Fish feed for aquaculture. Unidentified species of finfish, mollusks, crustaceans, and cnidaria from the trash fish component of nontargeted fisheries packaged and frozen for delivery for a fishmeal factory in Maoming, Guangdong province, China.

GLOBAL FOOD SUPPLY

China's aquaculture and the world's wild fisheries

Curbing demand for wild fish in aquafeeds is critical

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POLICY

China is the world's largest producer, consumer, processor, and exporter of finfish and shellfish (defined here as "fish"), and its fish imports are steadily rising (*1–3*). China produces more than one-third of the global fish supply, largely from its ever-expanding aquaculture sector, as most of its domestic fisheries are overexploited (*3–6*). Aquaculture accounts for ~72% of its reported domestic fish production, and China alone contributes >60% of global aquaculture volume and roughly half of global aquaculture value (*1*, *3*).

How China develops its aquaculture sector—and whether such development can relieve pressure on wild fisheries—are key questions for the future of the oceans. China's wild fisheries, used partially for aquaculture feeds, are both targeted and nontargeted (multiple species of fish captured indiscriminately at one time, including low-valued fish for direct human consumption and fish unfit for direct consumption, a.k.a. "trash fish") (see the photo) [supplementary materials (SM)]. The country's nonspecific and often erroneous reporting of fish production and trade (*7*, *8*) makes it especially difficult to assess the impact of China's aquaculture and aquafeed use on ocean fisheries. For example, roughly 300,000 tons of marine fish "nei" (not elsewhere included or unidentified species) are cultivated annually in China's aquaculture systems, and nei represent 31% of China's marine capture, surpassing the reported catch of any individual species in its ocean fisheries (*6*).

Here, we characterize and quantify the connections between China's aquaculture production and wild fisheries. We estimate fishmeal demand and trade, and document, to the greatest extent possible, the species and stock status of fish used for aquafeeds. We also assess the potential use of fish-processing wastes for aquafeeds as a means to reduce China's dependence on capture fisheries while increasing net fish supplies.

AQUACULTURE EXPANSION. China's total production of capture and farmed fish tripled during the past two decades (*2*, *3*). Virtually all of this increase came from aquaculture, the country's fastest growing food sector (5 to 6% annual growth in volume from 2000 to 2012) (*1*, *3*). China's aquaculture output reached 40 million metric tons (mmt; including shell weight, excluding algae) in 2012, four times the production volume in 1990, and the area devoted to fish farming doubled to 8 million hectares (*1*). China accounts for one-quarter of global fish demand, and despite rapid aquaculture growth, trends in domestic consumption portend a major shift in its trade position, from the world's leading fish exporter to a net importer in coming decades (SM). Aquaculture systems throughout the country are intensifying as producers seek higher returns on scarce land, water, and coastal zone resources (*2*). Intensification is reflected in higher stocking densities, greater reliance on commercial feeds, and more frequent water exchange and aeration (*9*, *10*). The sector is transitioning from low-input, multitrophic systems (e.g., traditional carp polycultures that do not require formulated feeds) to monocultures or polycultures containing high-valued species dependent on feeds (*2*, *11*).

Fish farming remains a highly diverse industry in China and is influenced by a variety of government directives and policies (SM). More than 100 freshwater and 60 marine fish species are raised in habitats and infrastructures that include ponds, cages in lakes and coastal waters, and raft and bottom-sowing systems in shallow seas and mud flats (*2*, *3*). Carps in polyculture, tilapia in monoculture and polyculture, and penaeid shrimp in monoculture are three of the largest subsectors, constituting over half of China's total aquaculture production by volume (see the table). In 2012, China produced >90% of the world's carp, 50% of global penaeid shrimp, and 40% of global tilapia (*3*).

