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Perspective

China at a Crossroads: An Analysis of China's Changing Seafood Production and Consumption

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China is a key player in global production, consumption, and trade of seafood. Given this dominance, Chinese choices regarding what seafood to eat, and how and where to source it, are increasingly important—for China, and for the rest of the world. This perspective explores this issue using a transdisciplinary approach and discusses plausible trajectories and implications for assumptions of future modeling efforts and global environmental sustainability and seafood supply. We outline China's 2030 projected domestic seafood production and consumption through an examination of available statistics, and qualitatively evaluate these in relation to key stated Chinese policy targets, consumer trends, and dominant political narratives. Our analysis shows that by 2030 China is likely to see seafood consumption outstrip domestic production. To meet the seafood gap China will likely attempt to increase domestic freshwater and offshore aquaculture, increase seafood imports, possibly expand the distant water fishing industry, and invest in seafood production abroad.

Introduction

As pressures grow for terrestrial agriculture to reduce environmental impacts, the world is looking toward aquatic environments to provide sustainable, nutrient-rich animal protein.[1–3] However, recent scientific assessments conclude that, while the potential for food production from oceans is greater than what exists today—if we radically improve governance of wild stocks and rely on technologies in aquaculture—there are also significant environmental constraints, technological challenges, and policy trade-offs to realize this growth.[4–7] Therefore, how access to and benefits of future finite volumes of seafood are likely to be distributed warrants consideration.

China is a key player in global seafood trade, and represents one of the largest producers, consumers, importers, and exporters of seafood in the world.[3,8] China's consumption is steadily growing and shifting toward an increasing amount of high-value marine species.[9] Given China's dominance in the sector, Chinese choices regarding what to eat, and how and where to source this seafood, are increasingly important; not just for China, but for the rest of the world.[10]

This perspective speaks to this issue by bringing together a range of perspectives rarely treated together (fisheries and aquaculture production, policy analysis, ecology, and environmental anthropology), to raise plausible trajectories and discuss their implications for environmental sustainability and seafood accessibility for China's consumers, and the world. We do so by outlining China's projected seafood consumption and domestic production by 2030 through an examination of available statistics. We qualitatively evaluate these in relation to key stated Chinese policy targets and review and analyze both consumer trends and dominant political narratives. Our analysis shows that by 2030, a misalignment of 6–18 Mt is likely to emerge in China as domestic seafood consumption outstrips production. This corresponds to a gap of 9%–27% from the 2020 targets for production. China will likely attempt to meet the seafood gap with increased domestic freshwater and offshore aquaculture, but this gap is unlikely to be met by domestic production alone. China will likely increase seafood imports, possibly expand the distant water fishing (DWF) industry, and invest in seafood production abroad. We thus end with a reflection on the implications of China's growing seafood demand for the world. Our hope is that the trajectories emerging from our analysis can stimulate a transdisciplinary debate about the assumptions of future modeling efforts and projections of seafood production and consumption in China and beyond.

A Systems Perspective on Seafood in China

Taking a systems perspective can mean multiple things, but at a minimum it requires illuminating a topic from multiple angles. Understanding the future of seafood in China is akin to understanding a complex adaptive system. The general equilibrium models conventionally used to deliver projections of supply and demand invariably struggle to account for all relevant variables,[11,12] and to deliver reliable estimates under such conditions of high uncertainty and lack of data.[13] The added value of our approach lies in bringing a transdisciplinary systems perspective to the discussion of a topic that has been widely recognized, but has mainly been explored through equilibrium models or from a disciplinary focus.[14] Below, we review China's dominant political narratives surrounding seafood, and illustrate how these narratives have shaped domestic policy, and thus Chinese seafood production. We also outline the recent consumer trends that should inform assumptions made about the development of Chinese seafood demand. Both angles are fundamental to speculations about the future development of China's seafood consumption and strategies to satisfy it. While China plays an important role in global seaweed production and consumption, seafood in this paper refers only to aquatic animals.

Policy Reform and Economic Considerations

Production and sourcing decisions in the Chinese fisheries and aquaculture sector are naturally influenced by specific policies for the sector, but also by larger national policy goals. Until recently, Chinese national policy was focused on pursuing economic growth, food security, and social stability. Although broadly successful, this approach has come at the expense of severe domestic environmental degradation.[15,16] The response by the central government has therefore been to shift toward slower-paced, but higher-quality economic growth, taking into account environmental sustainability. In 2007, the Communist Party of China (CPC) announced a policy of ''building an ecological civilization''—a post-industrial civilization more in balance with the environment.[17] The ''eco-civilization'' policy was later enshrined as one of the five pillars of ''socialism with Chinese characteristics'' in the 2018 constitution.[18] Policy in the seafood sector has mirrored this national-level development, as evident through the ''Marine Ecological Civilization Building Policy,'' announced in 2015. While the Chinese political discourse has experienced a significant ''greening'' recently, economic development and national rejuvenation remain important sources of legitimacy for the CPC and were the two key goals president Xi Jinping laid out in his 2017 address to the CPC National Congress.[19] Therefore, it is important to consider these priorities in any evaluation of future seafood production and consumption scenarios.

Especially relevant for an understanding of China's role in the future global seafood system is how the growth of China's ocean economy is promoted as a way to offset slowed economic growth on land and as a source of new resources. The central authority has long viewed economic development as a means to ensure social stability and to help achieve the goal of a ''moderately prosperous society'' by 2020. This policy dates back to the ''reform and opening up'' period instituted by Deng Xiaoping in 1978, with high growth rates in production (including food) as central features.[20] However, blue growth would also further China's ambition to regain its position as an international leader. The ''Belt and Road'' Initiative is pursued, in part, with the ambition to build China into a ''maritime power.'' Investments are currently being made to advance scientific and technological capabilities to contribute to the ''blue economy''[21]—another pathway to enhance China's global prestige, and thus national rejuvenation.

This brief review of concurrent political narratives shaping Chinese policy development highlights an inherent tension between economic and sustainability goals. In the coastal domain, this tension is exemplified by the trade-off between expanding sectors of the ocean economy, such as seabed mining, and their negative effect on production capacity of China's fishing and aquaculture sector through degradation of fishing grounds, environmental quality, or competition for space.[22]

Changing Modes of Production over Time

During the reform and opening up period, China's seafood production increased significantly, underpinned largely by the expansion of aquaculture starting in the mid-1980s.[20] Seafood production has since grown exponentially, but the production portfolio has changed.[23] In 1978, domestic capture fisheries played a central role and represented 57% of total production, while in 2014 this source had shrunk to a mere 15% (Figure 1). In contrast, aquaculture has grown to represent 72% of production in 2014 (from a mere 26% in 1978), with an approximate 40-fold increase in both freshwater aquaculture and mariculture.

Shifts in production modes over time were driven in part by depletion of individual stocks and exploitation of new ones[26,27] (see also Figure S1 and Table S1 for historical comparison of top species landed), and later by attempts to reduce domestic overfishing while maintaining rural livelihoods, by shifting people into aquaculture and DWF.[28]

Today China is the leading aquaculture producer in the world, accounting for 58% of global production in 2018.[3] Approximately 90% of freshwater volumes are finfish, dominated by carp (Cyprinidae) and tilapia, representing about 64% and 11% of global freshwater finfish, respectively.[24] Carp is produced mainly for domestic consumption, whereas tilapia is primarily exported as a low-cost alternative to other whitefish in many countries.[29] Even if recent large-scale offshore finfish initiative exists, to date, farming of marine fish occurs mainly in nearshore waters and around 75% of mariculture volumes produced (including salmon and shrimps) consist of molluscs.[24]

Growth of DWF began in the 1980s and stemmed from a combination of policy goals related to domestic fisheries conservation, rural employment, food security, and foreign policies to increase China's global maritime presence.[28] DWF was both a means to secure access in the global race for marine resources[28,30] but also an avenue through which China pursued aid and diplomacy with coastal states,[28] as reflected by the support for the DWF sector in the 2001–2005 10th Five-year Plan (FYP).[28,31] Today China fishes the largest area of the global high seas and lands the highest estimated catch.[32] The portion of this seafood supplying domestic Chinese markets ranges from 49% in 2009, to 66% in 2014, and slightly lower in recent years.[33] While constituting many vessels, China's average DWF fleet production capacity remains lower than many other DWF nations.[28] The fleet is heavily dependent on subsidies, which were estimated to represent about 20% of the overall value of the reported catch in China in 2010.[32] China provides an estimated US $7.2 billion to its fishing

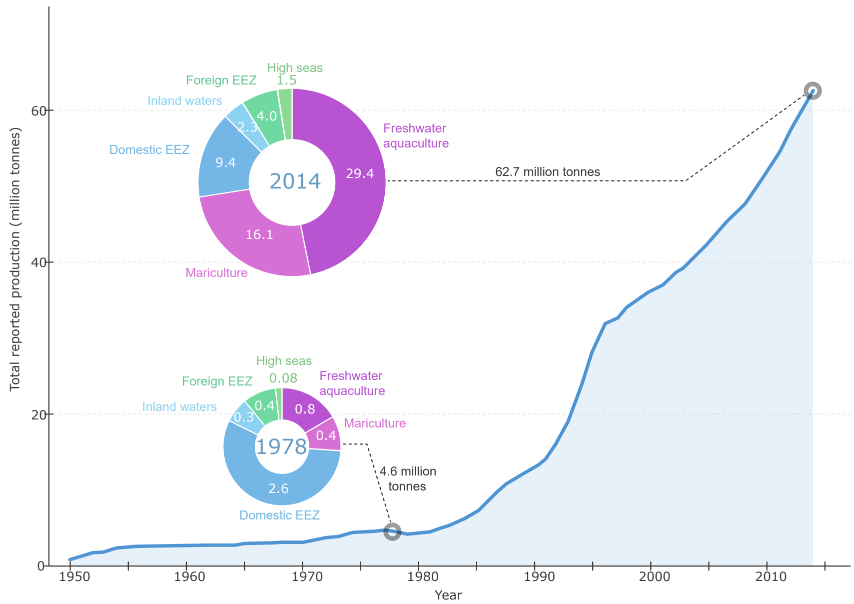

Figure 1. Chinese Seafood Production over Time

Circular charts highlight the shifting sources of production over time. Shades of purple represent domestic aquaculture, shades of blue are domestic capture fisheries, and shades of green are capture fisheries in international waters. Figures inside each segment of the circles indicate production (in Mt) of a particular subsector for each time period (1978 versus 2014). See Supplemental Experimental Procedures for justification for the chosen dates for comparison. The area attributed to the domestic EEZ is based on the claimed EEZ and thus includes disputed territories (see Figure S2 for exact delineation used). Data sources: FAO[24,25] (mainland China reported data used only).

industry, 21% of the global total,[34] and while efforts are underway to reduce subsidies for the domestic fleet, these cuts do not seem to hold for the DWF fleet. Some subsidies are known to promote overcapacity,[35] and while uncertainties still surround Chinese DWF catch, evidence suggests they may be under-reported.[36] Recently, China issued policies in line with a more sustainable approach toward the DWF industry, yet having the capability to access global resources to meet domestic seafood needs remains a national strategic priority, signaling uncertainty in the path China chooses going forward.

