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Comparative production of fisheries yields and ecosystem overfishing in African Large Marine Ecosystems

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ABSTRACT

Marine capture fisheries in African Large Marine Ecosystems (LMEs) are important from economic, cultural, social, and food provision perspectives. These African fisheries have a long history of high exploitation in the context of data-limited situations. There is a growing, global movement (both in terms of management requirements and scientific efforts) to develop measures of ecosystem overfishing (EOF) that detect overfishing of *an entire ecosystem* using readily available data and based on widely repeatable patterns. These EOF indicators extend the thinking beyond single stock overfishing to an entire ecosystem and are largely based on well-established trophic theory. Moreover, they need to be germane for data limited situations, easily interpretable, and simple to calculate. Here we introduce and present the results of several of these indicators—the Ryther index, Fogarty index, and Friedland index—as well as indices based on cumulative biomass-Trophic Level curve parameters for eight African LMEs. Significantly, all these EOF indicators also have thresholds beyond which EOF is indicated, particularly when coupled with other evidence. These thresholds were applied to the African LME EOF indicators to determine the degree to which EOF may be occurring. Five out of eight African LMEs exhibited symptoms of EOF, one with significant EOF, with at least one LME still currently experiencing EOF, and three more that may be close to EOF thresholds. One LME exhibited evidence of recovering trends. Additionally, EOF indicators detected changes in the LMEs five-ten years prior to major impacts that would be identified by piecing together fishing impacts on a stock-by-stock basis. We conclude that if EOF is detected, at the very least these relative simple measures should be monitored and means to mitigate total fishing pressure in an ecosystem should be explored.

1. Introduction

Fisheries and marine ecosystems that support them are important. Clearly fisheries are an important part of the global economy; the fisheries sector represents > 15% of the blue economy sector, is valued at > 232 US$ Billion, and contributes ~60 million jobs globally (FAO, 2018a). In addition to trade and jobs, fish provide the primary, consistent source of protein consumed (over 20% of all protein consumption) for nearly 50% of the world's population (FAO, 2018a). Approximately 30–35% of fish populations are fished unsustainably, with an additional 60% fully fished (FAO, 2018a). The implications of unsustainable fisheries extend beyond the

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simple status of fish populations and economic viability of fisheries into global food security, social stability, cultural survival, and even national security (Pauly et al., 2005; Allison et al., 2009; Badjeck et al., 2010; Srinivasan et al., 2010; Coulthard et al., 2011; Garcia and Rosenberg, 2011; Rice and Garcia, 2011; Sumaila et al., 2011; Barange et al., 2014; Jennings et al., 2016; Blanchard et al., 2017). Not only are fish populations, fleets and fishery systems impacted from unstainable fishing (Pauly et al., 2002; Hilborn et al., 2015; Link, 2018), but this also results in much broader impacts on marine ecosystems (Botsford et al., 1997; Jennings and Kaiser, 1998; Micheli, 1999; Jackson et al., 2001; Coll et al., 2008; Link, 2010, 2018). Unsustainable fisheries practices results in, for example, cascading effects that hamper key habitats and species (Scheffer et al., 2005), facilitate blooms of invasive species (Daskalov, 2002), impact sustainable human exploitations (Libralato et al., 2004) and enhance negative effects of climatic changes (Gaines et al., 2018). To address many of these challenges simultaneously, a broader, more systematic means of detecting and delineating overfishing, before it sequentially impacts fish population after fish population, fishery after fishery, and ultimately marine ecosystem functioning, is warranted (Link 2010, 2018; Fogarty, 2014; Link and Watson, 2019).

African fisheries are important and pose some unique challenges. They have similar statistics as noted for global fisheries features in terms of fisheries value, associated jobs, human consumption, food security, etc. (de Graaf and Garibaldi, 2014, Belhabib et al., 2015, FAO, 2018a; Satia, 2016; USAID, 2018). But what distinguishes African fisheries from those elsewhere is, generally speaking, the notable lack of capacity and infrastructure —to monitor, manage and govern—for these fisheries. Many of the fisheries in Africa are small-scale (i.e., artisanal) or else have fish that are caught and exported by large foreign vessels, making them difficult to monitor or trace. Combined, these conditions result in estimates of > US$ 10 Billion that are lost due to illegal, unreported and unregulated catch each year (World Bank and United Nations Department of Economic and Social Affairs, 2017a, World Bank, 2017b; USAID, 2018). This by no means implies that there is not any excellent and focused work on marine capture fisheries and Large Marine Ecosystems (LMEs) in Africa nor that there has been no progress toward improving fisheries; there most certainly is and has been (e.g., Sherman et al. 1993, Hempel and Sherman, 2003, Nielsen et al., 2004, Roux and Shannon, 2004, Santos et al., 2005, Cochrane et al., 2009, Satia, 2016, Sherman and Hamukuaya, 2016). Rather, the data limitations posed by the majority of African fisheries, and the resultant limited governance infrastructure in the majority of African LMEs have been identified as major challenges impeding growth for the African blue economy (World Bank and United Nations Department of Economic and Social Affairs, 2017a), arguably making Africa (along with Asia) one of the most challenging regions for fisheries in a sustainable development context (Coll et al., 2013; World Bank, 2017b). This makes it imperative to estimate and explore marine ecosystem overfishing (EOF) in African LMEs, as some methods for assessing ecosystem overfishing are specifically designed for data limited situations. Even in relatively data rich situations, national and international policies are increasingly calling for ecosystem indicator thresholds. Examples include the Good Environmental Status in the Marine Strategy Framework Directive (European Parliament and Council of the European Union, 2008) context in Europe, and Ecosystem-based Fisheries Management policies in the US context (NMFS, 2016); this has extended internationally via the Sustainable Development Goals in the UN context (United Nations, 2015). The call for such thresholds is highly germane for African LMEs (World Bank and United Nations Department of Economic and Social Affairs, 2017a,World Bank, 2017b; Satia, 2016; USAID, 2018; Link and Watson, 2019).

There are now measures to determine if ecosystem overfishing (EOF) is occurring. There have been several attempts to quantitatively characterize the impacts of overfishing on marine ecosystems (e.g., Pauly and Christensen, 1995; Murawski, 2000; Tudela et al., 2005; Gascuel et al., 2005; Bundy et al., 2005; Link, 2005; Coll et al., 2008; Libralato et al., 2008; Shin et al., 2010a; Halpern et al., 2012; Link et al., 2015). But there are few, if any, that have had clear thresholds and delineation of EOF (Libralato et al., 2008; Fay et al., 2015; Link et al., 2015; Large et al., 2015; Samhouri et al., 2017; Tam et al., 2017). Recently, definitions of EOF with limit thresholds have been proposed (Link et al., 2015; Link and Watson, 2019; Libralato et al., 2019), and we adopt those here for assessing African LMEs. Here we define EOF as an instance where the sum of all catches are flat or declining, total CPUE is declining, total landings relative to ecosystem primary production exceeds suitable limits as evinced by the bulk of evidence that the Ryther, Fogarty and Friedland indices (Link and Watson, 2019) exceed thresholds, and that the cumulative trophic curves parameters are below thresholds indicative of system-wide perturbation (Libralato et al., 2019). We describe these further below. The salient point is that these indicators of EOF are based on widely observed and repeatable patterns, use commonly available and widely reported data, and can be considered as a nascent standard to see if thresholds have been grossly exceeded. Our objective in this work is to estimate, present and examine these main indicators of EOF for African LMEs.

2. Materials and methods

2.1. A brief primer on ecosystem overfishing, EOF indicators, and cumulative biomass indicators

As noted, there has been much consideration of the ecosystem effects of overfishing (e.g., Pauly and Christensen, 1995; Murawski, 2000; Tudela et al., 2005; Gascuel et al., 2005; Bundy et al., 2005; Link, 2005; Coll et al., 2008; Libralato et al., 2008; Shin et al., 2010a; Halpern et al., 2012; Link et al., 2015). But only recently have there been quantifiable, repeatable, widely observed, and clearly defined facets of Ecosystem Overfishing (Link and Watson, 2019) that particularly have associated thresholds. Before delving into EOF, let us review the basics of single species overfishing. The dynamics of single population overfishing are well chronicled; as catch declines, effort increases, which is then repeated.

This is Graham's “Law of Overfishing” (Graham, 1943; Smith, 1994) implying that as catch-per-unit-effort (CPUE) declines, an increasing amount of time is spent fishing in an increasingly larger area. For an individual population, as the fishing rate (F) increases mortality up to an unknown maxima, while numbers of fish, biomass of the population, mean size (usually length), mean weight-at-age, mean size- and age-at-maturity, fecundity, recruitment, somatic and population growth, productivity and ultimately yield all

decrease.

As this occurs, the area fished and effort to catch fish goes up, resulting in a fishing rate that exceeds that for maximum sustainable yield (e.g. $F/F_{MSY} > 1$). There are various caveats to this regarding growth or recruitment overfishing (Murawski, 2000; Hilborn et al., 2015), but the general patterns hold based on population dynamic theory. This theory and practice of population overfishing have well demarcated features (Smith, 1994; Mace, 1994; Murawski, 2000; Hilborn et al., 2015) which lead to relatively clear thresholds of overfishing and overfished population status, representing important decision criteria for fisheries management.

Most measures of overfishing have focused on individual fish populations, yet the concept can be applied to delineate EOF. By extending definitions of single species overfishing, there is an analogous suite of overfishing dynamics for ecosystems (Murawski, 2000; Link, 2005; Link et al., 2015; Link and Watson, 2019). As individual population catch declines and effort increases, such that CPUE ultimately declines beyond what is economically viable for a given population, catch shifts towards a second, less preferred species and the cycle then repeats itself, *ad infinitum*.