All of these species, with the exception of filter-feeding carps, rely on formulated feeds. Fishmeal inclusion rates in feeds average 27% for shrimp, 6% for tilapia, and 3.2% for carp, whereas fish oil inclusion is minimal. Given the scale of carp and tilapia production in China, even small rates of fishmeal inclusion sum to a large demand for fishmeal (*11*). The efficiency of feeding practices and nutrient uptake by the fish, represented by the average feed conversion ratio (FCR), also determine the overall demand for fishmeal and, hence, fish inputs in aquafeeds. The average FCR for Chinese systems that use feeds is 1.7 for carp, 1.6 for tilapia, and 1.2 for penaeid shrimp. The relatively high FCR for carp reflects the use of poor-quality fishmeal and the integration of various high-value fish species into carp polyculture, which often results in poor feed targeting and inefficient feed practices (*11*). The use of trash fish to supplement or substitute for commercial feeds via direct feeding of higher-valued species is also common and contributes to poor FCRs.

DEPENDENCE ON WILD FISH. China is the world's largest importer of fishmeal, accounting for about one-third of the global fishmeal

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trade in any given year (SM). The country's entire aquaculture sector consumed an estimated 1.4 mmt of fishmeal in 2012 (*12*), equivalent to ~6.7 mmt of live-weight forage fish (e.g., anchovy, sardine, herring, menhaden) destined for reduction. More than one-quarter of the global fish catch (targeted and nontargeted) is composed of forage fish that are reduced into fishmeal and fish oil (*3*, *13*). Although these small pelagic fish reproduce rapidly, they are equally, if not more, vulnerable to collapse than larger predatory fish because of poor management, overfishing, and climatic fluctuations (*14*). Many forage fisheries are fully- or overexploited.

Assessing sustainability of fish inputs used for aquaculture feeds in China requires a focus well beyond targeted reduction fisheries (SM, table S1). Processing wastes from China's domestic fisheries and its fish reexport industry are used in feed production, and the wild fisheries contributing to these processing wastes are all fully- or overexploited or depleted. Large amounts of trash fish are also used for fishmeal production (*6*, *15*), and China's high-valued marine aquaculture uses around 3 mmt of trash fish each year for direct feeding (*16*, *17*). China's trash fish consist mainly of juveniles of commercially important species (~32 to 50%), small benthic and mesopelagic fish (e.g., sand lance, lanternfish), crustaceans, and cephalopods (*18*) (SM). Domestically produced fishmeal from trash fish and local processing by-products usually has a lower protein content (38 to 50%) and a high ash content (over 20%), and thus can be purchased at a relatively cheap price to supplement feeds of low-valued aquaculture species (*11*, *19*).

Our surveys indicate that imported fishmeal from the eastern Pacific (e.g., Peru, Chile, U.S.A.) and Russia, which tends to be higher in protein and price, is commonly reserved for high-value farmed species in China. In an effort to secure future supplies of high-quality fishmeal, Chinese companies and state subsidiaries have purchased fishing rights in foreign countries, including quotas for the Peruvian anchovy fishery (SM). As China commands an increasing global share of high-quality fishmeal, feed companies in other parts of the world are likely to move into the lower-quality fishmeal market, raising demand for trash fish. China also sources fishmeal from other Asian countries that is derived from nontargeted fisheries including trash fish (*6*).

Given the decline in marine catches in much of China's exclusive economic zone (EEZ) and its demand for fishmeal, the price of trash fish is expected to rise in China and elsewhere in Asia where nontargeted fisheries are common. As its value increases, so too will concerns over the impacts of nontargeted fishing on marine resources and ocean ecosystems (*6*, *17*). Unfortunately, the species composition of trash fish varies highly and is poorly recorded. We identified 71 trash fish species caught in China and used as feed inputs for aquaculture (table S2). Relatively few trash fish species have been assessed for their stock status, and of those that have, most are classified as overfished or fully-fished.

WASTE AS FEED. Recovery of feed ingredients from fish-processing wastes provides an important avenue for reducing aquaculture's dependence on targeted and nontargeted fisheries. Between 30 and 70% of the volume of processed fish biomass ends up as wastes depending on the type of fish and processing level (*20–22*). Because fish-processing wastes can be high in protein, minerals, and energy, their use in aquaculture feeds has gained attention (*3*, *21*, *23*). Recent estimates indicate that ~40% of China's domestically produced fishmeal (~0.25 mmt) is derived from processing wastes, with wide year-to-year variation (*24*).

