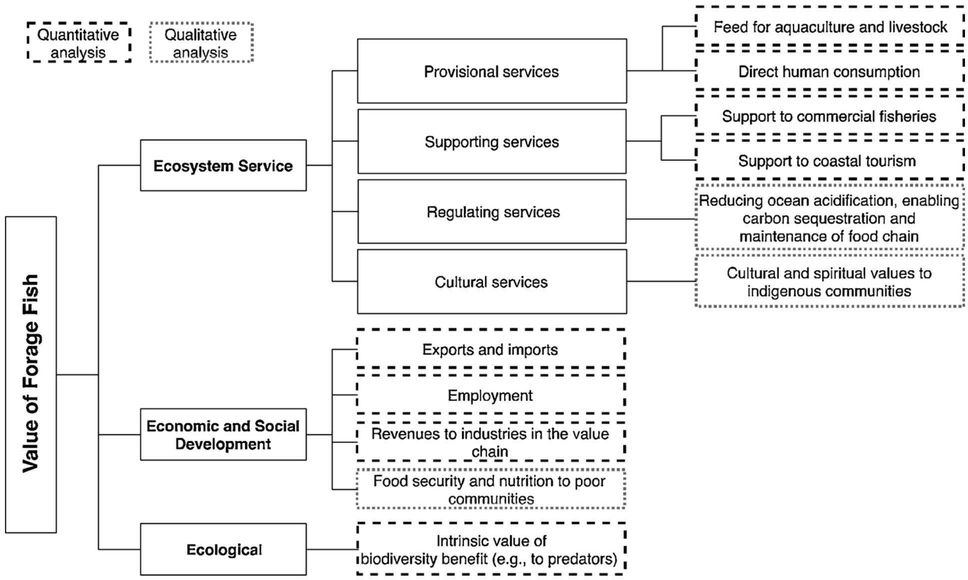

Fig. 1. Technical flowchart for assessing values of forage fish.

$$FM_A = \sum_1^i (Q_i \times FCR_i \times r_{fm}) \quad (1)$$

where Q_i is the annual global production of aquaculture species by tonnage (dataset FishStatJ, 2018), FCR_i is the average feed conversion ratio of each of the eight species groups (Tacon and Metian, 2008), and r_{fm} is the inclusion rate of fishmeal in the feed of the eight species.

Currently, commercial fishmeal is made of 33% of fish processing by-products and 67% of whole forage fish (FAO, 2018), and every unit of forage fish can produce 0.21 unit of fishmeal (Cao et al., 2015). The quantity of whole forage fish (referred to here as 'forage fish equivalence', ff_A) used to make fishmeal was estimated by the following equation:

$$ff_A = (FM_A \times 0.67)/0.21 \quad (2)$$

The value of forage fish (V_A) used in fishmeal production was estimated by multiplying ff_A with the weighted price (See Supplemental Table S1). The weighted price was calculated by multiplying the share of catch of each forage fish by its ex-vessel price. Ex-vessel price is the price of fishery products received by a captain at the point of landing.

$$V_A = ff_A \times \sum_1^i (w_i \times Ev_i) \quad (3)$$

where w_i is the weight based on the share of catch for each forage fish species (dataset FishStatJ, 2018), and Ev_i is the ex-vessel 5-year average (from 2008 to 2012) real prices that fishermen receive for their forage fish before processing (Melnychuk et al., 2017).

About 70%, 22%, 6% and 2% of global fishmeal was estimated to be used by aquaculture, pig, poultry and other livestock sectors, respectively (Sea Fish, 2018). Therefore, we considered fishmeal used by aquaculture is 70%, and 30% by livestock. The volume (FM_O) and value (V_O) of forage fish used by the livestock industry were calculated using the following set of equations:

$$FM_O = (FM_A/0.7) \times 30\% \quad (4)$$

$$V_O = [(FM_O \times 0.67)/0.21] \times \sum_1^i (w_i \times Ev_i) \quad (5)$$

Among all the forage fish captured, only 10% is used for direct human consumption (IFFO, 2012). The value of forage fish used for direct consumption (V_D) is calculated as follows:

$$V_D = [(V_A + V_O)/0.9] \times 10\% \times \sum_1^i (w_i \times Ev_i) \quad (6)$$

Our calculations depended on point values of four key factors, including the weighted ex-vessel price of forage fish, feed conversion ratios (FCRs) of the eight species, the market share of waste-based fishmeal production, and the fishmeal inclusion rate in aquafeed. To consider possible future changes of these key factors and further understand how those changes might affect the total quantity and value of forage fish used, a sensitivity analysis is conducted (Table 1). Scenario I explored the effect of ex-vessel price fluctuation of forage fish value of forage fish used. Scenario II considered future improvement in feeding efficiency and examined the impact of improved FCRs on the total quantity and value of forage fish used. Scenario III assumed an increased market share of waste-based fishmeal and assessed its impact on the total quantity and value of forage fish used. This scenario looked at the impact of significant improvement in technology that will allow more processing wastes or by-products to be included in the preparation of fishmeal (which in turn implies a reduction in whole forage fish

Table 1
Sensitivity analysis scenario description.