Overall catch in the ecosystem increases until total CPUE declines, escalating to the point of systemic degradation. This is the Law of Sequential Depletion (Smith, 1994; Murawski, 2000), a corollary to Graham's Law of Overfishing (Graham, 1943; Smith, 1994). The cycle of CPUE implies an expansion of both geographic and taxonomic scope as fleets pursue more and more distinct types of biomass in more and more distinct and distant habitats to maintain economically viable levels of CPUE (Watson et al., 2004, 2015; Swartz et al., 2010). For the system of populations, as total catch (or effort) increases when integrated across all species, the mean size (usually some measure of length; Watson et al., 2003), total biomass and total yield decline, whereas the size spectra slope increases (Link, 2005; Blanchard et al., 2012). Besides the facets noted above occurring across all species, other composite impacts are also observed. The species composition changes, and thus biodiversity may change, but not always in a clearly predictable manner as, by definition, any particular diversity estimate can result from multiple responses to a range of changes in multiple configurations of species composition. These caveats aside, the principles of sequential depletion generally hold as based on theories from community ecology in a perturbation context (Link et al., 2015). For energy flow and food webs effected by fisheries, as overall catch (or effort, or F) increases, the Loss in Production (or L) index (Libralato et al., 2008), total system throughput (sensu Odum, 1969), system ascendancy (sensu Ulanowicz, 1986), biomass of apex predators of conservation significance, cumulative biomass inflection points, cumulative production, mean trophic level (Pauly et al., 1998) and system redundancy all decline (Libralato et al. 2008, 2019; Link et al., 2015). Disruption in trophic linkages also typically occurs (e.g. forage fishes; Smith et al., 2011), resulting in changes in ecosystem functioning due to altered dynamics of energy flows (i.e. predator-prey dynamics, competition, etc.) which further highlights the need for ecosystem-level indicators.

Similar to the single population instance, as this occurs, the area fished and effort to catch all fish goes up, resulting in a system-level fishing rate that exceeds that for maximum sustainable yield of the system ($F_{System}/F_{SystemMSY} > 1$; c.f. Worm et al., 2009; Rindorf et al., 2017; Link, 2018; Thorpe, 2019).

In essence, one can extend the typical single stock yield curve from an individual population to an entire system of fishes with the same general properties and relationships (Gaichas et al., 2012; Link and Watson, 2019). Doing so links all fisheries removals to the nominal carrying capacity of the ecosystem. In other words, fishing effort should be at a rate that is less than the rate of ecosystem net primary production required to maintain the aggregate of all fished taxa. We acknowledge that there are many other potential facets of EOF relating to habitat, bycatch, biodiversity, apex predators, ecosystem functioning, etc. (Botsford et al., 1997; Jennings and Kaiser, 1998; Micheli, 1999; Jackson et al., 2001; Link, 2010, 2018; Smith et al., 2011; Hilborn et al., 2015). Yet we emphasize trophic transfer as a basis for determining the limits of fisheries production as that is intuitive, has had copious background studies establishing and describing these relationships (Graham and Edwards, 1962; Ricker, 1969; Schaefer, 1965; Ryther, 1969; Pauly and Christensen, 1995; Chassot et al., 2010; Conti and Scardi, 2010; Blanchard et al., 2012; Friedland et al., 2012; Watson et al., 2014; Fogarty et al., 2016; Stock et al., 2017), and most population-oriented definitions of overfishing similarly focus on production of the population while acknowledging that other facets of population productivity do not typically use those other features (i.e. links to habitat, predation, etc.) to delineate population overfishing (Mace, 1994; Hilborn et al., 2015).

To put this in context and establish quantitative thresholds for EOF, it has been recognized that there are clear limits to ocean primary production (Antoine et al., 1996, Carr et al., 2006). It then follows that there are limits to fisheries production (Graham and Edwards, 1962; Ricker, 1969; Schaefer, 1965; Ryther, 1969; Pauly and Christensen, 1995; Chassot et al., 2010; Conti and Scardi, 2010; Blanchard et al., 2012; Friedland et al., 2012; Watson et al., 2014; Fogarty et al., 2016; Stock et al., 2017). In essence, there are real limits to how much fish any ecosystem can produce (Pauly and Christensen, 1995), can store in the form of biomass (Schlenger et al., 2019), can be caught (Libralato et al., 2008), and from these facts there are associated thresholds that can delineate EOF based on these limits. A series of trophic transfer calculations, modeling, and global observations demonstrate these limits to fisheries production, as ultimately set by primary production (Pauly and Christensen, 1995, Chassot et al., 2010, Conti and Scardi, 2010, Friedland et al., 2012, Watson et al., 2014, Fogarty et al., 2016, D'Alelio et al., 2016; Stock et al., 2017, Link and Watson, 2019; Petrik et al., 2019).

Without providing all the details here (c.f. Link and Watson, 2019), we can calculate thresholds used to delineate Ecosystem Overfishing. These are the Ryther index, Fogarty index, and Friedland index (Link and Watson, 2019). These indices are based upon the ecological principle of trophic transfer, with specific thresholds developed for each index to delineate whether EOF is actually occurring. The Ryther index is comprised of total catch presented on a unit-area basis for an ecosystem. The Fogarty index is the ratio of total catches to total primary productivity in an ecosystem. The Friedland index is the ratio of total catches to chlorophyll in an ecosystem. The thresholds for these are:

- Ryther index ~ 1 (to a high of 3) t km-2 yr-1

- Fogarty index ~ 1‰
- Friedland index ~1

When an ecosystem has values near anyone of these index thresholds, it warrants further attention with respect to EOF. When it has values exceeding all three index thresholds, it is highly probable that EOF is occurring in that ecosystem. When the values are 3–5 times greater than the threshold for more than one of these indices, it is probable that significant EOF is occurring. These thresholds have been empirically tested with consistent and repeatable results of thresholds being at these levels (Bundy et al., 2012; Link et al., 2012; Large et al., 2015; Tam et al., 2017). Examining these thresholds globally suggests that ~50% of the worlds LMEs are experiencing EOF (Link and Watson, 2019). We want to further unpack these details of EOF indicators for African LMEs.

Additionally, cumulative trophic curves are the emergent ecosystem properties of examining cumulative biomass (cumB) and cumulative productivity (cumP) across trophic levels (TLs; Link et al., 2015). Notably such emergent properties are based on a clear theoretical background of biomass accumulation that is (log-) normally distributed (Fig. 1c) and transfers that efficiency-limited up through a food chain (Fig. 1b). Thus, if production at different trophic levels always results in pyramids because the transfer efficiency is always lower than 1, cumulative curves of production are monotonically asymptotic tending to plateau (near the sum of all system productivity). Fundamental trophodynamic features represented by overall system limits based on primary production (Fig. 1a), turn-over of populations, average growth efficiency and growth in size are the overall system limits that influence the production curve (c.f., Link et al., 2015). Additionally, classical biomasses across trophic levels are not necessarily pyramidal in marine systems but are more often rhomboidal due to high standing biomass at TL 2 (i.e., benthos and plankton; Fig. 1b): the cumulative biomass curve across trophic levels (cumB-TL) is thus a sigmoidal curve, i.e. a curve with an inflection point (Fig. 1e). The cumB-TL curves exhibit a typical “S” pattern that seem to hold regardless of type of ecosystem or type of data used to construct them (Pranovi and Link, 2009; Pranovi et al., 2014). The cumB-cumP curves similarly tend to consistently exhibit “hockey stick” curves as well (Fig. 1f). Broader examination has confirmed the existence and commonality of these curves from over 120 different marine ecosystems around the planet (Link et al., 2015) and demonstrated repeatable, consistent and predictable changes in curve shapes due to perturbations that can modify trophodynamic features of LMEs (Pranovi et al., 2012, 2014; 2020; Link et al., 2015; Libralato et al., 2019). In a stylized example of the cumB-TL curve reported in (Fig. 1g; adapted from Link et al., 2015), perturbations result in changes in the “S” curve over time that become less steep and move toward low TLs. Conversely, ecosystem recovery results in increased steepness and movement toward upper TLs of these curves. These situations imply measurable changes on the major curve parameters, primarily determinants of “S” curve such as Biomass inflection point, TL inflection point and steepness (or slope), which can be tracked over time to determine major shifts in condition in an ecosystem. These three simple curve parameters represent emergent properties of LMEs with a surprising degree of insight into ecosystem structure and functioning. Thus the cumulative curves hold some promise in delineating regions of ecosystem state that require management action.

