Title: Fishing for feed in China: facts, impacts and implications

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Abstract: China is the world's largest capture fisheries and aquaculture producer. Over recent decades, China's domestic marine catch composition has changed markedly, from large volumes of a few high-valued food species to multiple, small, low-valued, species, a significant proportion of which is primarily used as animal, especially fish, feed. Despite the growing volume and economic importance of the feed catches, their species composition, catch volumes and socio-environmental impacts are all poorly understood. Based on a nationwide survey of >800 fishing vessels, and the identification and measurement of >12,000 fish and invertebrate individuals, the present study provides an overview of the feed component of China's domestic marine catch, by volumes, species, and sizes, and found it to be substantial and biologically unsustainable. Half of the trawler catch (3 million metric tons, mmt), or 35% of the total catch (4.6 mmt) in China's exclusive economic zone are now comprised of low-valued 'feed grade fish'. The present study identified 218 fish species, 50 crustaceans and five cephalopods and of these, 102 fish species were food species with 80% in their juvenile size ranges. Feed grade fish were mainly used as aquaculture feed directly, or indirectly through the feed industry after reduction to fishmeal and fish oil. The unparalleled scale and poor fisheries resource condition of China's domestic marine fisheries, in parallel with severe overfishing of juveniles, creates a demand for fundamental changes to fishery management practices, including a significant reduction of fishing effort to ensure productivity and ecosystem resilience.

Keywords: biodiversity, feed grade fish, management, multispecies fisheries, trash fish, trawl

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1. Introduction

China is the world's largest capture fisheries and aquaculture producing country, accounting for 19.2% of global marine capture fisheries production and 61.5% of global aquaculture production in 2016 (FAO 2018). In 2016, China's total domestic marine capture fisheries production was 13.3 mmt (million metric tons), and total aquaculture (marine and freshwater) production was 51.4 mmt (MOA 2017a). Capture fisheries and aquaculture in China provide food and income, 13.8 million jobs, and livelihoods for nearly 20 million people (MOA 2017a).

Despite the introduction of a range of marine fisheries management measures at both national and local levels since the 1980s (Cao *et al.* 2017), fishing pressure has grown over the last four decades (Figure S1). Persistently high fishing pressure, together with other pervasive deleterious anthropogenic influences, such as runoff of fertilizers and habitat loss and degradation, have resulted in sharp declines in fishery biomass and catch per unit effort (CPUE) in China's major fishing grounds. In the Bohai Sea, the CPUE declined from >420 kg $haul^{-1}$ h^{-1} in 1959, to ~160 kg $haul^{-1}$ h^{-1} in 1982, ~30 kg $haul^{-1}$ h^{-1} in 1993, and <8 kg $haul^{-1}$ h^{-1} in 1998-2011 (Jin *et al.* 2013; Shan *et al.* 2013). In the Yellow Sea and East China Sea, the CPUE dropped from 73.54 kg $haul^{-1}$ h^{-1} to 39.19 kg $haul^{-1}$ h^{-1} in just ten years between 1991 to 2000 (Cheng and Yu 2004). In the northern South China Sea, the fishery biomass declined from 2.7 mt km^{-2} in the 1930s, to 1.5 mt km^{-2} in 1956, 1.1 mt km^{-2} in 1960-1973, and 0.3 mt km^{-2} in 1997-1999 (Qiu 2002).

In concert with biomass and CPUE declines, the species composition of China's domestic marine catches over the past six decades has undergone substantial changes from a predominance of a few medium to relatively large-sized, high-valued, high trophic level, demersal species to multiple small, low-valued, short-lived, low trophic fishes (Liu and Sadovy de Mitcheson 2008; Shen and Heino 2014; Cao *et al.* 2017) (Figure S2). These changes are largely attributable to the overfishing of these larger species driven by ineffective management resulting in increased numbers of smaller, lower trophic level species (Pauly *et al.* 1998; Lundgren *et al.* 2006; Shen and Heino 2014; Cao *et al.* 2017).

Since the 1990s fisheries production has increasingly been used to supply fishmeal and animal feed, particularly aquaculture feed, shifting away from its historic use for direct human consumption. This pattern is observed not only in China (Funge-Smith *et al.* 2005; Lundgren *et al.* 2006; Cao *et al.* 2015), but also in Vietnam (Edwards *et al.* 2004) and several other Asian countries and areas (Funge-Smith *et al.* 2005). The increasing importance of animal feed during a period when food fisheries were declining enabled some fisheries to remain viable; for example in Hong Kong after declines in traditional trawl fisheries occurred due to overfishing, fishers were increasingly able to earn money from smaller, poorer quality fish, being sold as animal feed for the burgeoning mariculture sector. This enabled the fisheries to remain economically viable and allowing overfishing to continue (e.g. Hong Kong, Cheung and Sadovy 2004).

Due to the highly diverse nature of the world's fisheries and because of different terminologies and histories among countries (FAO 2011b), there is no single or consistent definition or term for fisheries fishing for feed, or their product, that clearly describes the specific proportion of the catch that to be used as aquaculture (or livestock) feed. In the past, when fisheries were in good condition and aquaculture less developed, small-sized, low-valued fish were typically discarded and variously referred to as ‘discards’ or ‘bycatch’ or ‘trash fish’, reflecting the fact that they were not targeted, were incidental, or were of little or no economic value, and often being unfit for human consumption due to small size and/or poor condition (Alverson *et al.* 1994; Nguyen *et al.* 2009; FAO 2011a). In the early days of fishery development, this discarding in Southeast Asia was responsible for an estimated loss of some 3.4 mmt of fish catch per year (Chee 1997).

