SUPPLEMENTARY INFORMATION

Materials and Methods

Data

Catch data

Catch data were collated from the National Fishery Statistics Yearbook (中国渔业统计年鉴 [1]). Annual catches (by species or species group) during the years 1986-2014 from the East China Sea were calculated by adding the catch landed in Shanghai, Zhejiang, and Fujian provinces. The catch from these areas represent ~95% of the catch from the East China Sea and only small fractions of their catches come from other seas. Size frequencies of the catch are not available—catches were reported by species or species group in aggregate. Catch time series were used for groups that were reported to the species level (Table S1 and Fig. S1) and had been consistently reported since 1986. An additional group 'other fish' was also included in the analysis. The 'other fish' category includes species groups not identified to species, fish that were not identified to any group, and species for which reporting to species level only began in the last decade (see Fig. S1 for a breakdown). 'Other fish' includes both unidentified 'trash' fish (a small fraction of which are used for fishmeal [2]) and large species such as tuna. It is acceptable to lump many species with a range of life history parameters into this category because we are modeling fish in different size bins and size bin is the primary determinant of trophic interaction. One can think of this practice as modeling an ecosystem in two inter-connected pieces: a 'community' (in which we do not differentiate between species) and individual species that are of interest. We tuned the 'community's parameters based on the data to which we are fitting (the catch data in this instance) and their relationship to the other species in the system. The way in which the catch data decrease at the end of the time series suggests that the community is slower growing with some fish that reach medium size. Much of the size spectrum literature is performed with community-based models that do not explicitly model individual species (e.g. ref 3).

Catch data for Chinese fisheries have been a subject of scrutiny for many years, often under the assumption that the data are incorrectly reported (4, 5 ,6). Researchers have generated time series' of Chinese catch based on various assumptions about how they might be incorrect, but we have chosen to use the reported catch here for several reasons. First, although there are plausible explanations for why China might over-report its catches (e.g. incentives on the local scale to report increased production [4]), there are few hard data to back this assumption. The possibility that Chinese fishers are reporting catch from waters other than their own as caught in Chinese waters (5, 6) is another potential issue for which there is anecdotal evidence. However, the trends in the reported catch would be surprising if fishers were, in fact, fishing in other countries waters and reporting it as their own. Fisheries have been shown to develop based on the value of the fishery (7), yet the stocks showing increases in Chinese fisheries data are low value (e.g. round scad [*Decapterus maruadsi*] and butterfish, [*Pampus argenteus*]) and the high value stocks have shown decreases over time (e.g. large yellow croaker [*Larimichthys crocea*] and largehead hairtail [*Trichiurus lepturus*]). If it were the case that Chinese vessels were going elsewhere to buoy their domestic catches, one would expect them to target high value species rather than low value species, particularly given the costs associated with travel.

Ultimately, we chose to use the unaltered data in our analysis given that Chinese officials (and even the FAO) indicate that the catch records are roughly accurate. Trends in the data are the most important ‘signal’, rather than overall magnitude; and a recent study (6) suggests that the fisheries catch in the region China fishes is much higher than reported, but the adjusted time series are essentially scaled up versions of the reported catch. Scaling the catch data up or down will influence the overall estimate of recruitment parameters, but the result of the comparison of performance of management strategies would remain unaffected.

Life History data

Life history data were gathered from Fishbase (8) when available and from published literature when absent from Fishbase (Table S1 and S2; see below for description). When choosing life history parameters from FishBase, estimates from Chinese waters were given first preference. Estimates from nearby Korean or Japanese waters were taken if Chinese studies were not available and, finally, if none of those studies were available, estimates from populations in countries with similar average water temperatures to the East China Sea (~22 degrees C) were taken.

Price data

A price database was collated from the monthly price reports from 2009-2015 gathered from www.zjscxh.com/newslist/1068.html (9). The website collects the prices from different markets in Zhejiang province for a large number of species and as many as 5 different size classes (in terms of weight) for a given species. For example, largehead hairtail had prices reported for 5 size categories (0-100, 100-200, 200-350, 350-500, and 500-5000). Six species-specific time series of prices at size were available and used to calculate the value of a given catch for those species (Fig. S2). Although there is considerable within-year variation, prices for very few size classes exhibited significant trends overtime. It was not possible to look for relationships between catch and price because catches (reported by national statistics) were not reported by size, only species. Consequently, the average over the 6 year period for a given size class was used to assign values to projected catches.

Price data were not available for several of the species or the ‘other fish’ category. Ignoring the value of these groupings could bias our results, so we use the price data for the daggertooth pike conger as a proxy. Daggertooth pike conger was chosen because it had a range of size bins similar to the ‘other fish’ category and was relatively low valued. The ‘other fish’ category was modeled here as a species with a maximum weight of 5 kg (a medium-sized fish in the model), so it was important to have a range of weight bins. However, the ‘other’ category is also presumably low-value, otherwise they would be reported to the species level. So, using the conger price data is an acceptable assumption that prevents us from excluding 50% of the catch from the value analysis.

Methods and Auxiliary Results

Ecosystem-based modeling: Size-spectrum models

Building an ecosystem model in a data-limited system can be difficult. Most ecosystem modeling frameworks require a predator-prey matrix that describes the interactions between different species. Even when data are available, it is difficult to incorporate the changes over time in diet in models that require a predator-prey matrix. These data are often unavailable even for data-rich systems, so building these matrices in data-limited systems is not possible. Size-based ecosystem models can sidestep the predator-prey matrix requirement because they model these relationships based on size, rather than species. Size-spectrum models are a class of size-based models gaining popularity in the fisheries literature to answer ecosystem-based management questions (10-14). Foraging behavior in size-spectrum models is defined by a preferred prey size ratio for a given species, so predatory-prey interactions occur both between and within species. Size-spectrum models are particularly useful for modeling the East China Sea because size-based management can be considered (which is one of the main mechanisms of management in the East China Sea), but this is typically not possible with other commonly used ecosystem models (e.g. EcoPath with EcoSim; 15). Size-spectrum models can be built using relatively few parameters describing the characteristics of species (e.g. growth rates, maximum weight, weight at maturity, preferred prey size).

Blanchard *et al*. (14) tuned a size-spectrum model to the North Sea large marine ecosystem to compare the performance of management strategies in terms of conservation and production metrics. They used a model based on Hartvig, Andersen, and Beyer (16) that allows for individual species to be modeled. The model was coded as an R package (‘mizer’) and contains the documentation of the theoretical framework and equations (10), so they will not be included here. Each species is described by parameters related to physiology, life history, and foraging traits within ‘mizer’s ecosystem modeling framework. We use similar methods to Blanchard *et al*. (14) to tune a size-spectrum model to catch data for the East China Sea.

Model specification methods

Size-spectrum models require life history parameters (8 per species and several that are shared among all species [Table S1]), parameters that describe the fishing effort, and a parameter that describes the background production of the ecosystem (essentially primary productivity). We estimated 14 of these parameters (those determining recruitment and the shape of size-specific fishing mortality over time), and the rest are specified based on literature-reported values described below.

Eight species-specific life history parameters are required to parameterize a size-spectrum model: Maximum weight (w_inf), weight at maturity (w_mat), preferred prey size ratio (beta), variability around the preferred size ratio (sigma), maximum recruitment (r_max), Von Bertalanffy ‘k’ (k_vb), and parameters to relate length and weight in a power function (a and b; Fig. S3). Maximum weight, weight at maturity, Von Bertallanfy growth rate (K), and weight parameters were taken from FishBase when available (as described above) and found in the literature when not in FishBase. If weight at maturity was not available in FishBase, it was calculated from length at maturity and the weight at length parameters. Table S2 holds the references providing the parameter value and indicates if they are calculated (e.g. via ref. 17 for natural mortality) rather than based on species-specific studies. Life history parameters for the ‘other fish’ group were tuned to match the shape of the observed catch time series and resulted in parameters describing a mediums-sized, slower growing fish with high virgin recruitment.

Data were not available to specify preferred prey size ratios and these parameters are potentially influential in the model fitting. Two runs were done with different preferred prey size ratios to explore their influence. The run presented in the main text specified the preferred prey size ratio as 100 for all species (meaning that the preferred prey for a given size of predator is 100 time smaller in terms of body mass; *sensu* Jacobsen *et al*. [18]). Sigma was set to 2, which produces more generalist feeding behaviors. The background resource availability (‘kappa’) influences the shape of the yield trajectories and was tuned to produce the appropriate shape of catch time series, given the values of other parameters. Maximum recruitment for each species was estimated using ‘nlminb’ in the R programming language to match the magnitude and trends of the available catch time series. Maximum recruitment determines primarily the scale of predicted catch.

Several other parameters (related to food intake, search rate, metabolism, background mortality) are calculated from the input species specific parameters in table S1) were calculated from known relationships (see ref. 10). Input parameters related to activity, assimilation efficiency and reproductive efficiency are unable to be determined from the data available, so were left at the default values in the *mizer* package. A matrix can be input to size-spectrum models to describe the spatial overlap of different species (and therefore their trophic interaction), but this information was unavailable for the East China Sea, so a simplifying assumption of equal distribution was made here.

Three parameters determine the fleet dynamics of the fishery in a given year. Two of these parameters determine the selectivity of the fleet (L25 and L50) and specify the length at which 25% and 50% of individuals are selected in the fishery, respectively. These parameters determine the shape of a logistic selectivity function. Selectivity for the status quo fishing scenario was extrapolated from the experimentally measured length of 25% and 50% selection of largehead hairtail (*T. lepturus*) and small yellow croaker (*L. polyactis*) in the current 54mm minimum mesh size trawl nets (19). Catch from the trawl fleet composes ~50% of the total catch in the East China Sea and a large fraction of the catch for the species included in the analysis are primarily caught by trawlers (1). Consequently, using the selectivity from the trawl is a simplifying assumption about the overall selectivity of the fishing fleet in the East China Sea. Selectivity for each species within the trawl gear was estimated by a linear regression fitted to the selectivity data for largehead hairtail and small yellow croaker using weight at length as a predictor of L25 and L50 (see table S3 for estimated values). Other gear types are subject to less regulation, so the 'true' selectivity of the fleet is likely slightly smaller than assumed here, and this could influence the estimation of the 'scale' parameters for each species.

Current fishing mortality for the status quo was specified as 1.36 (exploitation rate of 0.74) based on an average range of assessments for species included in the analysis (see table S4 for references). Lin *et al*. (20) surveyed 18 commercially exploited species in the East China Sea and found 15 of those species had fishing mortalities between 0.6 and 2.52. The precision of this figure does not drastically influence the percentage change in metrics reported (i.e. catch, biomass, and value) because the surfaces for each of these metrics are relatively flat in the vicinity of the specified value (Fig. S4). To fit historic data, a logistic curve representing effort over the history of the fishery was estimated (see "Status quo" below).