Shifting Chinese Preferences and Consumption

Since 1978, China has moved from a diet rich in coarse grain, legumes, and vegetables; to one rich in fat, sugar, and animal protein.[37] Dietary changes were mirrored by equally significant changes in the food system—from supply chains structure, food procurement, and transportation within China, to changes in packing, processing, restaurant, and retail sectors[38,39]—making it difficult to deduce direct causal relationships between individual drivers and dietary change. However, evidence suggest several interlinked factors have contributed to the rapid increase in Chinese consumption of seafood and other animal products, including improved food availability through imports, urbanization, increased incomes, and changes in lifestyles and taste preferences.[37,39] These factors have also influenced how and what seafood is demanded. Significant food safety problems and rising middle-class expectations have shifted consumer focus toward quality and safety, reflected in the labels and retail marketing of seafood as "natural," "safe," "healthy," and "pollution-free."[40] Consumer notions of high-quality and safe seafood generally include wild (as opposed to farmed), marine (as opposed to freshwater), and imported (as opposed to domestically produced) seafood, particularly from countries considered to have "clean" waters, such as Australia, Norway, and North America.[9,41]

An important example of changing preferences is the rapid acceptance of various processed salmon products, being notably different from traditional live freshwater fish, both in palatability and price.[9] Chinese consumers have traditionally preferred fresh seafood, but frozen products are becoming increasingly acceptable as a more convenient alternative, particularly in urban areas.[9] Increased capacity for refrigerated transport and household ownership of refrigerators has enabled this growth in frozen seafood consumption.[33] Industry sources suggest an increasing proportion of frozen seafood is now sold on the domestic market,[42] some of which is domestically produced. However, national import statistics preclude differentiation between volumes of frozen seafood destined for processing and re-export versus domestic consumption. This lack of data granularity makes precise estimates of the origin of the increasing frozen seafood volumes consumed in China difficult, but because frozen seafood is currently mostly associated with marine rather than freshwater species (such as carp),[9] increased consumption of frozen seafood can nonetheless expected to result in greater consumption of marine species.

The various ways of estimating seafood consumption in China result in significantly different projections (Figure 2A). Government surveys of household consumption have measured a rise in national per capita consumption of seafood from 3.1 kg in 1985 to 11.4 kg in 2016, and this can be disaggregated by urban and rural populations.[43] As government data do not capture out-of-home consumption, they likely underestimate consumption by 20%–35% for both rural and urban areas.[29] Other figures often cited as consumption proxies are the Food and Agriculture Organization (FAO) food balance sheets, representing whole fish and originating from balanced government trade statistics.[44] FAO data show availability of food per capita, not actual levels of consumption, and tend to significantly overestimate consumption.[45] While providing a coarser-grained picture than household survey data, FAO data are comparable across countries over time, hence their dominant use in most economic models and other analyses.[14,46,47] To illustrate the elusive nature of the state-of-the-art knowledge around Chinese seafood consumption, Figure 2A shows both these estimates; not for comparison, but rather as estimates of upper and lower limits of

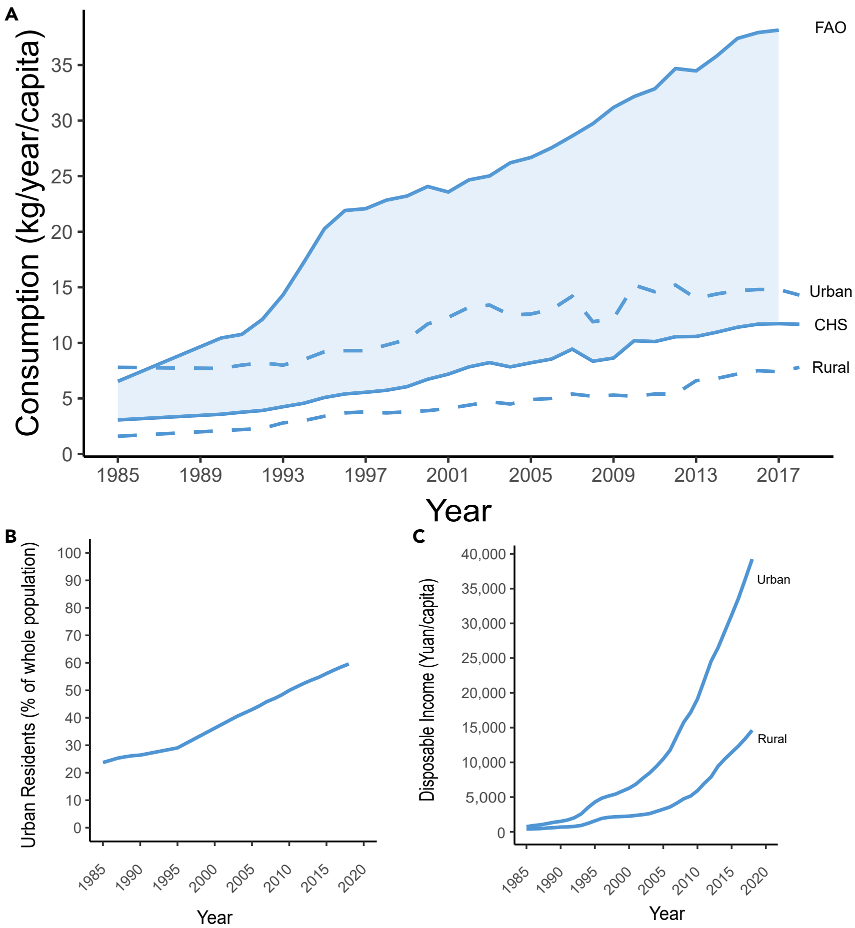

Figure 2. Chinese Seafood Consumption Trends and Drivers

(A) Seafood consumption within China; the upper limit represents the FAO food supply per capita (food balance sheets) and the lower estimated consumption is the weighted (for urban/rural) national average consumption based on government data through the Chinese national Household Surveys (CHS). The CHS data summaries from which data stem do not specify if reported figures are live or edible weight. We report them as live weight, see justification in Supplemental Experimental Procedures. Dashed lines are the household surveys split by rural and urban residents.

(B) Urbanization over time.

(C) Yearly disposable incomes across urban and rural households.

Data sources: National Bureau of Statistics[33,43] and FAO[44]

seafood consumption, and to highlight the wide range of possible consumption figures. We also show two key drivers believed to influence these trends: urbanization and income growth (Figures 2B and 2C), both of which are important to consider when discussing plausible future consumption trajectories.

Current Chinese Seafood Production and Consumption

China's regular iterations of FYPs constitute one of the most important platforms for outlining the direction of national development for the coming 5-year periods, both nationally and in specific sectors.[48] The 13th Five-year Plan for Fisheries (from hereon 13FYP), covering 2016–2020, lays out the most recent priorities relating to seafood and is therefore at the center of our analysis as we examine China's development of domestic seafood production and consumption. To avoid confusion with how the term demand is used in economic analyses, we use the term consumption throughout our analysis, while recognizing that Chinese citizens are not mere consumers without any agency to actively choose what they eat. Chinese purchasing decisions are a manifestation of this reality, and current trends will, at least to some degree, shape the nature of future seafood demand. As such, consumption here refers to deliberate consumption. We use production to denote domestically produced seafood (including via DWF), and total supply when referring to the total seafood resources likely to be required for China to meet projected consumption. Accounting for both capture fisheries and aquaculture, we synthesize national and international statistics to estimate a plausible range of Chinese domestic production and consumption in 2030 (Table 1), and discuss the findings in relation to the targets set out in the 13FYP.

Figure 3 shows volumes of Chinese seafood imports, exports, and domestic production based on the latest comparable datasets (limited to 2014 by Sea Around Us data availability, see Supplemental Experimental Procedures for justifications of this). The purpose of Figure 3 is to synthesize and compare available statistics on production and consumption to make explicit possible misalignments between these projections, and to allow us to discuss these in relation to the officially stated ambitions in the form of 13FYP targets, as well as the dominant political narratives and consumer preferences reviewed above.

Notably, the majority of imported seafood is not currently consumed, but is re-exported from China (Figure 3; Trade flows A and B), sometimes preceded by processing (Trade flow A) (see Supplemental Experimental Procedures for full methods). Domestic production is shown first by origin and mode of production (left). Next, domestic production is broken down to illustrate key salient groupings of seafood across marine and freshwater systems, based on the consumer preferences noted above. We then use FAO conversion factors to estimate how much of the 63 Mt of whole seafood produced that is likely to be edible (see Supplemental Experimental Procedures). Of these approximately 28 Mt we subtract 2 Mt that statistics show are exported, leaving 26 Mt of edible seafood available for domestic production. To compare production to consumption we use Chinese household consumption data for urban and rural populations, increased by 35% according to Chiu et al.[29] This adjustment is warranted as national statistics do not account for out-of-

Table 1. Seafood Production and Consumption of China in the Past and Projected for the Future

	2014	2020	2030
Million tons (Mt)	live weight	live weight	live weight
Production	63[a]	66[b]	misalignment?
Low consumption[c]	45[d]	56	72
High consumption[e]	–	58	84

As such, environmental or other constraints to production are not accounted for in these figures. Conversions between edible and live weight are made based on the conversion factors and "species" breakdown of the 2014 production data (Figure 3). See Table S4 for comparison with edible weight, and Supplemental Experimental Procedures for more details and calculations.