Other terms have been variously and inconsistently used, making comparisons across studies a challenge. Terms for the catch component not directly used for human food initially reflected what happened to the catch to, more recently, the fisheries that target fish used as feed. Catch terms range from ‘pig fish’ (Edwards *et al.* 2004; Funge-Smith *et al.* 2005), ‘low value/trash fish’ (Funge-Smith *et al.* 2005; Lundgren *et al.* 2006), ‘feed fish’ (Huntington and Hasan 2009), to ‘mixed fish feed’ (Chau and Sadovy 2005). Although reduction fisheries have existed for centuries for industrial purposes (Smith 1991), as the use of catches for animal feed became more important, specific fisheries terminology began to be identified, such as feed fisheries (Hasan and Halwart 2009) and forage fisheries (Watson *et al.* 2006) which were used alongside the term ‘reduction fisheries’ (Parker and Tyedmers 2011; Shepherd and Jackson 2013).

Some terms for this ‘feed’ component fisheries are no longer fit-for-purpose or are even misleading. The best example is the still widely used term ‘trash fish’. As fisheries focused on food fish declined and aquaculture increased, a growing proportion of ‘trash’ fish was retained and came to have economic value in the aquaculture (or other livestock) sector (Alverson *et al.* 1994; Funge-Smith *et al.* 2005; Zeller *et al.* 2018). Moreover, what may be bycatch in one fishery or in one season, may be valuable food fish in another or would become food fish if animals were retained in better condition or were taken at larger body sizes.

Along with the development of aquatic food processing technologies and improvements in the handling of fish, there was also a rapid expansion of markets for other human food products such as surimi, fish balls, sauces or pastes. Species used to be by-catch but suited for processing into surimi are increasingly targeted or diverted from the fishmeal supply chain and used as raw material (Siriraksophon *et al.* 2009; Funge-Smith *et al.* 2012; Anon 2016).

While in many parts of the world the ‘feed’ component is primarily (if not solely) caught from targeted forage (or reduction) fisheries (Hasan and Halwart 2009; FAO 2011a), the sourcing of it in China is more complicated. This is because multiple fishing gears are involved which take a complex mix of species that are both targeted and non-targeted and can be used as direct feed for aquatic animals and, indirectly, to produce fishmeal, or for direct human consumption, according to their condition, species and size. In the present study, we use the term ‘*feed grade fish*’ to describe those fish (and invertebrates) that are targeted or retained to be used as fish or livestock feed.

Over the past two decades, fishing for feed grade fish in China has become increasingly important, due to overfishing of food fish associated with poor fisheries management, and, growth in demand for feed grade fish, especially with the development of aquaculture (Naylor *et al.* 2000; Funge-Smith *et al.* 2005; Huntington and Hasan 2009; Cao *et al.* 2015). Into the new millennium, China's aquaculture has been greatly intensified with much more formulated feed and direct feeding of feed grade fish required (Edwards 2008a,b; Chiu et al. 2013), with a trend to 'farming up' the food web with increasingly more high value species, especially carnivore species, being farmed (Naylor *et al.* 2000; Miao and Liao 2007; Zhou 2007), further contributing to the increasing demand for feed grade fish.

The feed component is today a significant aspect of China's domestic marine fisheries. Estimates based on FAO data over a decade ago show that the feed component represented more than one-third of China's marine catch (Han and Xu 2004; Funge-Smith *et al.* 2005; FAO 2007) and was mainly constituted by unidentified 'nei' (not elsewhere included) species and forage species (Han and Xu 2004; Cao *et al.* 2015). Sporadic surveys also suggest that 26-90% of the fisheries catch by weight or number in China's EEZ are feed grade fish, especially from non-targeted trawls and stow nets, in some cases higher than the situation found in other Southeast Asian countries (Table S1) but similar to countries where targeted reduction fisheries are operating.

However, the feed component of China's domestic marine fisheries has not been documented systemically at the national level. Its scale, species composition, as well as biological, ecosystem and management implications are poorly understood. For example, 'nei' accounts for approximately 31% of China's domestic marine catch (Cao *et al.* 2015), but its composition is largely unknown. This situation makes it difficult to assess the impact of the source fisheries and seriously constrains the development of effective management.

Meanwhile, there are growing concerns that the demonstrable declines in large-scale, and unmanaged, fisheries bring substantial risks to the marine ecosystem, threaten biodiversity and endanger long-term marine ecosystem resilience. One critical risk is that further overfishing of a wide range of species and sizes in China EEZ will seriously reduce the future productivity of marine fisheries (Cao *et al.* 2015, 2017).

The objectives of the present study were to reveal the complicated nature of the feed component of China's domestic marine catch, related fisheries, volumes, species composition, destination/use of catches, and its impacts and implications without management. A better understanding of the current situation of China's domestic marine fisheries, especially the little-understood component used as feed can provide a solid basis for supporting future policy reforms in China's marine fisheries sector.

2. Methodology

The present study adopted an integrated, interdisciplinary methodology by combining both top-down and bottom-up approaches to develop a holistic understanding of the feed component of China's domestic marine catch. We started from systematic literature reviews then proceeded to a nationwide field survey of fishing vessels/gears and analysis of feed grade fish samples, collected in eight major fishing provinces (Tables S2 and S3; Figure S3).