From 2003 to 2012, the country's seafood-processing industry grew at an annual rate at 10.7%, twice that of its aquaculture sector (*1*). Although the reexport market is shrinking in China with rising domestic fish consumption, the volume of processing wastes remains large, especially when wastes from its expanding aquaculture sector are included. Use of aquaculture wastes provides an important opportunity for meeting domestic fishmeal and oil demands, reducing use of trash fish in feeds, and minimizing waste discharges and pollution from processing plants.

Feed efficiencies and wild fish inputs in feed for farmed species

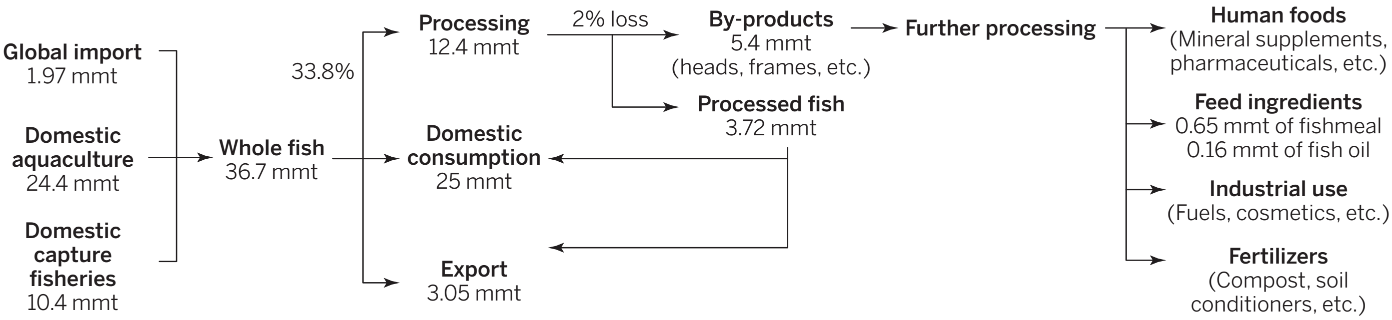
SPECIES	TOTAL PRODUCTION (MMT)	PRODUCTION WITH FEEDS (MMT)	AVERAGE FCR	AVERAGE FM IN FEED (%)	AVERAGE FO IN FEED (%)	TOTAL FM USED (MMT)	FORAGE FISH EQUIVALENT (MMT)
I. Carps							
Grass carp	4.8	2.6	1.7	1.5	0	0.07	0.32
Silver carp*	3.7	0	0	0	0	0	0
Bighead carp*	2.9	0	0	0	0	0	0
Common carp	2.9	1.6	1.7	6	0	0.16	0.77
Crucian carp	2.5	1.3	1.7	8	0	0.18	0.87
Bream	0.7	0.4	1.7	2.6	0	0.02	0.08
Black carp	0.5	0.3	1.7	2.6	0	0.01	0.06
II. Tilapa	1.6	1.3	1.6	6	0.5	0.13	0.60
III. Penaeid shrimp	1.6	1.5	1.2	27	2	0.50	2.36
Total	**21**	**9.1**	**—**	**—**	**—**	**1.06**	**5.07**

Feed efficiencies and wild fish inputs in feed for nine leading farmed species in China. Total production data in 2012 for each species from (*1*). Production with feeds was estimated based on (*28*). All other data were estimated from primary field surveys. Average economic FCR = total feed fed/total biomass increase. FM, fishmeal; FO, fish oil. An average reduction ratio of 21% for fishmeal and 5% for fish oil obtained from our field surveys were used to estimate wet weight equivalent of forage fish. *Filter-feeding species are not fed; they graze planktons proliferated through fertilization and the leftover feeds in the polyculture system.