Fits to the data

Trends in overall magnitudes of catches in the most recent years are well fit for most species (Fig. 1). Fits for some species that make up a relatively small portion of the catch (e.g. *T. modestus*) are not as good as other species—dynamics for these species may be influenced by changes in the environment or fishery not related to predator-prey dynamics (e.g. destruction of essential habitat, changes in targeting over time). In particular, Jung and Cha (21) suggested that decreases in habitat related to large-scale environmental changes were the cause of the collapse of the *T. modestus* population in the East China Sea. Given this collapse, decreasing catches in spite of large-scale increases in effort would be expected, yet not captured by our size-spectrum model dynamics. For some species (e.g. *S. sagax*), fast increases in catch may be related to recruitment pulses or targeting with other gears that are not captured by the equilibrium dynamics of size-spectrum models. The size structure of the entire ecosystem has been reported to decrease over time and the size structure from the model roughly matches these changes (Fig. S5). A change from catches including more 'high quality fish' (e.g. large yellow croaker, bigger largehead hairtail) to catches dominated by 'lower quality fish' (e.g. smaller hairtail, and sardines) is also well captured by the East China Sea ecosystem model presented here (Fig. S6).

Model suitability for projection and management evaluation

Size-spectrum models capture a key dynamic that single-species models often do not—the changing ecological impacts of exploited populations on one another. However, data are not available to capture all aspects of the dynamics of a system. This size-spectrum model does not have stochastic recruitment estimates and do not incorporate variability in carrying capacity/habitat quality/environmental influence, so our presented size-spectrum model will not be able to perfectly capture the dynamics of the East China Sea ecosystem. Nonetheless, dynamics for the majority of species modeled here are well matched and size-spectrum models provide a more holistic method to assess the potential impacts of fishery reform than single species models, particularly when large scale changes in size structure and trophic relationships will occur with reform.

The validity of the results of some size-spectrum modeling endeavors has been questioned recently (22, 23) (see reply by Andersen *et al.* [24]) especially in so far as they support balanced harvesting as an ecosystem-based fishery management strategy (25-27). Beyond the question of balanced harvesting (which we briefly discuss below), the outstanding critiques of size-spectrum models (22,23) are that some (26, 27): (i) predict peaks in cohort biomass at unrealistically small body sizes, because they assume very high senescence mortality (of 5 per-year for fish above half of maximum weight of 1000g), and because they do not assume density-dependence in the larval recruitment stage (and instead allow it to emerge later in life through cannibalism and other trophic interactions); (ii) assume allocations of energy to growth and reproduction are made from assimilated food rather than current body size (a proxy for available fat stores); and (iii) assume unrealistically restricted food chains (restricted to the set of species modeled—1 or 2 species in the most-criticized size-spectrum studies), and strong food limitation, which make predator releases especially pronounced.

Addressing (i), our model assumes density-dependent recruitment and does not assume extreme senescence mortality, and consequently peak biomass occurs in our model at realistic weights for all species (Fig. S7). Notably, this also results in system-wide maximum yields when selectivity is near 30 cm, in contrast to other size-spectrum models criticized for their support of balanced harvesting, which find maximum yield at a trivially small selectivity (27). Although density-dependent recruitment is assumed in the modeling framework (10) and recruitment parameters were estimated, the estimated relationship between spawning biomass and recruitment had very little density dependence (i.e. recruitment decreases very little as spawning biomass decreases). One reason for this is that the concept of a stock-recruitment relationship is more 'fluid' when considered in a multispecies framework. Traditionally, a stock-recruitment relationship predicts recruitment in a given year from two theoretical quantities and a rate: the virgin (unfished) recruitment, virgin (unfished) spawning biomass, and the rate of increase of recruitment with respect to spawning biomass at the origin. As trophic cascades arise in the size-spectrum modeling framework, the spawning biomass under a given fishing scenario can far exceed the virgin spawning biomass (Fig. S8). Consequently, one would not expect to see any relationship between recruitment and spawning biomass for the 8 species for which spawning biomass exceeds the virgin spawning biomass using traditional stock/recruit models (at least when using single species stock recruit models).

For the remaining species that are depleted to relatively low levels of their unfished biomasses, it is possible that very little relationship between spawning biomass and recruitment exists. Szuwalski *et al*. (28) reported that 60% of commercially harvested stocks for which recruitment estimates exist do not show an influence of spawning biomass on recruitment over the observed range of spawning biomasses. Another potential reason for no observable decrease in recruitment with declining spawning biomass could be related to the extensive stock enhancement and artificial reef building that China undertakes. All that said, density dependence in recruitment is a key driver of the results in an evaluation of management strategies such as ours, and as such should be carefully scrutinized. We attempted to fit scenarios in which density dependence was forced, but predicted catches from these scenarios were unable to fit the observed catch data. The observed decreases in catch emerge in our fitted model as a result of growth overfishing, rather than recruitment overfishing, which is intuitive when looking at the characteristics of fish that have decreasing catch trajectories (save *T. modestus*). Our model would project different impacts of management reform in a system in which density dependence was apparent, because recruitment overfishing could arise. Still, given the Chinese data, there is no evidence of recruitment overfishing for the major reported species (save for *T. modestus*, but even its decline has been suggested to be primarily environmentally driven). There are potentially many species that have overfished to the point that recruitment has been impacted in the 'other species' category, but we do not have the data available to parse these species out.

Addressing (ii), our model includes the 11 most commonly caught species—accounting for >95% of reported finfish catch—in the context of indiscriminate fishing, and therefore our model's food chains are unlikely to be unrealistically restricted (relative to the true ecosystem); and strong limitation of species' population growth by food, predation, and fishing is generally well supported (24). Point (iii) is largely semantic—individuals allocate energy to fat stores, and therefore energy is the root source of growth-reproduction allocations regardless—and unlikely to impact our broad results. The model we present therefore does not have the idiosyncrasies that have been criticized in other published size-spectrum models.

Ultimately, size-spectrum models are the best of available modeling techniques to explore the impact of ecosystem-wide changes in fishery management given the available data for the East China Sea (and likely other data-limited systems). Size-spectrum models present an attractive blend of complexity and simplicity, thought to be necessary in answering difficult ecological problems (29). Given the paucity of data in the East China Sea, this model cannot be expected to provide precise estimates of biomass or yield trajectories. The goal of the presented model is to provide a system that can mimic the reported trends in catch by incorporating key processes likely to influence the outcomes of management decisions, so that different management strategies can be tested. We believe this model achieves this goal.

To briefly address the issue of balanced harvesting (BH), BH definitions vary somewhat but much of the recent controversy surrounds the ideas of: (a) fishing all sizes in proportion to productivity, which typically means heavy fishing on the smallest juveniles; and (b) fishing all species in proportion to productivity, including those not currently profitable (46). Addressing (a): our projections suggested that maximizing yields and value requires *increasing* selectivity from the status quo, which means fishing the smallest sizes less hard rather than harder. However, the smallest sizes are already intensely fished, so it would require further analysis to determine 'optimal' fishing of small sizes. Addressing (b), we did not simulate perfect species-level targeting—instead focusing on trawl-based patterns more realistic for this fishery (see discussion below)—and thus we were unable to directly test the species-level BH strategy. However, given that we found substantial price differences across species, it is unlikely that BH would be a value-maximizing strategy at the species level, as, for example Jacobsen et al. (31) found for the North Sea and Baltic Sea ecosystems.

Management scenarios

Several management scenarios were evaluated in terms of catch, biomass, and value using the tuned East China Sea size-spectrum model; their specification and reasoning are described below. We reiterate that we recognize that a range of potential management strategies exist, but we considered only the following because they represent a shift to the 'international standard' of single species management (which is the focus of much of the Chinese literature on fisheries management) *or* they represent a management strategy that could be easily implemented within the status quo system (i.e. effort could be regulated by the length of seasons and selectivity could be modified by restricting the mesh size of the gear used). Follow up analyses should be aimed at a more thorough exploration of the management strategy space.

Status quo

A time series of effort for the status quo was generated by fitting a logistic curve representing fishing mortality to the observed total catches from the East China Sea and assuming that the current ‘zero growth’ policy (31) will remain in place. The slope and inflection point of the logistic curve were estimated to fit the catch time series. The current exploitation rate anchored the maximum of the logistic effort curve and the minimum was anchored at 5% of the current values based on Shen and Heino (31). The model was initiated in the year 1850 at the bottom exploitation rates to allow equilibration before raising fishing mortality in the latter half of the 20th century. The effort curve was transformed such that the maximum was equal to an exploitation rate of 0.74 (see references below). The ecosystem was projected forward under this exploitation rate and status quo selectivity until equilibrium. The assumption that effort has followed a logistic curve is supported by the time series of the ‘power’ of the fleet reported in the Chinese Fishery Statistic Yearbook (1).

Single species management

Single species management was implemented by specifying a fleet for each species in mizer. The selectivity of the fleets was logistic, with L25 and L50 equal to 61.5% and 100% (respectively) of the weight at maturity of a given species (Table S1). L25 was set at 61.5% to mirror the approximate relationship between these two parameters observed in the trawl fishery in the East China Sea (19). The rate of natural mortality is often used as a proxy for the fishing mortality that would produce close to maximum sustainable yield for stocks for which data are limited (32). Natural mortality is used as a proxy for F_{MSY} rather than determining the actual F_{MSY} in the system because the actual F_{MSY} will be unavailable to managers in the East China Sea; this analysis is meant to be a practical exploration of potential management, not a theoretical experiment in impossible-to-implement strategies. Furthermore, F_{MSY} for a given species can be arbitrarily changed by fishing its predators or prey more or less intensely. Given these tradeoffs when trying to calculate individual F_{MSY} for a suite of interconnected species, we chose to use an easily interpreted and implemented proxy for F_{MSY}—natural mortality. Experimentally determined natural mortality estimates for the species in the analysis from the East China Sea are often not available, so we collected estimates of natural mortality from the literature, giving preference to estimates from China, then East Asia, then global estimates (Table S2). When natural mortality estimates were not available, Jensen’s (17) method using von Bertalanffy growth rates (K) were used to estimate natural mortality.