Field survey and feed grade fish sampling were focused on the most important fishing months from August to December in 2016, which is right after the national fishing moratorium and prior to the winter when fishing activities were largely closed in the north. In 2016, the total capture fisheries production (both marine and freshwater) in the second half of the year was 11.69 mmt, which accounts for 66.4% of annual production (Economic Daily 2016; MOA 2017a).

2.1. Terms used

In the present study, domestic marine fisheries catches were classified into three categories: (1) *food species*; (2) *forage species*, particularly small pelagic and planktivorous species; and (3) all other *mixed species*, mainly used for aquaculture feed (Table 1). In relation to supplying the animal feed sector, we suggest that the term 'feed grade fish' for catch used as animal feed (either directly, or indirectly after reduction), which consists of a wide range of species and sizes from small-sized individuals of food species (category 1), forage species (category 2) to mixed species (category 3). Specifically, 'feed grade fish' refers to the mixture of poorly preserved, small-sized and low commercial-value fishes and invertebrates primarily used as animal feed. The term 'feed grade fish' refers to 'Xiao Za Yu' in Mandarin, which literal translation is 'small and miscellaneous fish'.

2.2. Fishing vessel/gear survey

Fishing vessel/gear surveys were conducted in December 2016. The sampling of fishing vessels for interviews followed a multi-stage sampling approach from provincial level to district and port levels. Eight major marine fisheries provinces were selected for the survey: Liaoning, Shandong, Jiangsu, Zhejiang, Fujian, Guangdong, Guangxi, and Hainan. The total marine catch in these eight provinces represented 97.7% of the national domestic marine catch in 2016 (Table S2). The most important one or two districts for marine capture fisheries in each province, in terms of the number of fishing vessels and landing volumes, giving a total of 22 fishing ports in 12 districts, were selected for the surveys (Table S3; Figure S3).

Surveys covered the following areas of interest. (1) Basic information about interviewees such as position, name, age, and contact information. (2) Vessel information such as registration number, length, and horsepower. (3) Major fishing areas and major fishing gears. (4) Total catch of food species in different taxonomic groups (i.e. fishes, cephalopods, crustaceans and others). (5) Total catch of feed grade fish (i.e. the fish is marketed as such). (6) Catches of major species among food species. (7) Major species of feed grade fish. (8) Destination and price of feed grade fish. Survey questions were designed to cover the whole fishing season in the second half of 2016 (August to December).

Fishing vessel surveys at port level were primarily conducted according to fishing gear type. Fishing gears were classified according to The International Standard Statistical Classification of Fishing Gear (FAO 2016) and standards in publications (Wang and Yu 2012; Hainan Aquaculture Institute 2013; Sun 2014). Survey sample sizes for each fishing gear category were at least 30, except for trawler. The trawler was the focus of the present study because trawlers produce half of China’s marine catch by weight in the EEZ (Figure S4) and account for a high proportion of feed grade fishes (Table S1). Survey sample sizes for trawler in each selected province were at least 30.

The term ‘trawler’ covers vessels that may target feed grade fish (especially midwater trawlers) and those that catch feed grade fish incidentally (generally bottom trawlers). Fishing vessels were randomly selected in each port, with interviewees being mainly fishing vessel owners, captains, or senior fishers.

2.3. Fish sampling, identification, and measurement

From August to December 2016, feed grade fish samples of up to 1 kg in weight were collected 2-3 times per month in each of eight provinces directly from fishing vessels. Species were identified, and individuals were counted and measured for body weight and length. Identified species from collected samples were classified as *food species*, *forage species*, or *mixed species* based on the opinions of four experts from different research institutes. Classifications also referenced major aquatic trading websites, and marine capture species lists in the FAO FishstatJ database (FAO 2017), China Fishery Statistical Yearbook (MOA 2017a), the list of commercially important aquatic animals and plants under special national protection for resources (MOA 2017b), the standard of catchable size of important fisheries species part 1 (economic marine species (MOA 2017c)), and marine capture species information in FishBase (Froese and Pauly 2017). The IUCN Red List Status of Threatened Species (www.iucnredlist.org) was referred to for conservation status of identified species. Stock assessments from fisheries in China or the wider SE Asia region were collected from FAO evaluations and related publications.

2.4. Data analysis

A multiple linear regression model was used to investigate factors contributing to different proportions of feed grade fish in catches using SPSS 22 statistics software (IBM 2013). All fishing vessels surveyed were classified into one of three length categories (<12 m, 12-24 m, >=24 m) according to the China Fisheries Yearbook (MOA 2017a). The proportion of feed grade fish in catches was calculated based on survey results for all major fishing gears surveyed across all eight provinces. Using marine fisheries production by province and fishing gear type as a weighting factor for proportion of feed grade fish, the overall proportion of feed grade fish for the whole country was calculated. Independent-samples Kruskal-Wallis test was used for significance test using SPSS 22 statistic software (IBM 2013). The Chinese Yuan (CNY) was converted to US dollars (USD) using the annual average exchange rate in 2016 as 1 USD=6.66 CNY (https://www.investing.com/).

Maturity stage was inferred from knowledge of recorded or estimated size (body length) at first maturity (Lm). Lm was collected from FishBase (Froese and Pauly 2017). When the recorded Lm for a species was missing, the estimated Lm in the FishBase Species Ecology Matrix was used; estimated Lm was calculated from the recorded asymptotic length of a species and an empirical relationship between length at first maturity and asymptotic length (Froese and Binohlan 2000; Froese and Pauly 2017).

