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Yield-per-Recruit, Utility-per-Recruit, and Relative Biomass of 21 Exploited Fish Species in China's Coastal Seas

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Based on growth and related fishery parameters, three approaches, yield-per-recruit (*Y/R*), utility-per-recruit (*U/R*) analyses, and relative biomass (B/B_0) analyses were applied to 21 economically important, trawl-caught species in China's coastal seas to estimate their relative yield, economic value and biomass under different schedules of fishing mortality and mean length at first capture. The results show that all species suffer from overfishing, given the high average fishing mortality ($F \sim 1$ year^{-1}) and small mesh size (~1 cm) used by trawlers. Long-term *Y/R* would double and *U/R* (expressed as price per landed weight) would increase 5-fold if mesh size were increased to about 10 cm. Comparing *Y/R* and *U/R* showed that the benefits of higher prices for larger individuals were detectable only if larger mesh sizes are used, so that individuals are caught only after they have been able to grow. The *Y/R* analyses also allowed estimating the biomass of the 21 assessed populations relative to their unexploited biomass, i.e., B/B_0. Species-specific B/B_0 values ranged from 0.01 to 0.58, with a mean of 0.16 (±0.03), i.e., much lower than the 50% reduction corresponding to Maximum Sustainable Yield (i.e., $B/B_{MSY} = 1$, or $B/B_0 = 0.5$). This confirms the many authors who reported systematic overfishing along China's coastlines, and suggests that rebuilding stocks should be the foremost goal of fisheries management in China.

Keywords: data-poor fisheries, Chinese coastal fisheries, yield per recruit, utility per recruit, biomass estimation, stock assessments

INTRODUCTION

According to statistics of the Food and Agriculture Organization of the United Nations (FAO, 2016), the People's Republic of China (hereafter referred to as "China"), was the top-ranking fishing country in the world with domestic marine catches of about 10 million t in the 2010s (www.fao.org and www.seaaroundus.org).

As part of its Thirteenth Five-Year Plan (2016–2020), China listed the need for improvement of its fishery management systems. Several policies aiming at stabilizing fisheries catches have been proposed, but their implementation has not necessarily been successful. Notably, many of the economic benefits that the policies we supposed to generate have failed to materialize.

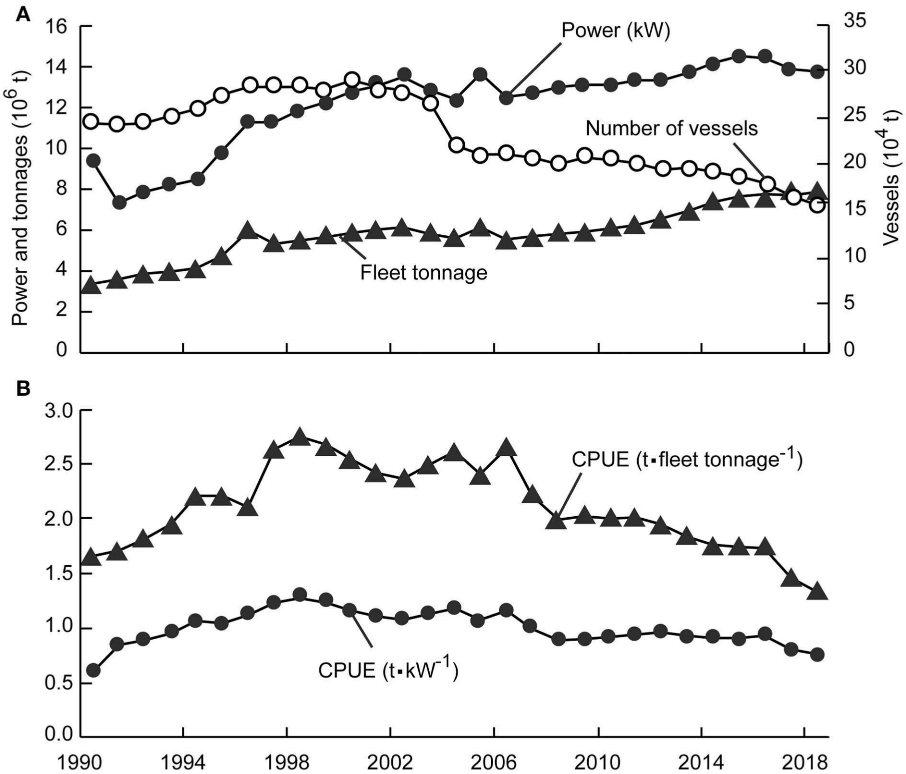

FIGURE 1 | Basic statistics on China's coastal fisheries (1990–2018). **(A)** Three proxies of fishing effort; **(B)** Two measures of catch per unit of effort (CPUE).

One of the most important management measures, the "Double Control" system, was proposed in the early 1990s to regulate fisheries by controlling the number of engine-powered fishing vessels and the cumulative power of the fleet (Shen and Heino, 2014). However, despite a decrease in the number of fishing vessels since 2004, cumulative fleet engine power and tonnages have increased (Anonymous, 1979–2019; **Figure 1A**), and CPUE and total catch continued decreases that began in 1998 (Shen and Heino, 2014; **Figure 1B**).

Mesh size studies in China's coastal have been conducted since 1980s (Ye et al., 1980; Li, 1990); however, the implementation of mesh regulation was initiated only in 2013 (Anonymous, 2013). The regulations allow mesh size ranging from 2.5 to 11 cm for different gear types and species. However, the average mesh size of commercial fishing in practice of China is 1 cm, far less than it legally allowed (Liang and Pauly, 2017a).

As a result, fish are caught that are extremely small and thus are considered "trash fish" and end up as fish feed, either directly, or after reduction to low-value fish meal (Cao et al., 2015). Moreover, the proportion of "trash fish" in the total catches appears to be steadily increasing (Lin et al., 2007), and currently contributes near 4×10^6 t annually (Greenpeace, 2017).

Historically, larger species were dominant in China's coastal seas, and were economically important. This applies *Larimichtyys polyactis* and *Trichiurus lepturus*, whose annual yield was more than 100,000 t, and for *Scomberomorus niphonius* and *Scomber japonicus*, which contributed over 10,000 t annually (Zhang and Liu, 1959). However, under intensive, decade-long fishing pressure, these dominant stocks were replaced by small, low-trophic level species, such as *Engraulis japonicus*, *Setipinna tenuifilis*, *Pholis fangi*, and *Chaeturichthys stigmatias* (Wang et al., 2011; Zhai et al., 2015), inducing a fishing down effect that is now well-documented (Liang and Pauly, 2017b). The degree of overfishing and the economic waste that this implies are key problems for China's fisheries.