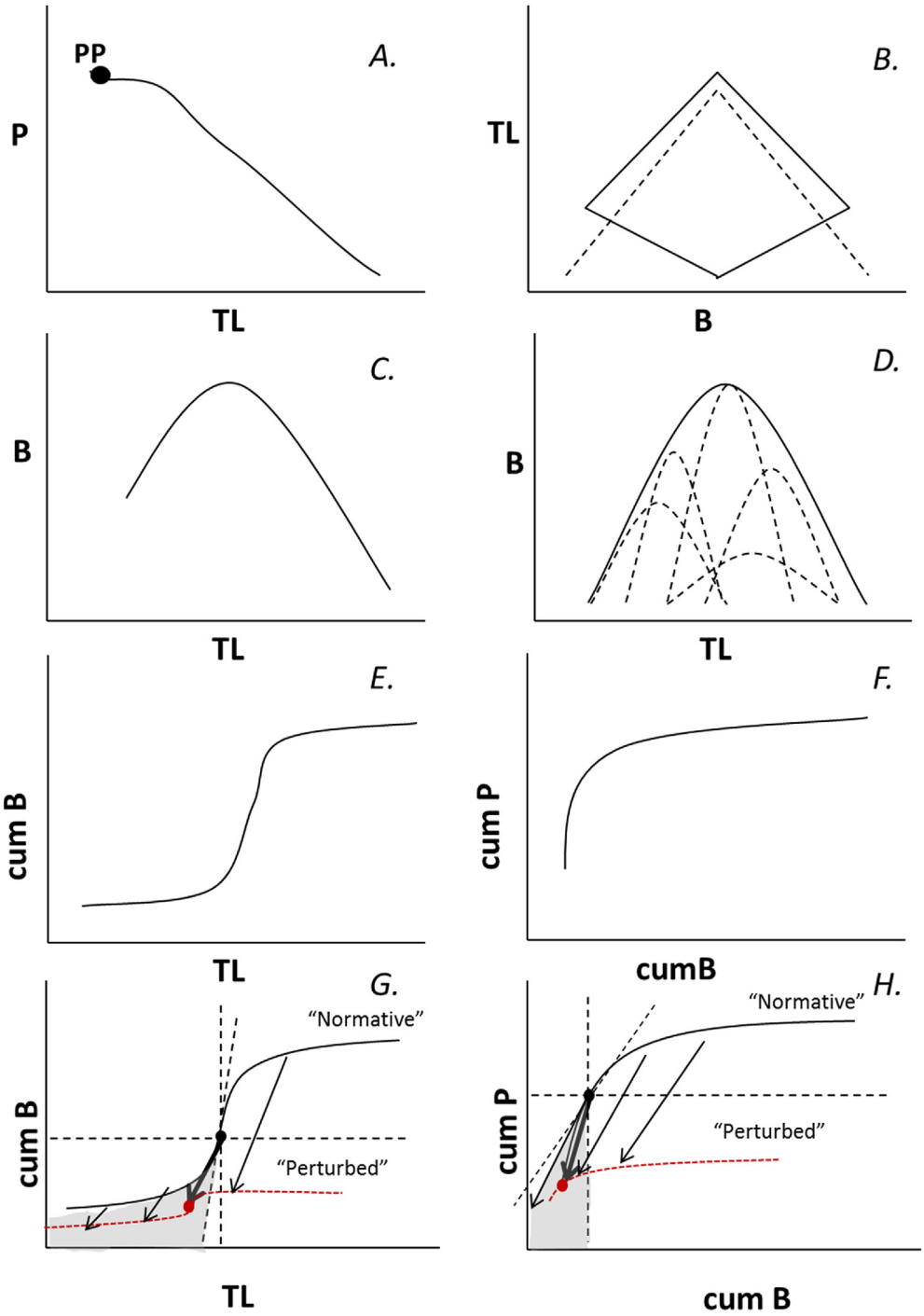
Essentially the cumulative trophic curve big “S” and shrinking hockey sticks are observed in every marine ecosystem, respond consistently to perturbation or recovery, and can inform marine ecosystem overfishing. Following the cumulative trophic “S” curve parameters tracks the dynamics of an ecosystem and indicates the degree of recovery or perturbation. From a global study of nearly all LMEs, important thresholds emerged for the “S” curve parameters (Libralato et al., 2019). The thresholds for these are:

- cumB inflection point ~33%
- TL inflection point ~3.4
- Steepness (slope) ~0.5

This implies that as these curve parameters move towards and pass, and then remain below, these thresholds that the “S” shape of the curve has in fact been stretched out in a manner consistent with perturbation (Fig. 1g). Empirical estimates had slightly higher thresholds (Pranovi et al., 2012; Link et al., 2015), but more refined and larger sample sizes have narrowed these curve parameter values down. Examining these thresholds globally suggest that curve parameters relative to the thresholds suggest ~33% of the worlds LMEs are experiencing perturbation (and in most instances, EOF), most have experienced some degree of transition, and that ~33% are actually in some state of recovery (Libralato et al., 2019, Pranovi et al., 2020). We want to further unpack the details of cumulative trophic curve indicators for African LMEs, particularly as possible indicators of EOF.

2.2. EOF main indicator data sources and analysis

Marine capture fisheries data was obtained from Watson (2017). This database represents a harmonized and mapped compilation of global catch from 1950 to 2014 sourced from the United Nations Food and Agriculture Organization's (FAO) Capture Production 1950–2015 dataset (Release date: March 2016 www.fao.org), International Committee for the Exploration of the Sea (ICES) 1950–2014 (www.ices.dk), Northwest Atlantic Fisheries Organisation (NAFO) Catch and Effort 1960–2014 (www.nafo.int), Southeast Atlantic (SEAFO) Capture Production 1975–2014 (Release date: June 2016) (www.seafo.org), General Fisheries Commission for the Mediterranean (GFCM) Capture production 1970–2014 (Release date: April 2016) (www.gfcm.org), Fishery Committee for the Eastern Central Atlantic (ECAF) Capture production 1970–2014 (Release date: May 2016) (www.fao.org/fishery/rfb/ecaf), Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) Statistical Bulletin 2016 Vol. 28 1970–2014 (www.ccamlr.org) and Sea Around Us project (SAU) – records for FAO area 18 (Arctic) v1 1950 TO 2010 (extrapolated to 2014) (www.seaaroundus.org). See prior descriptions (Watson et al., 2004; Anticamara et al., 2011; Watson, 2017; Rousseau et al., 2019; and references therein) for fuller details of data treatment.



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For comparison, data were downloaded from FAO using the Fish-StatJ v2.12.2 software and database package. Data were also downloaded from the Sea Around Us (SAU) project, by Large Marine Ecosystem (LME), using the online GUI to download CSV files. We explored these data across a range of taxa and taxa groups, across FAO statistical area, Regional Fisheries Management Organization (RFMO), countries, and (Economic Exclusive Zones (EEZs), and LME resolutions. We acknowledge that debates as to the exact magnitude of total marine capture fisheries yield persist (Watson and Pauly, 2001; Watson, 2017; Pauly and Zeller, 2016; Watson et al., 2014; Branch et al., 2010). These debates center around the actual magnitude of fishery production potential, whether the estimates are carrying capacity (K) or Biomass at MSY (K/2), whether the estimates adequately capture IUU fishing, the methods

Fig. 1. Schematic of general patterns of ecosystem dynamics resulting in the cumulative trophic theory (A–H). Panels A–C represent known theory and observations, D constraints, E-F the resultant theory, and G-H predictions from the theory. (A) The decline of productivity across increasing trophic levels, starting at the point where primary production is estimated (Pauly and Christensen, 1995; Lindeman, 1942; Strayer, 1991; Teramoto, 1993; Oksanen, 1997; Friedland et al., 2012; Link et al., 2012). (B) The trophic pyramid (dashed) and rhomboid (solid) of biomass with increasing trophic level (Elton, 1927; Lindeman, 1942). (C) The unimodal distribution of biomass over trophic levels (Lindeman, 1942; Strayer, 1991; Teramoto, 1993; Oksanen, 1997). (D) The trophic spectra of biomasses of individual populations within a total, systemic biomass constraint (Gascuel et al., 2005, 2008; Libralato and Solidoro, 2010). (E) The cumulative biomass sigmoidal pattern across increasing trophic level. (F) The "hockey stick" of cumulative production across cumulative biomass. (G) Prediction showing the shift in cumulative biomass over trophic level from a "Normative" system as it moves (depicted by arrows) to a perturbed system. Dashed lines intercepting axes represent inflection point values, and angled dashed line represents slope of the curve at the inflection point, the dot represents the inflection point, and shaded areas represents a zone of perturbation below some ecosystem threshold. (H) Similar to (G) but for cumulative production across cumulative biomass. B = biomass, TL = trophic level, P = production, PP = primary production, cumB = cumulative biomass, cumP = cumulative production. Adapted from Link et al. (2015).

for extrapolating data are appropriate, and other concerns over missing or misrepresented data. Regardless of these debated caveats as to the magnitude and source of the estimates, the total catch of global marine capture fisheries has been essentially flat for nearly 30 years. Furthermore, although there were differences among data sets in terms of magnitude, the same general trends and order of magnitude results were replicated (Watson and Pauly, 2001; Watson, 2017; Pauly and Zeller, 2016; Watson et al., 2014; Branch et al., 2010). Thus, we used the compiled, composite set from Watson (2017).

Upon examination of these data at multiple spatial scales, the clearest pattern in catches emerged from a half-degree by half-degree resolution of the data, as described previously (Watson et al., 2004; Anticamara et al., 2011; Watson, 2017). Effort data were similarly tallied and presented at this resolution (Anticamara et al., 2011). Catch data were analyzed using Large Marine Ecosystem designations (LME; see below). As noted above, similar data were explored from FAO and SAU based on a country, EEZ, LME and statistical area assignation, but assignments to latitudinal cells were more resolved and hence these other perspectives were not presented. We thus used the Watson (2017) data for each of the eight African LMEs. We acknowledge that aggregation across spatial scales could obfuscate some patterns among fisheries, but at the scale at which most fisheries operate (i.e., LME scale), the main patterns should be emergent. Estimates of primary production (below) were chosen at resolutions consistent with these scales. We also acknowledge that aggregating across taxa could also obfuscate some patterns among fisheries, but since our primary purpose was to explore total catches by ecosystem and this is a relatively simple integration, the total catch patterns would also emerge.

Estimates of chlorophyll a and net primary production were similarly estimated for all LMEs, from 1998 to 2014 using satellite imagery. These used a combined SeaWIFS and MODIS imagery set (http://oceancolor.gsfc.nasa.gov/). Chlorophyll *a* was adopted from the merged time series data (http://hermes.acri.fr/) at 25 km spatial resolution, and annually integrated using monthly time steps. Primary production (net) was estimated using the Behrenfeld method (Behrenfeld and Falkowski, 1997; c.f. Eppley, 1972), and was annually integrated using daily values and then summed for each LME.

Catches assigned to LME areas are expressed as t km^{-2}, which are presented as the Ryther index. The spatial catch data was compared to chlorophyll *a* values to calculate the Friedland ratio index. The same catch data was compared to estimates of net primary production (converted to wet weight) to calculate the Fogarty ratio index (Fogarty et al., 2016). All indices were estimated for each LME. We acknowledge that the LME areas tend to exclude open ocean ecosystems, and as such are areas where fish catches and primary production tend to concentrate; thus although the broader data set covers these open ocean areas, is not emphasized here. Thus, global phenomena need to be interpreted within regional and even local contexts for these LME data. Additionally, within an LME, other sources of production may be occurring at the sub-LME scale that might not be as readily detectable via satellite (upwelling, estuarine, etc. inputs) and thus sporadically and locally alter production estimates. Thus, we recommend that the indices proposed here be used cognizant of other potential sources of productivity and that are germane to the scale at which fisheries management mostly occurs. From these broad LME data, we extracted and examined in more detail the time series of EOF indicators for African LMEs.