Several potential sources of variation and uncertainty in the present study (Appendix S1) could affect the calculations of total feed grade fish volume as well as feed grade fish sampling. To estimate the aggregate impact of data uncertainty on feed grade fish production in China, a Monte Carlo analysis was conducted in Oracle Crystal Ball (Release 11.1.2.3.500). The Monte Carlo method is extensively used in fisheries research to estimate uncertainty by repeated random sampling based on predefined parameters of probability distributions (Pauly *et al.* 2014). The type of probability distributions and uncertainty parameters for the model were calculated by the Batch Fit module in Oracle Crystal Ball and based on survey data of the present study. The uncertainty parameters represented variations in the proportion of feed grade fish from different fishing gear category. We calculated uncertainty based on a distribution of 100,000 runs resulting from the Monte Carlo sampling method.

A sensitivity analysis was conducted to explore the juvenile percentages associated with variation of length at sexual maturity (Appendix S1). Instead of using the estimated Lms, body length at 50% of the maximum body length (L50) reported in the FishBase (Froese and Pauly 2017) was used as a comparable criterion for the size of sexual maturation.

3. Results

3.1. Proportion of feed grade fish in catch

A total of 886 interviews was conducted from domestic vessels in 22 major fishing ports in eight major fishing provinces in December 2016 (Tables S3 and S4). The multiple linear regression model shows fishing gear and sampling location (province) to be the major factors associated with different proportions of feed grade fish (including fishes and invertebrates) in catches ($p<0.05$; Table S5). The average engine power of fishing vessels, according to respondents willing and able to answer this question, was 410.5±343.3 kW (n=582) and the average vessel length is 31.3±10.0 m (n=851) (Figure S5). Although large fishing vessels produced significantly more catch per vessel than small fishing vessels (Table S6), vessel size (length) has little effect on the proportion of feed grade fish in catches (Table S7).

Trawls, stow nets, gillnets and entangling nets, and surrounding nets and seine nets were identified as the main fishing gears taking feed grade fish. Trawls accounted for the highest proportion of feed grade fish catch overall by weight (Figure 1), with nearly half (48.9±26.5%, n=538) of trawler catches being feed grade fish. This is not surprising as midwater trawls primarily target forage fishes, mainly anchovies in the Bohai and Yellow Seas, producing 71.5±31.2% (n=76) of feed grade fish as a proportion of their total catch by weight. This was significantly ($p<0.05$) higher than the proportion taken from bottom trawlers (43.6±21.3%, n=336) (Table 2) and probably reflects the fact that midwater trawls are used to target small pelagic species that are commonly used for animal feeds.

Three-fifths (58.5%) of trawlers, 46.6% of stow net vessels, 23.5% of gillnet and entangling net vessels, and 7.1% surrounding nets and seine nets vessels by number, were predominantly producing feed grade fish, which accounting for at least 50% of their total catch by weight (Figure 2). Trawlers in Liaoning, Shandong, Guangxi, and Hainan reported significantly higher proportions of feed grade fish in their catches than other provinces ($p<0.05$) (Table 3).

3.2. Feed grade fish production

The overall proportions of feed grade fish, according to 886 interviews, weighted by production by gear and province (Tables 4 and 5) show that 34.7% of China’s marine catch, or 4.6 mmt marine fisheries production, was feed grade fish. The Monte Carlo analysis also shows that about 4.6 mmt (95% confidence interval: 2.1–7.0 mmt) of total production was feed grade fish (Figure S6, Table S8).

The proportion of feed grade fish produced by all trawlers combined, weighted by production by province, was 48.7%, which is equivalent to 3.0 mmt of feed grade fish production from China's EEZ (Table 5). This is followed by stow nets 0.7 mmt, gillnets and entangling nets 0.6 mmt and surrounding nets and seine nets 0.2 mmt (Table 5). Shandong, Guangxi, and Zhejiang had the highest proportions of feed grade fish (Figure 3) in their catches, reflecting the reliance of these provinces on trawlers (Figure S7). The top capture fisheries provinces are also major feed grade fish producing provinces, especially Zhejiang and Shandong (Figure 4; Table S2).

3.3. Use and prices of feed grade fish

A total 88.2% of interviewees (n=781) reported that their feed grade fish catch was mainly used in the aquaculture and feed industries, either as direct feed (e.g. using unprocessed whole fish or fish parts directly in aquaculture cages/ponds) or indirectly to produce fishmeal and fish oil which is then used as raw material for aquaculture and livestock feed (Figure 5). Some mink and fox farms in Shandong and Liaoning, and, occasionally, chicken and pig farms in fish-producing areas, also use feed grade fish but the scale of this use is not known. A low proportion (4.9%) of the interviewees (n=43) reported discarding feed grade fish because of poor condition, while 6.7% (n=59) reported their catch was mainly used for human consumption after processing into minced products such as fish balls, dried or salted product, or sauces and pastes. The consumption of feed grade fish (4.6 mmt) was estimated according to survey data

(Figure 6).

Prices of feed grade fish purchased from fishing vessels or at fishing ports varied from USD 0.1 to 0.8 per kg and averaged USD 0.2±0.1 per kg (n=684) depending on province, freshness/quality, species composition, the type of utilization intended, and the demand for feed grade fish by the aquaculture sector (Figure S8). Small size and poor condition of feed grade fish led to particularly low prices, making them affordable for purchase and use whole by aquaculture producers or for manufacturing of fishmeal.