Therefore, yield- and utility-per-recruit approaches were applied to 21 species commercially exploited along China's coast, which allowed a combination of fisheries biology and bio-economics to assess the extent of the reduction if their biomass by fishing, and their optimum exploitation levels terms of both yield and value. The ultimate goal of this contribution was to produce evidence required for a review of present policies for fisheries management.

MATERIALS AND METHODS

Methods and Data Sources

We performed utility-per-recruit assessments, which allows consideration of different values per length or age group to be used in a yield-per-recruit context (Die et al., 1988), and hence allows the introduction of simple bio-economics into stock

TABLE 1 | Parameters used for assessing 14 species in China's coastal seas (*a* refers to weight in g; *K* in year^{-1}; L_{inf} and TL_{inf} in cm; *T* in °C).

Species	Survey location	Survey time	*a*	*b*	*K*	t_0	L_{inf}	TL_{inf}	*T*	References
Yellow croaker (*Larimichthys polyactis*)	Liaodong Bay	2012–2013	0.012	3	0.47	−0.30	26.00	29.64	13.80	Liu et al., 2018
Largehead hairtail (*Trichiurus lepturus*)	Bohai Sea and Yellow Sea	1962–1963	0.013	3	0.44	−0.06	50.10	172.91	15.00	Hong, 1980; *T* from (www.fishbase.org)
Fang's gunnel (*Pholis fangi*)	Qingdao coastal water	2008	0.005	3	0.63	−0.63	19.00	20.42	14.50	Huang, 2010
Whitespotted conger (*Conger myriaster*)	Shandong coastal waters	2015–2016	0.002	3	0.60	−0.49	92.80	92.80	15.00	Zhang, 2018; *T* from (www.fishbase.org)
So-iuy mullet (*Planiliza haematocheila*)	Bohai Sea		0.016	3	0.11	−0.82	121.20	124.23	12.47	Geng et al., 2001; *T* from Lin et al., 2001
Red tonguesole (*Cynoglossus joyneri*)	Southern Sea of Korea	2001	0.005	3	0.19	−2.40	28.43	29.06	16.51	Baech and Huh, 2004; *T* from (www.nifs.go.kr/)
Japanese Spanish mackerel (*Scomberomorus niphonius*)	Coastal waters of Shandong Province	2015–2016	0.010	3	0.52	−0.10	76.20	91.69	12.47	Zhang, 2018; *T* from Lin et al., 2001
Bastard halibut (*Paralichthys olivaceus*)	Jiaozhou Bay, Bohai Sea	1980–1986	0.016	3	0.21	−0.10	79.66	101.63	15.00	Zhu et al., 1991; *T* (www.fishbase.org)
Korean rockfish (*Sebastes schlegelii*)	Zhangzidao Artificial Reef, near Dalian	2011–2012	0.025	3	0.21	−0.65	41.25	50.55	20.00	Yin et al., 2016
Silver pomfret (*Pampus argenteus*)	Bohai Sea	2007	0.030	3	0.44	−1.01	26.79	32.80	15.00	Cui et al., 2008; *T* from (www.fishbase.org)
Pointhead flounder (*Cleisthenes herzensteini*)	Bohai, Yellow and East China Seas	1978–1985	0.013	3	0.11	−1.29	47.30	53.70	16.00	Chen et al., 1992; *T* from (www.fishbase.org)
Chub mackerel (*Scomber japonicus*)	Coastal waters of Shandong Province	2015–2016	0.017	3	0.22	−0.12	41.02	44.50	12.47	Zhang, 2018; *T* from Lin et al., 2001
Yellow goosefish (*Lophius litulon*)	Bohai and Yellow Seas	2010, 2013–2014	0.028	3	0.28	−0.44	57.64	66.55	20.00	Yin et al., 2015
Blackhead seabream (*Acanthopagrus schlegelii*)	Taiwan and northern South China Sea	2011–2012	0.033	3	0.22	−1.59	43.70	50.98	22.25	Chu et al., 2011; Law and Sadovy de Mitcheson, 2018

TABLE 2 | Parameters used to estimate relative biomass (B/B_0) for seven fish species in China's coastal seas[a].

Common name	Scientific name	*K* (year^{-1})	*M* (year^{-1})	*F* (year^{-1})	L_c/L_{inf}	L_{inf} (cm)
Pacific rudderfish	*Psenopsis anomala*	0.41	0.85	0.98	0.08	21.94
Japanese grenadier anchovy	*Coilia nasus*	0.35	0.68	0.70	0.22	37.61
Osbeck's grenadier anchovy	*Coilia mystus*	0.54	1.12	0.88	0.28	21.31
Japanese anchovy	*Engraulis japonicus*	0.51	1.00	0.93	0.24	15.73
Scaly hairfin anchovy	*Setipinna tenuifilis*	0.31	0.70	0.60	0.12	18.60
Japanese scad	*Decapterus marusadsi*	0.89	1.45	0.44	0.22	27.71
Bombay-duck	*Harpadon nehereus*	0.62	1.12	1.12	0.15	31.32

[a] *From Liang and Pauly (2017a).*

assessments. Here, the values considered were simply the market price per kilogram of the fish in question, which tended to sharply increase with size.

Also, relative biomass (B/B_0) was estimated using a new set of equations, based on Beverton and Holt (1966), and derived by Froese et al. (2018). This method allows estimating B/B_0 under different levels of fishing mortality and L_c values, using the same parameters as for yield-per-recruit analyses, i.e., von Bertalanffy growth parameters (L_{inf}, K), natural mortality (M) and a and b from length-weight relationships (Froese et al., 2018).

Growth parameters can change over time, both because of fishing itself, which removes large individuals and gradually reduce the alleles associated with large sizes in an exploited population (Dieckmann et al., 2005; Enberg et al., 2012), and via ocean warming which will tend to modify growth parameter in the same direction as fishing itself (Cheung et al., 2013). However, these changes are much smaller than the rapid population truncation and size reduction that are due to removal of large individuals by intense fishing, and which are reflected in *Y/R* and related analyses.

