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Supplementary Materials for

Global ecosystem overfishing: Clear delineation within real limits to production

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Recall that overfishing of either populations or ecosystems (Fig. 1) follows common and similar patterns, ultimately with the resulting yield curve exhibiting a catch (C) maxima at some intermediate level of effort (E) resulting in a decline of catch-per-unit-effort (CPUE) (fig. S1). A suite of other effects is observed in Ecosystem Overfishing (EOF; EQ 2, 4) that collectively provides evidence that EOF is occurring. A well-defined threshold helps to clearly establish EOF. The proposed thresholds for the three indices (Ryther, Fogarty, Friedland) should have efficacy in detecting EOF and should align with the bulk of other evidence that EOF is occurring in a particular ecosystem.

These three indices indicated that many tropical, especially Southeast Asian, and many temperate Large Marine Ecosystems (LMEs) were experiencing EOF, with many exceeding even extreme threshold values (Fig. 3- main text). Here we examine further evidence for EOF in example ecosystems.

The yield curves exhibit the classical patterns one would expect from theory (fig. S1) for the Gulf of Thailand (fig. S2a). The countries surrounding the Gulf of Thailand have been significant fish producers, not only in aquaculture but also marine capture fisheries (1). Historically catches have focused on smaller, lower trophic level (TL) clupeids, engraulids, and scombrids, with some catches shifting to invertebrate species. There have been high catches at low effort, leading to low catches at high effort. A corresponding classical decline in CPUE has been observed. Almost all the catches during the past 60+ years have been above the recommended threshold, and many are above the extreme threshold. The Gulf of Thailand has had a noted history of sequential overfishing of its fish populations (1), and many of its fish taxa are not only experiencing overfishing and are in an overfished state, but are also increasingly smaller-sized fish (1,30-31). Now many (30-40%) “trash” species are retained or even targeted in the catch. The Gulf of Thailand LME is recognized as being in a highly perturbed state, with significant pressures on the fishery ecosystem (56), with other, non-fishing pressures impacting and exacerbating environmental conditions of the ecosystem (56). Other tropical ecosystems exhibit very similar patterns of total yield and CPUE (fig. S2b,c) as noted for the Gulf of Thailand, with both the East China Sea and the Canary Current having most catches above the proposed thresholds, although the latter has had some lower effort-lower catch conditions (fig. S2b). Much of these catches exceed even the extreme threshold values, suggestive that EOF would be detected. Certainly there are nuances among these tropic ecosystems, but the same result of EOF being observed and all the ancillary evidence as described for the Gulf of Thailand and confirming responses noted in EQ 4 are all also well documented for the East China Sea (1) and the Canary Current (1,56). When effort is low and catches are below the proposed threshold, the CPUE in the Canary Current is higher, implying that maintaining catches below the threshold does have a positive impact. The caveat for this LME is that it is relatively more susceptible to upwelling and oceanographic dynamics than other systems (57), but this is accounted for in other, productivity-based thresholds and reflected in the catches. It could very well be that these tropical examples could have higher transfer efficiencies, catches at lower trophic levels, and higher primary productivities than is typically estimated, thus the extreme threshold value would be more appropriate. Yet even that extreme value indicates that the catches for these fishery ecosystems has been historically quite high.

Example temperate ecosystems exhibit similar patterns in their yield curves (fig. S2d,e). Both the Yellow Sea (56) and the North Sea (57) have also seen the classical signs of EOF, with evidence for sequential depletion, smaller fish sizes, increased effort, lower biomasses, etc. (EQ. 4). The catch in these ecosystems were both over the proposed ecosystem overfishing thresholds, and continue to exhibit responses consistent with EOF. These example ecosystems have experienced continuous, well-documented histories of overfishing, and the proposed thresholds clearly detect this phenomenon for EOF. For instance, the North Sea shows a series of populations exhibiting sequential overfishing ($F/F_{MSY}>1$) even as total catches peaked around 3-3.5 M t yr^{-1}, and these population estimates of fishing are all at or over overfishing rates (DOI: 10.17895/ices.pub.3721), reinforcing the EOF delineation. Yet what if there is a recovery from overfishing; can these thresholds detect that response as well? Another temperate example, the Scotian Shelf, exhibited similar patterns for part of it's history, but after several populations were near collapse, governance interventions notably lowered fishing effort (fig. S2g). After effort was lowered, evidence for a recovery of the fishery ecosystem emerged, ultimately resulting in an increase in CPUE (fig. S2g; 56,57). The Scotian Shelf catches are now below the proposed threshold and are mostly fished in a sustainable manner relative to definitions of ecosystem overfishing (56,57).