A nationwide feed grade fish value chain has developed, and a stable market and price structure for feed grade fish now exists. Feed grade fish transactions take place both within the capture fisheries sector and across a trade chain that links feed grade fish capture to transportation networks by sea or by land and involving cold storage, with aquaculture farms and fishmeal factories as major end-users. The trade network runs across the country; for example, feed grade fish caught in Zhejiang could supply aquaculture farms in Fujian, and fishmeal factories in Shandong.

3.4. Species composition

A total of 80 samples of feed grade fish, with a total weight of 64.4 kg, after removing unidentifiable fish and invertebrate body parts and garbage, were collected from 22 fishing ports surveyed throughout eight major marine fisheries provinces. A total of 12,206 individuals were measured, the majority being fish, with 10,796 (88.5%) individuals, followed by 1,263 (10.4%) crustaceans, and 147 (1.2%) cephalopods.

Species identification focused on fishes; 98.0% of fish individuals were identified to species level. A total of 218 fish species were identified (three to genus level only), including three Chondrichthyans (two orders and two families) and 215 Actinopterygiians (19 orders and 84 families) (Figure 7; Figure S9, Tables S9-S11). The most numerous fish families were Engraulidae (3,668 individuals from 10 species), Gobiidae (1,852 individuals from 14 species), Clupeidae (752 individuals from 8 species), Synodontidae (734 individuals from 5 species), Bregmacerotidae (632 individuals from 1 species), and Sciaenidae (488 individuals from 17 species). In addition, 50 crustaceans (2 orders and 20 families) and five cephalopods were identified (Tables S12 and S13). Many crustaceans and cephalopods were small-sized and/or body damaged; therefore, body size/weight measurements were not made.

3.5. Food fish species and proportion of catches composed of juveniles

Of 218 identified fish species, 102 (46.8%) were food species, 19 (8.7%) were forage fish and 97 (44.5%) mixed fish. Of the 10,580 fish individuals identified to species, 3,112 (29.4%) were food fish, 4,392 (41.5%) forage fish, and 3,076 (29.1%) mixed fish. A total of 9,377 (88.6%) individuals had measurable body length. Three-quarters (7,225 individuals, 77.05 %) of these fish individuals were estimated to be in the juvenile phase in terms of the criterion of Lm’s (Tables S9-S11). The majority (88.9%) of food fish were likely to be in their juvenile stage while 71.8% and 73.1% of forage fish and mixed fish were juveniles respectively (Figure 8).

The percentages of juveniles were lower (food fish 79.7%, forage fish 60.9%, mixed fish 37.3% and overall 59.9%) when the criterion for size of maturity was set for the criterion of L50 (Figure S10). The reduced percentage of juveniles is mainly because the estimated Lm tends to be longer in small fish than in large fish (Froese and

Binohlan 2000; Tsikliras and Stergiou 2014; Froese and Pauly 2017). Most of the fish species identified in this study are small-sized species (Tables S9-S11), and their estimated Lm's are more likely longer than the sizes of 50% of the maximum body length.

3.6. Stock assessment and conservation status

Of 218 fish species identified, stock assessments published in reports, books or papers from 2005 to 2015 were found for 32 species and taxonomic groups (to genus level), of which 28 (87.5%) were over-exploited, and 4 (12.5%) were fully exploited or starting to decline at the time of reporting, all were Actinopterygiians (Tables S14 and S15).

In terms of conservation status, 143 fish species have not been evaluated (NE) against the IUCN Red List Criteria. Among the 72 species evaluated, one was endangered (EN, *Evynnis cardinalis*), one vulnerable (VU, *Nemipterus virgatus*), 59 least concern (LC), and 11 data deficient (DD) (Tables S9-S11).

Eight species of fish, one crustacean, and one cephalopod have been important for China's national stock enhancement projects (Table S16). Of these ten species, most individuals taken in samples of the current study were still in their juvenile stage. National stock enhancement projects, therefore, are likely being compromised by uncontrolled fisheries that catch feed grade fish as these projects rely on the dispersal of juvenile fish into the wild.

4. Discussion

4.1. Fishing for feed in China is substantial and biologically unsustainable

Although the reported production from China's fishing grounds remained stable over multiple years, an increasing and significant proportion of domestic marine catch comprises poorer quality fish, less marketable as direct human food than previously, and now primarily used as animal feed. The loss of historically major food fisheries, declining fisheries biomass and CPUE, changing species composition, declining fish size, and shifting end use of marine catch, primarily driven by severe overfishing and excessive capture of juveniles, are trends that have largely been obscured by this stable reported production.

At the global level, around one-quarter, or 20 mmt, of fisheries landings were used for purposes other than direct human consumption (FAO 2018). The present study found that about 35% (4.6 mmt) of China's marine catch is now sold at low prices as feed grade fish, 40% higher than the global average. Considering China's feed grade fish production alone would rank it fourth among World's leading marine fisheries countries (Figure 9).

Thirty percent (29.4%) of feed grade fish catch was identified as food fish species, with most of these (79.7%) in their juvenile size range. If allowed to reach marketable size, these fish could potentially have gone directly to human food use and gained higher prices, which in turn would maximize yield or, at least, optimize individual value per recruit (Beverton and Holt 1993; Froese *et al.* 2016; Cashion *et al.* 2017) (also see Table S17). Forage fish are also overfished in China, with 71.8% of the individuals sampled being juveniles. This is in contrast to many of the World's major reduction fisheries that specifically target forage fish which are effectively managed using a variety of catch control tools, such as quotas and effort limits (Tveteras *et al.* 2011; Pikitch *et al.* 2012).