A total of 21 species were analyzed in this paper. The growth parameters (a, b, K, L_{inf}, and t_0) of 14 fish species were assembled (**Table 1**) from the scientific literature and from FishBase (www.fishbase.org) to serve as basis for the 3 approaches

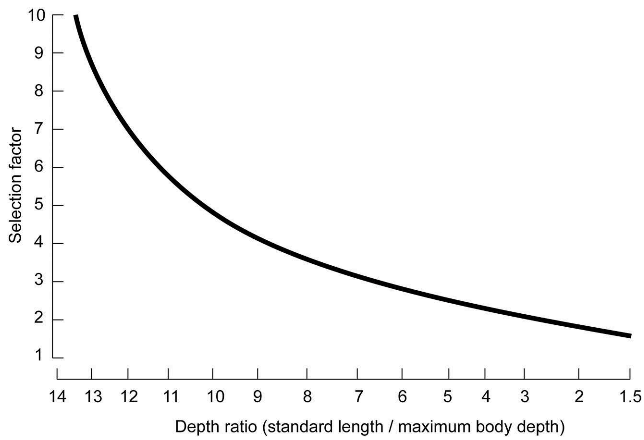

FIGURE 2 | Nomogram for the estimation of selection factors of fishes from their body proportion (modified from Pauly, 1983).

mentioned above. To facilitate computations and between-method comparisons, the multiplicative term in all length-weight relationship ("*a*") where recalculated such that the exponent ("*b*") could be set at a value = 3. Given the cube law (Froese, 2006), $b = 3$ is a good approximation, and deviation from this will have only a negligible impact on the results. For the other 7 species (**Table 2**), *Y/R* analyses had already been performed (by Liang and Pauly, 2017a); thus, Equations (12)–(15) were used to convert the results of their *Y/R* estimates into estimates of B/B_{MSY} and B/B_0, so that they could also be included in overall evaluation of the status of Chinese fisheries (in **Table 7**).

Fish and Fishery Parameters

Fish growth parameters commonly estimated by the von Bertalanffy Growth Function (VBGF; von Bertalanffy, 1934, 1938), as presented by Beverton and Holt (1957), i.e.,

$$L_t = L_{inf}\left(1 - e^{-K(t-t_0)}\right) \tag{1}$$

where L_t is the mean length at age t of the fish in question, L_{inf} is their asymptotic length, i.e., the mean length attained after an infinitely long time, K is a growth coefficient (here in year^{-1}) and t_o is the (usually negative) age the fish in question would have had at a length of zero if they had always grown in the manner predicted by the equation (which they have not; see e.g., Pauly, 1998).

Following Geng et al. (2018) who recommended its use for assessments in China, the empirical formula of Pauly (1980) was used to estimate natural mortality (M), i.e.,

$$\log M = -0.0066 - 0.279 \log L_{inf} + 0.6543 \log K + 0.4634 \log T \tag{2}$$

where L_{inf} (in cm) and K are as defined for Equation (1) and T is the annual average water temperature (in °C) of the habitat for each species analyzed here (**Table 1**).

As Equation (2) requires L_{inf} values as total length (TL), conversion from standard length (SL), fork length (FL), and vent length (VT, for *T. lepturus*) were performed as required based on drawings or photos of the species in question in FishBase (www.fishbase.org).

The mean length at first capture (L_c in cm), i.e., the length at which 50% of fish will be retained in the gear, was estimated for all species from

$$L_c = S.F. \times mesh\ size \tag{3}$$

wherein *S.F.* is the selection factor of the gear, largely determined by the shape of the fish body.

S.F. estimates were derived from a simplified version of the nomogram constructed by Pauly (1983) on the basis of a large number of mesh selection experiments (**Figure 2**). Here, we applied the depth ratios from images in FishBase (www.fishbase.org).

As about 50% of all catches in the Chinese coastal fisheries are actually made by trawlers, and the rest is taken by nets also designed to retain large fish when they are caught (see China's successive *Fishery Statistical Yearbooks*, 1979–2019), it is assumed that all nets in question have trawl-like selection curves. Thus, Equation (3), Pauly's (1983) nomogram were applied here to infer mean length at first capture for the 14 species in **Table 1**.

As we could not find estimates from China, the growth parameters for red tonguesole (*Cynoglossus joyneri*) are from South Korean waters (Baech and Huh, 2004), i.e., from the same latitude as China's Yellow Sea, to which South Korean waters are adjacent. As temperature is the major factor behind differences in the growth parameters of wild fish (Pauly, 2010), and temperature varies mainly with latitude, it is considered that the effect of this substitution is negligible.

Estimation of Yield-per-Recruit (*Y′/R*)

The original equations derived by Beverton and Holt (1957) allowed the computation of absolute yield-per-recruit (*Y/R*, typically in g·year^{-1}). However, subsequent consideration by Beverton and Holt (1966) allow a for a simplified approach, based on relative yield-per-recruit (Y'/R), i.e.,

$$Y'/R = EU^{M/K}\left\{1 - \frac{3U}{(1+m)} + \frac{3U^2}{(1+2m)} - \frac{U^3}{(1+3m)}\right\} \tag{4}$$

where $E = F/Z, Z = F + M$;

$$U = 1 - (L_C/L_\infty);$$
$$m = (1-E)/(M/K) = K/Z$$

where E is the exploitation rate, F is the fishing mortality, Z is the total mortality and the other parameters are defined as same as above (Equations 2, 3).

The relationship between Y/R and Y'/R, is

$$Y/R = \left(Y'/R\right)\left(W_{inf}\ e^{-M(t_r-t_0)}\right) \tag{5}$$

where M and t_0 is the same definition with Equations (2) and (1), respectively, W_{inf} is the asymptotic fish weight (corresponding to L_{inf}), and t_r is age at recruitment to the stock in question.

TABLE 3 | Fish price for different length class in China's aquatic products market.