[a]Production in 2014 calculated based on FAO and Sea Around Us (SAU) data (Supplemental Experimental Procedures).

[b]Projected production in 2020 based on the targets set in the 13th FYP.

[c]Linear model estimate of consumption: based on overall average calculated from consumption data from 1978 to 2016 and linearly extrapolated to 2030; where urban and rural data are weighted according to UN urbanization population projections, and overall consumption augmented by 35%.[29]

[d]2014: total consumption = ((rural consumption × 1.35) × rural population) + ((urban consumption × 1.35) × urban population).

[e]Exponential model estimate of consumption: based on overall average calculated from consumption data from 1978 to 2016 and then applied as a yearly increase until 2030; where urban and rural are weighted according to UN urbanization population projections, and overall consumption augmented by 35%.[29]

home consumption. The percentage is comparable with other estimates of Asian out-of-home consumption for seafood,[52,53] but somewhat lower than noted for purely urban Chinese environments,[9] suggesting that our consumption estimates are salient but could slightly underestimate future demand. Through this calculation we arrive at a total consumption of approximately 20 Mt (in 2014), well within range of the estimated 26 Mt of available seafood, which concurs with observations that, as of 2014, China's domestic production was enough to cover domestic demand. However, what does a projection of current domestic production and consumption statistics tell us about the future?

Chinese Seafood Production and Consumption up to 2030

Forecasting is notoriously difficult, and we note that 2030 is an arbitrary reference year. However, a much-cited World Bank analysis used 2030 as a reference to model global fish supply, demand, and trade,[14] and 2030 also aligns with China's FYP periods. Furthermore, simple projections of current trends can be misleading, but attempting to model complex systems with limited or uncertain data can be equally deceiving. For example, the equilibrium model used in "Fish to 2030" did not account for labor and improved cost-effectiveness,[11] nor did it account for biophysical limitations, such as availability of wild fish for fishmeal production, land, or freshwater.[12] We therefore opt for a simple but transparent arithmetic to highlight plausible misalignment between Chinese seafood production and consumption based on current observed trends (Table 1), and interpreting these in light of observed consumer preferences, population development, urbanization, technological development, and environmental constraints to domestic production; all key to understanding China's likely seafood sourcing needs and strategies.

Table 1 summarizes comparisons between the observed 2014 production and consumption figures and the 13FYP production targets for 2020. Table 1 also compares these figures with projections of domestic consumption for 2020 and 2030, arrived at through extrapolation of data from 1978 to 2016, using both a linear and an exponential model estimate, to create a range of low and high projected consumption (more detail in Table S4). For 2020 this range is between 56 and 58 Mt, and for 2030 it is between 72 and 84 Mt (in live weight). The low consumption scenario most likely underestimates future consumption by neglecting to account for the sharp upward turn in both rural and urban seafood consumption in the recent past (Figure 2A). Conversely, the high consumption scenario likely overestimates consumption closer to 2030. However, even if actual seafood consumption develops closer to the lower bound, this suggests that in 2030 China would need a minimum of 6 Mt of additional seafood to cover projected demand (compare 66 Mt production in 2020 with 72 Mt lower consumption estimate for 2030, Table 1) (see Supplemental Experimental Procedures). The less-conservative assumptions about demand suggest a misalignment of 18Mt in 2030 (calculated as the difference between 2030 high consumption and 2020 production estimates). Contemplating this gap, it is also important to acknowledge the adjustments that are regularly made to official production data. While not included in this analysis, it is noteworthy that Chinese national statistics on total seafood production were adjusted downward by the government for both 2016 and 2015, by 4–5 Mt each year. This uncertainty regarding actual production volumes indicates that the misalignment could be even larger than indicated here. So how likely is it that a majority of the projected seafood demand can be supplied by domestic production alone?

Constraints to Domestic Production

Any attempt at forecasting China's future seafood production necessitates a discussion (albeit brief) about key production constraints. These constraints emanate from environmental change, technology, and feed development, and the interaction of political narratives and policy development outlined above, and have implications for domestic production potential. Furthermore, the constraints relate not only to China's own seafood production development, but also to availability of seafood and feed resources globally.

Table 2 outlines key factors affecting production, highlighted based on their recurrence and prominence in the academic literature. Empirical evidence for the development trajectories of each is patchy, at best, but can provide an indication of key factors and plausible "game changers." First, domestic supply will depend largely on whether more stringent regulations will actually affect capture quotas and ultimately allow regeneration of domestic wild stocks, and the implications of this for domestic feed resources available for aquaculture growth. However, availability of fish-based feed resources could also be increasingly derived from more efficient utilization of domestic processing wastes, but may be counteracted by a limited supply of imported higher-quality fishmeal and fish oil,[49] or by increased

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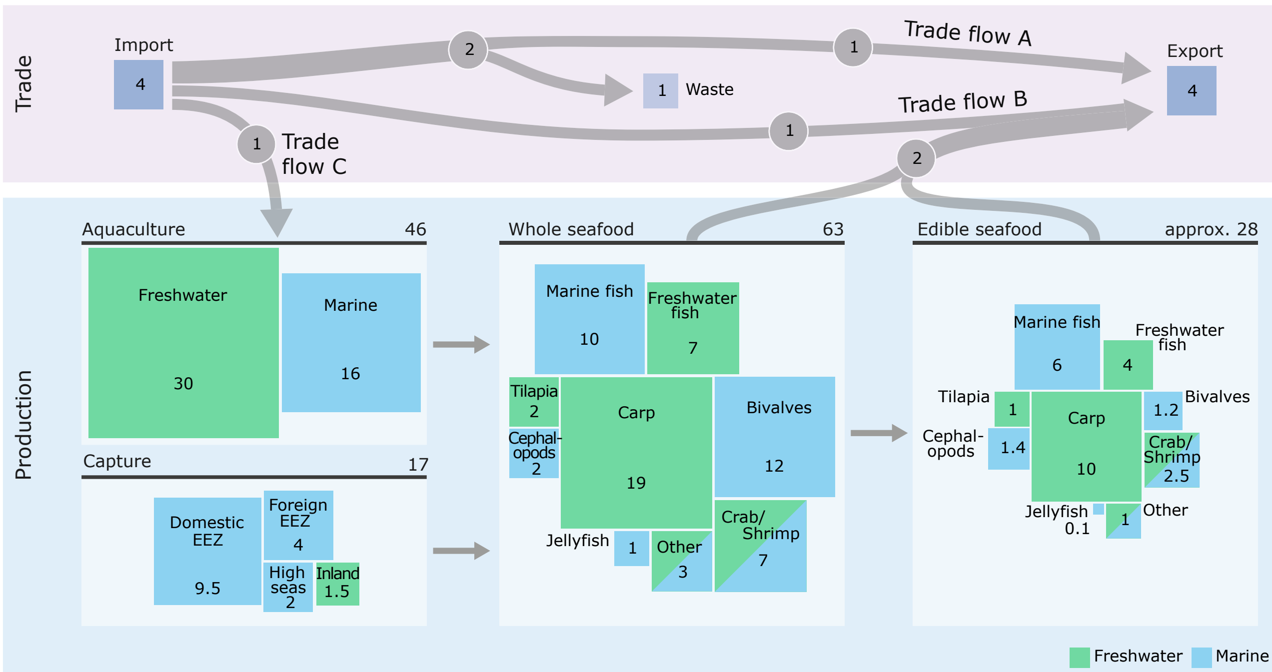

Figure 3. A Disaggregated View of Production

Data are in Mt and represents 2014 as this is the latest year with complete data available to allow disaggregation (see Supplemental Experimental Procedures for motivation of data choice). Note that all trade flows are given in net weight, whereas "Production" (capture and aquaculture) and "Whole seafood" are in live weight. Edible seafood is an approximation from whole seafood volume to edible yield using conversion factors (see Supplemental Experimental Procedures). Trade flow A represents the "pure" processing trade, i.e., seafood that is imported, processed, and exported. Waste products from processing are increasingly being turned into fishmeal for domestic aquaculture,[49] but this cannot be quantified currently. Trade flow B is a less clear flow, where seafood is imported but mixed with domestic production and re-exported. Trade flow C represents the flow of imported fishmeal to domestic aquaculture production. A detailed breakdown of all seafood groups and trade flows can be found in Supplemental Information (Tables S2 and S3). Data sources: FAO,[24] Pauly and Zeller,[25] Cao et al.,[50] and Bai et al.[51]

competition for fishmeal and oil from livestock production.[54] Ingredients for novel feeds are rapidly developing, especially for marine and brackish water species. Production has already increased for some new feeds, such as microalgae and insect meal, but there remain large uncertainties about implementation at the scale needed.[55]

Mussels and seaweeds already play a significant role in China's aquaculture portfolio. Their expansion is not limited by feed development, but instead by competition for space with other industries, and is highly affected by degraded water quality. Current trends already indicate increasingly degraded coastal water quality,[61,77] but the stated ambition to strengthen pollution regulation could change this trajectory. Suitable space and access to freshwater and healthy environments are thus two key factors that could limit expansion of aquaculture on land and along coasts.[62,64] Offshore areas may offer alternative routes for expansion of innovative culture systems but, even though large-scale systems have recently been installed, there are large uncertainties related to future development potential, including durability of the technology, cost-effectiveness, access to feed resources, and in some areas competition for space within the Exclusive Economic Zone (EEZ).[5,67]