Protecting juveniles is a core component of fisheries management and sustainable resource use (Garcia *et al.* 2003; Crowder *et al.* 2008; Pinsky *et al.* 2011; Froese *et al.* 2016). There are examples of fisheries collapses of multiple different individual species stocks associated with depletion of adult individuals and an increasingly high proportion of juveniles in catches. For example, the large yellow croaker was heavily exploited to the point of severe depletion in the 1980s with an increasingly heavy take of juveniles (Liu and Sadovy de Mitcheson 2008) (Figure S11). Trends of increasingly higher proportions of juveniles in catches were also observed with many other major food species such as Largehead hairtail (*Trichiurus lepturus*), Yellow croaker (*Larimichthys polyactis*), Silver pomfret (*Pampus argenteus*) and Japanese Spanish mackerel (*Scomberomorus niphonius*) (Figure S12).

The outcomes of decades of overfishing and excess fishing capacity in China's domestic marine fisheries resulted in depletions of some 'traditionally taken' species by the 1970s and 1980s. By the 1980s and 1990s, some forage species and recently exploited food species such as the scaly hairfin anchovy (*Setipinna taty*) and the filefish (*Thamnaconus modestus*) had also become over-exploited (Figure S2). The mean trophic level of China's marine catch has declined from 3.7 to 3.46 during the past half-century (Cao et al. 2017), which is linked to the expanding proportion of low-trophic-level forage species in catches, eroding biodiversity and degrading marine ecosystem structure, functioning and resilience (Smith *et al.* 2011). Unmanaged over the long term, there is a real risk that the fishery resources underpinning the feed component of China's marine catch will also inevitably collapse (Beverton 1990; Costello 2017) (Figure S2).

4.2. Effective management is needed for both food and feed components

China has regulations, policies and measures aimed at controlling fishing capacity, including a fishing license system, fishing moratorium, and minimum mesh size regulation (Cao *et al.* 2017). However, these efforts have clearly been inadequate in part due to ineffective compliance/enforcement of regulations but also because these measures do not control fishing effort. For example, along with depleted traditional fisheries resources, fishers tend to reduce their mesh size to maintain or increase their catches (Yu 2003); the legal minimum stretched mesh size requirement of 25 mm (which is still lower than 40 mm recommended by the APFIC Trawl Guidelines (FAO 2014a)) is poorly implemented. Cod-end mesh sizes net of 10 mm or less are extensively used by Chinese trawlers (Liang and Pauly 2017).

China's fisheries resources have been over-exploited since the 1970s, well before the development of intensive feed and aquaculture industries. Indeed, the aquaculture industry could be considered a beneficiary of changed marine catch composition. Although aquaculture development and intensification was not the direct cause of over-exploited fisheries resources in China, the rapid development of the feed and aquaculture industries in China fueled a high market demand for feed grade fish and provided new incentives to continue fishing even as traditional fisheries were being depleted. In this way, the high demand for feed exacerbated the already overfished state of resources allowing fishers to continue making money even as the ecosystem became further degraded.

With globally expanding aquaculture, fishmeal prices in the international market have more than tripled over the past decade (FAO 2014b) (also see Figure S13), and the price of domestically produced fishmeal has increased in tandem. The high demand for fish feed from the aquaculture sector is supported by a large number of fishmeal factories. Their operation, often well below full capacity (20-45% in 2016 (Wang 2017)), suggests increasing competition for scarce supplies. Such pressures place further stress on overexploited fishery resources.

The fishery fuel subsidy policy was introduced in 2006 in China and became the most important type of fishery subsidy in the country, accounting for 94% of overall fishery subsidies (Mallory 2016). The fuel subsidy covers about one-third of the total cost of marine capture fisheries (Zhu and Huang 2014). Without fuel subsidies, more than 90% of fishing vessels would lose money (Guo 2015). Economic incentives, from increasing demand for feed grade fish, high fuel subsidies, along with depletion of traditional fishing target species, further increase the motivation for overfishing.

The unparalleled scale (i.e. high volume) and poor fisheries resources condition (i.e. highly depleted) of China’s domestic marine fisheries make them distinctive and the solutions to the problems created need to be large-scale and must significantly reduce current levels of fishing effort. China, like many other tropical and sub-tropical

Asian countries (Leadbitter 2013), has a high biodiversity of fishes. The best option for managing the take of hundreds of different species, on the one hand, while addressing conservation principles that reduce threats to species and maintain functional marine ecosystems, may not be to seek Maximum Sustainable Yield (see for example Sainsbury 1984 (Sainsbury 1984)). One alternative is to generate a 'Pretty Good Yield' (Rindorf *et al.* 2017a,b) conditions with acceptable trade-offs where marine ecosystems are able to satisfy diverse societal needs ensuring most stocks and the ecosystem are protected or remain biologically viable (Cheung and Sumaila 2008; FAO 2014a; Costello 2017). Conservation measures, such as marine protected areas, can be used to safeguard key spawning and nursery areas that enable species to replenish themselves (Edgar *et al.* 2014; Hastings *et al.* 2017; Roberts *et al.* 2017).

By reducing excess fishing capacity, safeguarding key life history times and/or places, and effectively enforcing the current minimal mesh size requirement, fishery collapse could be averted, fisheries biomass, total catch and value could be increased, and the catch profile could be shifted to favor a greater proportion of larger fish (Jacobsen *et al.* 2013; Costello 2017; Szuwalski *et al.* 2017). This could also produce a better mix of products for direct human consumption, and indirectly via fish and livestock feed.