Species		Group 1	Group 2	Group 3	Group 4	Group 5
Yellow croaker (*Larimichthys polyactis*)	Length group	≤10	10 < L ≤ 20	>20		
	Price	25	35	45		
Largehead hairtail (*Trichiurus lepturus*)	Length group	≤15	15 < L ≤ 25	25 < L ≤ 35	35 < L ≤ 45	>45
	Price	55	160		200	
Fang's gunnel (*Pholis fangi*)	Length group	≤10	10 < L ≤ 15	>15		
	Price	40	50	80		
Whitespotted conger (*Conger myriaster*)	Length group	≤20	20 < L ≤ 40	40 < L ≤ 60	60 < L ≤ 80	>80
	Price	30	40	60	80	100
So-iuy mullet (*Planiliza haematocheila*)	Length group	≤40	40 < L ≤ 60	60 < L ≤ 80	80 < L ≤ 100	>100
	Price	40	60	80	100	120
Red tonguesole (*Cynoglossus joyneri*)	Length group	≤5	5 < L ≤ 15	15 < L ≤ 25	>25	
	Price	20	40	60	200	
Japanese Spanish mackerel (*Scomberomorus niphonius*)	Length group	≤30	30 < L ≤ 50	50 < L ≤ 70	>70	
	Price	30	40	50	80	
Bastard halibut (*Paralichthys olivaceus*)	Length group	≤20	20 < L ≤ 40	40 < L ≤ 60	>60	
	Price	40	60	80	100	
Korean rockfish (*Sebastes schlegelii*)	Length group	≤10	10 < L ≤ 20	20 < L ≤ 35	>35	
	Price	20	30	80	120	
Silver pomfret (*Pampus argenteus*)	Length group	≤10	10 < L ≤ 15	15 < L ≤ 20	>20	
	Price	30	40	80	160	
Pointhead flounder (*Cleisthenes herzensteini*)	Length group	≤15	15 < L ≤ 25	25 < L ≤ 35	>35	
	Price	60	70	100	150	
Chub mackerel (*Scomber japonicus*)	Length group	≤10	10 < L ≤ 25	25 < L ≤ 35	>35	
	Price	10	24	45	60	
Yellow goosefish (*Lophius litulon*)	Length group	≤15	15 < L ≤ 30	30 < L ≤ 45	>45	
	Price	8	10	14	24	
Blackhead seabream (*Acanthopagrus schlegelii*)	Length group	≤15	15 < L ≤ 25	25 < L ≤ 35	>35	
	Price	40	50	60	80	

Length in cm; price in Yuan/Kg, Yuan is Chinese RMB. Based on survey in Chinese market (2019).

TABLE 4 | Estimates of mortality, mean length at first capture and derived parameters in 14 species of fish exploited along Chinese coasts (M and Z in year^{-1}; L_c in cm)[a].

Common name	Scientific name	*M*	*Z*	*E*	Depth ratio	*S.F.*	L_c	L_c/L_{inf}
Yellow croaker	*Larimichthys polyactis*	0.79	1.79	0.56	3.50	2.30	2.30	0.13
Largehead hairtail	*Trichiurus lepturus*	0.48	1.48	0.68	15.67	10.00	10.00	0.20
Fang's gunnel	*Pholis fangi*	0.92	1.92	0.52	8.94	4.25	4.25	0.27
Whitespotted conger	*Conger myriaster*	0.70	1.70	0.59	20.14	10.00	10.00	0.25
So-iuy mullet	*Planiliza haematocheila*	0.19	1.19	0.84	5.33	2.80	2.80	0.08
Red tonguesole	*Cynoglossus joyneri*	0.48	1.48	0.68	3.89	2.40	2.40	0.37
Japanese Spanish mackerel	*Scomberomorus niphonius*	0.59	1.59	0.63	5.54	2.75	2.75	0.05
Bastard halibut	*Paralichthys olivaceus*	0.35	1.35	0.74	2.60	2.15	2.15	0.03
Korean rockfish	*Sebastes schlegelii*	0.48	1.48	0.68	2.89	2.25	2.25	0.13
Silver pomfret	*Pampus argenteus*	0.76	1.76	0.57	1.81	2.10	2.10	0.36
Pointhead flounder	*Cleisthenes herzensteini*	0.28	1.28	0.78	2.78	2.20	2.20	0.13
Chub mackerel	*Scomber japonicus*	0.41	1.41	0.71	4.40	2.51	2.51	0.06
Yellow goosefish	*Lophius litulon*	0.53	1.53	0.65	1.93	1.86	1.86	0.12
Blackhead seabream	*Acanthopagrus schlegelii*	0.51	1.51	0.66	2.27	2.05	2.05	0.30
Means[b]	–	0.53 ± 0.05	1.53 ± 0.05	0.66 ± 0.02	–	–	3.54 ± 0.75	0.18 ± 0.03

[a] *The depth ratios are based on drawings in FishBase (www.fishbase.org); the selection factors (S.F.) were obtained from the nomogram (**Figure 2**); the current F (1 year^{-1}) and mesh size (1 cm) are based on Liang and Pauly (2017a).*
[b] *Means with standard error.*

TABLE 5A | Current and optimum yield-per-recruit and mean first capture length of 14 species in China's coastal seas.

Common name	Scientific name	Current level		Optimum level			
		L_c (cm)	Y'/R	Opt. L_c (cm)	Opt. Y'/R	Mesh size (cm)	Increase (%)
Yellow croaker	*Larimichthys polyactis*	3.4	0.024	13.5	0.041	5.9	71
Largehead hairtail	*Trichiurus lepturus*	10.0	0.078	28.1	0.102	2.8	31
Fang's gunnel	*Pholis fangi*	5.0	0.027	9.1	0.033	2.1	22
Whitespotted conger	*Conger myriaster*	23.6	0.052	55.7	0.074	5.6	42
So-iuy mullet	*Planiliza haematocheila*	10.1	0.006	72.7	0.044	26.0	633
Red tonguesole	*Cynoglossus joyneri*	10.4	0.020	13.4	0.021	5.6	5
Japanese Spanish mackerel	*Scomberomorus niphonius*	3.9	0.033	46.5	0.079	16.9	139
Bastard halibut	*Paralichthys olivaceus*	2.2	0.009	46.2	0.046	21.5	411
Korean rockfish	*Sebastes schlegelii*	5.3	0.010	20.2	0.025	9.0	150
Silver pomfret	*Pampus argenteus*	9.6	0.035	13.9	0.039	6.6	11
Pointhead flounder	*Cleisthenes herzensteini*	6.3	0.006	23.2	0.020	10.5	233
Chub mackerel	*Scomber japonicus*	2.5	0.010	22.6	0.037	9.0	270
Yellow goosefish	*Lophius litulon*	6.7	0.015	30.6	0.035	16.5	133
Blackhead seabream	*Acanthopagrus schlegelii*	12.9	0.019	21.4	0.025	10.4	32
Means[a]	–	–	0.016 ± 0.005	–	0.037 ± 0.006	10.6 ± 1.9	128 ± 48.4

[a] *Means with standard error.*

TABLE 5B | Current and optimum utility-per-recruit and mean length at first capture of 14 species in China's coastal seas (L_c and mesh size in cm; U/R in Yuan).