2.3. Cumulative curve data sources and analysis

We used landings data for the eight African Large Marine Ecosystems (LMEs) obtained from the Sea Around Us Project (SAU) database (http://www.seaaroundus.org/). These data are the widest sampling of the species and, although not covering the whole spectrum of species in the ecosystem, are used here as a proxy for ecosystem status definition. Data consists in landings weight (ton) by taxa caught each year for the period (1950–2010 included, i.e., 61 years). Taxa represent species or genera for the most important commercial invertebrates and fish species, while some general groups are also present (e.g., bony fish). LMEs span the entire global latitudinal gradient and include all oceans (c.f. Sherman et al., 1993; Hempel and Sherman, 2003).

Each taxa was associated with a trophic level (TL) as obtained from Fishbase (www.fishbase.org) and Sealifebase (www.sealifebase.org); for a few species, TL were assigned according to literature and available ecosystem model outputs (e.g., Stergiou and Karpouzi, 2002). Landings by TL were then determined for each LME.

The catch data for each LME and each year were ordered by increasing TL and a cumulative curve of catches vs TL was generated (i.e. the cumB-TL curve, c.f. Link et al., 2015). The cumB vs TL data resemble an S-shape curve, consistent with prior theory and observations (Pranovi et al., 2012, 2014; Link et al., 2015). For each LME and each year the data were fit independently to an S-shaped curve using a 5-parameter logistic nonlinear regression model (Ricketts and Head, 1999; i.e., using the 'drc' package (Ritz

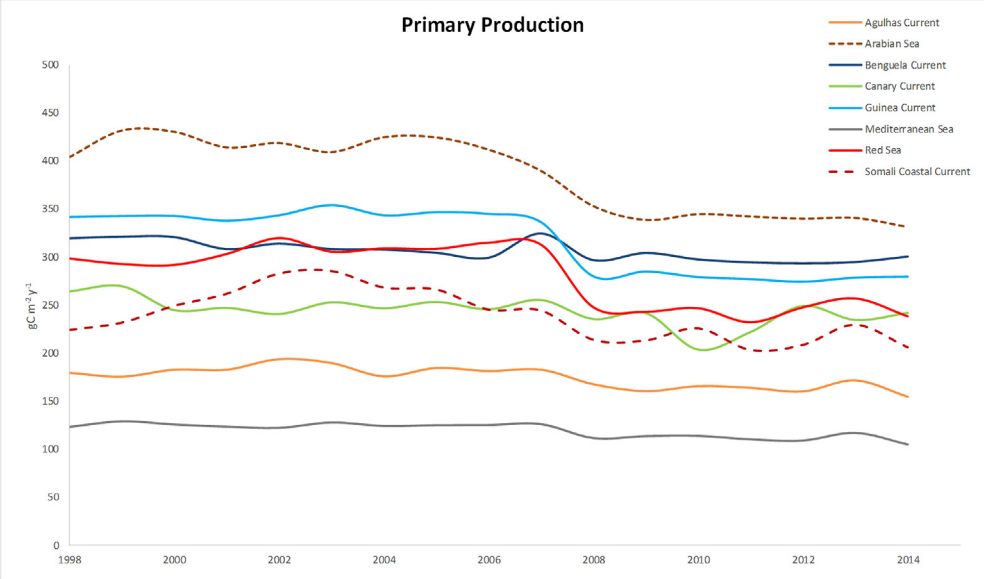

Fig. 2. Primary production estimates for the eight African LMEs. This sets the stage for any subsequent fisheries production.

et al., 2015) for R (v3.5.2; R Core Team 2018)). The main curve parameters, steepness (or slope at the inflection point; Slope), Trophic Level at the inflection point (TL_Infl), and biomass at the inflection point (B_Infl) were estimated through a fitting process. This was executed on an annual basis for each LME, resulting in fitted curves represented by the values of the three estimated parameters (Steep, TL_Infl, B_infl). More details on the method for fitting and estimating the parameters can be found in works by Pranovi (c.f. Pranovi et al., 2014; Pranovi et al., 2020). From these broad LME data sets, we extracted and examined in more detail time series of curve parameters for African LMEs.

2.4. Presentation and comparison

Here we present primary production, catch, effort, catch-per-unit-effort, the EOF indicators (the Ryther index, the Fogarty index, and the Friedland index) over time for the eight African LMEs. We also present the cumulative biomass-trophic level "S" curve parmaeters over time, B_infl versus TL_infl, and slope versus TL_infl, for the eight African LMEs. The biomass at the inflection point is presented as a normalized percentage relative to the maximum in the time series. Both the latter "S" curve plots are intended to show the trajectory of the ecosystem dynamics in response to various known perturbations or recovery efforts.

For comparison, we present examples of major single species or aggregated groups of species catches for the Canary and the Benguela Currents (based on the Watson (2017) data). The aim of that comparison was to contrast the EOF and cumB-TL curves with more traditional data, particularly to highlight detection of the timing of major changes in the ecosystem and landings.

3. Results

Most measurements of primary production (PP) are on the order of 250–350 g C m^2 yr^{-1} (Fig. 2). Of note is the higher PP observed in the Arabian Sea, and lower PP observed in the Mediterranean Sea. Also noteworthy is the shift for many LMEs around 2008; whether this represents a consistent and actual change in PP or reflects a change in treatment of satellite data is not clear. Based on PP alone, one would expect higher potential catches in the Arabian Sea, Guinea Current, Benguela Current and perhaps the Red Sea. Conversely, one would expect relatively lower catches in the Agulhas Current and Mediterranean Sea.

All LMEs have exhibited a notable increase in catch over the past 60 years, perhaps with the exception of the Agulhas and Benguela Current LMEs (Fig. 3). We clearly see much higher catches in the Canary Current LME. The Arabian Sea LME, Guinea Current LME, and Benguela Current LME have also exhibited high levels of catch. The Red Sea and Somali Current LME catches are low, which could reflect actual low exploitation levels or under-reporting of catches. Effort in most African LMEs has steadily increased over time (Fig. 3). Consistent with catches, there have been recent declines in effort in the Benguela Current LME. The Guinea Current LME also exhibited a stabilization of effort in recent years. All other African LMEs fishing effort has increased by a factor of at least five over the past 60 years.

The catch-per-unit-effort (CPUE) has declined over time for all African LMEs (Fig. 4). Most LMEs exhibited peaks in CPUE in the late 1970s and early 1980s. Some have exhibited a steady decline such as the Arabian Sea LME, whereas others have been more abrupt like the Somali Coastal Current LME, Red Sea LME, or Agulhas Current LME. Many of these LMEs are relatively quite low in CPUE, with only the Canary and Benguela Current LMEs exhibiting values above 0.1.

Examining the Ecosystem Overfishing (EOF) indicators reveals a consistent pattern. The Ryther index suggests that the Canary

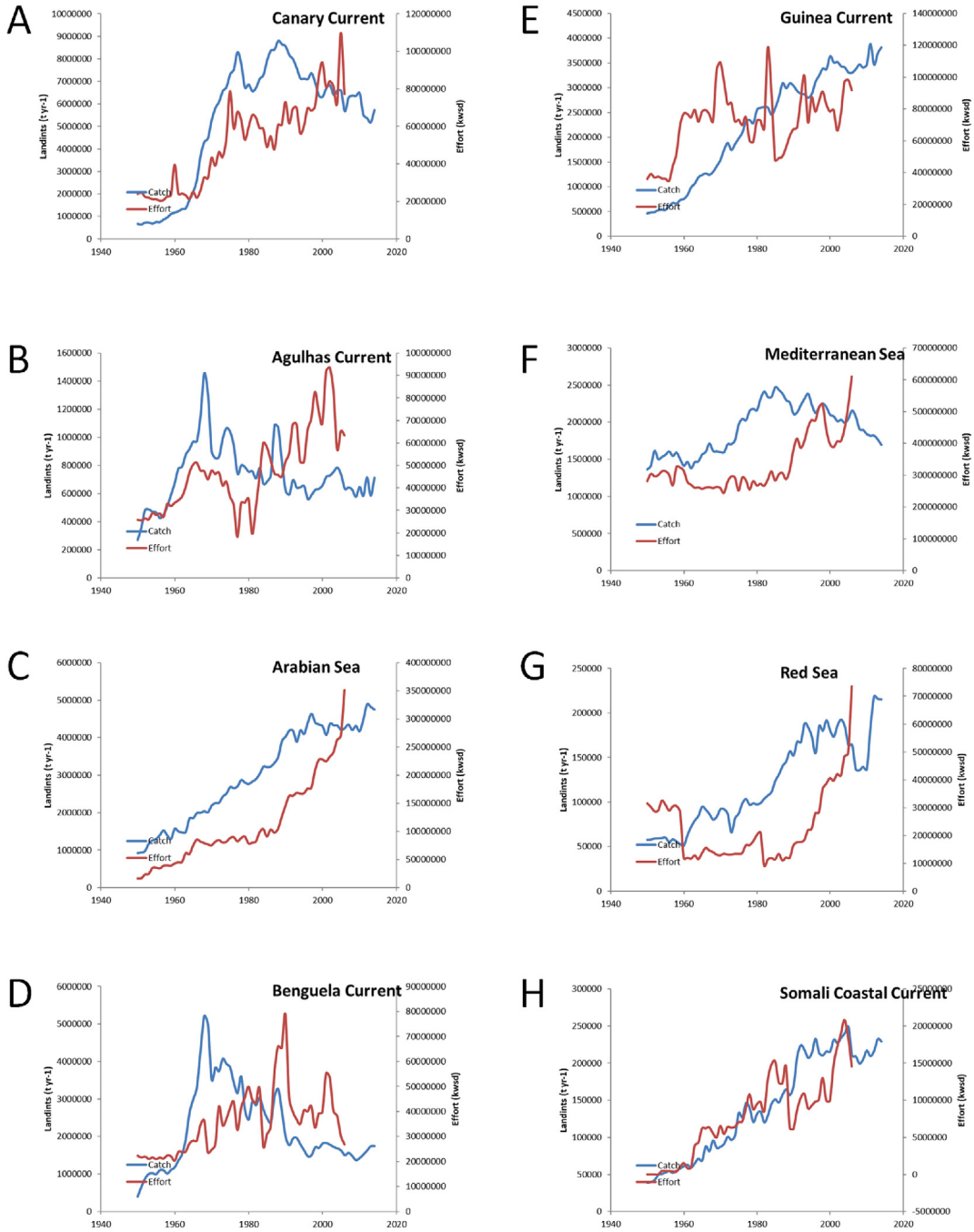

Fig. 3. Total catches and effort for the eight African LMEs. A. Canary Current, B. Aghulas Current, C. Arabian Sea, D. Benguela Current, E. Guinea Current, F. Mediterranean Sea, G. Red Sea, and H. Somali Coastal Current. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Current LME is experiencing significant EOF (Fig. 5) with values well above the global threshold, as do the Fogarty (Fig. 6) and Friedland (Fig. 7) indices. The Ryther index (Fig. 5) also suggests that the Benguela Current LME has improved but may still be experiencing EOF, and that the Guinea Current and Arabian Sea LMEs may be undergoing EOF in more recent years. The Mediterranean Sea is not over the EOF threshold, but it is close (Fig. 5). Conversely, no other LMEs besides the Canary Current LME are experiencing EOF according to the Fogarty index (Fig. 6), but nearly all are according to the Friedland index (Fig. 7). Acknowledging that the Friedland index may be too sensitive and the Fogarty index may be too unresponsive (Link and Watson, 2019), and that these indices are by their underlying data shorter than the Ryther index, it is not trivial that all three indicators suggest the Canary Current is experiencing EOF. That the Ryther index (Fig. 5) and Friedland index (Fig. 7) suggest that the Guinea Current LME is experiencing