5. Conclusions

Significant changes in species composition in catches, the high proportion of catch comprised of juveniles, and loss of or severe declines in traditionally important fisheries are clear evidences of weak fisheries management and decades-long history of persistent overfishing and excess fishing capacity in China's domestic marine fisheries. The growing proportion of catch used to supply the aquaculture sector since the 1990s has meant that pressure continues to be high across the coastal ecosystem, even as these declines and shifts occur. To date, commitments to resolve fishery issues remain unfulfilled and existing management measures have been ineffective.

Under current fishery policy, China's fisheries risk a further downwards shift due to intensification of both fishing down and farming up the food web (Pauly *et al.* 1998; Naylor *et al.* 2000; Tacon *et al.* 2010). Unchecked, this trajectory will continue and could ultimately result in an ecosystem shift towards species that have little or no human value and other challenges of ecosystem degradation, some of which may not be reversible, and which may not even be able to supply feed grade fish into the future. There is also a long-term threat associated with loss of marine biodiversity and loss of ecosystem function and resilience.

Based on the outcomes of the present study, it is clear that the feed component of China's marine catch should be documented and managed as part of the overall national planning for sustainable fisheries resources use and marine ecosystem management. A biologically sustainable balance between fishing for food and fishing for feed could be achieved to produce a better mix of products by effectively managing China's multispecies fisheries and reducing excessive fishing capacity, while not further compromising the ecosystem and associated biodiversity. Overall, a more ecosystem-level and precautionary approach is needed for fisheries management, aquaculture development (such as a better selection of species cultured), including management of the feed component of China's marine catch to ensure long-term sustainability.

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Table 1. Characteristics of three fisheries catch categories.

Category	Food species	Forage species	Mixed species
Targeted	Yes	Yes	No
Utilization†	Human food	Mostly feed	Mostly feed
Production scale	Medium to large	Small to large	Small to large
Commercially importance	High	Medium	Low
Planktivorous	Yes/No	Mostly Yes	Mostly No
Pelagic/Demersal	Demersal/Pelagic	Mostly pelagic	Mostly demersal
Market value	Medium to high	Low to medium	Low
Primary fishing gear	All	Midwater trawl	Bottom trawl
Example species	Groupers, yellow croaker (*Larimichthys polyactis*)	Anchovies, sardines	Pinkgray goby (*Amblychaeturichthys hexanema*)

† Marketed and used as such, and dependent on size of fish, quality of handling, volume available, time of year and location.

Table 2. Proportions of feed grade fish in catches (by weight) from different fishing gears (n=886 interviews)

Vessel type	**Proportion of feed grade fish (%)**
Midwater trawler	71.51±31.20 (n=76) [a]
Bottom trawler	43.59±21.25 (n=336) [b]
Unspecified trawler †	49.57±29.01 (n=126) [b]
Stow nets	40.94±26.31 (n=151) [b]
Gillnets and entangling nets	27.54±25.26 (n=55) [cd]
Surrounding nets and seine nets	17.18±19.21 (n=87) [d]
Other ‡	7.63±6.37 (n=19) [d]
Transport ship	43.50±29.56 (n=36) [bc]

Note: † Unspecified trawler include both midwater trawler and bottom trawler, but not specified by the interviewees; ‡ 'Other' category includes hooks and lines, pots, rakes and other miscellaneous gears. Independent-samples Kruskal-Wallis test was used for significance test using SPSS 22 statistic software (IBM 2013). Means superscripted by different letters indicate significant differences ($p<0.05$).

Table 3. Proportions of feed grade fish in catches (by weight) from trawlers in eight provinces (n=538 interviews)

Province	**Bottom trawler (%)**	**Midwater trawler (%)**	**Unspecified trawler (%)†**
Liaoning	36±35 (n=15) [b]	94±8 (n=21) [a]	23±40 (n=3) [abc]
Shandong	35±26 (n=41) [b]	85±13 (n=27) [ab]	67±23 (n=15) [a]
Jiangsu	33±29 (n=15) [b]		33±33 (n=9) [abc]
Zhejiang	56±13 (n=51) [a]	57±16 (n=5) [bc]	35±32 (n=24) [bc]
Fujian	40±18 (n=63) [b]	26±34 (n=14) [c]	9±12 (n=10) [c]
Guangdong	31±13 (n=73) [b]		0±0 (n=3) [bc]
Guangxi	58±11 (n=63) [a]	51±0 (n=3) [bc]	60±9 (n=11) [ab]
Hainan	62±11 (n=15) [a]	62±27 (n=6) [bc]	65±14 (n=51) [a]

Note: † Unspecified trawler include both midwater trawler and bottom trawler but not specified by the interviewees. Independent-samples Kruskal-Wallis test was used for significance test using SPSS 22 statistic software (IBM 2013). Means superscripted by different letters indicate significant differences ($p<0.05$).