Climate change naturally poses a threat to seafood production in both marine and freshwater ecosystems.[78] The IPCC has shown that China is already experiencing more frequent and intense drought and flooding events[79] and the maximum catch potential and fisheries revenues in the EEZ of China are projected to decrease by 12% and 9%, respectively.[80] China is also projected to be one of the most vulnerable countries to climate change impacts on its inland fisheries and both freshwater and marine aquaculture.[78] Therefore, when combined with other anthropogenic drivers, climate change adds uncertainty to China's ability to maintain its food supply in the future.[79]

Given the production constraints outlined above, it is unlikely that a majority of the seafood needed to cover projected consumption in 2030 can be supplied by domestic production alone. Furthermore, the 13FYP notably states specific targets to decrease overall seafood production by 1 Mt and decrease domestic capture by a minimum of 3 Mt, suggesting that a minimum of 2 Mt of additional seafood will have to be produced in other seafood subsectors to simply compensate for the projected shortfall from domestic capture (see also Szuwalski et al.[81]). DWF has been a strategy by which China has increased domestic seafood supply in the past, but the 13FYP target for DWF is only 0.1 Mt higher than 2015 catch, while vessel numbers are set to be reduced (Table S5). Without significant increase in DWF activity in the next (14th) FYP it is therefore hard to see this sector as a major contributor in the future. Instead, aquaculture will have to increase—from 49.4 Mt in 2015 to 53.7 Mt by

Table 2. Factors Influencing Domestic Seafood Production in China

Factors	Effected Production System	Place/Origin	Implications for Supply	Effect on Production Volume	Key References
Domestic Opportunities and Constraints					
Strengthened regulations in Chinese marine/inland capture fisheries	domestic and foreign marine capture fisheries; domestic aquaculture/inland capture fisheries	Chinese EEZ; foreign EEZs; high seas	less available food fish from marine/inland capture fisheries in the short term; less fish for fishmeal, fish oil, and trash fish used in aquaculture production	↘	Costello et al.,[56] Szuwalski et al.[57]
Increased utilization of domestic fish processing waste	domestic aquaculture	China	better use of fish from current processing waste and increased volumes of fish processed due to urbanization and changes of lifestyle could increase availability of fish resources for aquaculture feed	↗	World Bank,[14] Costello et al.,[56] Shepherd et al.,[58] Mo et al.[59]
Increased domestic livestock production	domestic aquaculture	China	increased competition for existing feed resources would negatively impact feed availability; but larger supply of livestock waste products for use in feed could counterbalance this	↘ ↗	Bai et al.[54]
Strengthened regulations on pollution in Chinese waters	domestic aquaculture and capture fisheries	China	high pressure on aquaculture industry, closures of many cage farms in lakes, reservoirs, and rivers; could also be beneficial for domestic wild stocks but effect unknown	↘ ↗	Wang et al.[60]
Pollution of domestic waters	domestic capture fisheries; domestic aquaculture	Chinese EEZ	reduced fish and shellfish production from marine/inland capture fisheries and inland/coastal aquaculture; less suitable areas for expansion of inland/coastal aquaculture	↘	Cao et al.,[61] Liu and Su,[62] Cai et al.[63]

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Table 2. *Continued*

Factors	Effected Production System	Place/Origin	Implications for Supply	Effect on Production Volume	Key References
Decreased land and freshwater availability	domestic aquaculture	China	increased competition for land and freshwater use may limit expansion of freshwater aquaculture and land-based coastal aquaculture; integrated technologies could enable increased production	↘ ↗	Gephart et al.,[64] Higgins et al.[65]
Decreased coastal sea space availability for farming	domestic aquaculture	China	increased competition with other users in the coastal zone, as well as reduction of environmental pressure, will reduce marine aquaculture area according to the 13th FYP for Fisheries	↘	Ma et al.[66]
Game changers (e.g., GMO in aquaculture, innovative recirculating aquaculture systems), biosecurity, and feed innovations	domestic aquaculture	China	higher efficiency and production, less competition for resources, reduced disease outbreaks, and improved environmental performance	↗	Gui et al.[55]
Technology innovations in offshore aquaculture	domestic aquaculture	Chinese EEZ (and beyond)	potential for expansion of marine aquaculture (including both finfish and bivalves)	↗	Gentry et al.,[4] Oyinlola et al.,[67] Froehlich et al.,[68] Buck et al.,[69] Troell et al.[70]
Better logistics in the value chain system	domestic aquaculture/fisheries	China	minimize spoilage in supply chains	↗	HLPE,[71] Hanson et al.,[72] Godfrey,[73] Godfrey[74]
International Opportunities and Constraints					
Increased utilization of fish processing waste from outside China	domestic aquaculture	world	more fishmeal will be produced from processing by-products in the world according to FAO and IFFO	↗	Cao et al.[49]
Diseases, antimicrobial resistance development together with degradation of natural genetic resources and germplasm	domestic aquaculture; international aquaculture; potentially capture fisheries	China/world	reduced production	↘	Stentiford et al.[75]

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Table 2. *Continued*

Factors	Effected Production System	Place/Origin	Implications for Supply	Effect on Production Volume	Key References
Increased international aquaculture production (through, e.g., farms abroad)	international aquaculture	China/world	Belt and Road Initiative is promoting aquaculture in countries of the "Maritime Silk Road" and also overseas	↗	Jing et al.[76]

The table shows key factors likely to affect (constrain) domestic Chinese seafood supply. It does not include factors, such as climate change, or instability in global economy, such as emerging trade wars, which are likely to affect most nations and where effects are less likely to be discernable in the timeframe of this paper. Arrows indicate plausible increasing versus decreasing trends, as described in the reviewed literature. Solid arrows indicate some certainty of trend direction (as backed by References), while dashed arrows are highly uncertain. Where not indicated otherwise, aquaculture refers to both marine and freshwater production.

2020, and to approximately 60 Mt by 2030 (i.e., an increase of 10.5 Mt) (Table S5). This target is potentially achievable given the approximately 11-Mt production increase reported in the previous 5-year period.[33] However, growth rates of overall freshwater and carp production have actually declined in the last decade, from 36% to 21%, and from 32% to 21%, respectively,[44] and this production has been blamed for the increasingly acute pollution of inland and coastal waters,[16,55,82] indicating limits for future expansion. The 13FYP notes an obligatory target of a 120,000-hectare reduction of coastal mariculture area by 2020, and the documented severe coastal pollution (partly as a result of existing mariculture)[61,62] signals limited possibilities for significant expansion in nearshore production (Table 1). Offshore mariculture is therefore the most promising option, but, as noted above, current feed costs and limited testing of technologies in offshore locations makes predictions regarding this production mode difficult at present. Finally, most farmed marine finfish are carnivorous (or omnivorous) and will not constitute net fish protein addition if feeds continue to rely on fish resources other than seafood processing wastes and other protein sources not suitable for human foods.[83]

Given the likely misalignment between Chinese seafood demand and domestic supply by 2030, what are plausible Chinese strategies to address this? And what are the possible implications of these strategies on the rest of the world? In discussing these issues we need to consider not only the quantity of the fish protein, but also the quality and type, as the price of bulk fish, such as carp and tilapia already indicates a saturated Chinese market.[84] This development suggests that at least some Chinese consumers are looking for other seafood to put on their plates.

A New "Business as Usual"?

Exploring future development trajectories requires an anchoring point in the present. This undertaking is commonly achieved by grounding discussions in the current state of affairs. However, to label the 13FYP business as usual would be misleading, as the plan notes a clear ambition to move beyond simple extrapolation of past production trends and sets a lofty goal to achieve an ecologically sustainable civilization.[17] The fact that the "eco-civilization" policy is now incorporated into the constitution,[18] combined with the increasing evidence of codification of this narrative,[17] also strengthens it as a baseline to discuss plausible Chinese trajectories and strategies to address future alignment between seafood production and consumption. Below we elaborate and contrast two trajectories that China may follow, outlining empirical evidence supporting these, and highlighting the key challenges and likely implications associated with each.

Diverging Trajectories

The preceding analysis makes it clear that, while 2020 production and consumption figures are relatively aligned, by 2030 China is likely to need an additional 6–18 Mt to satisfy projected consumption. While the higher consumption figure (18 Mt) is unlikely, our analysis nonetheless provides data-driven upper and lower boundaries to frame a discussion on China's future seafood needs. Such a discussion can be developed by elaborating two contrasting scenarios. The first takes a productionist stance (*sensu*).[85,86] The productionist stance assumes China will aim to meet its own future seafood needs through domestic aquaculture. While China's food security policies focus mainly on agriculture, and food security concerns have declined since the 1980s, improved food security is a stated goal of fisheries and aquaculture policy,[23] and aquaculture and DWF are generally held up as important means to achieve this goal.[28] However, the 13FYP targets simultaneously aim to reduce domestic capture and coastal mariculture area, while allowing a limited increase in DWF (Table S4). These policies leave freshwater and offshore aquaculture as the only realistic sources of increased domestic production (see, e.g., Cao et al.[23]). Molluscs and carp are the primary species looked to for this future increase, but higher trophic species are also possible, for example in offshore waters, but may be limited by feed supply.[5]

Chinese freshwater aquaculture is unquestionably important, and has shown impressive growth in production (for more detailed review of China's aquaculture sector,[60,55,87,88]). However, its possibility for future expansion may be strongly affected by the central government policy on food security, which favors major crop self-supply and farmland protection. Furthermore, the Chinese policy shift in recent years to prioritize quality over quantity in seafood production, along with Chinese statistics showing the quick production decline in many freshwater environments,[44] all suggest that a trajectory of rapid growth of freshwater aquaculture may not be materializing.

Offshore aquaculture is a field that is currently attracting significant attention worldwide, but it is still in its infancy, with only few commercial operations in place (see, e.g., Gentry et al.[4,67] and Oyinlola et al.[67]). Recent investments indicate this direction is a road Chinese industry is keen to take,[89] but the timescale at which such offshore farms will be fully operational and viable remains unclear. Offshore aquaculture also comes with its own set of general uncertainties and challenges,[4,5,67] where environmental impacts and geopolitical conflicts linked to siting decisions are arguably highly salient to China.