Common name	Scientific name	Current level		Optimum level			Increase (%)
		L_c	U/R	Opt. L_c	Opt. U/R	Mesh size	
Yellow croaker	*Larimichthys polyactis*	3.4	260	14.0	490	6.1	89
Largehead hairtail	*Trichiurus lepturus*	10.0	13,957	34.6	35,015	3.5	151
Fang's gunnel	*Pholis fangi*	5.0	39	9.1	47	2.1	21
Whitespotted conger	*Conger myriaster*	23.6	5,549	59.4	9,862	5.9	78
So-iuy mullet	*Planiliza haematocheila*	10.1	7,451	78.8	128,582	28.1	1,626
Red tonguesole	*Cynoglossus joyneri*	10.4	107	14.8	150	6.2	40
Japanese Spanish mackerel	*Scomberomorus niphonius*	3.9	6,432	49.5	18,169	18.0	182
Bastard halibut	*Paralichthys olivaceus*	2.2	4,562	47.0	31,637	21.9	593
Korean rockfish	*Sebastes schlegelii*	5.3	763	37.1	3,757	16.5	392
Silver pomfret	*Pampus argenteus*	9.6	1,442	19.6	2,681	9.3	86
Pointhead flounder	*Cleisthenes herzensteini*	6.3	573	24.6	3,115	11.2	444
Chub mackerel	*Scomber japonicus*	2.5	281	24.7	2,023	9.8	620
Yellow goosefish	*Lophius litulon*	6.7	927	31.1	2,862	16.8	209
Blackhead seabream	*Acanthopagrus schlegelii*	12.9	2,830	24.5	4,079	11.9	44
Means[a]	–	–	3,227 ± 1,073	–	17,319 ± 9,093	12.0 ± 2.0	437 ± 113.9

[a] *Means with standard error.*

The Estimation of Utility-per-Recruit (*U/R*)

The utility of length class i for each species was computed from the Equations (6)–(11) by (Thompson and Bell, 1934):

$$V_i = Y_i\, v_i \tag{6}$$

where Y_i is the yield for class i, v_i is the unit value (or "price") for class i, and Y_i was obtained from

$$Y_i = C_i\, W_i \tag{7}$$

where the mean body weight in a class, computed by

$$\overline{W}_i = \left(\frac{1}{L_{i+1} - L_i}\right)\left(\frac{a}{b+1}\right)\left(L_{i+1}^{b+1} - L_i^{b+1}\right) \tag{8}$$

and where the parameter of a and b are the coefficients of the length-weight relationship and L_i and L_{i+1} are the lower limit and the upper limit of the length class i, respectively (Beyer, 1987).

C_i was obtained from:

$$C_i = (N_i - N_{i+1})\,(F_i/(M + F_i)) \tag{9}$$

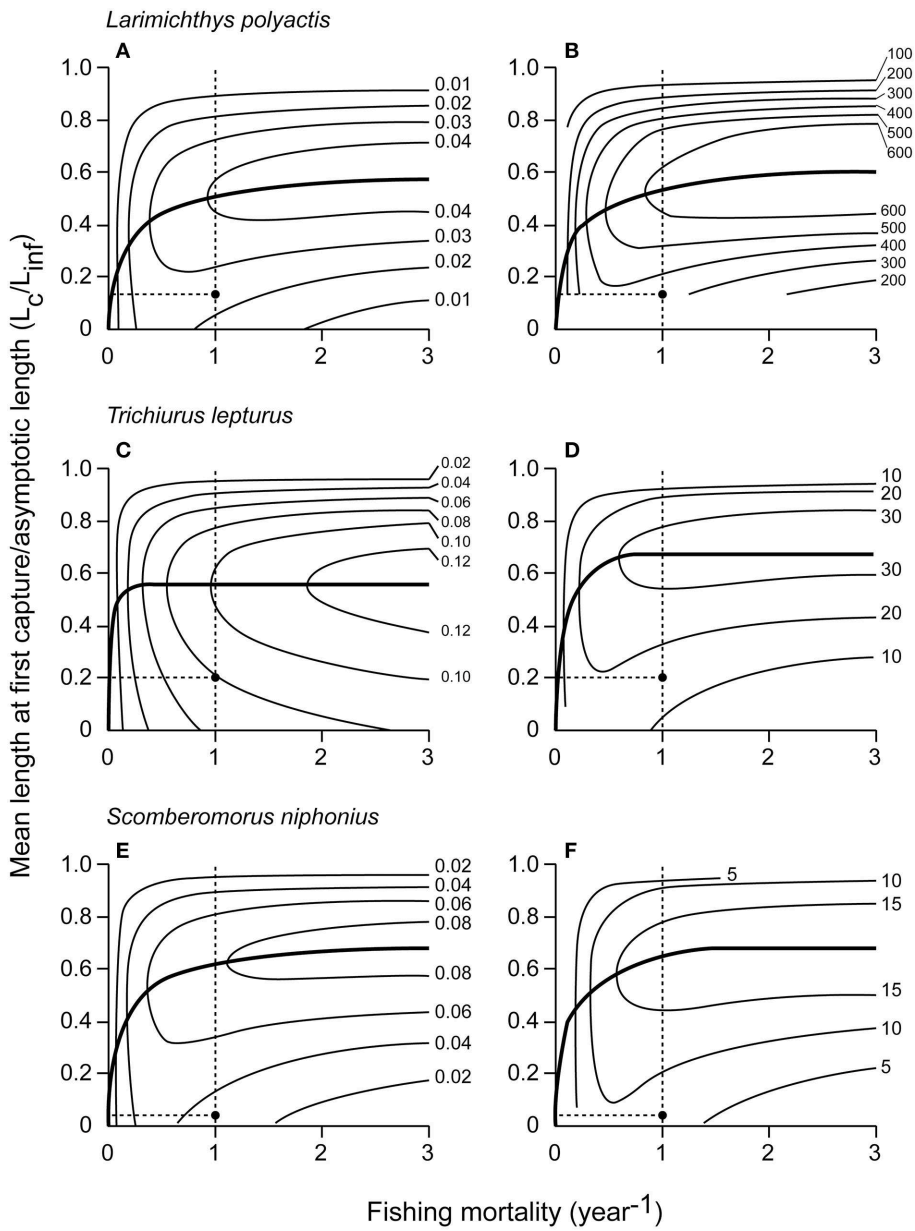

FIGURE 3 | Assessments of 3 fish species from Chinese coastal waters: *Y′/R* (left) and *U/R* (right) isopleth diagrams vs. fishing mortality and L_c/L_{inf}. The solid curves connect optimum sizes for different every level of fishing mortality and the black dots and dotted lines show the current status of the fishery status in level. U/R for *L. polyactis* is in Yuan, and in 1,000 Yuan for *T. lepturus* and *S. niphonius*. **(A)** *L. polyactis Y′/R* vs. fishing mortality and L_c/L_{inf}. **(B)** *L. polyactis* U/R vs. fishing mortality and L_c/L_{inf}. **(C)** *T. lepturus Y′/R* vs. fishing mortality and L_c/L_{inf}. **(D)** *T. lepturus* U/R vs. fishing mortality and L_c/L_{inf}. **(E)** *S. niphonius Y′/R* vs. fishing mortality and L_c/L_{inf}. **(F)** *S. niphonius* U/R vs. fishing mortality and L_c/L_{inf}.

where N_i is the cohort strength, as predicted by:

$$N_{i+1} = N_i \, e^{(-(M+F_i)\cdot\Delta t_i)} \tag{10}$$

and

$$\Delta t_i = (1/K) \ln\left(\left(L_{inf} - L_i\right)/\left(L_{inf} - L_{i+1}\right)\right) \tag{11}$$

where Δt_i is the elapsed time from L_i to L_{i+1}.