Scenarios	Parameter Change	Description
I	Price of forage fish	(1). Use price of forage fish for direct human consumption (Tai et al., 2017); (2). Use weighted price based on catch data; (3). Use a higher price for Norway pout (*Trisopterus esmarkii*) and Peruvian anchovy (*Engraulis ringens*) (Melnychuk et al., 2017).
II	Feed conversion ratio	Assuming due to technical innovation, improve FCR by 10%, 20% and 30%.
III	Market share of waste-based fishmeal*	Increase from current 33% to 50%.
IV	Fishmeal inclusion rate in aquafeed	Assuming due to advances in fishmeal replacement, decrease current fishmeal inclusion rates by 10%, 50% and 90%.

Notes: * We recognized that the quality of waste-based fishmeal is inferior compared to fishmeal derived from whole forage fish. However, our modelling scenario assumed that technological progress would bring improvement in their quality leading to their increase use in fishmeal production.

used). Scenario IV tested the sensitivity of the estimates by decreasing fishmeal inclusion rates due to technical advances in fishmeal replacement.

2.1.2. Supporting services

As a part of valuing ecosystem services, supporting services are not directly analyzed to prevent double counting and thus are at a risk of being neglected (Bateman et al., 2011). This is because their value is already captured in the value of the three 'final' ecosystem services that they contribute towards (provisioning, regulating and cultural services). However, for the purposes of this analysis we do specifically assess supporting values, as we are trying to appreciate all the hidden values of forage fish, especially in maintaining the marine food web. We address the double counting issue by following the Pikitch et al. (2012) methodology and apportioning a part of final commercial and coastal tourism ecosystem values of the predators to forage fish based on the diet dependency of their predators.

We assess the following supportive services forage fish provides to industry and local economies: (1) by being a key part of the diet of commercially important fisheries, and (2) by being a key source of diet for important tourism species. The value of supportive services to commercial fisheries is quantified by converting predator fishes into their forage fish diets, then multiplying the amount of forage fish consumed by the weighted price. An existing inventory of 32 species of predators and their forage fish dependency rates is used for the calculation (Pikitch et al., 2014; Hilborn et al., 2017).

On average, only 10% of energy will transfer from one trophic level to the next (Andersen and Pedersen, 2010). Therefore, the amount of food consumed by predator is roughly ten times the weight of the predator, and the value of forage fish consumed (V_{SC}) was calculated by the following equation:

$$V_{SC} = \sum_{1}^{i} [(P_i/10\%) \times D_i] \times \sum_{1}^{j} (w_j \times Ev_j) \tag{7}$$

where P_i is the catch-level of each predator fish species (dataset FishStatJ, 2018), and D_i is the average forage fish dependency rate of each predator fish.

We reviewed the existing literature that estimate the tourism related expenditure attributable to species of seabirds, marine mammals and recreational fishing, which depend on forage fish across a range of geographical locations. Specifically, we reviewed seabirds (e.g., shearwater, guillemot, puffin, gull, kittiwake and ganne) viewing in the UK (RSPB, 2010), African penguin in South Africa (Lewis et al., 2012), whales and cetaceans watching globally (O'Connor et al., 2009), and recreational fishing (e.g., grouper, snapper, tuna, swordfish and flounder) in the US (Stokes et al., 2013). For each of these species identified, we assessed to what extent their diet depends on forage fish (Hamer et al., 2000; Pikitch et al., 2012; Hilborn et al., 2017). We then apportioned the tourism expenditure to forage fish using these diet dependency estimates.

2.1.3. Regulating and cultural services

To determine regulating services provided by forage fish, we reviewed the literature to assess qualitatively the role forage fish can play in the "biological pump". First, we took a broad view of the biosphere's contributions to ocean health, including mechanisms for "ocean mixing" and exporting particulate organic matter. Then we narrowed our scope to examine the roles that marine vertebrates specifically play in sequestering carbon and how those roles will likely change in response to anthropogenic factors. We explored the potential benefits forage fish provide in terms of mitigating impacts of ocean acidification and sequestering carbon from the atmosphere. Due to data limitation, we assessed and discussed their values qualitatively, highlighting the areas where further research is needed.