Finally, it is important to note that, while domestic production of carp and molluscs may be a theoretically plausible way of filling a growing seafood demand in China, a key challenge remains: namely how to shift observed consumer trends away from marine, carnivorous, and imported species in a context of a rapidly urbanizing and wealthier population. Current trends indicate increasing Chinese demand for marine and higher trophic level species that will require larger volumes of fish-based feed, unless suitable alternatives are developed. Better utilization of domestic or foreign processing waste could initially fill such a feed gap (Table 1),[49] but the degree to which it can satisfy the total projected feed demand remains uncertain. Aligning production and consumption in a productionist-focused trajectory would thus entail either solving the feed equation or drastically curtailing Chinese consumer choices.

In China, as in many nations, the conflict between economic development and environmental protection is a prominent source of policy incoherence for fisheries and aquaculture.[17,90] However, against the backdrop of noted environmental production constraints, consumer trends, and 13FYP targets, a second trajectory characterized by increased imports appears as a feasible alternative for China to supply the volumes necessary, while minimizing negative domestic environmental footprints—especially considering consumer perceptions relating to the increased health benefits of imported seafood.[9] Such a strategy is one taken by many industrialized economies over the last century.[91]

Along with rising purchasing power, there is growing evidence that China is pursuing this path for a number of commodities, with varied effects on global market prices.[92] In fact, the 40-year anniversary of China's "opening up" policy was marked by China's first International Import Expo organized in Shanghai in 2018. Agricultural (including fisheries) products are one of eight major markets China intends to open to international trade. Chinese trade values of imported agricultural products reported by WTO have increased from 20 (2000) to 180 (2016) billion USD over the last two decades, and seafood imports have risen dramatically (ranging from 26% to 400% increase since 2014 depending on product type).[93] This trend is a strong indication of China's current trajectory toward a market-based, demand-driven economy for these commodities. However, this path requires accessing sufficient production internationally, and the strategies China pursues to do so will have implications for the rest of the world.

Chinese Choices—Implications for the Rest of the World

While China appears to be on a trajectory toward increased seafood sourcing outside its borders, to date no study exists that comprehensively examines the implication of this on global seafood production, markets, and availability. Such an analysis is beyond this paper, but three areas of interest are worth highlighting.

One way to source seafood is trade. At 4 Mt per year (approximate as of 2016) China is already the world's largest seafood and fishmeal importer by volume. An increase of 6 Mt, or anything beyond (Table 2, 2030 projections), is certain to have implications for seafood availability and markets in the rest of the world (cf.[8,14]). But imports do not tell the whole story. In fact, China's current role in the global seafood system is primarily as a value-adding hub, with a large portion of the seafood imported simply passing through the country via various value-adding processes. This explains the value-based trade surplus that has earned China its status as a "seafood trade giant" (Figure S3), and indicates that currently China's fisheries imports are not contributing significantly to domestic consumption (with the exception of the fishmeal used for domestic aquaculture production) (Figure 3). Could this change in the near future? Our analysis concurs with others predicting a likely increase in imports of the commodities that are currently primarily re-exported, such as salmon and whitefish.[14,94] But increasing Chinese demand will compete with other large consumers, such as the EU and the US.[8] Current trade reports suggest this is already happening.[95] It is also plausible that imports from Asian neighbors will increase. Import price differences between the EU, the US, and China are declining, and regulations relating to anti-dumping, labor standards, and illegal, unreported, and unregulated landings are less stringently applied in China than in other major importing nations.[96] Combined with past tit-for-tat tariff exchanges and import bans between China and other nations (notably the US and Norway) these developments may increase the likelihood that trade flows are redirected to China should its demand rise. Finally, the current pandemic is having an immense impact on seafood supply chains everywhere, with dwindling demand, and effects on production and supply chain logistics.[97] Consumer food safety concerns have also come to the fore in seafood trade again, particularly in China.[98] The long-term effects of this turmoil on seafood trade patterns is uncertain, but will affect both imports and exports.

Another sourcing strategy is to catch it yourself. While current targets suggest a decline in DWF, this mode of securing raw material may once again come to play a key role. While there is some confusion over the exact number of China's DWF vessels,[99] nonetheless, China is already estimated to account for the biggest share of catch in the high seas, and like many nations its fleet is heavily subsidized.[32] Plans to modernize the fleet could improve profitability, and reduce energy use and negative climate impact, but the increased efficiency could also create or enhance overcapacity and threaten already dwindling stocks in other nations' EEZs and areas beyond, which are not currently safeguarded by adequate regulation and enforcement (cf.[100]). An increased DWF presence would align with Chinese ambitions of increasing sea power, but could damage the efforts being made to appear as a responsible global actor worthy of international leadership. Rising fuel prices as a result of climate change policies could of course affect all DWF expansion possibilities. As such, Chinese strategies in this domain remain to be seen.

A third path to sourcing food supplies is by investing in production in other countries. The Belt and Road Initiative provides the overarching framework for this possibility, and large foreign direct investments are already deployed to this end.[101] Chartered access to fishing grounds is another pathway projected to become more common in the future,[102] and recent corporate attempts at acquisitions signal Chinese efforts to take control of key fish meal supplies abroad.[103] Some of these large-scale overseas investments in seafood production could arguably offer employment and development opportunities in receiving nations but the environmental and social impacts of Chinese business practices are poorly documented and remain a topic of intense debate.[17,104] Many wild stocks in the high seas and in EEZs of developing countries remain poorly understood and managed, and the environmental impacts associated with intensive aquaculture in China are likely to be replicated in settings lacking strong governance to ensure social and environmental sustainability.

The three pathways to Chinese impact on the global seafood system discussed here can serve two purposes. First, they can inspire future models of seafood supply and demand, and the preceding review can provide a basis for contextually grounded assumptions regarding demand, production constraints, and trade. Second, these pathways deserve to be considered in the context of global seafood production trends, where many countries around the world are facing similar limits to domestic production as China. Increasing imports is only feasible if production surplus exists elsewhere and nations possess the purchasing power to acquire it. As the world may be approaching the constraints of a finite, global, seafood production capacity,[6,7] all nations' sourcing trajectories need to be considered together. Our analysis has provided a transdisciplinary dive into China—the largest actor on the global seafood arena today. This article raises more questions than it can answer, and notes many uncertainties; but by exploring political, environmental, and consumer perspectives it hopes to provide a basis for a multifaceted discussion of China's (and other nations') future seafood needs and possible implications for global seafood system sustainability. As China scholars Geall and Ely[17] note, because of its global impact and its dynamism, China is critical for unlocking the transformative innovation needed to reconfigure patterns of global development, in fisheries and other sectors.

SUPPLEMENTAL INFORMATION

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AUTHOR CONTRIBUTIONS

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One Earth, Volume *3*

Supplemental Information

China at a Crossroads: An Analysis of China's Changing Seafood Production and Consumption

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Supplemental Information

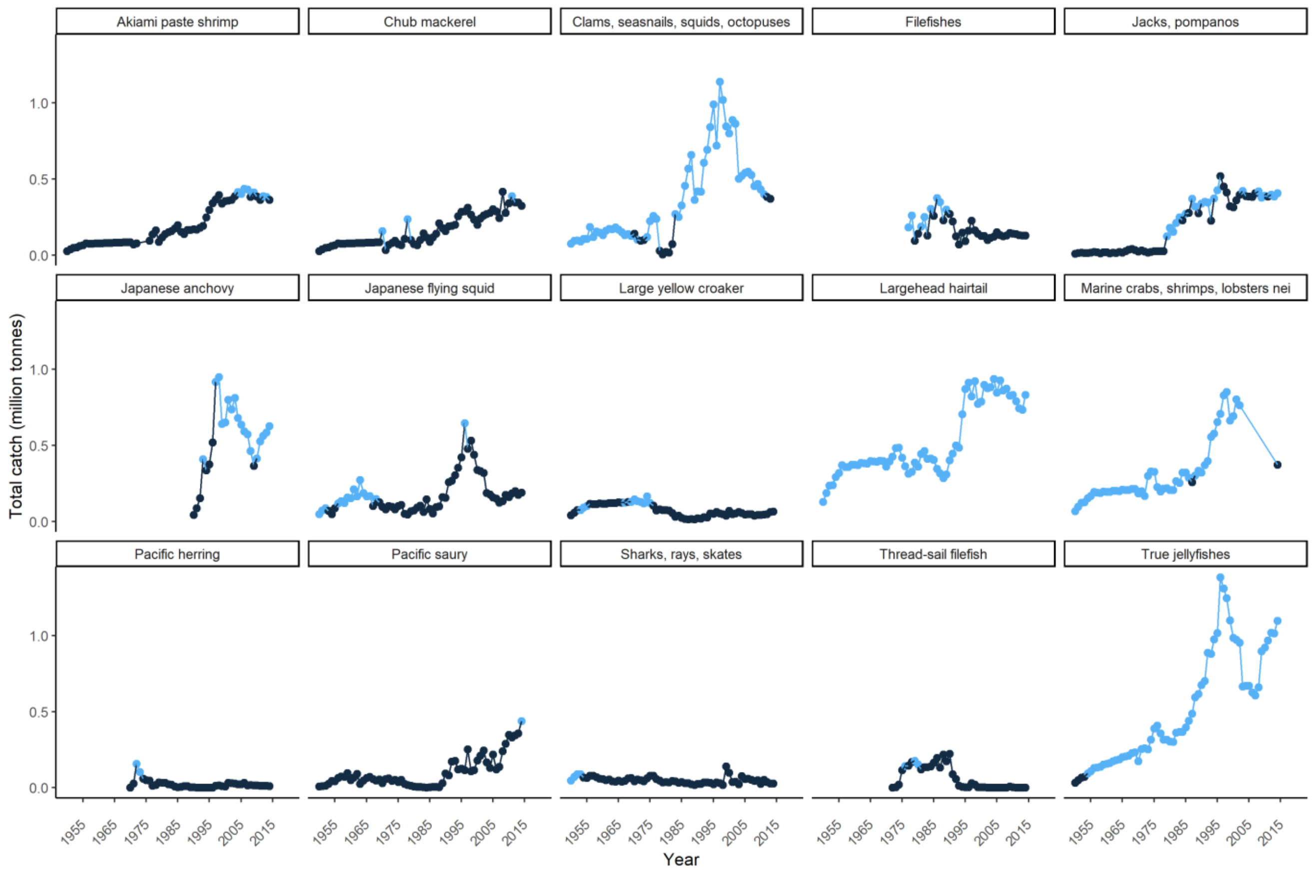

Figure S1. Catches of top five "species groups" in Chinese domestic Exclusive Economic Zone (EEZ) through time. *Each panel represents a "species group" that has been in the top five in Chinese domestic EEZ catch (based on tons caught) for the data collection period. The light blue color indicates the year(s) in which the species group was in the top 5 and dark blue in the years it was not. Panels are ordered in alphabetical order based on "species group" names. In years prior to establishment of EEZ, the equivalent EEZ is used, see figure S2 for full delineation. Source:*[1]