An additional sensitivity to the assumption about single species selectivity was performed in which selectivity was assumed to be knife-edge, rather than ‘sloped’. The rationale for the ‘sloped’ selectivity assumption that produced the results in the main body of the paper is that Chinese fisheries will still be prosecuted as trawl fisheries even when moving to single species management, so the relationship between the selectivity parameters (which allows a ‘sloped’ selectivity) should be preserved. It is possible that, by further modifying fishing practices (e.g. more targeted fishing practices and beginning discarding—two things not likely to happen in the near future for China), knife-edge selectivity could be achieved. Changing to knife-edge selectivity for single species management roughly preserved the relationship between the results from different management strategies. Comparing knife-edge selectivity single species management to the status quo and sloped selectivity single species to the status quo (respectively), biomass increased 112% vs. 109%, catch decreased 36% vs. 46%, but value actually increased 7% under knife-edge selectivity vs. a 13% decrease under sloped selectivity. So, knife-edge selectivity slightly decreased the downsides of single species management, but would require larger modifications to status quo management.

Ultimately, single species management has two drawbacks in terms of total ecosystem production. First, it recovers predator populations and then doesn’t allow fishing on a large portion of them. Second, the exploitation rates are much lower under single species management. In the status quo, although the average value is lower, the catch is high, so a large amount of low value species make up for the lack of high value species and sizes. So, although the biomass increases under single species management compared to status quo, much of the biomass is both made up of and/or consumed by predators. It’s possible that different combinations of selectivity and effort for each species could yield better results than presented here, however, the number of potential combinations increases exponentially with added species.

Maximizing objectives

Grid searches were performed over a range of selectivities (3-65 cm) and fishing mortalities (0.0-3.5) within scenarios with indiscriminant fishing practices to develop surfaces of catch, biomass, and value (Fig. S4). Fishing mortalities higher than 3.5 were not considered because of the logistic difficulties of implementing ecosystem-wide fishing mortalities of 97% and higher.

Objective functions designed to weight the objectives differently were created by normalizing the surfaces to have an average value of 0, multiplying the normalized surface by a weighting factor (e.g. if each were equally valued by managers, they would each be multiplied by 1 [or any other constant]), and summing the three surfaces. The selectivity (see Fig. S9) and effort combination that returned the maximum combined score represented the optimal management for a desired 'portfolio' of benefits described by the weightings.

Additional indiscriminate fishing results

One of the most important results of plotting surfaces of catch and value was illustrating a change in the shape of the yield curve (and therefore optimal exploitation rates) as selectivity increased (Fig. S10). When selectivity is low, the yield curve is dome-shaped—i.e. as fishing pressure increases, a point exists where fishing more produces less total catch. However, as selectivity increases, the total yield curve becomes asymptotic—more fishing produces more catch, albeit with diminishing returns. This occurs because at very low selectivity and high effort, even the most productive, early maturing fish are not allowed to grow to their 'potential' before harvest. This phenomenon is important because it implies an absolute bottom for selectivity beneath which a lower selectivity should never be allowed. This result parallels single species yield per recruit models, but requires the ability to implement size-selective fisheries. Catch and value surfaces are similar in character—each is dome-shaped at low selectivity and shifts to asymptotic at higher selectivities. However, the peak in value occurs at a higher selectivity than for catch, which reflects the increase in value associated with larger fish.

Surfaces of catch and the proportion of virgin biomass by species show the relative magnitude of trophic release for different species occurs at different selectivity and effort combinations (Figs. S11-13). For example, *L. polyactis* has a large trophic release when selectivity is medium, but increase in biomass only happen at very high selectivities for *L. crocea* (Fig. S11). A trophic release does not always translate to larger catches: *S. japonicus* had increased biomass relative to virgin levels at high selectivity, but catches for *S. japonicus* are largest at low selectivity, where abundance is much less than virgin levels. So, biomass may increase from trophic cascades, but this only translates to more catch if that biomass is selected in the fishery.

Primary productivity demands and changes in trophic level

Watson *et al*. (33) suggested that the catch from fisheries far outpaces the primary productivity of the East China Sea. Their analysis was performed by taking the catches by species or species group in the East China Sea, converting wet weight of catch to dry weight, then calculating the amount of primary productivity that would be required to produce the catch given a10% conversion efficiency between trophic levels and the reported trophic level from FishBase (8). We replicated Watson *et al*.'s analysis with the published SeaAroundUs data and solved for the proportion trophic levels for secondary consumers and above must be reduced by to put fishery yield and primary productivity in balance. A change of only 14% (Table S5) can achieve this balance.

Given the size at which many of the species are caught in the East China Sea, their effective trophic level is much lower than those reported in FishBase, and empirical evidence exists showing similar declines in the neighboring Yellow and Bohai Seas (34). For example, largehead hairtail is reported as a trophic level of 4.4 in FishBase, which is similar to a reported 4.06 in the Bohai Sea in the 1960s, but it declined to 3.41 in the late 1990s (35). These trends in declining trophic level are mirrored in our size-spectrum model. We calculated the trophic level of a given size of fish in our size-spectrum model based on the assumed preferred predator-prey size ratio of 100 and a cutoff of 1 gram to mark the size beneath which biomass in the model was assumed to be trophic level 2. From the cutoff, the sizes at which trophic level 3 and 4 begin are defined by the predatory-prey size ratio. The trophic levels for the sizes between the sizes at trophic levels 3 and 4 (and 2 and 3) are assumed to be linear interpolations between the two points.

If the largest fish in our models are taken as examples, the trophic levels calculated from our model are similar to those reported by FishBase (8) and used in Watson *et al*. (35) at unfished states. However, the majority of the catch of a given species is made up of smaller individuals than those existing at unfished levels, and with lower trophic levels. For example, the trophic level of the largest largehead hairtail in the model is 4.56 in the 1960s, but the average trophic level of a largehead hairtail in the catch is only 3.44 (which declines to 3.18 by the late 2000s). This trend is seen in all of the higher trophic level fish in the model.

Other caveats

Other benefits for recovering all species in an ecosystem not included in "catch, value, and biomass" may exist. For example, resilience of compressed food webs in the face of climate change is not well understood, but is an important aspect of food security. Truncating the age structure of species eliminates some of the 'insurance' provided by the reproductive potential of larger old fish. It is also uncertain how easily the selective pressure for maturity at a younger body size or faster growth rates can be reversed (or even if this change in maturity was a result of selective pressure or just a plastic response to an environmental change), which has implications for calculating the 'true' virgin biomass for a population. In any event, careful thought about the current and historic state of an ecosystem informed by focused data collection should be undertaken before drastically altering the structure of an ecosystem upon which communities depend for food and livelihoods, particularly in cases in which the production has been sustained for a long period of time.

Supplementary References

1. China Fisheries Yearbook. (中国渔业统计年鉴; 1986-2012) (in Chinese)
2. Cao L, *et al*. (2015) China's aquaculture and the world's wild fisheries. *Science* 347(6218): 133-135.
3. Jacobsen NS, Gislason H, Andersen KH (2014) The consequences of balanced harvesting of fish communities. *Proc. R. Soc. B Biol*. Sci. 281(1775), 20132701.
4. Watson R, Pauly D (2001) Systematic distortions in worldwide fisheries catch trends. *Nature* 414: 534-536.
5. Pauly D, *et al*. China's distant water fisheries in the 21st century. (2014) *Fish Fish*. 15: 474–488.
6. Pauly D, Zeller D (2016) Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. *Nature Comm*. 7:10244.
7. Sethi SA, Branch TA, Watson R (2010) Global fishery development pattern are driven by profit but not trophic level. *Proc. Natl. Acad. Sci.* 107(27): 12163-12167.
8. Froese R, Pauly D Eds. FishBase. (2015; www.fishbase.org) (Accessed 04/2015)
9. Zhejiang aquatic product website. www.zjscxh.com/newslist/1068.html (accessed Dec. 2016; in Chinese)

10. Scott F, Blanchard JL, Andersen KH (2014) Mizer: an R package for multispecies, trait-based and community size spectrum ecological modelling. *Meth. Ecol. Evol*. 5: 1121-1125.
11. Andersen KH, Jacobsen NS, Farnsworth KD (2016) The theoretical foundations for size spectrum models of fish communities. *Can. J. of Fish. Aquat. Sci*. 73: 1-14.
12. Silvert W, Platt T (1978) Energy flux in the pelagic ecosystem: a time- dependent equation. *Limnol. Oceanogr*. 23(4): 813–816.
13. Benoît E, Rochet MJ (2004) Continuous model of biomass size spectra governed by predation and the effects of fishing on them. *J. Theor. Biol*. 226(1): 9–21.
14. Blanchard JL, Andersen KH, Scott F, Hintzen NT, Piet G, Jennings S (2014) Evaluating targets and trade-offs among fisheries and conservation objectives using a multispecies size spectrum model. *J. Appl. Ecol*. 51(3): 612–622.
15. Christensen V, Walters CJ (2004) Ecopath with Ecosim: methods, capabilities and limitations. *Ecol. Mod*. 172(2): 109-139.
16. Hartvig M, Andersen KH, Beyer JE (2011) Food web framework for size- structured populations. *J. Theor. Biol*. 272(1): 113–122.
17. Jensen AL (1996) Beverton and Holt life history invariants result from optimal trade-off of reproduction and survival. *Can. J. Fish. Aquat. Sci*. 53(4): 820-822.
18. Jacobsen NS, Gislason H, Andersen KH (2014) The consequences of balanced harvesting of fish communities. *Proc. R. Soc. B Biol*. Sci. 281(1775), 20132701.
19. Huang H-L, Wang M-Y, Xu B-S, Zhang X, Tang Z-M (2005) Study on selectivity of mesh size of cod-end trawl in the East China Sea region. *Journal of Fisheries of China* 29(2): 232-237. (in Chinese)
20. Lin L-S, Zheng Y-J, Cheng J-H, Liu Y, Ling J-Z (2006) A preliminary study on fishery biology of main commercial fishes surveyed from the bottom trawl fisheries in the East China Sea. *Marine Science* 30(2): 21-25. (in Chinese)
21. Jung, S and Cha HK (2013) Fishing vs. climate change: An example of filefish (*Thamnaconus modestus*) in the northern East China Sea. *J. Mar. Sci. Tech.* 21: 15-22.
22. Froese R, *et al*. (2015) A critique of the balanced harvesting approach to fishing. *ICES J. Mar. Sci.* doi:10.1093/icesjms/fsv122.