Recent refinement of the ecosystem services framework emphasized that culture is central to all of the links between people and nature, and thus it is more important than ever to recognize other knowledge systems such as local communities and indigenous people (IPBES, 2018). To determine the role that forage fish play in shaping the cultural identity of indigenous communities, we specifically focused our analysis on indigenous communities in British Columbia of Canada and the United States. We assessed how these cultural values inform future conservation and management decisions. Given the lack of valuation studies and literature in this area, we did not restrict our review to only peer reviewed journal-based published studies but also consider articles, information provided by tribes to governments and relevant policy documents that highlight the significance of the species to these communities.

2.2. Measuring the contribution towards economic and sustainable development

Ecosystem services are important for measuring societal well-being, however they do not reflect all the parameters that governments consider when making resource-based management decisions. For example, these values do not show the impact of the resources across the supply chain (e.g., indirect revenues), on international trade and employment.

We already estimated the provisioning service or gross revenue received by fishers before processing forage fish as described above. Forage fish can also generate further revenues across the range of industries in the supply chain. To analyze this multiplier effect we estimated the gross revenues generated from both aquaculture (focusing on species reliant on fishmeal and fish oil for feed) and fishmeal production. We used official statistics (dataset FishStatJ, 2018) to estimate the total production of major aquaculture species reliant on fishmeal. We multiplied it with the reconstructed global ex-vessel prices of fish species data (Melnychuk et al., 2017) to estimate the gross revenue of the sector reliant on forage fish. By multiplying the total production of fishmeal with the real market price data (dataset IndexMundi, 2018), we estimated the gross revenues derived from fishmeal production.

For forage fisheries we estimated the total direct employment in the sector. Data regarding the employment generated by forage fish are extremely limited. To calculate the total employment, a list of countries that provide the employment data was collected, and the proportion of forage fish fishermen to all fishermen was calculated for each of the countries. In the eight countries and regions selected, which are the only countries/regions with data, Peru, India, South Africa, and Indonesia-Java Sea are top fishmeal producing countries, and their average forage fish fishermen proportion is about 48%. The other four countries and regions (southern Australia, southern Angola, Tanzania, and Ghana) are not actively producing fishmeal, and their forage fish fishermen proportion is only 6%. We then estimated the global number of fishers (N_{ff}) employed by forage fish fisheries based on the best available data using the following equation:

$$Nff = 48\,\% \times \Sigma top + 6\,\% \times \Sigma rest \tag{8}$$

where Σtop is the total number of fishers in top fishmeal producing countries and $\Sigma rest$ is the total number of fishers in the rest of the world.

Trade of forage fish products also plays an essential role in boosting fish consumption and production, providing employment and generating income for a number of people working in a range of industries and activities around the world. Using public data (dataset FishStatJ, 2018) we summarized top exporting and/or importing countries by three categories of products related to forage fish - fishmeal, fresh catch and processed catch (dried, smoked, salted or in brine). By presenting the import and export data of these countries, we qualitatively discussed the role of forage fish in supporting international trade.

We also looked at the role of forage fish in helping developing countries to meet the targets set under SDG 2, which aims to end hunger, achieve food security and nutrition by 2030. In particular, we focused on SDG indicator 2.1 (end hunger and ensure access by all people, in particular the poor) and 2.2 (end all forms of malnutrition), and qualitatively discussed how healthy forage fish stocks can help achieve these indicators. Based on a review of peer-reviewed journal articles, we assessed the dependence of developing countries on forage fish as an inexpensive source of protein and micronutrients.

2.3. Ecological value

Ecological value, though often hard to monetize, acknowledges the role forage fish play in the marine ecosystem by supporting a range of marine predators which rely on a healthy functioning ecosystem to survive. Understanding ecological values, and the limits of our understanding of how complex systems function can lead to a natural increase in human health and well-being (Seddon et al., 2016). Methods to quantify these values are evolving and while it is challenging to quantify the full value of environmental stewardship, yet we only need to quantify enough to make well-informed decisions (Rea and Munns, 2017). For the purpose of this paper, we reviewed the existing literature to provide an estimate of the number of species that are highly dependent on forage fish and hence demonstrate the significant value at stake if forage fisheries were to collapse.

3. Results

3.1. Ecosystem service value

Based on our calculation, the value of provisional services provided by forage fish is about 7 billion USD per annum. This consists of approximately 700 million USD of direct consumption by humans and 6.4 billion USD of indirect consumption per annum by the aquaculture and livestock sectors (Table 2).