Herein, the length class are $0.01{\cdot}L_{inf}$, i.e., the computations involved 100 classes, and the market prices for the different length class of fish are given in **Table 3**.

The Estimation of Relative Biomass

Relative yield-per-recruit (Y'/R), as estimated by Equation (4), also can be expressed by (Froese et al., 2018)

$$Y'/R = \frac{F/M}{1+F/M}\left(1-\frac{L_c}{L_{inf}}\right)^{\frac{M}{K}}\left(1-\frac{3\left(1-L_c/L_{inf}\right)}{1+\frac{1}{M/K+F/K}} + \frac{3\left(1-L_c/L_{inf}\right)^2}{1+\frac{2}{M/K+F/K}} - \frac{\left(1-L_c/L_{inf}\right)^3}{1+\frac{3}{M/K+F/K}}\right) \tag{12}$$

TABLE 6 | Ratio of *U/R* vs. *Y/R* (i.e., *U/Y*, in Yuan) for 14 species in China's coastal seas, with the corresponding L_c (in cm).

Common name	Scientific name	L_{c_peak}	Current *U/Y*	Peak *U/Y*	Mean *U/Y*
Yellow croaker	*Larimichthys polyactis*	0.8	36	47	39
Largehead hairtail	*Trichiurus lepturus*	0.9	112	302	179
Fang's gunnel	*Pholis fangi*	0.2	44	44	43
Whitespotted conger	*Conger myriaster*	0.9	69	104	78
So-iuy mullet	*Planiliza haematocheila*	0.8	61	147	98
Red tonguesole	*Cynoglossus joyneri*	0.9	52	218	79
Japanese Spanish mackerel	*Scomberomorus niphonius*	0.9	44	84	52
Bastard halibut	*Paralichthys olivaceus*	0.8	67	108	85
Korean rockfish	*Sebastes schlegelii*	0.8	57	171	102
Silver pomfret	*Pampus argenteus*	0.7	76	176	109
Pointhead flounder	*Cleisthenes herzensteini*	1.0	103	275	162
Chub mackerel	*Scomber japonicus*	0.9	26	66	41
Yellow goosefish	*Lophius litulon*	0.8	15	32	20
Blackhead seabream	*Acanthopagrus schlegelii*	0.8	57	89	66

Given that CPUE can be seen as proportional to biomass, dividing Equation (12) by F/M gives

$$\frac{CPUE'}{R} = \left(\frac{Y'}{R}\right)/\left(\frac{F}{M}\right) = \left(\frac{1}{1+\frac{F}{M}}\right)\left(1-\frac{L_C}{L_{inf}}\right)^{\frac{M}{K}} \left(1-\frac{3\left(1-L_c/L_{inf}\right)}{1+\frac{1}{M/K+F/K}}+\frac{3\left(1-L_c/L_{inf}\right)^2}{1+\frac{2}{M/K+F/K}} -\frac{\left(1-L_c/L_{inf}\right)^3}{1+\frac{3}{M/K+F/K}}\right) \quad (13)$$

The relative biomass of fish with length $>L_c$ when no fishing occurs is expressed by

$$\frac{B_0>L_c}{R} = \left(1-\frac{L_C}{L_{inf}}\right)^{\frac{M}{K}}\left(1-\frac{3\left(1-L_c/L_{inf}\right)}{1+\frac{1}{M/K}} +\frac{3\left(1-L_c/L_{inf}\right)^2}{1+\frac{2}{M/K}}-\frac{\left(1-L_c/L_{inf}\right)^3}{1+\frac{3}{M/K}}\right) \quad (14)$$

where B_0 is the unexploited biomass. From this, the relative biomass of exploited fishery can be obtained by

$$B/B_0 = \left(\frac{CPUE'}{R}\right)/\left(\frac{B_0{}'>L_C}{R}\right) \quad (15)$$

(Froese et al., 2018). The limitations of this approach lie in its assumptions, i.e., that growth follow the von Bertalanffy model, that fishing and natural mortality rates behave as expressed in the above equations, that gear selection is of the trawl type and, most importantly, that the parameters of these various relationships are not density-dependent. These assumptions are generally accepted in fisheries science and we lack the data from Chinese fisheries that would allow us to replace these assumptions by locally-derived empirical relationship.

RESULTS

Estimation of Mortality and Mean Length at First Capture

The growth parameters and hence the M values for these species, combined with $F = 1$ year^{-1} for Chinese waters (Liang and Pauly, 2017a), generates exploitation rates well over 50%, for example in *P. fangi*, *P. haematocheila*, *C. herzensteini*, *P. olivaceus*, and *S. japonicus.* The average exploitation rate of our 14 species was 66% (**Table 4**).

The estimated mean size at first capture (L_c) of 11 of 14 species were smaller than their predicted length at age zero, i.e., with the current mesh size, most of the fish are predicted to be caught as soon as they are hatched, i.e., as larvae. Therefore, considering that the von Bertalanffy equations does not represent well the growth of very young fish (Pauly, 1998), the L_c/L_{inf} were slightly increased, such that L_c matched, in these cases, length at age zero. The exceptions were *T. lepturus*, *P. olivaceous*, and *S. japonicus* (**Table 4**).

Y′/R and *U/R* Analyses

The Y'/R and U/R values for 14 species were reported (**Tables 5A,B**). *L. polyactis*, *T. lepturus*, and *S. niphonius* are provided as illustrated examples (**Figure 3**); figures for the 11 other species are provided in the **Supplementary Material**. Overall, these results suggest that the fisheries in China's coastal seas have neither optimized yield, nor utility as expressed in fish prices.