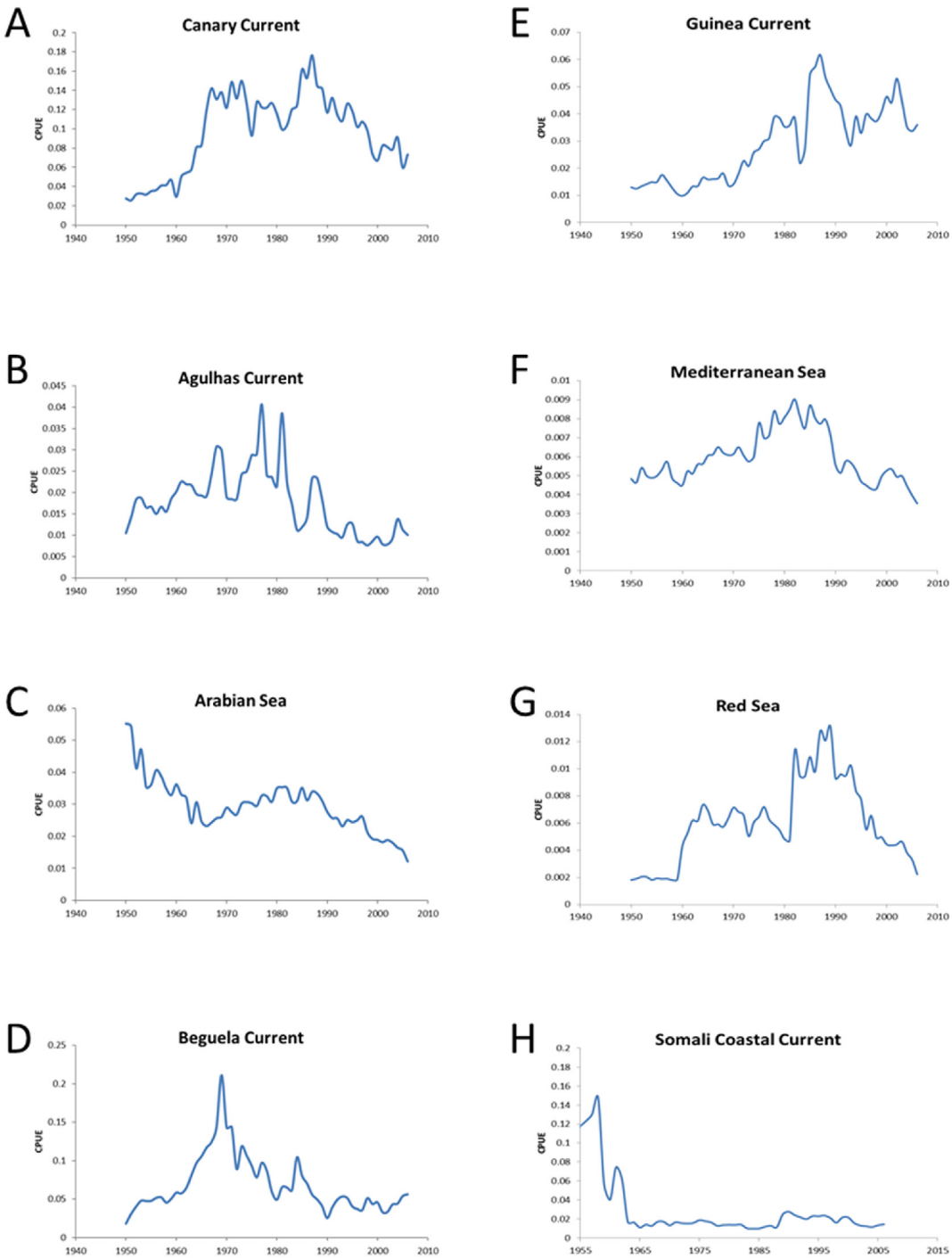

Fig. 4. Catch-per-unit-effort (CPUE) for the eight African LMEs. A. Canary Current, B. Aghulas Current, C. Arabian Sea, D. Benguela Current, E. Guinea Current, F. Mediterranean Sea, G. Red Sea, and H. Somali Coastal Current. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

EOF at a factor of at least twice the index threshold suggests that this LME too may be subject to EOF. We can not rule out the Benguela Current, Mediterranean Sea or Arabian Sea LMEs (Figs. 5 and 7) as being subject to EOF either. Thus one of the eight African LMEs is experiencing significant EOF, one other is experiencing EOF, and up to three more LMEs likely are (although one is improving). That is, five out of eight African LMEs exhibit symptoms of EOF (not only these EOF indicators, but declines in aggregate CPUE as well; Fig. 4). Whether the other three are not or are subject to misreported or underreported catch is uncertain.

The cumulative biomass and trophic level "S" curves were again commonly observed in African LMEs, with obvious dynamics

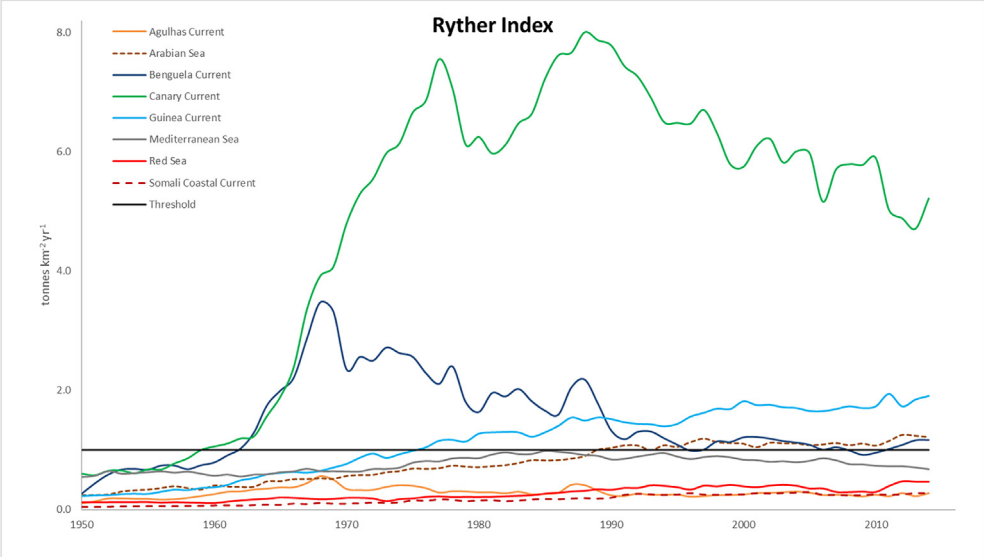

Fig. 5. The Ryther index of ecosystem overfishing for the eight African LMEs. The black line corresponds to globally derived thresholds of ecosystem overfishing (EOF) as determined by Link and Watson (2019).

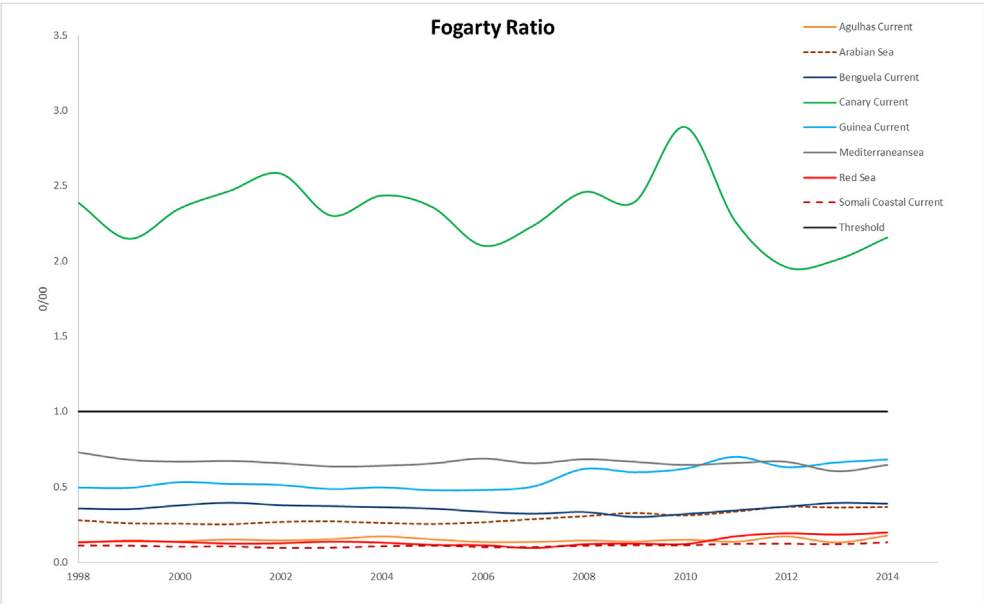

Fig. 6. The Fogarty index of ecosystem overfishing for the eight African LMEs. The black line corresponds to globally derived thresholds of ecosystem overfishing (EOF) as determined by Link and Watson (2019).