The value of forage fish is sensitive to the ex-vessel prices of the species used in the model (scenario I), provided they dominate a large proportion of the catch level (Table 3). Peruvian anchovy alone contributes about 24% of the total catch of forage fish, therefore any change of Peruvian anchovy price will have a huge impact on the weighted price and consequently the value of provisional services estimated.

It is also clear that quantity of whole forage fish and fishmeal used for feed purposes reduces significantly with the improvement in the FCR (scenario II) and fishmeal inclusion rate (scenario IV) (Table 3). Reducing FCR from 10 to 30 percent will save 0.98 million to 2.94 million tonnes of whole quantity of whole fish being used and reduce costs to industry by 0.46 to 1.3 billion USD due to reduction in the usage of fishmeal. Similarly, 10% to 50% decline in fishmeal inclusion rate saves 0.98 to 4.9 million tonnes of forage fish and 450 million to 2.2 billion USD cost of fishmeal to the industry. It is important to note that in reality, the extent to which these savings will be realized will depend on the cost of alternative ingredients (such as amino acid supplements, single cell proteins, oilseed meals, algae meals and insect meals) used in the feed to replace fishmeal. In addition, result of scenario III (use more fish processing by-products to produce fishmeal) showed that if the by-product inclusion rate increases from 33% to 50%, then 3.4 million tons of whole forage fish will be saved, which values at 1.6 billion USD.

Using diet dependencies of 32 commercially important predator species (Pikitch et al., 2012; Hilborn et al., 2017), we estimated the value of forage fish to commercial fisheries to be $11.6 billion (Table 4).

Based on regional case studies, the eco-tourism related values we estimated (Table 5) provide a snapshot of tourism related activities of the predators of forage fish. They are not additive and do not provide a global estimate that encompasses the total value that forage fish contributes towards the tourism industry. However, they aim to show the scale of reliance of the tourism industry on forage fish. We found that the magnitude of these values is significant to regional tourism and range in the low millions to billions for charismatic species such as whales and other marine mammals that have an established global tourism industry.

Results from the literature review implicate forage fish in having a role in providing regulating services that benefit the ocean carbon cycle. The predators of forage fish play an important role in sequestering carbon by storing it in their tissues and bodies for decades and centuries (Pershing et al., 2010; Lutz and Martin, 2014). This large biomass sinks to the deep ocean with the sinking of their carcasses, transporting carbon from the surface to the deep ocean where they are stored. This results in a net effect in the 'pumping' of CO_2 from the atmosphere to the deep ocean. The exact nature of this relationship needs to be further explored, since forage fish as a CO_2 sink only occurs when they support tissue deposition (and not just metabolic maintenance). This natural ability of the ocean and marine species to sequester carbon from the atmosphere and store it deep within the ocean waters, exerts an important control on the global climate. Forage fish species enable this function given their role in the marine food web in supporting larger predators. Large predators of forage fish and marine vertebrates (such as whales) have been associated with the mixing of nutrient rich water through the water column, enabling the production of phytoplankton in nutrient poor waters (Dewar et al., 2006; Lavery et al., 2012). Predators of forage fish such as bony fish including tuna and forage fish species themselves such as parrot fish and herring, are shown to play an important role in buffering ocean acidification by producing calcium carbonate in their guts and in their fecal pellets to rid themselves of excess calcium ingested from seawater (Wilson et al., 2009).

We found that forage fish are of cultural significance to many indigenous and coastal communities and decline in stocks not only impacts their livelihood, resulting in lower employment and reduced access to nutritious food supply, but can also lead to tension in social relationships with the central government and commercial fishery industries (Lam, 2016; von der Porten et al., 2016; Jones et al., 2017; Pitcher et al., 2017; Raman et al., 2018; Lam et al., 2019). For example, herring for indigenous communities in British Columbia and the United States, notably the Haida, Heiltsuk, Nuu-chah-nulth First Nations, and Tlingit in Southeast Alaska, is more than just food and plays a unique role in creating important ties between families and individuals as well as shaping their cultural identity, traditional beliefs, legends and spirituality (Bassett, 2014; Cooke and Murchi, 2015; Thornton, 2015; Gauvreau et al., 2017; Jones et al., 2017; Uu-a-thluk, 2018). These cultural values have been used to inform conservation plan for these regions to create a balanced and informative picture of the state of fisheries management for policymakers.

Table 2
Forage fish consumed by aquaculture, livestock and humans.

	Fishmeal use (mmt)	Forage fish equivalent (mmt)	Value of forage fish (million USD)
Aquaculture	3.1	9.8	4,500
Livestock	1.3	4.2	1,900
Direct human consumption	0.5	1.6	700

Note: Fishmeal use for aquaculture was estimated based on 2016 FAO data from FishStatJ (2018).