Both example polar ecosystems have also exhibited either notable (the Newfoundland-Labrador Sea; 57) or moderate (the Barents Sea; 56,57) instances of EOF, followed by a lowering of fishing effort such that now catches are below the proposed thresholds (fig. S2f,h). Both the Newfoundland-Labrador Sea (57) and the Barents Sea (56,57) exhibit fishing patterns consistent with evidence for sustainable levels of catch. The proposed thresholds seem to capture both when fishing is excessive for the entire ecosystem, especially as seen in the capelin collapses seen in both ecosystems that permeated the food web (especially the Barents Sea; 57), and also the recovery of the fishery ecosystem.

An important caveat is worth noting regarding the empirically-based curves (fig. S2) compared to the classical yield curve (fig. S1). The peak values observed for these ecosystems more likely represent instances of excessive fishing rather than approximating levels of maximum sustainable yields (MSY), with perhaps the exception of the Barents Sea (fig. S2f). The peaks shown here correspond to overfishing levels of catch that continue to degrade CPUE and biomass over time. Independent estimates of multispecies or system-level MSY for many of these ecosystems correspond more with the thresholds noted (13,15,26) than the peak values observed here.

In sum, empirical evidence demonstrates that the ecosystem level yield curves exhibit behaviors as expected with increased catches relative to fishing effort. The proposed thresholds were also able to detect both EOF, indicative of instances where catches would ultimately decline (which they did), and to detect and delineate recovering fishery ecosystems.

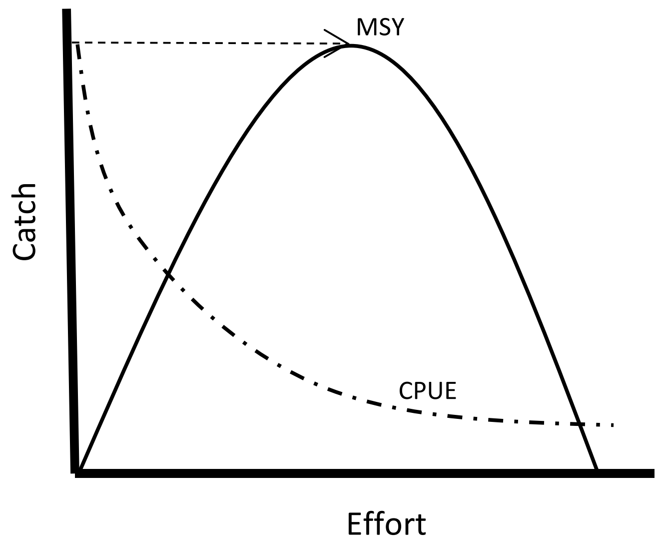

Fig. S1. The classical fishery yield curve showing catch and CPUE compared to effort. Typical yield curve, exhibiting a general pattern of overfishing, with catches (C) reaching maximum sustainable yield (MSY) at approximately one-half the carrying capacity of the population; this corresponds to an intermediate level of effort (E) to maximize catches. Also shown is the catch-per-unit-effort (CPUE) generally declines as effort increases; biomass (B, not shown) typically follows the pattern exhibited by CPUE as effort increases. In the ecosystem instance, this curve behaves similarly as for a population, but is understood to be referring to multispecies maximum sustainable yield (MMSY) or total system-level yield with similar patterns for CPUE and B.