over time. The cumulative biomass versus trophic level plot shows that all the African LMEs, except the Arabian Sea and Somali Current, tend to be below the global trophic level threshold of about TL 3.4 (Fig. 8). Of note is that the trajectories of these curves show that for part of the time the Red Sea and Agulhas Current LMEs are above the global trophic level threshold, indicating a shift in ecosystem dynamics. None are consistently below the cumulative biomass threshold of approximately 33%, but the Canary Current, Benguela Current and Agulhas Current LMEs have all been close at certain points in time (Fig. 8). The slope and trophic level at inflection point plot show the classic major phase shift (Libralato et al., 2019; Link et al., 2015) for the Benguela and Agulhas Current LMEs and the Red Sea LME, with particular note in the magnitude of the change in slope (Fig. 9). These symptoms are less clear but also present for the Mediterranean Sea and Canary and the Somali Coastal Currents LMEs (Fig. 9). These are indicative of major ecosystem changes, as the "S" curve has "stretched out" due to perturbation. This is consistent with EOF indicators (Figs. 5–7) for these same LMEs. The Arabian Sea LME exhibits a classical "arch" response, but may actually be improving as the TL is higher and the magnitude in the change in slope is relatively minor (Fig. 9). There are also observable dynamics for the Guinea Current LME, but

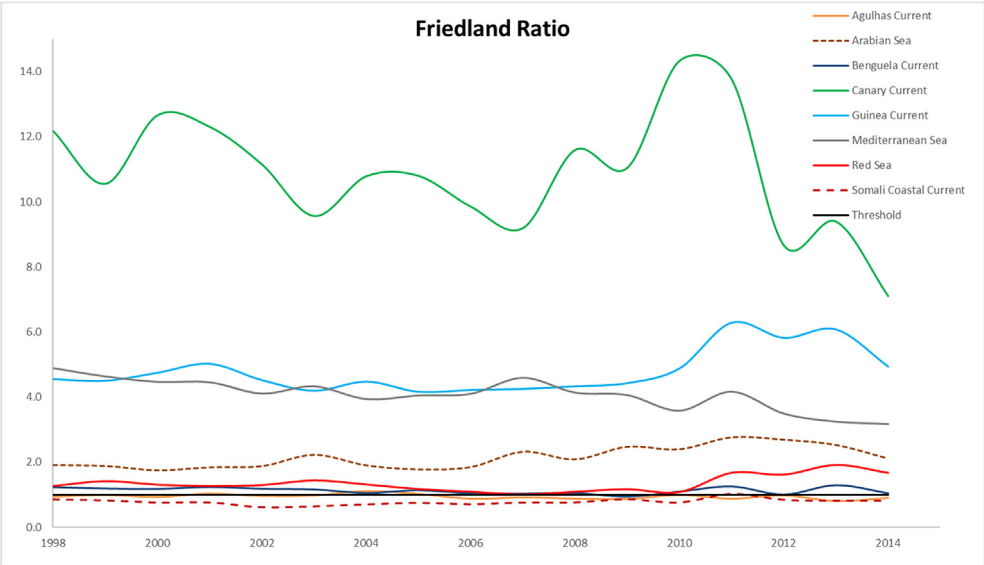

Fig. 7. The Friedland index of ecosystem overfishing for the eight African LMEs. The black line corresponds to globally derived thresholds of ecosystem overfishing (EOF) as determined by Link and Watson (2019).

with no clear pattern and with relatively small changes in magnitude (Fig. 9). Thus, we can infer that although the ecosystems are dynamic for all these LMEs, for six of the eight there has been directional change towards a more perturbed state, albeit with one (Benguela) on a recovery trajectory (Fig. 9). That the same LMEs are similarly detected using both this cumB-TL approach (Figs. 8 and 9) and the EOF indices (Figs. 5–7) confirms that both methodologies detect EOF.

As an example of some of the more specific dynamics of these fisheries in these LMEs, we present landings for major taxa and taxa groups from the Canary Current (Fig. 10). Undoubtedly whenever we present the EOF indicators, it begs the question of the catch composition, so this example is informative for multiple reasons. Of note is a major shift in the late 1960s to early 1970s in the amount of fish caught and then what was targeted. The emphasis was on European pilchard and then jacks and horse mackerels, followed by sardinellas (Fig. 10). There was then a decline in catch in the late 1970s, and then the pattern repeated, with an increasing emphasis on pilchard and a decreasing emphasis on jacks and horse mackerels. Sardinellas and other mackerels increased in importance in the 2010s. The unclassified pelagic fishes (Fig. 10) are likely represented by most of the other taxa noted, as these are all mainly pelagics. Of note is that EOF indicators (Figs. 5–7) track these patterns. In particular, the onset of EOF was seen in the early 1960s (Fig. 5), prior to the increase in catches seen here in the late 1960s and early 1970s (Fig. 10) and subsequent decline in the late 1970s. As the targeted species shifted in the late 1970s and early 1980s, the EOF index (Fig. 5) exhibited a prior peak in the mid 1970s. The patterns stabilize and persist for the rest of the time series, with other, ancillary species comprising a larger portion of the catch over time. Thus, there also appears to be not necessarily strong sequential overfishing, but certainly a shift to targeting additional taxa over time (i.e. fishing through, not necessarily down, the food web; Essington et al., 2006; Pauly et al., 1998). Although shorter time series, the other EOF indicators (Figs. 6–7) similarly exhibit similar patterns pre-staging shifts in what is caught and major changes in the amount of what is caught (Fig. 10). Thus, it appears that the EOF indices for the Canary Current detect major changes at least half a decade if not a full decade prior to what can be pieced together on a species-by-species basis.

A similar example is seen for the Benguela Current (Fig. 11). There is a clear increase in catch in the late 1960s. This primarily targeted Pacific sardine, and then abruptly stopped in the early 1970s, followed by targeting of hakes, which then declined in the late 1970s-early 1980s, followed by an emphasis on anchovies and horse mackerel (Fig. 11). This exemplifies sequential depletion, albeit in the context of an shifting upwelling ecosystem with various oceanographic and climatalogical regimes (Roux and Shannon, 2004, Cochrane et al., 2009, Shannon, 2014; Jarre, 2016 and references therein). That the major taxa caught shifted over time in response to overfishing is a classical sign of EOF. Also telling is that EOF indicators (Figs. 5–7) similarly detected shifts in this ecosystem. The Ryther index (Fig. 5) detected signs of EOF in the early 1960s, much earlier than the peak and then collapse seen in the late 1960s and early 1970s. Thus, it also appears that the EOF indices for the Benguela Current detect major changes at least half a decade if not a full decade prior to what can be pieced together on a species-by-species basis. These examples highlight the potential value of these EOF indicators as an early detection signal.

4. Discussion

Are these measures useful and indicative of ecosystem overfishing? We assert they are probably indicative of ecosystem overfishing, at least where there is a modicum of confidence in the data. By our definition, when the sum of all catches are declining, effort has increased until it is no longer profitable, total CPUE is declining, total landings relative to ecosystem production exceeds

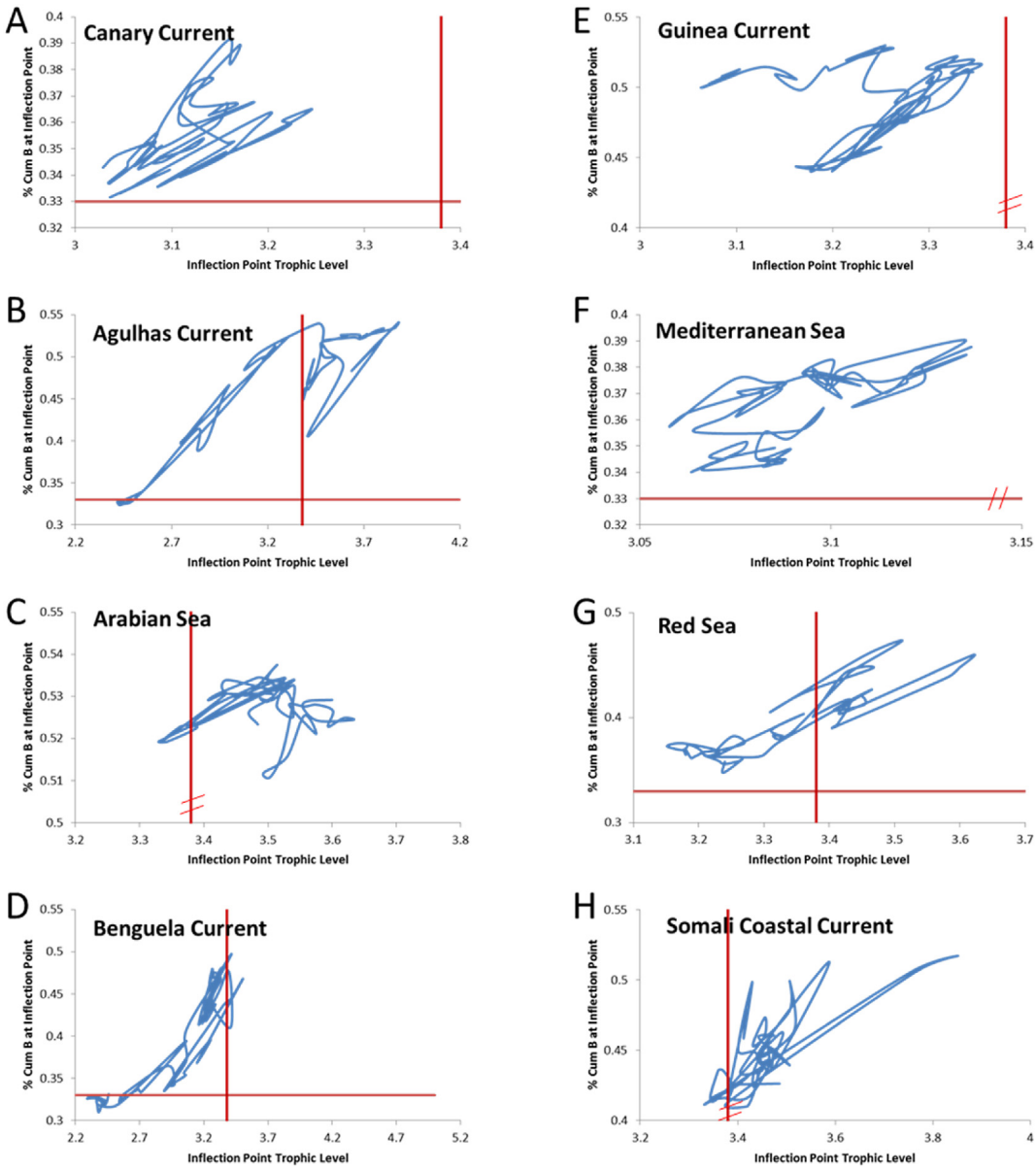

Fig. 8. Percent of the total biomass versus trophic level at the inflection point of the "S" curve over time for the eight African LMEs. The lines correspond to globally derived thresholds of perturbation/recovery as determined by Libralato et al. (2019). A. Canary Current, B. Aghulas Current, C. Arabian Sea, D. Benguela Current, E. Guinea Current, F. Mediterranean Sea, G. Red Sea, and H. Somali Coastal Current. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