23. Froese R, *et al*. Reply to Andersen *et al*. (2016) Assumptions behind size-based ecosystem models are realistic. *ICES J. Mar. Sci.* doi:10.1093/icesjms/fsv273
24. Andersen KH, Blanchard JL, Fulton EA, Gislason H, Jacobsen NS, van Kooten T (2016) Assumptions behind size-based ecosystem models are realistic. *ICES J. Mar. Sci.* doi:10.1093/icesjms/fsv211.
25. Burgess MG, Diekert FK, Jacobsen NS, Andersen KH, Gaines SD (2016) Remaining questions in the case for balanced harvesting. *Fish Fish*. 17: 1216-1226. doi:10.1111/faf.12123.
26. Law R, Kolding J, Plank MJ (2015) Squaring the circle: Reconciling fishing and conservation of aquatic ecosystems. *Fish Fish*. 6(1): 160-174. doi:10.1111/faf.12056.
27. Law R, Plank MJ, Kolding J (2014) Balanced exploitation and coexistence of interacting, size-structured, fish species. *Fish Fish*. doi:10.1111/faf.12098.
28. Szuwalski CS, Vert-Pre K, Punt AE, Branch T, Hilborn R (2015) Examining common assumptions about recruitment: a metaanalysis of worldwide marine fishery dynamics. *Fish Fish*. 16(4): 633-648.
29. Plagányi EE *et al*. (2014) Multispecies fisheries management and conservation: Tactical applications using models of intermediate complexity. *Fish Fish*. 15: 1–22.
30. Jacobsen, NS, Burgess, MG, Andersen, KH. (2016) Efficiency of fisheries is increasing at the ecosystem level. *Fish Fish*. doi: 10.1111/faf.12171.
31. Shen G, Heino M (2013) An overview of marine fisheries management in China. *Marine Policy* 44: 265-272 .
32. Hilborn R (2010) Pretty good yield and exploited fisheries. *Marine Policy* 34(1): 193-196.
33. Watson R, Zeller D, Pauly D (2014) Primary productivity demands of global fishing fleets. *Fish Fish*. 15: 231-241.
34. Zhang B, Tang Q, Jin X (2007) Decadal-scale variations of trophic levels at high trophic levels in the Yellow Sea and the Bohai Sea ecosystem. *J. Mar. Sys*. 67: 304-311.
35. Ling J-Z, Li S-F, Yan L-P, Cheng J-H (2008) Utilization and management of *Trichiurus japonicus* resources in East China Sea based on Beverton-Holt model. Chin. J. Appl. Ecol. 19(1): 178-182. (in Chinese)

36. Wang X-H, Qiu Y-X, Zhu G-P, Du F-Y, Sun D-R, Huang S-L (2011) Length-weight relationship of 69 fish species in the Beibu Gulf, northern South China Sea. *J. Appl. Ichtyol.* 27: 959-961. (in Chinese)
37. Liu Q, Xu B-D, Ye Z-J, Ren Y-P (2012) Growth and mortality of small yellow croaker (*Larimichthys polyactis*) inhabiting haizhou bay of China. J. Ocean. Univ. China 11(4): 557-561. (in Chinese)
38. Ye Y-G, Xu Z-L, Chen J-J, Kang W (2012) Resource status analysis of large yellow croaker in Guanjinyang using von Bertalanffy growth equation and fishing mortality parameters. *J Fish China*. 36(2): 238-246. (in Chinese)
39. Kim Y, Yoo J-T, Lee E, Oh T-Y, Lee D-W (2011) Age and growth of largehead hairtail *Trichiurus lepturus* in the East China Sea. *Kor J Fish Aquat Sci* 44(6): 695-700.
40. Watari S, Murata M, Hinoshita Y, Mishiro K, Oda S, Ishitani M (2013) Re-examination of age and growth of daggertooth pike conger *Muraenesox cinereus* in the western Seto Inland Sea, Japan. *Fish Sci* 79: 367-373.
41. Kim J-H, et al. (2012) Age, growth, and reproductive biology of filefish *Thamnaconus modestus* in the Southern Sea of Korea. North Pacific Ecosystem Today and Challenges in Understanding and Forecasting Change. PICES meeting proceedings.
42. Supongpan S, Krajangdara T, Chalee P (2003) Reproductive biology of round scad, *Decapterus maruadsi* (Timminck and Schlegel, 1842) and shortfin scad, *D. macrosoma* Bleeker, 1851, in the Andaman sea of Thailand. *Thai fisheries gazette* (Warasan kanpramong). 56(2): 167-171. (in Thai)
43. Hiyama Y, Yoda M, Ohshimo S (2002) Stock size fluctuations in chub mackerel (*Scomber japonicus*) in the East China Sea and the Japan/East Sea. *Fish Oceanogr*. 11(6): 347-353.
44. Chen G-B, Qiu Y-S (2003) Study on growth, mortality, and reasonable utilization of *Decapterus maruadsi* in northern continental shelf waters of South China Sea. *J. Oceanog. Taiwan Strait*. 4. (in Chinese)
45. Zhou Y-D, Xu H-X (2007) Biomass estimates of *Muraenesox cinereus* calculated by LCA in the East China Sea. *J. Zhejiang Ocean University*. 4 (in Chinese)

46. Shu L-M, Qiu Y-S (2005) Estimation of growth and mortality parameters for *Pampus argenteus* in Pearl River Estuary and adjacent waters. *Shuichan Xuebao*. 29(2): 193-197. (in Chinese)
47. Lu Z-B, Du J-G (2008) Growth and mortality character of *Nemipterus virgatus* in southern Taiwan Strait. *J Trop Oceanog*. 5. (in Chinese)
48. Oshimi S, Tanaka H, Hiyama Y (2009) Long-term stock assessment and growth changes of the Japanese sardine (*Sardinops melanostictus*) in the Sea of Japan and East China Sea from 1953 to 2006. *Fish. Oceanogr*. 18(5): 346-358.

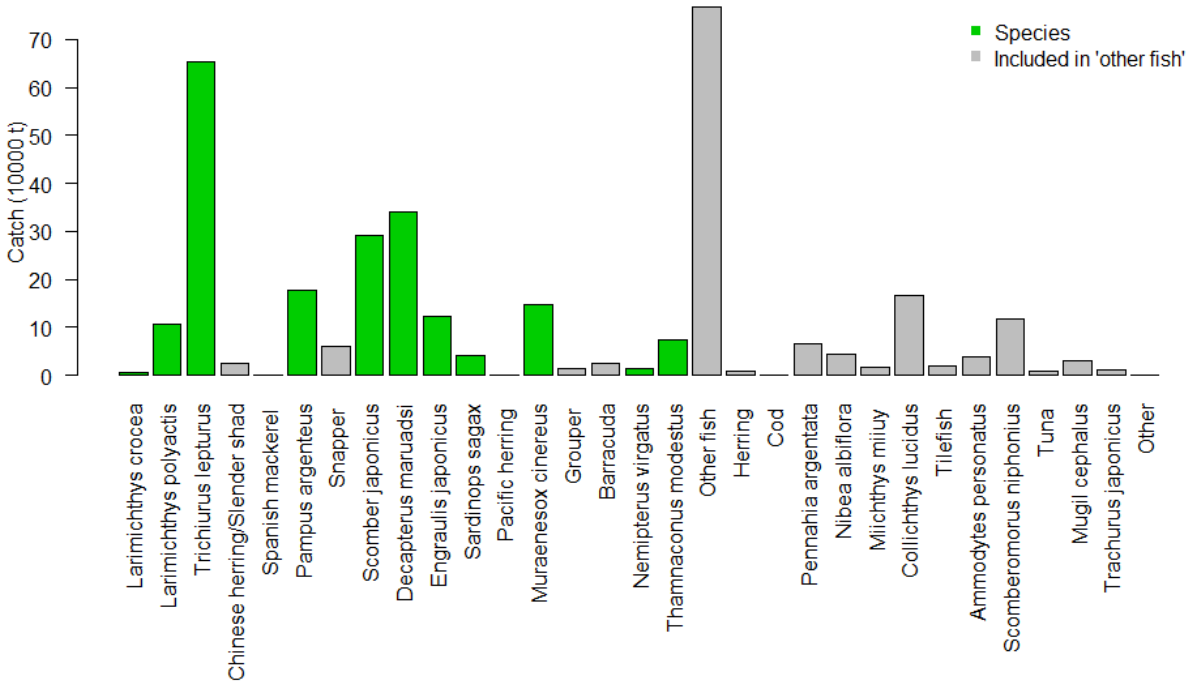


Fig. S1. Breakdown of species include in the model. Species in green were modeled explicitly with individual parameters; species in grey were lumped into the ‘other species’ category. Catch data for species to the right of the ‘other fish’ category were only recently collected and do not have a sufficiently long time series to be useful for fitting. Consequently, they were lumped into ‘other fish’.

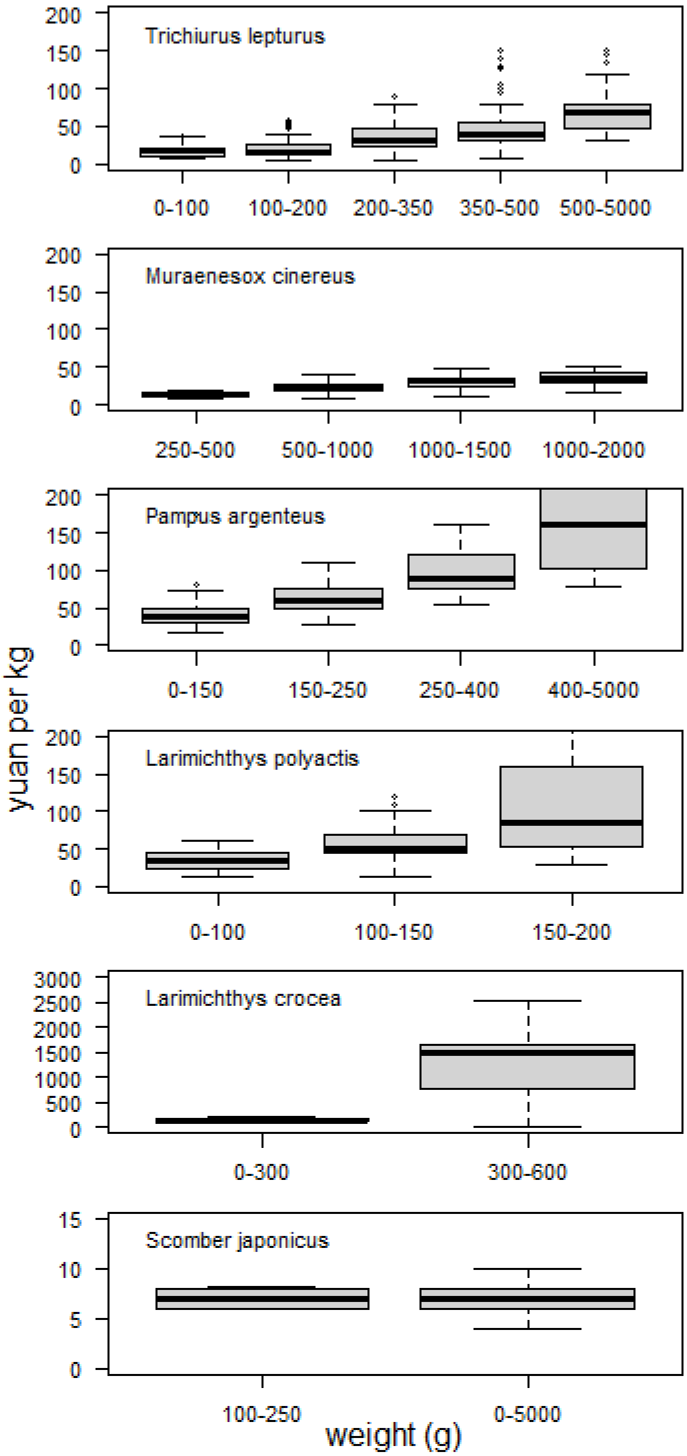


Fig. S2. Size specific prices for species within the analysis.