Table S1. Top five "fish groups" in domestic EEZ catch. *Shows top 5 "fish groups" by production volume in Chinese claimed EEZ area (or EEZ equivalent). Data source:*[1]

Position	1950	1978	2014
1	Largehead hairtail	Largehead hairtail	True jellyfishes
2	Clams, seasnails, squids, octopuses	True jellyfishes	Largehead hairtail
3	Marine crabs, shrimps, lobsters nei	Filefishes	Japanese anchovy
4	Japanese flying squid	Chub mackerel	Pacific saury
5	Sharks, rays, skates	Marine crabs, shrimps, lobsters nei	Jacks, pompanos

Figure S2. Delineation of China's EEZ. *This corresponds to the delineation used in the Sea Around Us data, followed in this article. As seen, it is based on the claimed area and thus includes disputed territories.*

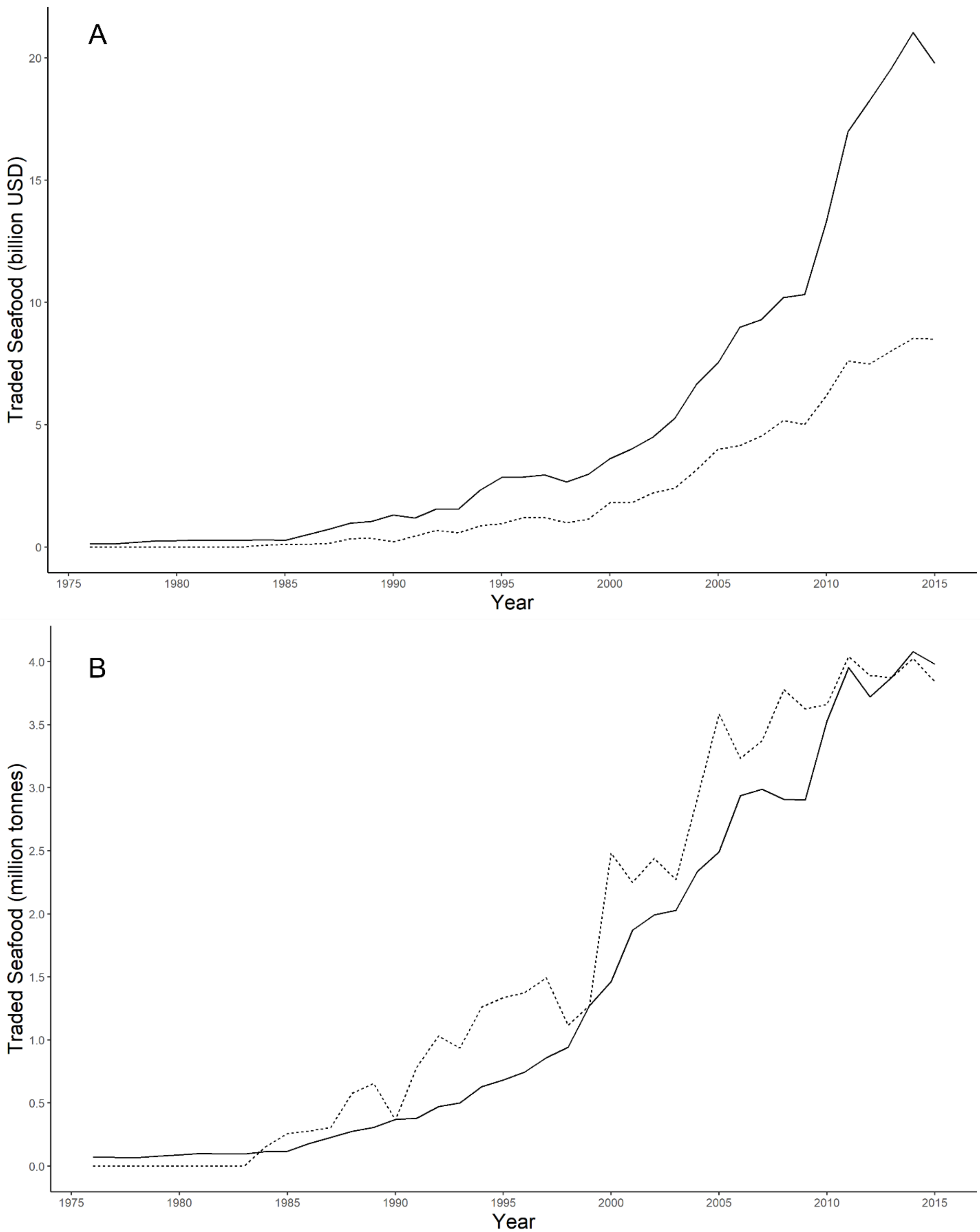

Figure S3. Chinese imports and export of seafood, by value and volume. *Panel A: value in billion USD. Panel B in volume (million metric tonnes). Seafood imports indicated in dashed line, and exports in solid line. Value in. Only mainland China data used. Source:* [2]

Table S2. Breakdown of processing trade flow (A) into mainland China, as depicted in Figure 3. *Source:* [2]

Trade Flow	Seafood Group	Includes	Import (mmt)	Export (mmt)
Trade flow A (processing trade)	Whitefish	Alaska Pollock, saithe, hake, haddock, toothfish, cod, blue whiting and gadiformes	1.02	0.58
	Salmonids[1]	Salmonoids, salmon, Atlantic salmon, Atlantic and Danube salmon, Pacific salmon and sockeye salmon	0.20	0.12
	Flatfish	Flatfish nei, common sole, halibut and plaice	0.19	0.11
	Herring	Herring	0.17	0.08
	Hairtail	Hairtail	0.07	0.01
	Shrimp and prawns	Cold-water shrimps and prawns (Pandalus spp and Crangon spp)	0.01	<0.01
	Trout	Trout and trout and chars	<0.01	<0.01
	Crustaceans	Miscellaneous crustaceans and crustacean meal	<0.01	<0.01
	Total		**1.66**	**0.90**

Note: Imports are generally composed of Pacific salmon (72%) and Atlantic and Danube salmon (23%), however exports are generally Salmon (i.e. not specified, 96%).

Table S3. Breakdown of non-processing trade flow (B), as depicted in Figure 3. *Trade flow B is a less clear flow, where seafood is imported but mixed with domestic production and re-exported. Category 1 represents commodities that are imported in low volume and exported in higher volume indicating a mixing with domestic production, note that this category is dominated by tilapia exports. Category 2 is the least clear flow where imports and exports are fairly similar (slightly higher exports). Source:* [2]

Trade Flow	Seafood Group	Includes	Import (mmt)	Export (mmt)
Trade flow B, category 1 (low imports high exports)	Tilapia	Tilapia	<0.01	0.40
	Clams	Clams, cockles and arkshells	<0.01	0.15
	Sardines	Sardines, sardinellas, brisling and sprat	<0.01	0.12
	Octopus	Octopus	<0.01	0.09
	Marine fish	Pufferfish, Seabass, Croaker and Pomfret	<0.01	0.07
	Carp	Carp	<0.01	0.05
	Freshwater fish	Miscellaneous freshwater fishes	<0.01	0.05
	Crayfish	Freshwater Crayfish	<0.01	0.03
	Abalone	Abalone	<0.01	0.01
	Oysters	Oysters	<0.01	0.01
	Broodstock	Fish, Shrimp, Crustacean and mollusc broodstock	<0.01	0.01
	Inverts	Miscellaneous aquatic invertebrates	<0.01	0.01
	Caviar/ roe	Caviar, caviar subsitutes, herring roe	<0.01	0.01
	Jellyfish	Jellyfish	<0.01	0.01
	Swordfish	Swordfish	<0.01	<0.01
	Urchins	Urchins	<0.01	<0.01
	Total		**0.02**	**1.01**
Trade flow B, category 2, (high imports, higher exports)	Fish	Fish nei (generic)	0.31	0.84
	Cuttlefish and squid	Cuttlefish and squid	0.41	0.41
	Mackerel and anchovies	Anchovies, Mackerels, Jack and Horse Mackerels	0.15	0.23
	Shrimp	Shrimps and prawns	0.07	0.23
	Tuna	Tuna, Atlantic, Pacific and Southern Bluefin, skipjack, yellowfin , albacore and bigeye	0.09	0.18
	Crab	Crab	0.06	0.08
	Molluscs	Miscellaneous molluscs	0.05	0.06
	Scallops	Scallops	0.03	0.04
	Offal	Livers, roes, milts and other edible offal	0.01	0.01
	Catfish	Catfish	0.01	0.01
	Sharks and rays	Sharks, shark fins, rays and skates	<0.01	<0.01
	Ornamental	Ornamental salt and freshwater fishes	<0.01	<0.01
	Marine fish	Miscellaneous coastal, demersal, pelagic and saltwater fishes	<0.01	<0.01
	Total		**1.18**	**2.09**

Table S4. Past and projected edible weight. Figures supplement Table 1. *Edible weight indicated in grey columns. White column represent live weight and are the same figures as in Table 1. [1]Production in 2014 calculated based on FAO and Sea Around Us (SAU) data. [2]Projected production in 2020 based on the targets set in the 13th FYP. Conversions between edible and live weight are made based on the conversion factors and "species" breakdown of the 2014 production data (Figure 3). All weights in million tonnes. See Supplemental Experimental Procedures (Table 1: Consumption projections) for additional calculation details.*

	2014		**2020**		**2030**	
	Edible weight	Live weight	Edible weight	Live weight	Edible weight	Live weight
Production	28[1]	63	30[2]	66	?	?
Low consumption[a]	20[c]	45[c]	25	56	32	72
High consumption[b]	--	--	26	58	38	84

[a] Linear model estimate of consumption: based on overall average calculated from consumption data from 1978-2016 and linearly extrapolated to 2030; where urban and rural data are weighted according to UN urbanization population projections, and overall consumption augmented by 35% (see[3]).