suitable limits for the Ryther, Fogarty and Friedland indices, and the cumulative trophic curves parameters fall below thresholds that are known to indicate system-wide perturbation (e.g. over ⅔ of the biomass has been removed from the ecosystem), there is compelling evidence that ecosystem overfishing is occurring. We are not proposing that if only one of these EOF indicators exceeds its threshold by a very minor and precise amount that EOF is occurring, rather that the composite body of evidence needs to be consistent across multiple indicators and multiple contributing data inputs. If an LME is consistently exceeding EOF thresholds for all indicators by a factor of 5–10, then it is probable that EOF is occurring. The coherence of assessment of EOF using both the cumB-TL approach and the EOF indices is confirming the robustness of the approaches used, and also confirms that there is compelling evidence that EOF is occurring for some African LMEs.

The challenge for most parties involved in fisheries science and management when thinking about a concept like EOF is that they have been trained to think about one single stock (taxa, species, fleet, etc.) at a time from a population dynamics perspective, rather than a more systemic approach (Fogarty, 2014; Link, 2018). Treating the entire set of catches and fleets as a composite system may be a philosophical or intellectual stretch, even though a more systemic approach has been demonstrated to have greater value (c.f. Link,

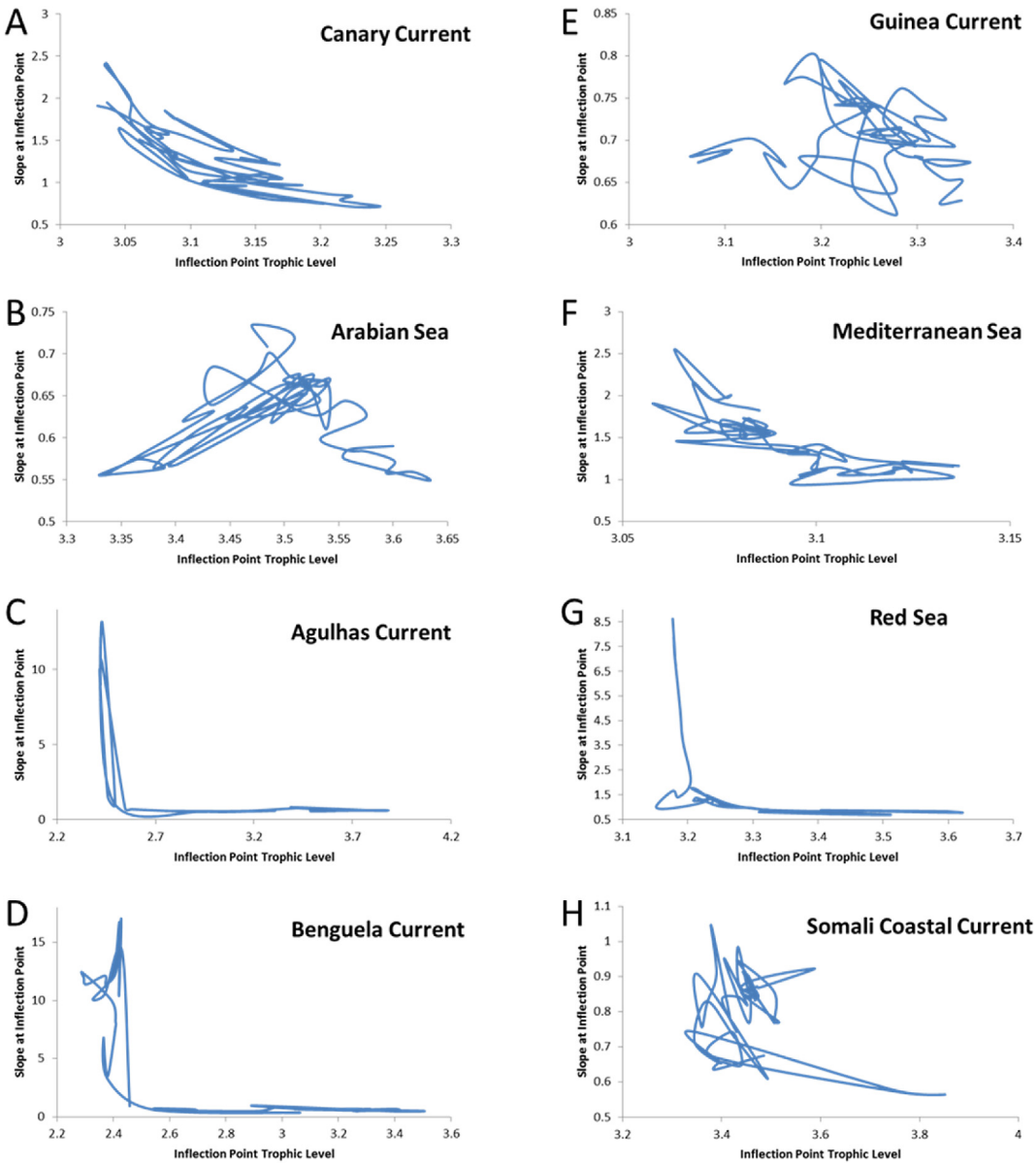

Fig. 9. Slope versus Trophic Level at the inflection point of the "S" curve over time for the eight African LMEs. A. Canary Current, B. Aghulas Current, C. Arabian Sea, D. Benguela Current, E. Guinea Current, F. Mediterranean Sea, G. Red Sea, and H. Somali Coastal Current. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2018; Fulton et al., 2019). Thus, we would argue from our experience discussing EOF with colleagues that the objections to EOF are not about the evidence that it is actually occurring, but rather the thinking behind actually being able to define and determine overfishing *for an entire ecosystem* in the first place. We trust that most readers will at least be able to acknowledge the concept and objectively weigh the evidence we provide.

Several African LMEs have exhibited signs of EOF, and at least one African LME continues to experience significant ecosystem overfishing. Clearly the Canary Current is experiencing EOF. That we detected EOF in this LME is not surprising given what we know from other sources about this LME. There has been notable and ongoing fishing pressure in this LME for some time, primarily for small pelagic fishes (e.g., Arístegui et al., 2004; FAO/GEF, 2009; Conti and Scardi, 2010, FAO, 2018a, Sambe et al. 2016). We acknowledge the fishing at lower trophic levels could allow for increased catches (Link and Watson, 2019), albeit the EOF indicators for this LME are consistently 3–5x higher than the thresholds. Additionally, the Canary Current LME's primary and secondary production have been explored relative to fisheries production, with acknowledgements that some of the potential production in this LME is subject to significant variability due to upwelling, positional shifts in major current, and related physical oceanographic phenomena (Santos et al., 2005, Sambe et al. 2016) resulting in highy variable fisheries dynamics; thus we acknowledge that this

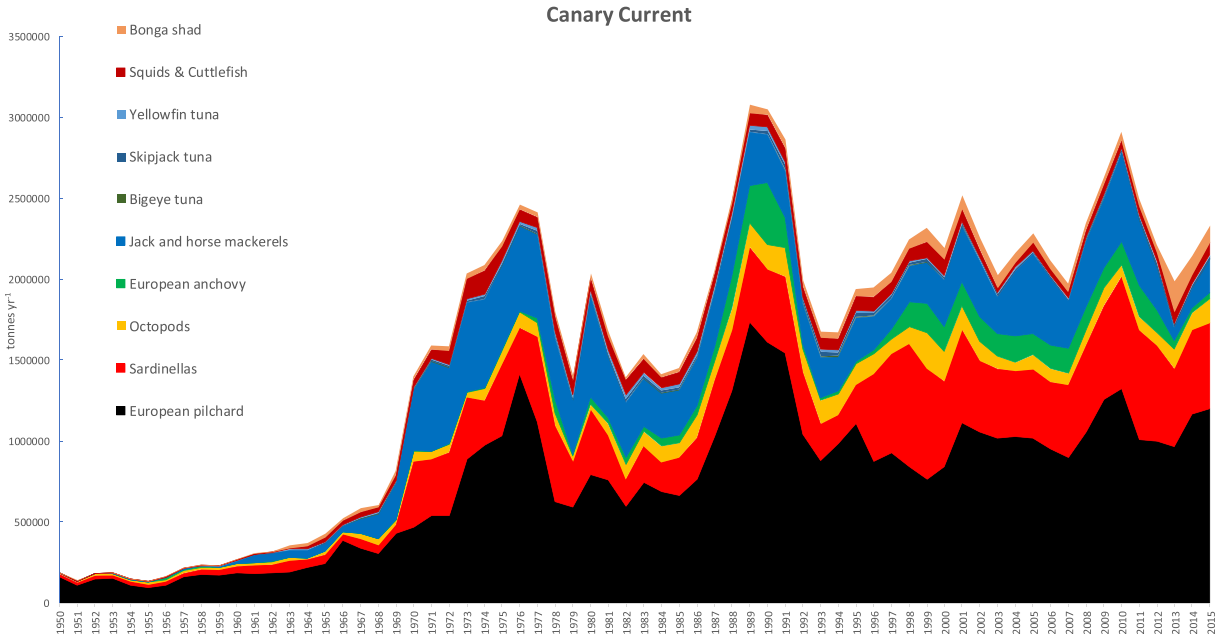

Fig. 10. Catches from the Canary Current ecosystem for major taxa or taxa groups over time. Adapted from the Watson (2017) data set.