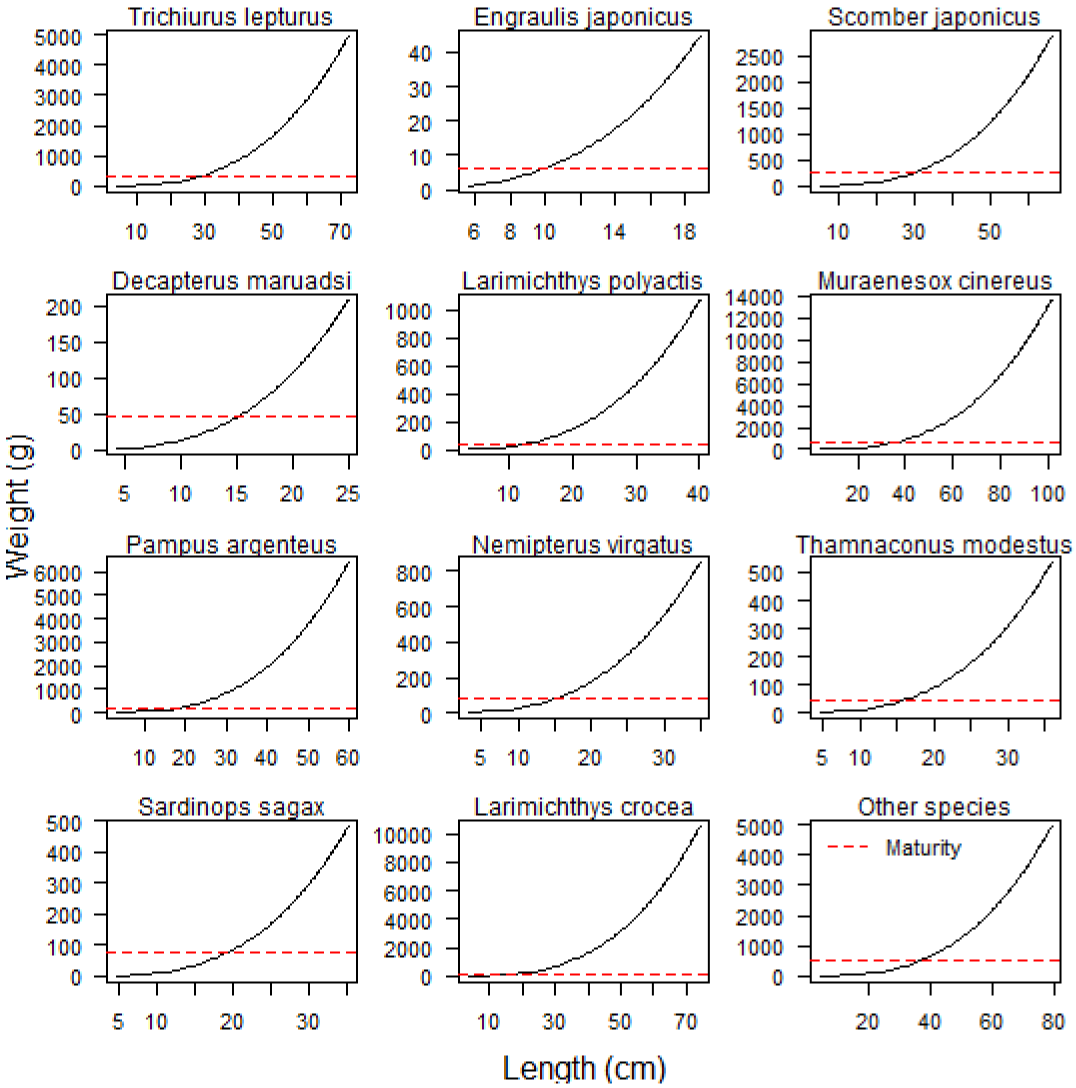
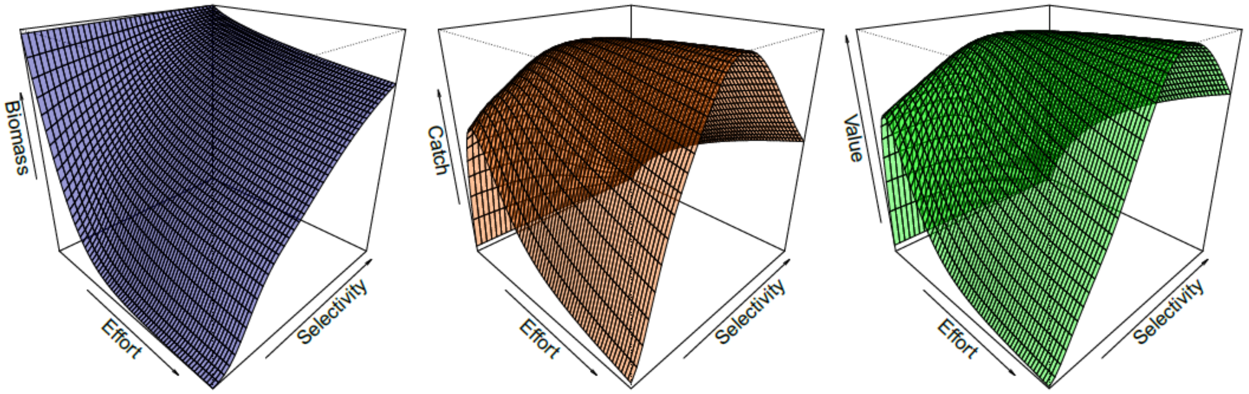


Fig. S3. Weight at length relationships (black line) for modeled species. Maximum weight modeled in the model is the maximum value on the y axis for each species. Red dashed lines represent the assumed maturity at weight.



Fig, S4. Surfaces of total biomass, catch and value over effort and selectivity. Note that catch and value move from dome-shaped to asymptotic curves as selectivity increases.

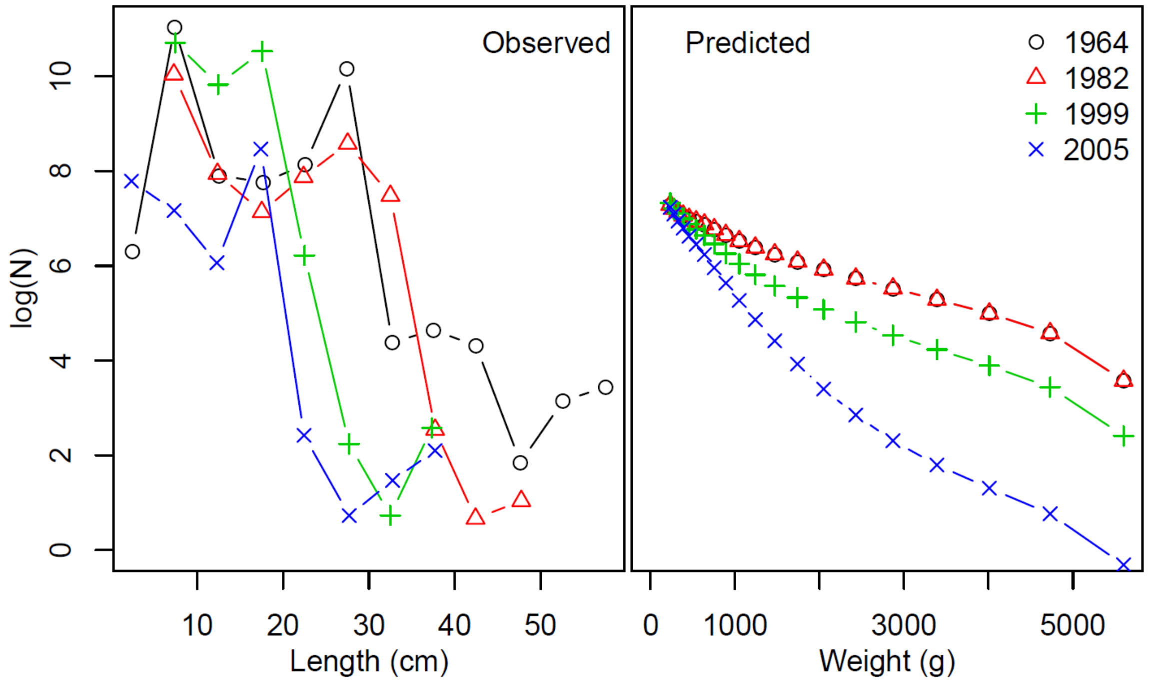


Fig. S5. Observed total ecosystem size structure in the East China Sea (data from Cheng *et al*., 2009 [27]) and predicted size structure from the size-spectrum model. Note that the units are different between panels due to a lack of data to facilitate conversion. The key points to be taken from this figure are 1) the observed size structures of 1964 and 1982 were similar, 1999 was more truncated than 1982, and 2005 even more truncated than 1999, and 2) the predicted size structure mirrors these relationships.