Table 3
Results of sensitivity analysis.

Scenarios		Original value	New value	Forage fish saving	
				By quantity (mmt)	By value (million USD)
I	Price for direct human consumption	455 usd/ton	1900 usd/ton	0	−2249
	Weighted price	455 usd/ton	456 usd/ton	0	−16
	Higher price	455 usd/ton	580 usd/ton	0	−1946
II	Improve FCRs (FM less by 10%)	1.3-1.9	1.2-1.7	0.98	446
	FCRs decrease by 20%	1.3-1.9	1.0-1.5	1.96	892
	FCRs decrease by 30%	1.3-1.9	0.9-1.3	2.94	1, 338
III	Market share of waste-based fishmeal	33%	50%	3.55	1617
IV	10% fishmeal substitution	2.0-25%	1.8-22.5%	0.98	446
	50% fishmeal substitution	2.0-25%	1.0-12.5%	4.90	2,230
	90% fishmeal substitution	2.0-25%	0.2-2.5%	8.83	4,014

Table 4
Annual global production, forage fish[*] (FF) dependency rate, and the value of FF consumed by highly-dependent commercial fish.

Species	Scientific Name	Annual Global Production[†] (ton)	Average FF Dependency[‡] (%)	Value of FF consumed (million USD)
Atlantic bluefin tuna	*Thunnus thynnus*	22,117	71.6	72
Atlantic cod	*Gadus morhua*	1,329,450	51.2	3,097
Bigeye tuna	*Thunnus obesus*	394,841	61.8	1,110
Blacktip shark	*Carcharhinus limbatus*	487	50.4	1
Bluefish	*Pomatomus saltatrix*	19,133	24.6	21
Common Dolphinfish	*Coryphaena hippurus*	102,316	39.7	185
Finetooth shark	*Carcharhinus isodon*	25	74.7	0
Fourspot flounder	*Hippoglossina oblonga*	4	26.4	0
Goosefish	*Lophius piscatorius*	2,461	43.4	5
Night shark	*Carcharhinus signatus*	911	38.8	2
Offshore hake	*Merluccius albidus*	1	53.1	0
Pollock	*Pollachius*	298,086	35.6	483
Shortfin mako shark	*Isurus oxyrinchus*	12,950	55.8	33
Silver hake	*Merluccius bilinearis*	14,250	26.9	17
Spinner shark	*Carcharhinus brevipinna*	76	67.1	0
Spiny dogfish	*Squalus acanthias*	9,023	31.2	13
Striped bass	*Morone saxatilis*	2,258	54.8	6
Summer flounder	*Paralichthys dentatus*	3,789	19.8	3
Swordfish	*Xiphias gladius*	125,636	47.9	274
White hake	*Urophycis tenuis*	3,260	31.0	5
White marlin	*Kajikia albidus*	616	54.1	2
Yellowfin tuna	*Thunnus albacares*	1,462,540	50.6	3,364
Small wahoo	*Acanthocybium solandri*	3,526	63.0	10
Atlantic bonito	*Sarda sarda*	55,752	55.0	140
Black rockfish	*Sebastes melanops*	165	60.0	0
Adult Sablefish	*Anoplopoma fimbria*	17,176	50.0	39
Coho salmon	*Oncorhynchus kisutch*	20,865	70.0	66
Adult Pacific cod	*Gadus macrocephalus*	462,262	73.4	1,544
Red snapper	*Lutjanus campechanus*	40,518	51.2	94
Longbill spearfish	*Tetrapturus pfluegeri*	80	63.8	0
Carangids	*Caranx hippos*	224,883	55	563
Barracudas	*Sphyraena*	198,321	54.2	489

Note: [*]Forage fish here refer to all lower trophic level species, and are not limited to commercially exploited forage fish. [†]Annual global production data were from FishStatJ (2018). [†]Average FF dependency ratios were calculated based on literature review (Pikitch et al., 2012; Hilborn et al., 2017).

Table 5
Recreational values attributable to forage fish.

Tourism industry[*]	Region	Existing estimates[†]	Updated estimates[‡]	Diet dependency (%)[§]	Benefits attributable to forage fish[#]
Seabird viewing	UK	$1.995 m	$2.2 m	50-75	$1.15-1.72 m
	South Africa	$2 m	$2.2 m	> 50	> $1.1 m
Marine mammal watching	Global	$2.1 bn	$2.4 bn	25-75	$0.6-1.8 bn
Recreational fishing	US	$4 bn	$4.4 bn	25-75	$1.1-$2.2 bn

Notes: [*]Species in seabird viewing in UK include shearwater, guillemot, puffin, gull, kittiwake and gannet (RSPB, 2010), while mainly African penguin in South Africa (Lewis et al., 2012). Global marine mammal watching includes whales and cetaceans (O'Connor et al., 2009). Species in recreational fishing in US include grouper, snapper, tuna, swordfish and flounder (Stokes et al., 2013).