Indeed, the data suggest that Y/R would increase by over 80% on average if average L_c/L_{inf} was increased to 0.53, which would correspond to a mesh size of about 10 cm (**Table 5A**). In general, the predicted increase was bigger in species that could potentially grow to larger sizes, for example in *P. haematocheila*, *P. olivaceus*, *S. niphonius*, and *L. litulon.*

The average U/R for 14 species was predicted to increase by five times under the present fishing mortality ($F = 1$ year^{-1}) if

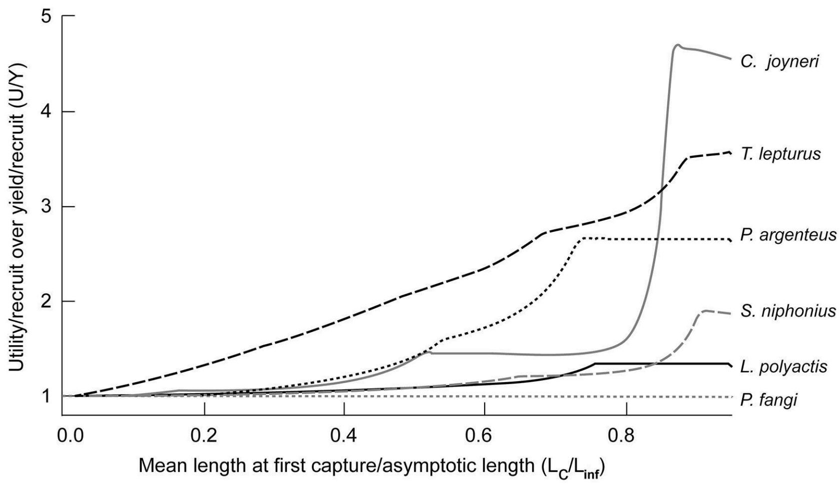

FIGURE 4 | Ratio of utility-per-recruit (*U/R*) to yield-per-recruit (*Y/R*) for different L_c/L_{inf} for 6 of the species caught in China's coastal seas. Note that this ratio is near 1 when L_c/L_{inf} is low.

TABLE 7 | Estimates of current relative biomass (B/B_0) for 21 fish species in China's coastal seas.

Common name	Scientific name	L_{c_MSY}	B/B_0	B_{MSY}/B_0
Osbeck's grenadier anchovy	*Coilia mystus*	10.2	0.32	0.35
Japanese grenadier anchovy	*Coilia nasus*	19.1	0.22	0.35
Pacific rudderfish	*Psenopsis anomala*	11.0	0.13	0.35
Yellow croaker	*Larimichthys polyactis*	14.0	0.15	0.36
Largehead hairtail	*Trichiurus lepturus*	32.8	0.09	0.38
Fang's gunnel	*Pholis fangi*	9.8	0.23	0.35
Whitespotted conger	*Conger myriaster*	57.6	0.17	0.38
So-iuy mullet	*Planiliza haematocheila*	72.8	0.01	0.36
Red tonguesole	*Cynoglossus joyneri*	13.8	0.15	0.34
Japanese scad	*Decapterus marusadsi*	13.4	0.58	0.36
Japanese Spanish mackerel	*Scomberomorus niphonius*	48.5	0.09	0.38
Bastard halibut	*Paralichthys olivaceus*	46.8	0.02	0.36
Korean rockfish	*Sebastes schlegelii*	20.9	0.06	0.34
Silver pomfret	*Pampus argenteus*	14.6	0.22	0.36
Pointhead flounder	*Cleisthenes herzensteini*	23.7	0.02	0.34
Chub mackerel	*Scomber japonicus*	22.8	0.04	0.36
Japanese anchovy	*Engraulis japonicus*	7.9	0.25	0.35
Yellow goosefish	*Lophius litulon*	31.3	0.07	0.35
Scaly hairfin anchovy	*Setipinna tenuifilis*	8.7	0.22	0.35
Blackhead seabream	*Acanthopagrus schlegelii*	21.9	0.13	0.34
Bombay-duck	*Harpadon nehereus*	16.4	0.18	0.36
Mean[a]	–	–	0.16 ± 0.03	0.36 ± 0.003

[a] *Means with standard error.*

mesh sizes were increased to 12 cm, i.e., if L_c/L_{inf} were increased from 0.18 to 0.62.

Ratio of *U/R* vs. *Y/R*

The ratios of *U/R* against *Y/R* (*U/Y*) correlate with L_c/L_{inf}, i.e., large fish are more sensitive to change of L_c than smaller species (**Table 6**). Thus, *T. lepturus*, *C. joyneri*, and *P. argenteus* increased more than *P. fangi* and *L. polyactis*. Perhaps more importantly, the values of *U/Y* appear to be sensitive to L_c only when $L_c/L_{inf} = 0.3–0.4$ (**Figure 4**), i.e., utility-per-recruit differs from yield-per-recruit substantially only if fish are allowed to grow before they are caught. Indeed, peak *U/Y* appeared at L_c/L_{inf} values of 0.79 on average. With current *U/R* at 58.5 and maximum *U/R* at 133 Yuan/kg, current practices cause an average loss of 75 Yuan/kg per recruit.