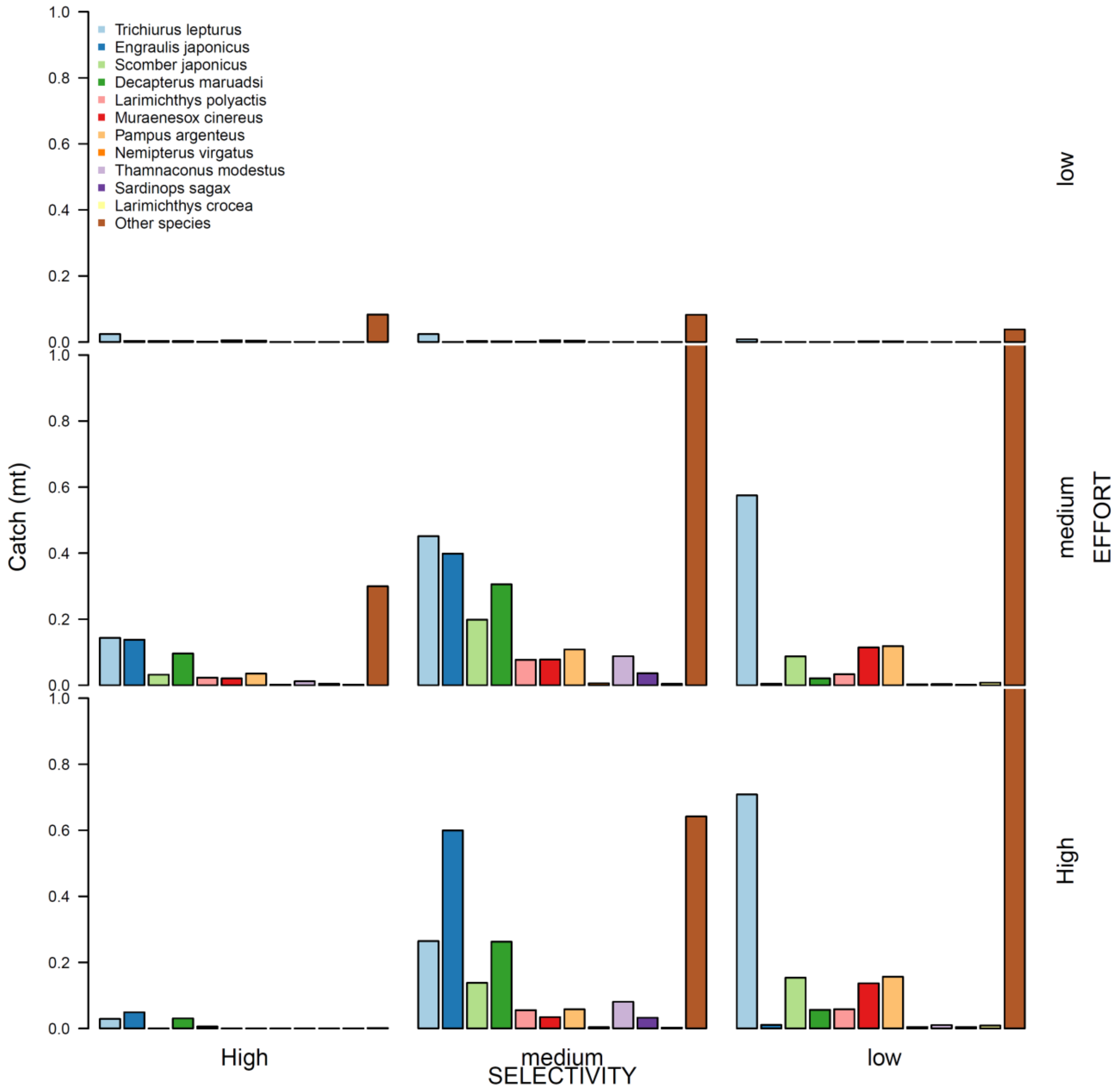


Fig. S6. Catch composition for different effort/selectivity combinations. High, medium, and low effort are fishing mortalities of 3.46, 1.71, and 0.1, respectively. High, medium, and low selectivities are 3, 0.8, and 0.1 times the status quo selectivities.

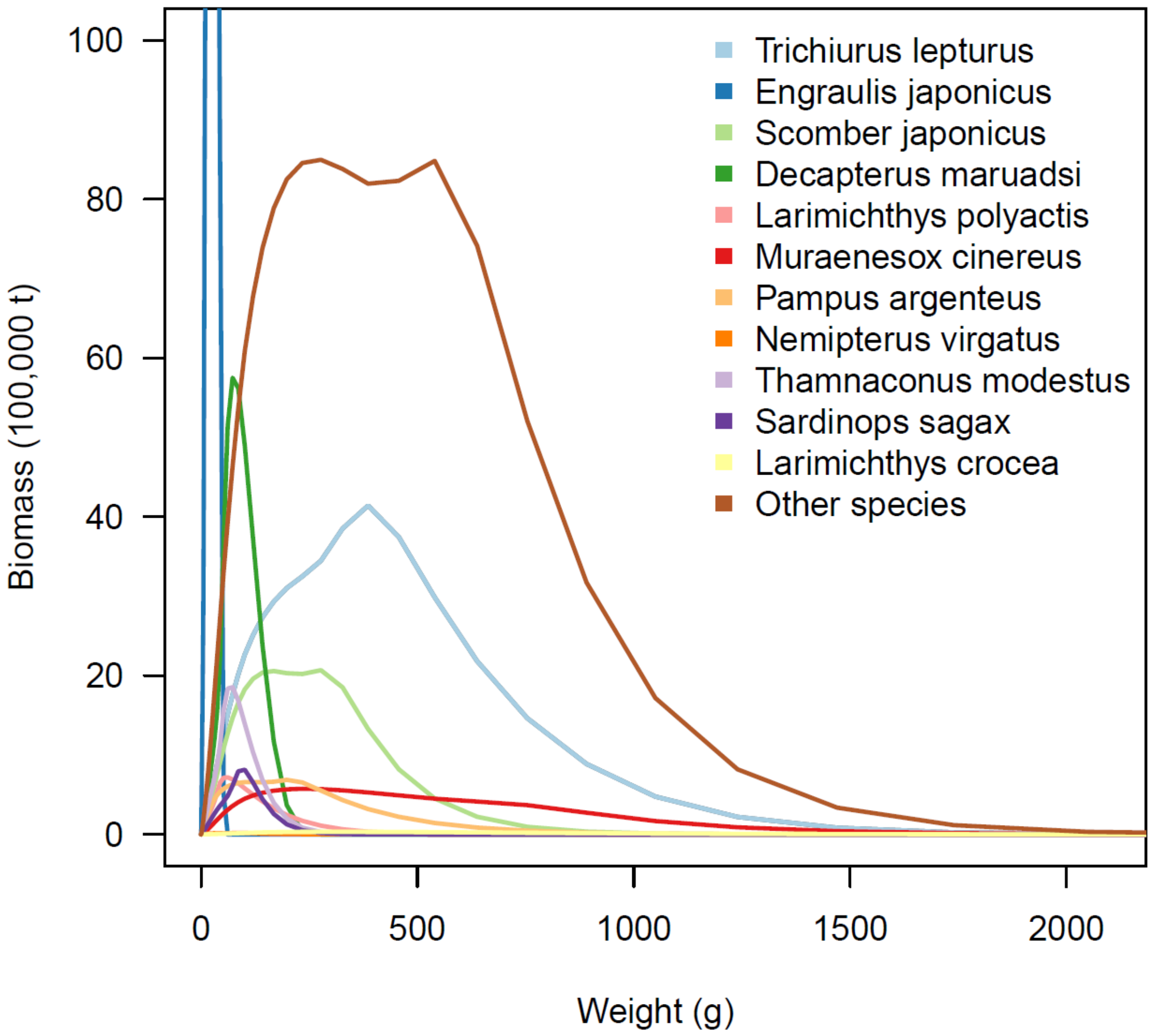


Fig. S7. Biomass spectrums for individual species from the status quo management scenario.

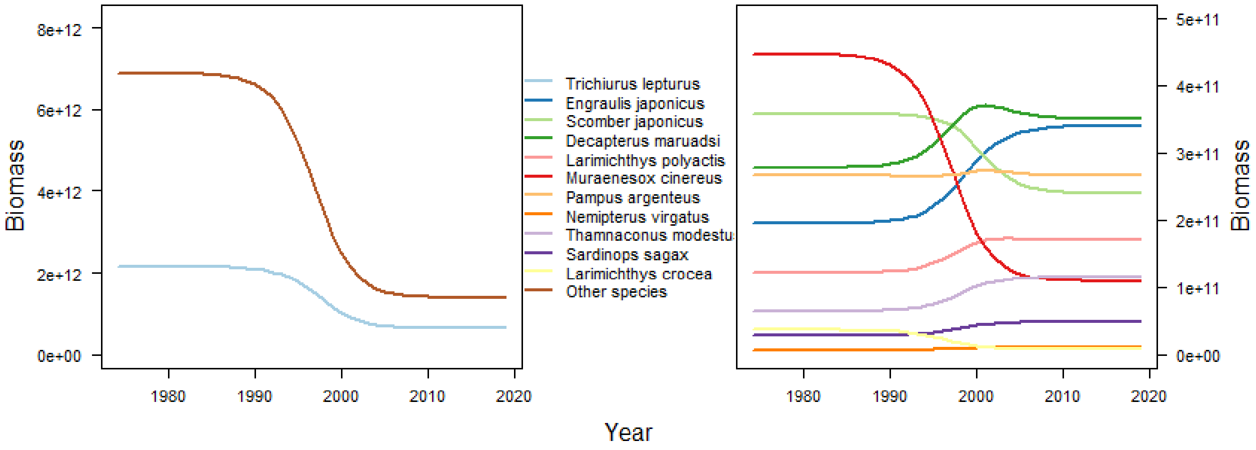
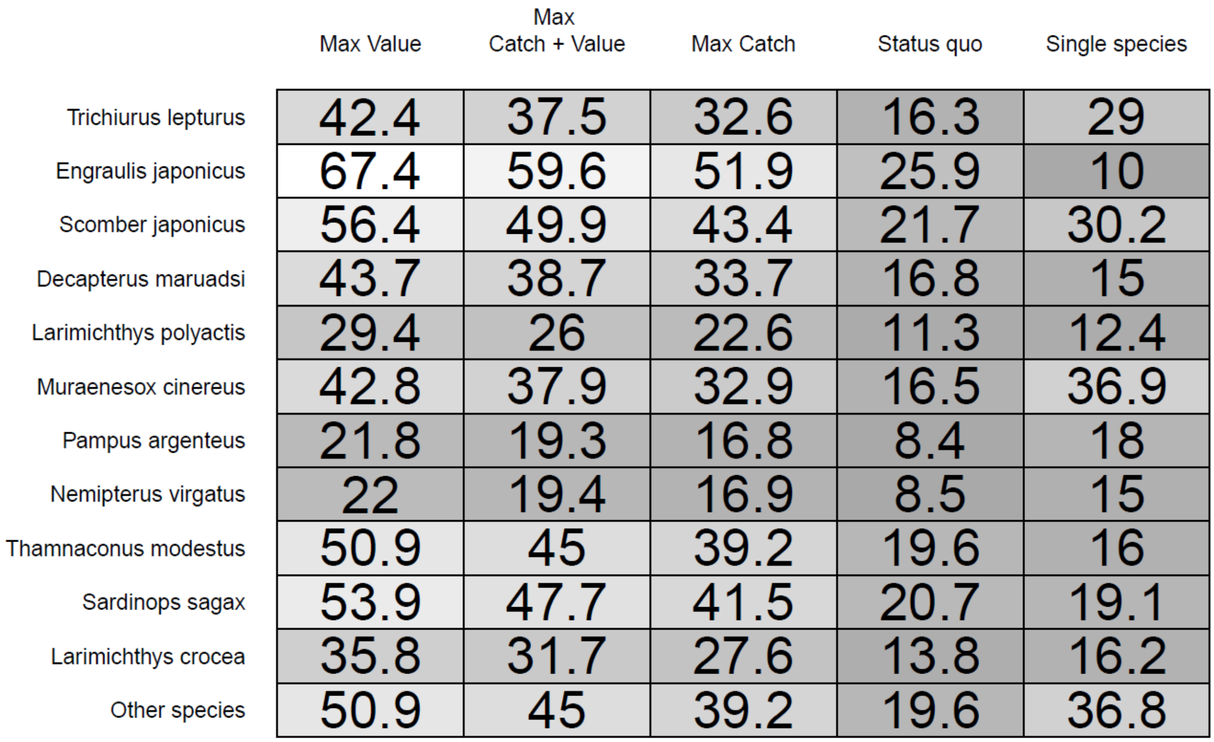