[†] Estimates taken from the literature, referring to travel expenditure incurred by tourists visiting the sites or gate revenues. For Recreational Fishing, the original study estimates $8bn in annual revenue but only 50% related to trip-based expenditure.

[‡] Estimates updated by authors using GDP deflators (dataset World Bank, 2018).

[§] Diet dependency is estimated based on literature review.

[#] Calculated by multiplying the diet dependencies with the value of the uprated recreational expenditure estimates associated with the predator species.

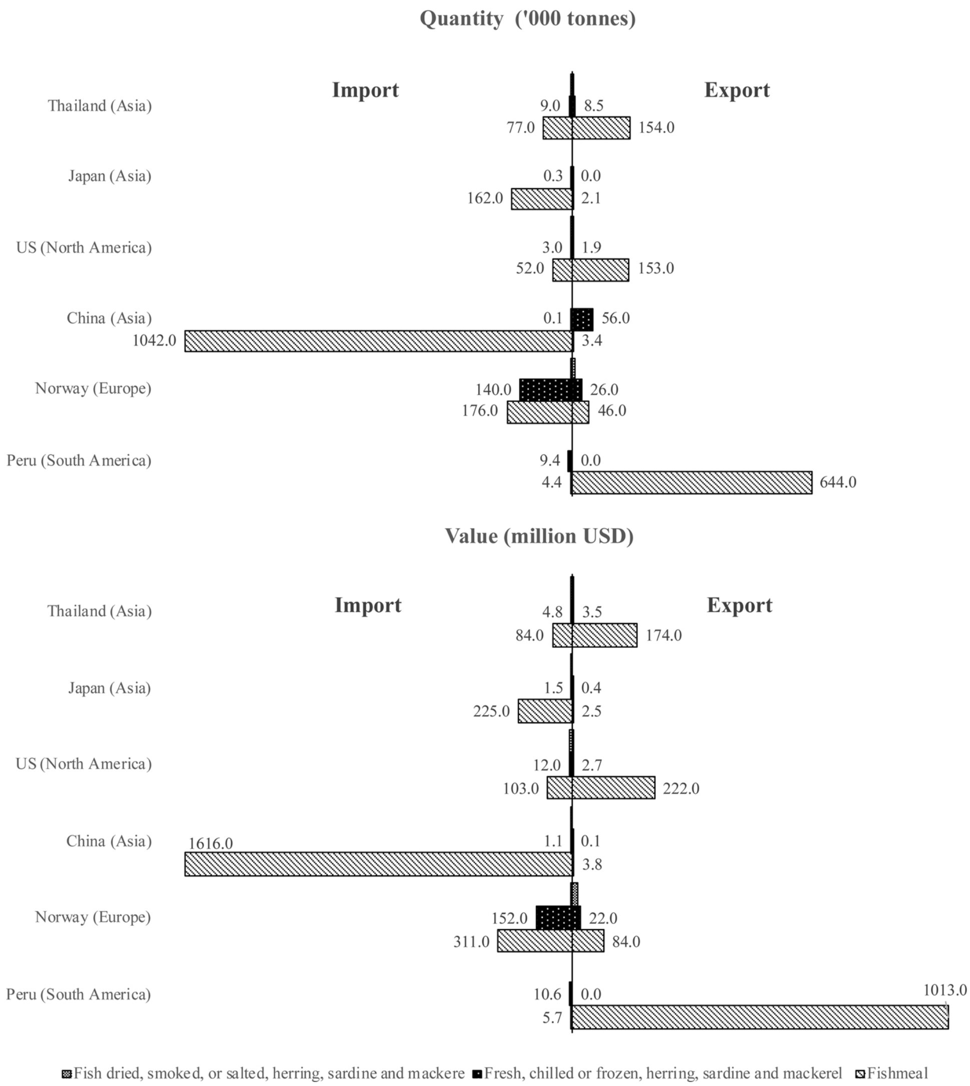

Fig. 2. Top exporting or importing countries of forage fish derived products (Data source: FishStatJ, 2018).

3.2. Measuring contribution towards economic and social development

We estimate the total revenue of aquaculture species reliant on forage fish to be 79 billion USD and the total annual production is estimated to be 43 million tonnes. This figure also includes the value of fishmeal, estimated to be 7.3 billion USD. The total annual production of fishmeal was estimated to be 4.9 million tonnes. Peru, China, and Thailand are the largest producers of fishmeal (dataset FishStatJ, 2018).