Table 4. Weighting factors and weighted proportion of feed grade fish in different fishing gears

Fishing gear	Province	Proportion of feed grade fish collected from interview (Pp, %)	Marine catch in China's EEZ in 2016 (Pd, mt)†	Weighting factors (Wt)‡	Weighted proportion of feed grade fish of each fishing gear category (WPp, %)§
Trawls	Liaoning	66.01	397,894	0.065075	48.70
	Shandong	56.91	1,398,197	0.228673	
	Jiangsu	32.85	78,717	0.012874	
	Zhejiang	49.62	2,103,225	0.343980	
	Fujian	33.80	778,343	0.127297	
	Guangdong	29.70	749,572	0.122592	
	Guangxi	58.20	425,929	0.069660	
	Hainan	63.76	182,511	0.029849	
Surrounding nets and seine nets	Shandong	60.01	36,735	0.033672	20.34
	Jiangsu	55.56	5,724	0.005247	
	Zhejiang	15.00	220,102	0.201749	
	Fujian	1.51	311,547	0.285569	
	Guangdong	37.50	143,089	0.131158	
	Guangxi	25.18	62,174	0.056990	
	Hainan	28.77	311,597	0.285615	
Gillnet	Liaoning	8.33	491,656	0.220880	20.20
	Shandong	39.24	416,024	0.186902	
	Jiangsu	35.26	163,291	0.073360	
	Zhejiang	27.88	319,057	0.143339	
	Fujian	2.00	318,118	0.142917	
	Guangdong	3.89	433,718	0.194851	
	Guangxi	90.00	84,030	0.037751	
Stow nets	Liaoning	21.92	95,891	0.065429	47.53
	Shandong	51.69	190,367	0.129892	
	Jiangsu	31.00	211,978	0.144638	
	Zhejiang	47.18	613,130	0.418355	
	Fujian	62.82	346,156	0.236191	
	Guangdong	58.64	8,052	0.005494	
Others ¶	All	0.00	1,360,431	-	0

Note: †: Data source: (MOA 2017a); ‡: Weighting factors (Wt_i) are calculated separately for each fishing gear category and based on production in each province (Pd_i), as $Wt_i = Pd_i / \sum_{i=1}^{n} Pd_i$, for each fishing gear category $\sum_{i=1}^{n} Wt_i = 1$; §: Weighted proportion of feed grade fish of each fishing gear category (WPp) are calculated separately for each fishing gear category and based on proportion of feed grade fish collected from interview (Pp_i) and its weighting factors (Wt_i), as $WPp = \sum_{i=1}^{n} Pp_i \times Wt_i$; ¶: 'Others' category includes hooks and lines, pots, rakes and other miscellaneous gears. The proportion of feed grade fish from ‘Others’ category was set at 0% due to the limited sample size of it.

Table 5. Weighted means of proportion and production volume of feed grade fish in total landings in China

Fishing gear	Weighted proportion of feed grade fish (WPp, %)†	Marine catch of each fishing gear category in China's EEZ in 2016 (GPd, mmt)‡	Overall weighting factors (OWt)§	Overall weighted proportion of feed grade fish (OWPp, %)¶	Feed grade fish production (FFPd, mmt)#
Trawls	48.70	6.23	0.469	**34.69**	3.03
Surrounding nets and seine nets	20.34	1.10	0.083		0.22
Gillnets and entangling nets	20.20	3.04	0.229		0.61
Stow nets	47.53	1.55	0.117		0.74
Others ⊥	0.00	1.36	0.102		0.00
Total catch in China's EEZ in 2016 (mmt)					**13.28**
Total feed grade fish production in China in 2016 (mmt)					**4.61**

Note: †: The weighted proportion of feed grade fish of each fishing gear category (WPp) please see Table 4. ‡: Data source: (MOA 2017a); §: Overall weighting factors (OWt_j) are calculated based on marine catch production of each fishing gear category in China's EEZ in 2016 (GPd_j), as $OWt_j = GPd_j / \sum_{j=1}^{n} GPd_j$, and $\sum_{j=1}^{n} OWt_j = 1$; ¶: Overall weighted proportion of feed grade fish (OWPp) are calculated based on weighted proportion of feed grade fish of each fishing gear category (WPp_j) and overall weighting factors (OWt_j), as $OWPp = \sum_{j=1}^{n} WPp_j \times OWt_j$; #: Feed grade fish production (FFPd) are calculated based on weighted proportion of feed grade fish of each fishing gear category (WPp_j) and marine catch production of each fishing gear category in China's EEZ in 2016 (GPd_j), as $FFPd = WPp_j \times GPd_j$; ⊥: 'Others' category includes hooks and lines, pots, rakes and other miscellaneous gears. The proportion of feed grade fish from 'Others' category was set at 0% due to the limited sample size of it.

Figure legends

Figure 1. Proportions of feed grade fish in catches (by weight) from different fishing vessels classified by fishing gears and transport ship. 'Other' category includes hooks and lines, pots, rakes and other miscellaneous gears.

Figure 2. Proportions of feed grade fish in catches (by weight) from all types of trawlers in eight provinces (A) by proportion of feed grade fish and (B) by province (n=538).

Figure 3. Proportions of feed grade fish in marine fisheries catches in different provinces.

Figure 4. Contribution of feed grade fish production (by weight proportion) in China by major producing province.

Figure 5. Feed grade fish consumption and other use, in different provinces. Using feed grade fish as direct feed or produce fishmeal was not specified in surveys conducted in Zhejiang province.

Figure 6. Estimated production and consumption of marine catch in China's EEZ. The proportions of forage and mixed species are based on data in Figure S2; the use of feed grade fish in Zhejiang was set at national average (Figure 5); the unit for all numbers is mmt.

Figure 7. Taxonomic coverage of feed grade fish samples. (A) Class (B) Order (C) Family

Figure 8. Number and the proportion of juveniles and adults in the samples in three categories (Food fish, Forage fish, Mixed fish). Unidentified individuals are those

individuals identified to species level, but no available measurable body length.

Figure 9. Production of top 10 World's leading marine (domestic + distant) fisheries countries and production of feed grade fish in China's marine catch in 2016. Data source: (FAO 2017); Aquatic plants excluded.