[b] Exponential model estimate of consumption: based on overall average calculated from consumption data from 1978-2016 and then applied as a yearly increase until 2030; where urban and rural are weighted according to UN urbanization population projections, and overall consumption augmented by 35% (see[3]).

[c] 2014: Total consumption = ((rural consumption*1.35)*rural population) + ((urban consumption*1.35)*urban population)

Table S5. Comparison of figures for fisheries related targets in 13th five year plan. *The tables allows comparison between the stated targets for 2020 in the 13th Five-year plan and the production volume in 2015. All catch/production and trade is in million tonnes. Value is in billion USD. Aquaculture area is in 10,000 hectares. Fishing vessel power is in MW (megawatt. Population is in billion people.*

Variable	13th Five-Year Plan - Target to 2020	China Statistical Yearbook 2015
All production (aquaculture + capture)	66	67.0
All capture	-	
Domestic marine catch	≤10	13.2[2]
Domestic freshwater catch	-	2.3
Distant Water Catch (foreign)	2.3	2.2[2]
Aquaculture production (all)	53.7*	49.4
-Freshwater	-	30.6
-Marine	-	18.8
Percentage aquaculture (of total production)	81.3%*	73.7%*
Import	-	-
-value	-	6.3
-tonnes	-	-
Export		-
-value	20.0	19.6 (20.3[2])
-tonnes	-	3.9
No. of fishing vessels	57,095	65,398[2]
Total power of fishing vessels (above 12 m)	9,822	11,173[2]
Consumption kg/per capita[1]	-	11.2 14.7 7.2
Population	-	1.374
Consumed fish	-	15.4*
Aquaculture area	-	-
-Freshwater	-	-
-Marine	220	232[2]

Notes

* Indicates the figure was not stated, but calculated/estimated from stated values (see below).

Aquaculture production = All production – Domestic catch (ambiguous) – Distant water catch
Percentage aquaculture = Aquaculture production/Total production
Consumed fish (in million tonnes) = Consumption per capita times population. (For FAO calculation, uses the stated population and will, of course, be supplied fish). Calculation only done for nationwide estimate of consumption.

[1] Consumption data from household survey.
Top row: consumption per capita nationwide
Middle row: Consumption per capita urban
Bottom row: Consumption per capita rural
[2] For 2015: but data source: 13th Five-Year Plan

Supplemental Experimental Procedures

Data, assumption and calculations to produce all figures and tables in the article.

Figure 1: Trends in seafood production	
Data	Sea Around us data: Marine seafood capture. Citation:[1] FAO FishStatJ: Inland/freshwater capture and aquaculture production. Citation: [2]
Assumptions	FAO capture data aggregates all capture within FAO area 61, which includes China's domestic waters but also vast areas of the Pacific. Sea Around Us (SAU) data provides a breakdown of capture in domestic EEZ, foreign EEZ and high seas, which is a very relevant differentiation in relation to access rights, hence the use of SAU data for marine capture. Due to 2014 being the latest available data for Sea Around us, this was used as the upper temporal range. 1978 represents the start of the "reform and opening up" era and is therefore the lower bounds of the comparison. Only using reported data within SAU since we wish to keep a non-normative stance against China's reporting of fisheries catches. Sea Around Us has assigned the area claimed by China, including disputed territories, to the Chinese EEZ (see Figure S2 for exact delineation used). Only data for mainland China was used. Due to ambiguity regarding how much of produced algae is used for direct human consumption, all algal production was excluded. It is true that this in part will underestimate available seafood as some algal products are eaten.

Figure 2: Seafood Consumption trends and drivers	
Data	FAO STAT data: Aggregated Food Supply per capita. Citation: [4] China Statistical yearbook (various years) data: Chinese population, income per capita and household consumption of aquatic products (China Household Survey, CHS) Citation: [5,6]
Assumptions	Since no nationwide data on household consumption, this was calculated from the rural and urban household consumption data of the CHS. CHS summary tables and introduction, do not clearly specify whether figures are reported in live or edible weight. The rural household sample used by[3], notes that nearly all carps and tilapia consumed were purchased as live fish. Prior experience and expertise in the author group supports this. Yet, for urban consumers, there is likely to be a proportion reported that is edible weight because of some frozen fish purchases (e.g. fillets). However, our combined assessment is that CHS seafood consumption likely represents a mix of live and edible weight reports, but with a strong bias towards live, with a small proportion edible weight reports. Hence we report figures as live weight. Only data for mainland China was used. Several reasons underpinned this decision, 1) data for Hong Kong, Macau, Taiwan are often reported separately in China's own statistics, FAO data and SAU 2) consumption is very different in these satellite territories than in mainland China, mixing the data would bias the national averages.
Calculations	Nationwide per capita consumption = ((urban per capita consumption * urban population) + (rural per capita consumption * rural population))/ nationwide population

Figure 3: Seafood Production breakdown	
Data	Production data same as in figure 2, only data from 2014 used. FAO FishStatJ: seafood import and export data. Citation: [2]
Assumptions	Only data for mainland China was used. Due to ambiguity regarding how much of produced algae is used for direct human consumption, all algal production was excluded.
Calculations	Trade commodity categories were grouped into wider seafood categories according to tables S1 and S2. Conversion factors were obtained for as many species within the production data as possible. Since there is very limited information available on food conversion factors and it is therefore important to acknowledge that these estimations are generalisations and could be both an over and underestimation of actual edible seafood production. For each wider category, the mean conversion factor was used for calculations into edible yield. See below for full details.

Table 1: Consumption projections	
Data	China Statistical yearbook (various years) data: Chinese population, income per capita and household consumption of aquatic products. Citation:[5,6] UN Urbanisation Population projections[7] Production data same as in figure 2, only data from 2014 used. Production predictions for 2020 from 13FYP
Assumptions	Household consumption data was augmented with 35% to take account for out of home consumption (see[3]). To calculate conversion between whole and edible seafood consumption predictions, the assumption was made that the relative breakdown between seafood products corresponds to the 2014 production data.
Calculations	2014 consumption = ((rural consumption*1.35)*rural population) + ((urban consumption*1.35)*urban population) Linear consumption model was calculated through and lm model on the augmented (+35%) household consumption data. R version 3.5.0. Exponential consumption model = (((household urban consumption in 2016*1.35)*mean percentage increase in consumption$^{(\text{years between 2016 and 2020 or 2030})}$)* predicted urban population) + (((household rural consumption in 2016*1.35)*mean percentage increase in consumption$^{(\text{years between 2016 and 2020 or 2030})}$)* predicted urban population)

Conversion factors

Note: In column "Conversion factor data source", number (before comma) refers to source in reference list. Text after comma refers to which conversion factor per seafood group was used within that source.

Carp

Seafood group	Scientific name	Volume (mmt)	Conversion factor	Conversion factor data source
Grass Carp	*C. idella*	5.38		
Silver Carp	*H. molitrix*	4.23	0.53	[8], fillets including skin
Bighead Carp	*H. nobilis*	3.20		
Common Carp	*C. carpio*	3.17	0.51	[8], fillets including skin
Crucian Carp	*C. carassius*	2.77		
Black Carp	*M. piceus*	0.56		

Tilapia

Seafood group	Scientific name	Volume (mmt)	Conversion factor	Conversion factor data source
Nile Tilapia	*T. nilotica*	1.28	0.38	[8], source 3
Blue-Nile Tilapia, hybrid		0.42	0.38	*Using same as Nile tilapia*

Freshwater Fishes

Seafood group	Scientific name	Volume (mmt)	Conversion factor	Conversion factor data source
Freshwater fishes nei		2.53		
Wuchang Bream	*M. amblychephala*	0.78		
Snakehead	Channidae	0.51		
Amur catfish	*S. asotus*	0.45		
Asian swamp eel	*M. albus*	0.36		
Largemouth black bass	*M. salmoides*	0.35		
Pond loach	*M. anguillicaudatus*	0.34		
Yellow catfish		0.33		
Mandarin fish	*S. chuatsi*	0.29		
Channel catfish	*I. punctatus*	0.25	0.30	[9], fillet, raw
Japanese eel	*A. japonica*	0.22		
Pirapatinga	*P. brachypomus*	0.10		
Sturgeons nei	Acipenseridae	0.08		
Rainbow Trout	*O. mykiss*	0.03	0.62	[9], fillet, raw
Chinese longsnout catfish	*T. dumerili*	0.02		
Clearhead icefish	*P. hyalocranius*	0.02		
Pond smelt	*H. olidus*	0.01		
Salmonoids nei		0.01		

Included freshwater fish species with production volume lower than 0.01 mmt: Obscure pufferfish