Based on the data gathered in Fig. 2, we showed China is the largest importer of fishmeal (1.04 million tonnes per annum and 1.6 billion USD), with the size of imports accounting for more than twice of volume of combined import of fishmeal by Japan and Norway (the second and third largest importers). Peru, Denmark and Chile are the largest exporters of fishmeal, with Peru accounting for 16% of the world's production of fishmeal (AgroChart, 2017). Exports of fishmeal and fish oil from Latin America make a significant contribution to the national economies of Peru and Chile. In addition, to fill the data gap in the total number of fishermen working on forage fisheries, we estimated the direct employment in the production and capture of forage fish to be 5.6 million.

Through literature review, we confirmed that small pelagic fish play a critical role in the provision of nutrition (e.g., protein and micronutrients) in low-income developing countries and hence enable the governments to meet their food security targets. Aquaculture represents 53% of all aquatic production globally with 92% in Asia (predominantly in China and Indonesia), but it is as low as 2% in Africa and 0.2% in small island developing states (dataset FishStatJ, 2018). Therefore, forage fish in those low-income developing countries/regions are an important source of micronutrients for local populations. Competition for the use of these resources, can divert these resources from poorer consumers and thus negatively affect food availability for low-income communities especially in developing countries (Tacon and Metian, 2009).

3.3. Ecological value

Based on literature, we estimated that over 33 species of seabirds, 19 species of marine mammals and 64 species of commercially important fish are highly or extremely dependent on forage fish (see Supplemental Figure S2) (Pikitch et al., 2012; Hilborn et al., 2017). These include seabird species such as Brandt cormorant (*Phalacrocorax penicillatus*) and Elegant tern (*Thalasseus elegans*) in California (Horn and Whitcombe, 2015) and marine mammals such as fin whale (*Balaenoptera physalus*) and harbour porpoise (*Phocoena phocoena*) in the Gulf of Maine (Gannon et al., 1998; Overholtz and Link, 2007) whose diets are estimated to be significantly dependent on forage fish. Maintaining sustainable stocks of forage fish is essential to ensuring a healthy marine ecosystem, crucial to delivering the SDG14 (conserve and sustainably use oceans). It is also important for meeting biodiversity conservation goals and delivery of the Aichi biodiversity targets (Target, 1, 3, 4, 6, 12 and 18).

4. Discussion

In this paper we presented the important role forage fish plays across all the ecosystem services. Where possible we estimated the monetary value for each of these services, and where there are gaps in the data we either provided an indication of the scale of impact or qualitatively described the benefits. We estimated the provisional service of forage fish to be 7.1 billion USD per year, greater than the prior estimate of $5.6 billion (Pikitch et al., 2012). Using more recent data we found a marginal change in the prior estimate on annual benefits to commercial fisheries, increasing from 11.2 billion (Pikitch et al., 2012) to 11.6 billion USD. Given the high diet dependencies of predator species, the eco-tourism values we attribute to forage fish can be in the range of millions for regional economies and billions when looking at global estimates. In addition, some of these marine mammals and seabirds have high non-use (e.g., conserving the species for future generations to experience or for the enjoyment of others) and amenity values associated with them. Given the lack of data on these non-use estimates for all forage fish predators, we have not been able to attribute these values to forage fish species. However, under a scenario where depletion of forage fish stocks drives their predators to switch towards less nutritious alternatives, these high values show that significant decline in health and abundance of these charismatic predator species could lead to a substantial loss in revenues and amenity values for the coastal tourism industries, and decline in societal well-being.

For the valuation of regulating service, we qualitatively discussed the role forage fish species play in mitigating ocean acidification and sequestering carbon, directly or indirectly through their predators. The exact nature of this relationship needs to be further explored and researched, as there are still gaps in our understanding of their contribution to the ocean's biological pump. We found that forage fish species can have substantial cultural value for indigenous communities in British Columbia and the United States. Although indigenous people make up only 4 percent of the world's population, they represent 95 percent of the world's cultural diversity (Sobrevila, 2008). Further assessment of the cultural values of forage fish to communities reliant on this resource is key to defining links between nature and people, and can ultimately help the growing efforts to protect the rights, values and culture of indigenous communities (Díaz et al., 2018).