Our analysis shows that 0.65 mmt of fishmeal [±0.26 mmt, 95% confidence interval (CI)] and 0.16 mmt of fish oil (±0.07 mmt, 95% CI) could be produced from China's fish-processing industry (see the figure) (SM and table S3). These results suggest that fish-processing wastes could meet almost half (based on the average value), and potentially two-thirds (based on the upper 95% confidence limit), of China's current demand for fishmeal in aquafeeds. A more conservative estimate, based only on processing of fish for export (versus domestic consumption), indicates 0.42 mmt of fishmeal and 0.1 mmt of fish oil could be produced from processing wastes (table S4).

Serious constraints exist, however, on utilization of fish-processing wastes for aquafeeds in China. First, nutritional quality of fishmeal from processing wastes tends to be inferior to fishmeal produced from wild fish (*23*). Conventional fishmeal made from wild forage fish often has a crude protein content between 67% and 90%, whereas fish-

Potential of fishmeal and oil production



Estimated potential of fishmeal and oil production from China's fish-processing industry. The 95% CIs are (0.39, 0.92) for fishmeal and (0.09, 0.22) for fish oil. Authors' calculations based on 2012 data from (*1*, *27*). Details in SM.

meal derived from processing wastes usually contains between 57% and 80% crude protein (*25*). Nutritional deficiencies caused by using offal-based fishmeal can be overcome with alternative feedstuffs; e.g., plant-based products such as algae and ethanol yeast developed through the biofuels industry (*26*). Alternatives to fishmeal must have comparable nutritional values, ready availability, digestibility, and reasonable palatability at competitive cost (*23*).

Second, use of fish-processing wastes in aquafeeds presents food safety risks related to bioaccumulation of contaminants, cross-species transmission of pathogens, and, possibly, prions (*21*, *23*). To avoid disease transmission, the Europe Union forbids the use of farmed fish by-products in finfish feeds but allows them to be used in crustacean diets or vice versa (*21*). Although China has no such food safety regulations, there is increasing awareness on traceability and quality in aquafeed inputs (SM). China is examining a new national standard for regulating dioxins and usage of multiple species in fishmeal and oil. Development may be hindered however by the predominance of small-scale processing plants with outdated equipment and by inefficient or costly collection of raw materials along the supply chain. Overcoming these constraints is not insurmountable but will require substantial investments in research and development, and strict enforcement of advanced food safety regulations.

Strategic design of an aquafeed sector based on processing wastes from aquaculture makes perfect sense for China, especially if food safety risks can be monitored. China's massive aquaculture sector yields a steady and consistent stream of processing wastes. If processing facilities are colocated with fishmeal and feed plants, the problems of perishability, transportation costs, and supply chain barriers can be minimized. Such a strategy would require improving facilities to meet environmental standards. Colocation would then support China's current Five-Year Plan (2011–2015), which aims to promote energy and water efficiency and to minimize waste discharges and pollution (SM).

ADDING OR DEPLETING? The scale and complexity of China's aquaculture sector places it in a precarious position between adding and depleting global seafood availability. The diversity and low-trophic-level base of China's aquaculture sector provides substantial opportunity for positive change, but the use of feeds containing fishmeal remains profitable in most systems. If China is to increase its net production of fish protein, its aquaculture industry will need to reduce FCRs and the inclusion of fish ingredients in feeds and to improve fishmeal quality. Fish-processing wastes have potential to substitute increasingly for imported fishmeal in China's aquaculture sector if appropriate technology and supply chains are developed, if nutritional qualities can be improved, and if food safety can be guaranteed.

Even if fish-processing wastes are recycled as feeds, China's aquaculture industry will continue to strain wild fisheries unless the country commits to stricter enforcement of regulations on targeted and nontargeted fishing within and outside of its EEZ and to responsible sourcing of fishmeal and/or oil (SM). Using fishmeal derived from by-catch or by-products of wild fisheries as a means of reducing pressure on wild fisheries remains controversial and should be monitored (*23*). Without such measures, China's aquaculture sector is destined to diminish wild fish stocks worldwide. ■

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SUPPLEMENTARY MATERIALS

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