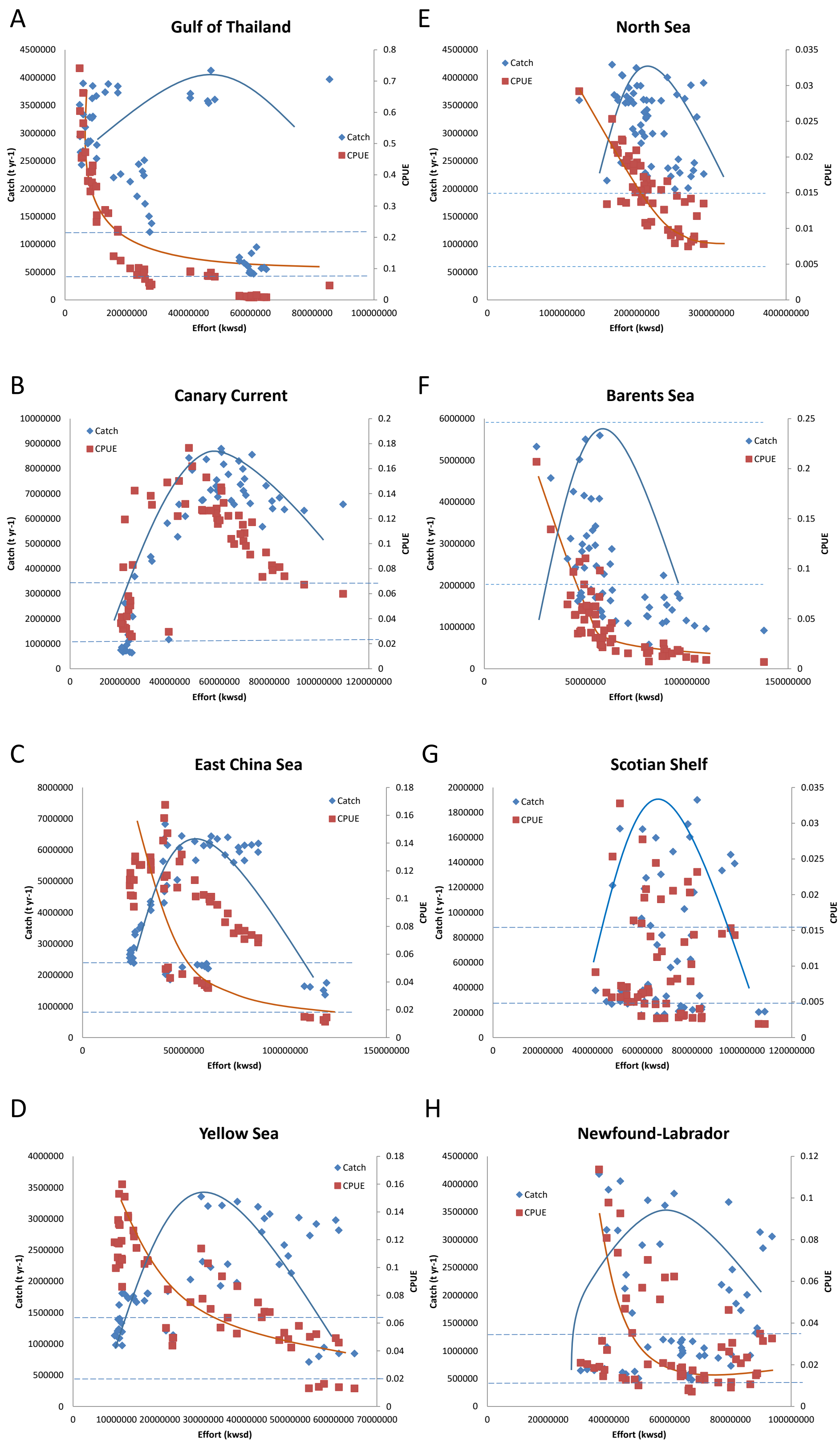

Fig. S2. Fishery yield curves for all fish (total) catches for example LMEs. Yield curves showing total catch (t yr^{-1}) and total catch-per-unit-effort (CPUE) across all taxa against all fishing effort (kwsd) in an ecosystem. The colored lines correspond to curves for the Catches or CPUE; the dashed line corresponds to the Ryther index threshold, and the extreme value of that threshold (i.e., 3x, or what would be the very high end of observed catches, transfer efficiencies, and lower trophic level situations) near the top of each graph. (A) Gulf of Thailand. (B) East China Sea. (C) Canary Current. (D) Yellow Sea. (E) North Sea. (F) Scotian Shelf. (G) Barents Sea. (H) Newfoundland-Labrador Sea.