We demonstrated the reliance of many high-valued ocean-based industries on the forage fish production. These sectors including fish processing, fishmeal production and aquaculture, are also an important source of employment for coastal and regional communities. We estimated gross revenue generated by aquaculture and fishmeal production to be 79 billion USD and 7.3 billion USD respectively. We estimated the direct employment to be 5.6 million in the capture and production of forage fish, and further significant indirect jobs created across the fish value chain. If we try to grow these industries and neglect that they are underpinned by the existence of forage fish we will be jeopardizing the commercial viability of sectors that are important for the economic development of countries. Similarly, a number of countries import and export traded goods that are derived forage fish, which helps to meet the diverse need of domestic consumers, increases earning from exports, generates higher profits for firms and creates employment.

Healthy forage fish stocks are important for meeting food security targets under the UN Sustainable Development Goals, as they are an inexpensive source of nutrients for poor subsistence communities globally. The extent to which declines in forage fish in these communities will affect nutrition and food security (caused by either decline in supply of stocks or increase in substitution of these resources towards aquaculture) will depend on the extent to which diets in these communities are diversified. Where the world's poorest are most heavily dependent on small fish and higher trophic species from capture fisheries (e.g., in Bangladesh and coastal communities in West Africa) and consumption of other animal-source and nutrient-rich foods is infrequent and limited, such a reduction in consumption might have significant implications for nutrition, health and culture in these already deprived populations. By contrast, for urban dwellers in middle-income countries, such shifts may be of limited importance given greater access to animal products, vegetables and fruits.

Finally, with enormous ecological and intrinsic values, forage fish have the right to exist (like other parts of the marine environment) irrespective of their usefulness to human beings. Our analysis on the wide range of species it supports show that there are significant values at stake if forage fish stocks collapse. Protecting forage fish is important if we want to protect our healthy ocean system. We need all the parts of the marine ecosystem to function properly for the overall marine ecosystem to continue generating benefits that are important for the prosperity and well-being of our communities, industries and national economies.

5. Conclusions

The paper sets out with the purpose to understand the multiple benefits that forage fish provide, by systematically identifying the beneficiaries and ecosystems reliant on forage fish and using a range of approaches to capture the environmental, social and economic value of forage fish. Under ecosystem services, we estimated the quantifiable ecosystem benefit provided by forage fish to be 18.7 billion USD per annum. This was a partial estimate of the total benefits. We estimated forage fish production generates 5.6 million in direct employment in marine fisheries and is responsible for creating further jobs (e.g., fish processing, distributing, and retailing) in sectors that are reliant on forage fish as a key input.

In addition, we assessed a number of benefits qualitatively. This included: ecological benefits; indirect contribution towards coastal tourism; regulating services; cultural services to indigenous and coastal communities, where these species hold deep traditional and irreplaceable cultural values; food security contribution, where the decline of forage fish stocks is likely to lead to malnourishment in the absence of access to affordable alternatives. While we used both quantitative and qualitative methods (in the absence of data) to present our analysis valuation of forage fish, data for these fisheries are lacking, and as such, the estimates provided are likely to be an underestimate of the true value that forage fish holds to other interlinked species and ecosystems and therefore ultimately to humans.

It is clear under our current use trajectory that the future of forage fish is highly uncertain. If these fisheries collapse, the consequences would be disastrous for both wild species and will cascade into impacts for aquaculture, with a subsequent cascade into a humanitarian crisis as a good portion of 1/5 of the world's protein will suddenly become unavailable. However, there are multiple measures that can be taken for the future of forage fish. An important step would be to implement ecosystem-based management strategy so that these species would be managed in a broader ecosystem context to reduce collapse risk caused by high fishing intensity especially when stock productivity and abundance is low. Restricting the removal of forage fish through seasonal or permanent bans in protected areas so that forage fish have opportunities to reproduce and replenish is also a much-needed step. Encouraging innovation and the creation of nutritionally equivalent and responsibly sourced substitutes for forage fish-based fishmeal and oil is necessary to create an alternative supply, but this must be coupled to the cost effectiveness of producing these products. These alternatives cannot be expected to be viable except for small, high end consumer segments that demand sustainability until alternatives are mass produced at prices equal to or lower than fishmeal and fish oil. Substitutes also need to be targeted for markets with the greatest demand, such as aquaculture and terrestrial animal feeds. Currently, the majority of companies that create nutritionally equivalent substitutes are at seed or early stages, and their cost structure is not suitable for replacing forage fisheries yet. Governments can play a large role in encouraging innovation and mass production in this fledgling market for forage fish substitutes, through multiple policy tools, such as tax breaks, research and development tax credits, commercialization grants, and guaranteed procurement as they have done to encourage clean, renewable energy and the development of local electronics industries. Encouraging innovation can make valuable contributions to the future scalability and lower prices of substitutes as forage fish resources become scarce, and can eventually avert an ecological and humanitarian crisis in feed and food.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2019.104456.

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