Marine Fishes

Seafood group	Scientific name	Volume (mmt)	Conversion factor	Conversion factor source
Marine fishes nei		1.55		
Largehead hairtail	*T. lepturus*	1.18		
Japanese anchovy	*E. japonicus*	0.93		
Jacks, pompanos	Carangidae	0.60	0.56	[8], average for Caranx spp.
Pacific saury	*C. saira*	0.49	0.64	[8]
Chub mackerel	*S. japonicas*	0.48	0.57	[8]
Spanish mackerel	Scomberomorini	0.43	0.67	[8], average of all species
Threadfin breams	Nemipterus	0.41		
Daggertooth pike conger	*M. cinereus*	0.38		
Drums, croakers	Sciaenidae	0.37		
Yellow croaker	*L. polyactis*	0.34		
Silver pomfrets	Pampus	0.33		
Porgies, seabreams	Sparidae	0.23		
Large yellow croaker	*L. crocea*	0.23		
Filefishes	Monacanthidae	0.19		
Pacific sardine	*S. sagax*	0.15		
So-iny mullet	*L. heamatocheilus*	0.15		
Flathead grey mullet	*M. cephalus*	0.13		
Pacific sandlance	*A. personatus*	0.12		
Seabasses, hinds	Epinephelus	0.11		
Silver croaker	*P. argentata*	0.11		
Japanese seabass	*L. japonicas*	0.11		
Snubnose pompano	*T. blochii*	0.11		
Groupers nei	Serranidae	0.09		
Elongate illisha	*I. elongata*	0.08		
Mi-iuy croaker	*M. miiuy*	0.07		
Lefteye flounders, nei	Bothidae	0.07		
Red drum	*S. ocelattus*	0.07		
Turbot	*P. maxima*	0.06		
Japanese jack mackerel	*T. japonicus*	0.04	0.60	[8], includes skin
Japanese Spanish mackerel	*S. niphonius*	0.04	0.75	[8], includes skin and bone
Mackerels, tunas, bonitos	Scombridae	0.04		
Cobia	Rachycentridae	0.04		
Amberjacks	Seriola	0.04	0.55	[8], based on *Seriola grandis,* including skin
Albacore	*T. alalunga*	0.03	0.69	[8], source 9
Oilfish	*R. pretiousus*	0.03		
Sharks, rays, skates	Elasmobranchii	0.03		
Skipjack tuna	*K. pelamis*	0.03	0.62	[8]
Yellow striped flounder	*P. herzensteini*	0.03		
Bigeye tuna	*T. obesus*	0.02	0.63	[8], source 8
Chilean jack mackerel	*T. murphyi*	0.02	0.52	[8], no data for this species, so jack mackerel mean
Common dolphinfish	*C. hippurus*	0.02		
Pacific herring	*C. pallasii*	0.02	0.60	[8]

Whitespotted conger	*C. myriaster*	0.02		
Tiger pufferfish		0.02		
Bastard halibut	*P. olivaceus*	0.01		
Bullet and frigate tunas	Auxis	0.01		
Chinese gizzard shad	*C. thrissa*	0.01		
Japanese sandfish	*A. japonicas*	0.01		
Moonfishes	Menidae	0.01		
Pacific cod	*G. macrocephalus*	0.01		
Pacific rudderfish	*P. anomala*	0.01		
Perch-likes	Perciformes	0.01		
Yellowfin tuna	*T. albacares*	0.01	0.62	[8], source 11
Righteye flounders nei	Pleuronectidae	0.01		

Included marine fish species with production volume lower than 0.01 mmt: (Alfonsinos, redfishes), Antarctic dragonfishes, Antarctic silverfish, Atlantic horse mackerel, Atlantic sailfish, Barracudas, (Barracudas, sennets), Barramundi, Bartail flathead, (Basses, groupers, hinds), Billfishes, Black marlin, Black pomfret, Black rockcod, Blackfin icefish, Blackhead seabream, Blackmouth croaker, Blue marlin, Blue shark, Bluefin gurnard, Bobo croaker, Bonga shad, Cassava croaker, Cod icefishes, Cutlassfishes, Dolphinfishes, European anchovy, European hake, European pilchard, Flatfishes, Flyingfishes, Giant African threadfin, Goatfishes, Gobies, Golden threadfin bream, Goosefishes, Greater lizardfish, Grey rockcod, Groundfishes, Hakes, (Herrings, sardines, menhadens), Indo-Pacific King mackerel, Indo-Pacific Sailfish, (Jacks, horse mackerels), Japanese halfbeaks, Japanese sardinella, Lesser African threadfin, Mackerel icefish, Mako sharks, Milkfish, Narrowbarred Spanish Mackerel, Parrotfishes, Pelagic fishes, (Puffers, tobies), Red bigeye, Royal threadfin, Salmonids, Sardinellas, (Sea catfishes, coblers), Shortfin Mako, Silver pomfret, Silver seabream, Silverstriped round herring, Smelt-whitings, Snappers, Sompat grunt, South Georgia icefish, Southern Bluefin Tuna, Spiny icefish, Striped marlin, Swordfish, Thread-sail filefish, Torpedo scad, (Tunas, bonitos, billfishes), West African geryon and Whiptail stingrays.

Bivalves

Seafood group	**Scientific name**	**Volume (mmt)**	**Freshwater or Marine**	**Conversion factor**	**Conversion factor data source**
Cupped oysters nei	Crassostrea spp	4.35	Marine	0.10	[8]
Japanese carpet shell	*R. philippinarum*	3.99	Marine		
Scallops nei		1.65	Marine		
Sea mussels nei	Mytilidae	0.82	Marine	0.24	[8], raw flesh average for Mytilidae species
Contricted tagelus	Sinonovacula	0.79	Marine		
Blood cockle	*A. granosa*	0.35	Marine		
Swan mussel	*A. cygnea*	0.09	Freshwater		
Asian clam	*C. fluminea*	0.02	Freshwater		
Pen shells nei	Pinnidae	0.02	Marine		
Clams nei	Bivalvia	0.01	Marine	0.18	[8], average for available Bivalvia spp.

Included bivalve species with production volume lower than 0.01 mmt: (Abalones, earshells), (Arks, turkey wings), Japanese hard clam, Korean mussel, Yesso scallop, Freshwater mussel shells and Pearl oyster shells nei.

Cephalopods

Seafood group	Scientific name	Volume (mmt)	Conversion factor	Conversion factor data source
Squids nei	Theutida	0.42	0.67	[8], average of all squid
Argentine shortfin squid	*I. argentines*	0.34		
Jumbo flying squid	*D. gigas*	0.33		
Japanese flying squid	*T. pacificus*	0.19		
Cuttlefishes, bobtail squids	Sepiida	0.14	0.78	[9], flesh, raw
Octopuses, argonauts	Octopoda	0.12	0.79	[8], general estimate
Squids, cuttlefishes, octopuses	Cephalopoda	0.04		
Common pencil squids	Loliginidae	0.01		

Crabs, shrimps and lobsters

Seafood group	Scientific name	Volume (mmt)	Freshwater or Marine	Conversion factor	Conversion factor source
Whiteleg shrimp	*P. vannamei*	1.58	Both (50:50)	0.57	[8], average for all Penaeus spp.
Chinese Mitten Crab	*E. sinensis*	0.85	Freshwater		
Red swamp crawfish	*P. clarkii*	0.66	Freshwater		
Gazami crab	*P. trituberculatus*	0.58	Marine		
Marine crabs, shrimps, lobsters nei		0.55	Marine		
Akiami paste shrimp	*A. japonicas*	0.54	Marine	1	[8]
Oriental river prawn	*M. nipponense*	0.40	Freshwater		
Southern rough shrimp	*T. curvirostris*	0.32	Marine		
Squilla mantis shrimp	Squillidae	0.29	Marine		
Crabs, lobsters, shrimp nei	Decapoda	0.24	Marine		
Fleshy prawn	*F. chinensis*	0.19	Marine		

Indo-Pacific swamp crab	*S. serrata*	0.14	Marine	0.2	[9], raw
Siberian prawn	*E. modestus*	0.14	Freshwater		
Giant river prawn	*M. rosenbergii*	0.13	Freshwater		
Penaeus shrimps nei	Penaeus spp.	0.12	Marine	0.57	[8], average for all Penaeus spp.
Portunus swimcrabs nei	Portunus spp.	0.12	Marine	0.2	[9], Swimming Crabs, raw
Marine crabs	Decapoda	0.12	Marine		
Blue swimming crab	*P. pelagicus*	0.08	Marine	0.2	[9], raw
Giant tiger prawn	*P. monodon*	0.07	Marine	0.57	[8], average for all Penaeus spp.
Whirlpool swimming crabs	Charybdis	0.06	Marine		
Kuruma prawn	*M. japonicus*	0.05	Marine		
Tanner, snow crabs	Chionoecetes	0.03	Marine		
Freshwater prawns, shrimp nei		0.02	Freshwater	0.57	[9], River prawns, raw

Included crab/lobster species with production volume lower than 0.01 mmt: Blue and red shrimp, Commercial shrimps and prawns, Deepwater rose shrimps, Giant tiger prawns, Indo-Pacific Prawns, Longlegged spiny lobster, Redtail prawn, Scarlet shrimp, Shiba shrimp, Slipper lobsters, Spiny lobsters and Swimming crabs nei.

Jellyfishes

Seafood group	**Scientific name**	**Volume (mmt)**	**Conversion factor**	**Conversion factor data source**
True jellyfishes	Scyphozoa	1.10	0.1	[10]
Jellyfishes nei		0.07		

Other

Seafood group	**Scientific name**	**Volume (mmt)**	**Freshwater or Marine**	**Conversion factor**	**Conversion factor data source**
Marine molluscs nei		0.89	Marine		
Chinese softshell turtle	*P. sinensis*	0.34	Freshwater		
Aquatic invertebrates nei		0.32	Both (50:50)		
Freshwater molluscs nei		0.29	Freshwater		
Sea snails		0.24	Marine		
Japanese sea cucumber	*A. japonicus*	0.20	Marine		

Abalones nei	Haliotidae	0.12	Marine	0.42	[9], muscle, raw
Chinese mystery snail	*C. chinensis*	0.11	Freshwater		
Frogs		0.09	Freshwater		
Antarctic krill	*E. superba*	0.05	Marine		
River and lake turtles nei		0.04	Freshwater		
Sea urchins nei		0.01	Marine		

Included 'other' species with production volume lower than 0.01 mmt: (Clams, seasnails, squids, octopuses), Horned turban, (Sea urchins, sea hedgehogs), Freshwater crustaceans nei.

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