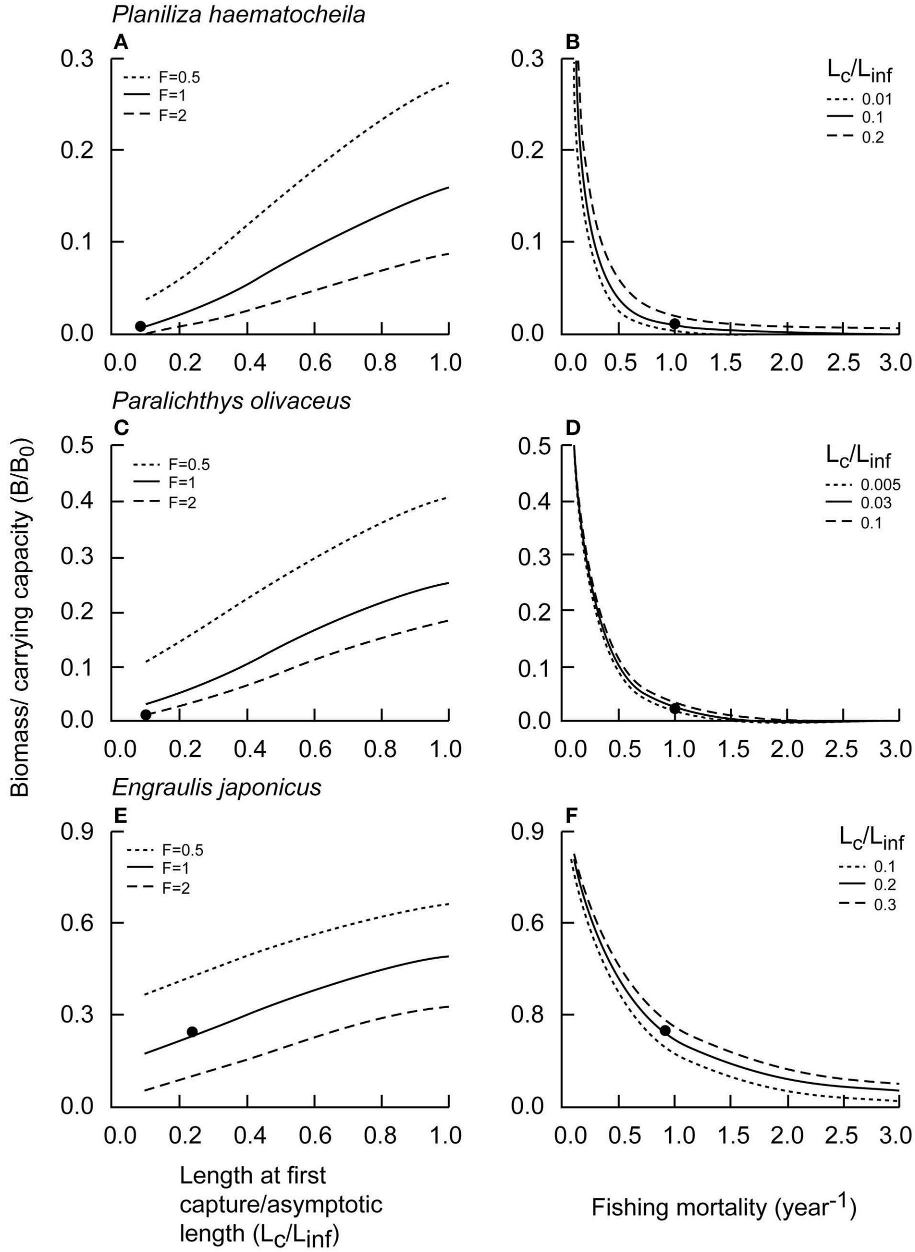

FIGURE 5 | Relative biomass (B/B_0) under different L_c and F in China's coastal seas; respectively; the black dots represent current relative biomass levels. **(A)** *P. haematocheila* B/B_0 vs. L_c/L_{inf}. **(B)** *P. haematocheila* B/B_0 vs. Fishing mortality. **(C)** *P. olivaceus* B/B_0 vs. L_c/L_{inf}. **(D)** *P. olivaceus* B/B_0 vs. Fishing mortality. **(E)** *E. japonicus* B/B_0 vs. L_c/L_{inf}. **(F)** *E. japonicus* B/B_0 vs. Fishing mortality.

Relative Biomass Analyses

If F was kept constant while L_c was increased to L_{c_MSY}, relative biomasses would increase by 77% on average (**Table 7**); the average mesh size generating B_{MSY} was about 9 cm.

Relationships between different levels of F or L_c and B/B_0 were illustrated for *P. haematocheila*, *P. olivaceus*, and *E. japonicus* (**Figure 5**). Relative biomass increased almost linearly with increasing L_c (**Figures 5A,C,E**). For large and medium species, such as *P. haematocheila* and *P. olivaceus*, relative biomasses (for $F < 0.8$ year^{-1}) was rather insensitive to increase in fishing mortality (**Figures 5B,D**). However, for small species, such as *E. japonicus*, relative biomass, i.e., B/B_0 was impacted by a wide range of fishing mortality (**Figure 5F**).

DISCUSSION

It has been often assumed that fisheries produce the maximum sustainable yield (MSY) when $E = M/Z = 0.5$, i.e., $F = M$

(Alverson and Pereyra, 1969), while other authors have suggested that $F_{opt} < M$ (Die and Caddy, 1997; Zhou et al., 2012). This issue is moot, however, as the *E* values estimated here were much higher than 0.5. Indeed, the extremely small mesh size (∼1cm) used along the coast of China leads to the bulk of the catch consisting of fish at the fingerling stage, too small for human consumption, leading to the "trash fish" and end use problems mentioned earlier.

The analyses in this contribution allowed to address these problems by considering both catch and value, since both the catch and its value were much lower than optimum levels, China's fisheries would substantially benefit from increased mesh size. Indeed, in view of difficulties in reducing fishing mortality, China's fisheries managers have attempted to increase the mesh sizes used by the commercial fisheries. Thus, mesh regulation for important species have been published (Anonymous, 2013), covering *L. polyactis*, *T. lepturus*, *P. haematocheila*, *S. niphonius*, *P. argenteus*, *C. herzensteini*, *S. japonicus*, and many other fish and invertebrates. While some of these new legal mesh sizes are still below the size shown here to be optimal, we hope that these new regulations will be respected.

The comparison of the yield- with utility-per-recruit for our species showed, unsurprisingly, that the benefit from large mesh sizes were more pronounced in the utility-per-recruit than in the yield-per-recruit analyses. Thus, Y'/R and U/R are essentially the same for *P. fangi*, because this fish remains small and its market price does not change much with size, whereas the opposite is true for species, such as *L. polyactis*, *T. lepturus*, or *C. myriaster*. As an aside, we also note that *T. lepturus*, which is most popular and high-value fish in China, is one of the few species that cannot be farmed; thus, its price remains high, especially when large, because there is no substitute to wild-caught fish. Therefore, *T. lepturus* is assumed to be the species from which most economic benefits would be derived if lengths at first capture were increased.

The relative biomass (B/B_0) for 21 species in China's coastal seas assessed here was 0.16 on average, which implied a depletion rate of 84%. The result was similar to the 80% average depletion obtained by applying the CMSY method of Froese et al. (2016) to catch time series of 15 species exploited by Chinese fisheries (Zhai et al., submitted).

Overall, this contribution provided evidence that support efforts to increase the mean length at first capture (L_c) of fish exploited along the Chinese coasts, both in terms of yield- and utility-per-recruit, because higher L_c will produce benefits even if fishing mortality is not reduced (Teh et al., 2019). However, it must be realized that the results of yield-per-recruit and utility-per-recruit analyses, as presented here, are longer-term average. In the short term, yields and catch values would decrease upon introduction of the larger mesh sizes. Therefore, supportive policies would be appropriate, which could be running parallel to existing programs to support workers transiting from fisheries to land-based occupations (Song, 2007).

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

LZ was responsible for the data collecting, formal analysis, and writing the original draft. DP was responsible for the conceptualization, methodology, and supervision.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2019.00724/full#supplementary-material

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