Fig. S8 Trajectories of biomass predicted from fitting to the reported catch data. Left panel represents the two largest 'species' (hairtail and 'other species') and is on a different scale than the right panel.



	Max Value	Max Catch + Value	Max Catch	Status quo	Single species
Trichiurus lepturus	42.4	37.5	32.6	16.3	29
Engraulis japonicus	67.4	59.6	51.9	25.9	10
Scomber japonicus	56.4	49.9	43.4	21.7	30.2
Decapterus maruadsi	43.7	38.7	33.7	16.8	15
Larimichthys polyactis	29.4	26	22.6	11.3	12.4
Muraenesox cinereus	42.8	37.9	32.9	16.5	36.9
Pampus argenteus	21.8	19.3	16.8	8.4	18
Nemipterus virgatus	22	19.4	16.9	8.5	15
Thamnaconus modestus	50.9	45	39.2	19.6	16
Sardinops sagax	53.9	47.7	41.5	20.7	19.1
Larimichthys crocea	35.8	31.7	27.6	13.8	16.2
Other species	50.9	45	39.2	19.6	36.8

Figure S9. Table of the length (cm) at 50% selection for different management strategies presented in the main text.

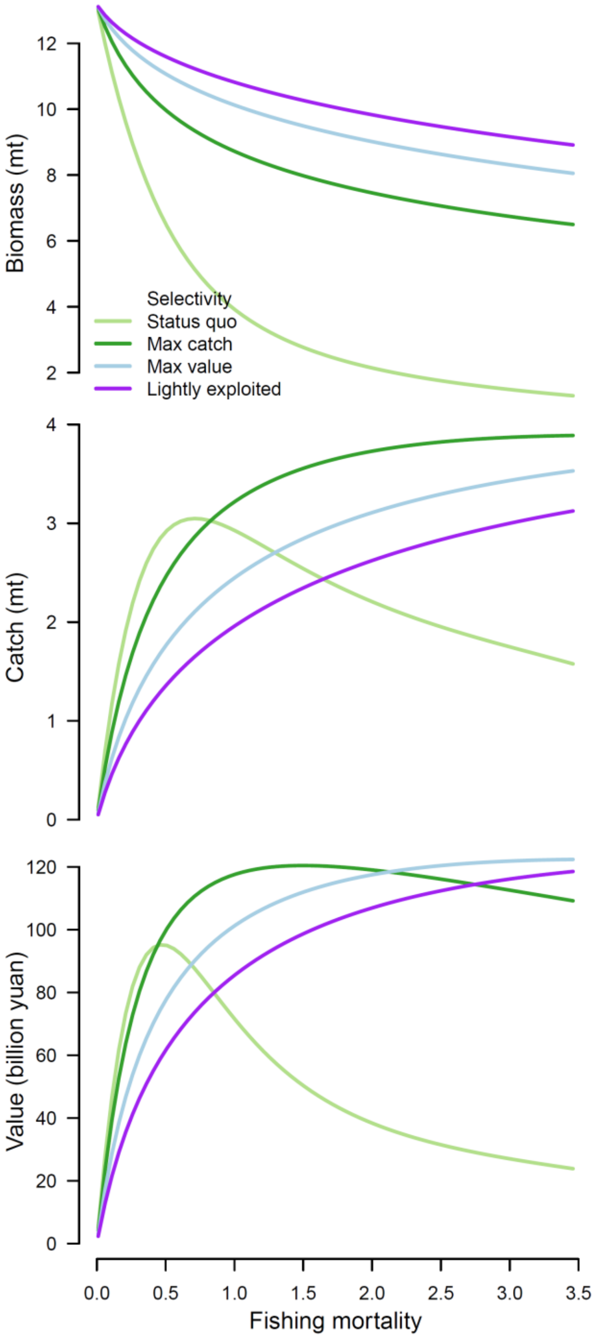


Fig. S10. Biomass, catch, and value at effort for selectivity patterns representing the different management strategies in Figure 2. This figure pulls the yield, value, and biomass curves (over effort) from Fig. S4 for the selectivities that were identified for each of the scenarios (i.e. status quo, max catch, max value, max catch + value) to allow for an easier comparison between the character of the curves for each strategy.

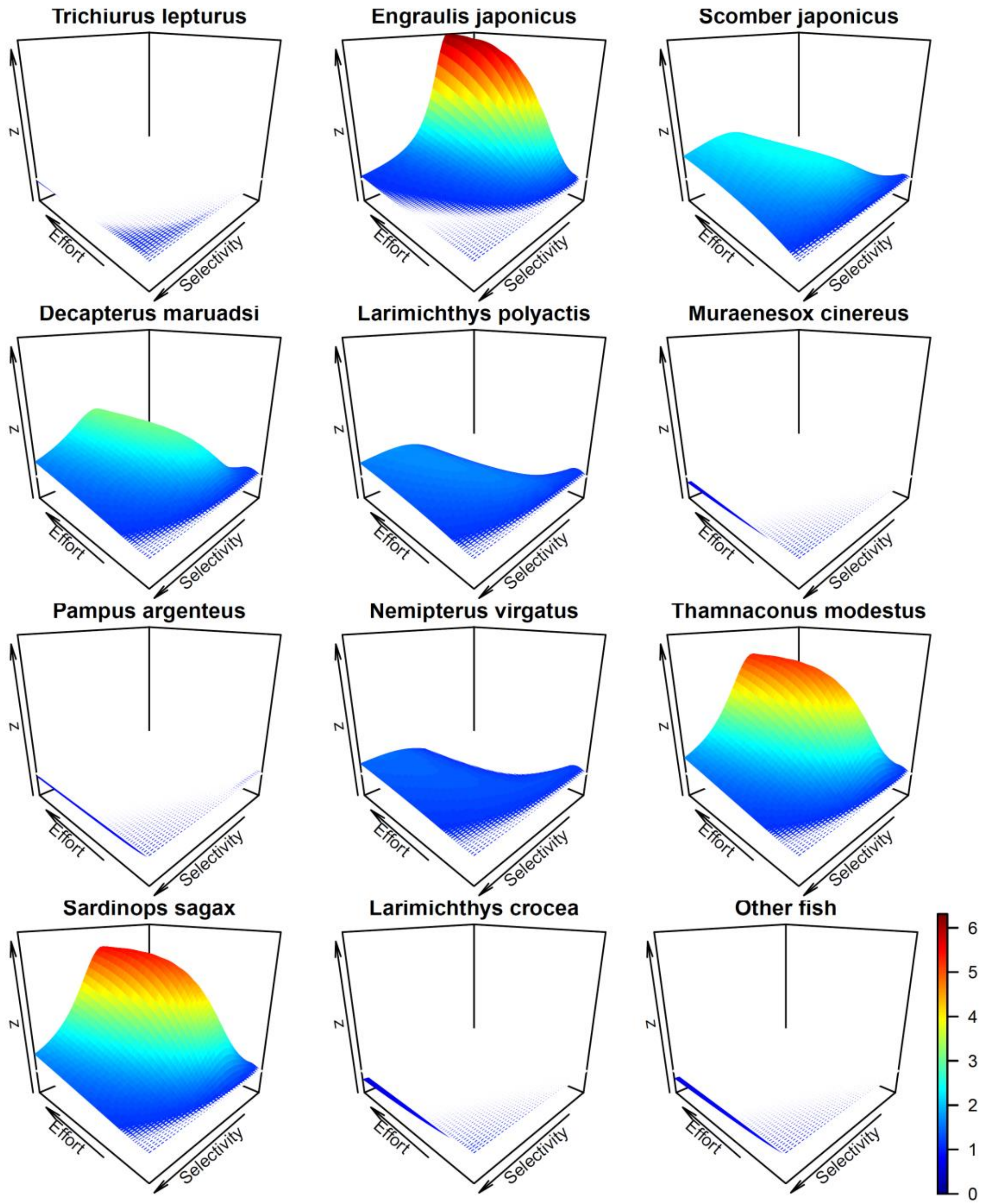


Fig. S11. Proportion of unfished biomass for different combinations of selectivity and effort in an indiscriminant fishery for the East China Sea. The white plane in each figure represents the unfished biomass. These figures represent the impacts of trophic cascades by species. Larger species never exceed their virgin biomass once fishing begins, but smaller species do.

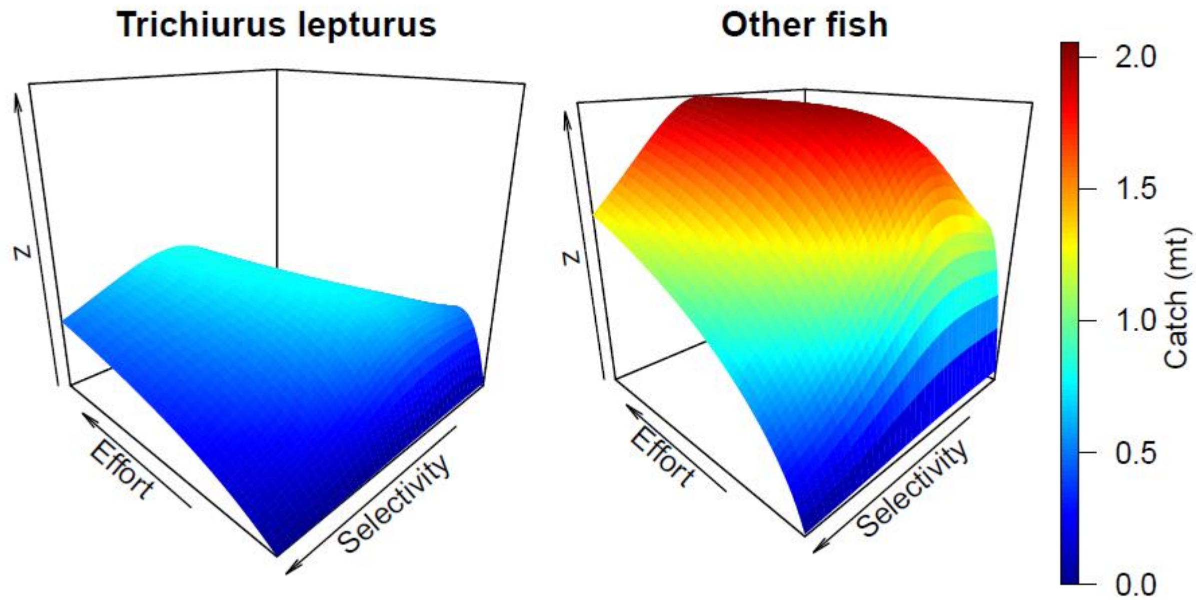


Fig. S12. Catch surfaces by effort and selectivity combination for the two most abundant 'species' in the East China Sea.

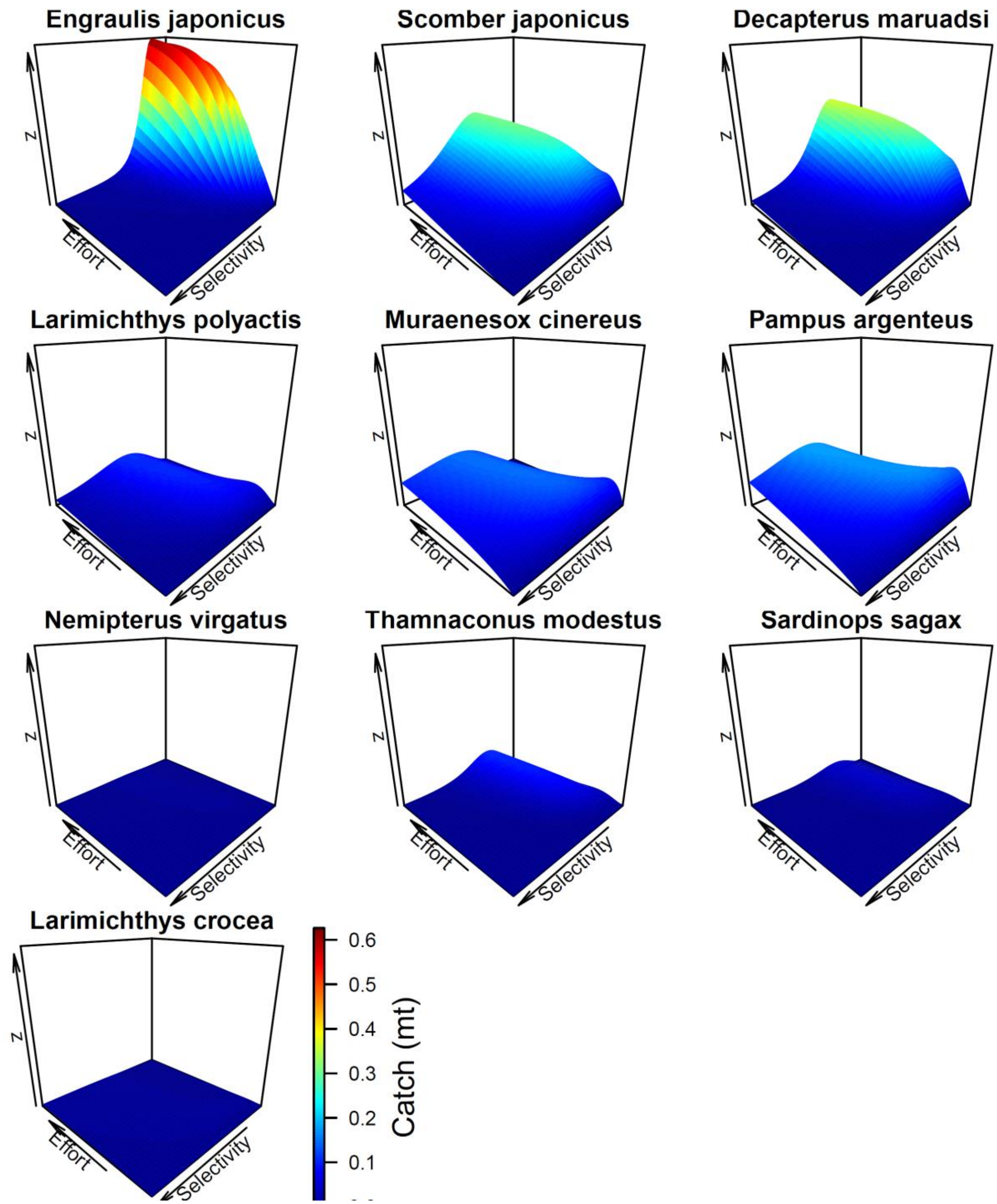


Fig. S13. Catch surfaces by effort and selectivity combination for the remaining species in the East China Sea.

Table S1. Input parameters for mizer (a size-spectrum ecosystem modeling framework). “Kappa” is specified as 9e12.

species	Common names	w_inf (g)	w_mat (g)	Beta	sigma	r_max	k_vb	a	b
Trichiurus lepturus	Large head hairtail	5000	326.27	100	2	5.12E+09	0.42	0.0148	2.97
Engraulis japonicus	Japanese anchovy	45	6.16	100	2	1.03E+11	0.6	0.00468	3.12
Scomber japonicus	Chub mackerel	2900	263.56	100	2	3.41E+09	0.3	0.00776	3.06
Decapterus maruadsi	Japanese scad	210.3	45.65	100	2	8.27E+09	0.98	0.0139	2.99
Larimichthys polyactis	Small yellow croaker	1081.15	36.75	100	2	2.85E+09	0.44	0.0269	2.87
Muraenesox cinereus	Daggertooth pike conger	13860.78	680.1	100	2	9.78E+08	0.5	0.00145	2.98
Pampus argenteus	Silver pomfret	6437.09	186.82	100	2	3.53E+09	0.25	0.0381	2.94
Nemipterus virgatus	Golden threadfin bream	854.6	78.35	100	2	3.42E+08	0.38	0.0378	2.82
Thamnaconus modestus	Black scraper	538.46	45.76	100	2	3.81E+09	0.34	0.01	3.04
Sardinops sagax	Sardine	486	75.12	100	2	1.4E+09	0.35	0.00871	3.07
Larimichthys crocea	Large yellow croaker	10659.05	101.33	100	2	37704463	0.43	0.02	3.06
Other fish		5000	500	100	2	1.20E+10	0.4	0.01	3

Table S2. Reference for input parameters and intermediary parameters used to calculate parameters in Table S1.

Species	maxLen (Fishbase)	w_inf		Wt_ a	Wt_b	(ref)	vbK	(ref)	LenAtMat	(ref)	diet (Fishbase)	M	(ref)
T. lepturus	234.00	5000.00	Fishbase	0.00	2.97	36	0.34	39	29.00	Fishbase	fish	0.44	35
E. japonicus	18.00	45.00	Fishbase	0.00	3.12	FishBase	0.60	FishBase	11.00	Fishbase	copepods	0.63	FishBase
S. japonicus	64.00	2900.00	Fishbase	0.01	3.06	FishBase	0.52	Fishbase	26.10	Fishbase	fish	0.40	43
D. maruadsi	25.00	210.31	calculated	0.01	2.99	36	0.79	Fishbase	15.00	42	copepods	0.85	44
L. polyactis	40.00	1081.16	calculated	0.03	2.87	37	0.26	37	18.10	Fishbase	fish	0.48	37
M. cinereus	220.00	13860.78	calculated	0.00	2.98	FishBase	0.26	40	80.00	40	fish	0.15	45
P. argenteus	60.00	6437.09	calculated	0.04	2.94	36	0.25	Fishbase	18.00	Fishbase	zoops	0.59	46
N. virgatus	35.00	854.60	calculated	0.04	2.82	36	0.31	Fishbase	18.00	Fishbase	fish crusts	0.67	47
T. modestus	36.00	538.47	calculated	0.01	3.04	FishBase	0.34	41	16.00	Fishbase	plankton	0.26	41
S. sagax	39.50	486.00	Fishbase	0.01	3.07	FishBase	0.35	Fishbase	9.00	Fishbase	copepods	0.40	48
L. crocea	80.00	10659.05	calculated	0.02	3.06	38	0.43	38	17.00	Fishbase	fish	0.65	calculated

Table S3. Reference for input parameters and intermediary parameters used to calculate parameters in Table S1.

Species	L25	L50
T. lepturus	13.5	16.3
E. japonicus	21.2	25.9
S. japonicus	17.8	21.7
D. maruadsi	13.9	16.8
L. polyactis	9.5	11.3
M. cinereus	13.6	16.5
P. argenteus	7.2	8.4
N. virgatus	7.2	8.5
T. modestus	16.1	19.6
S. sagax	17.0	20.7
L. crocea	11.5	13.8
Other fish	16.1	19.6

Table S4. References for fishing mortality in the East China Sea and surrounding ocean.

Fishing mortality	year	reference	Species
2.8	2003	35	*T. lepturus (ECS)*
1.02	2004	44	*D. maruadis (SCS)*
1.3	2004	45	*M. cinereus (ECS)*
0.94	1997	46	*P. argenteus (ECS)*
1.01	2002	47	*N. virgatus (SCS)*
1.21	2002	43	*S. japonicus (ECS)*

Table S5. Reported trophic levels from Fishbase used in Watson *et al*. (8) to determine primary productivity needs and adjust trophic levels required to balance fishery yields with primary productivity.

Species	Used trophic level	Adjusted trophic level
Engraulis japonicus	3.14	2.71
Sardinops sagax	2.84	2.84
Trichiurus lepturus	4.42	3.81
Mackerels	3.65	3.15
Scyphozoa	3.46	2.98
Trachurus japonicus	3.40	2.93
Todarodes pacificus	4.28	3.69
Scomber japonicus	3.38	2.91
Cololabis saira	3.71	3.20
Molluscs	2.27	2.27
Others	3.14	2.70