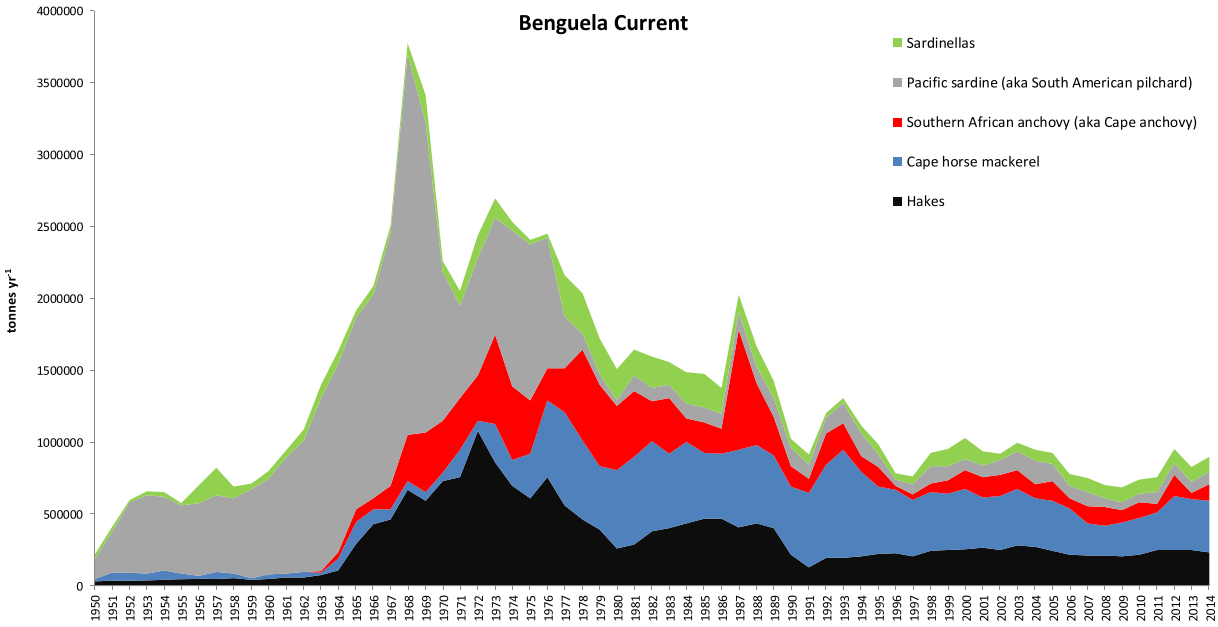

Fig. 11. Catches from the Benguela Current ecosystem for major taxa or taxa groups over time. Adapted from the Watson (2017) data set.

could result in some uncertainty regarding how much could reasonably be expected to be caught here. But this LME is also well known for highly competitive fishing conditions among international operators; thus the patterns detected here are likely reflective of the dynamics of the fishing pressures being experienced in this LME. It may be wise to perhaps review EOF, and options to address it, in an RFMO-type of context (e.g., FAO/GEF, 2009; Bianchi et al., 2016; sensu Satia, 2016) for the Canary Current LME.

Other African LMEs have likely experienced EOF, with five out of eight African LMEs exhibiting symptoms of EOF. Whether the other three are not or are subject to misreported or underreported catch is uncertain (Belhabib et al., 2016). We acknowledge that for those instances, and admittedly perhaps for all these LMEs, data sufficiency and verification certainly needs to temper the interpretation of these results. But we do think the data we have is sufficient to detect EOF when evidence for it emerges, even given potential lapses in some reporting. An important rationale to solidify what may be uncertain data is that if in fact the confidence in these data are high, it could indicate underutilization of fisheries resources if EOF thresholds were not crossed, thereby suggesting

options for additional fishing opportunities. Doing so would have significant social, culture, economic, and food security implications (Allison et al., 2009; Badjeck et al., 2010; Srinivasan et al., 2010; Garcia and Rosenberg, 2011; Rice and Garcia, 2011; Sumaila et al., 2011; Barange et al., 2014; Jennings et al., 2016; Blanchard et al., 2017).

Of the five out of eight African LMEs that have exhibited symptoms of EOF, the results are not surprising and generally consistent with what we know about the Guinea Current (e.g., McGlad et al., 2002; Mensah and Quaatey, 2002; Ukwe et al., 2006, FAO, 2018a), Benguela Current (e.g., Shannon et al., 2006; Cochrane et al., 2009, Shin et al., 2010b, Shannon et al. 2014; Blamey et al., 2015, Jarre, 2016; FAO, 2018a), Mediterranean Sea (e.g., Tudela, 2004; Pranovi et al., 2014; FAO, 2018a; Stergiou et al., 2016; FAO, 2018a; 2018b; Russo et al., 2019), and Arabian Sea (e.g., Siddeek, 1999; FAO, 2018a; Lam and Pauly, 2019) LMEs. These is also consistent with six of these 8 LMEs being classified as in a transition state with respect to the "S" curves (Pranovi et al., 2020; Libralato et al., 2019). All have exhibited histories of notable stock overfishing and changes to the ecosystem; hence that we see evidence for ecosystem overfishing is not surprising. The implications for ongoing EOF are generally not positive, by definition.

Some African large marine ecosystems exhibit signs of ecosystem recovery or have at least more recently experienced minimal levels of EOF. The Benguela has shown evidence for improving conditions in not only the EOF indicators, but also in the stabilization of total CPUE and in the recovery trajectory of the cumulative biomass curves. This is consistent with significant management interventions in the fisheries of this region (Cochrane et al., 2009; Shannon et al. 2014; Mukvari et al., 2016). This instance should be encouraging such that with some management intervention, marine ecosystems and their fisheries can recover, as seen in these EOF metrics.

We also note that EOF was detectable at least half a decade prior to major taxa or taxa group collapses in some of these LMEs. Even if EOF was not detected, EOF indicators provided early warning signals at least half a decade prior to other observable changes in the ecosystem. Again, this is consistent with major ecosystem shifts that have been documented for some of these LMEs (Mensah and Quaatey, 2002; Shannon et al. 2006; Cochrane et al., 2009; Conti and Scardi, 2010; Shin et al., 2010b; Shannon et al. 2014; Blamey et al., 2015; FAO, 2018a; Sambe et al. 2016; Stergiou et al., 2016; Vousden, 2016). Instead of attempting to piece together major, significant shifts in how ecosystems function by a single taxa-at-a-time meta-analytic approach, it seems more efficient and effective to monitor what are in essence early warning signals of major ecosystem shifts. Thus, we assert that even if the thresholds of these EOF metrics are debatable, there is value in monitoring them as early warning signals to detect major patterns and trends of potential overfishing before significant and subsequent damage has occurred. Detecting and acting on the ecosystem-level information can prevent both continued EOF and sequential stock overfishing, identify coming regime shifts, as well as save money.

The question begs, what should one do if EOF is detected? As noted previously (Link and Watson, 2019), we don't want to get too prescriptive given local governance and policy practices. That said, there are a few simple suggestions that emerge. First would be to continue to monitor these metrics and disseminate both them and the methods to calculate them broadly. Essentially, if one can track landings (we acknowledge that sometimes this is a big *if* but global data sets are increasingly bounding this challenge rather helpfully (e.g. Watson, 2017; Pauly and Zeller, 2016; FAO, 2018a; Rousseau et al., 2019)), and one can obtain satellite data on productivity and the area being fished, the three main EOF indicators can be readily tracked. The cumulative biomass curve data is admittedly more involved, but there are numerous LME landings and catch data from which those curves can be also estimated. So we propose adoption and ongoing monitoring of these EOF metrics. Second, if EOF is strongly suggested (as for example in the Canary Current LME), then regional management bodies at some level and in some way need to limit the fishing pressure in that ecosystem. How specifically best to do that is not a suite of details that we want to prescribe, but it amounts to a lowering of overall fishing. Enacting management to ultimately lower fishing pressure has many potential avenues (Mace, 1994; Hilborn et al., 2015), and all should be explored given a local or regional context. We are sensitive to the challenges of governance and infrastructure in many of these African LMEs, as well as the challenges of sufficient fisheries data and reporting there. That said, there has been substantial and significant progress in these LMEs, there are in fact some well-established regional LME-scale management organizations (FAO/GEF, 2009; Abe et al., 2016, Barros Neto et al., 2016; Bianchi et al., 2016; Hamukuaya et al., 2016), and the methods we propose are rather simple to implement and track. So we are proposing if EOF is detected, then at least some attempt to lower fishing might be considered. In the one example African LME where this lowering of overall fishing has happened (i.e., the Benguela Current LME), we see positive responses in EOF indicators, better indicators of ecosystem status (Shin et al., 2010b, Shannon et al. 2014; Mukvari et al., 2016) and ultimately better social and economic outcomes (Jarre, 2016, Sumaila, 2016; sensu Allison et al., 2009, Sumaila et al., 2011, Barange et al., 2014, Jennings et al., 2016).

The value of these three EOF measures lies in their simplicity. Even apart from any specific action, we assert that they are useful to track. The salient point here is that the value of having international standards would be that any party could obtain and calculate these estimates from readily available sources, and if the indicators exceeded the commonly noted thresholds, then a clear agreement and obvious consensus on whether overfishing was occurring, or not, would then not be debatable. Rather, what appropriate actions to best mitigate EOF would be (specifically via particular management measures, beyond generally a lowering of fishing pressure) open for discussion, and that would shift the burden of proof to one that would better emphasize sustainability. It would also highlight data gaps and inconsistencies, as well as elucidate the parties that are likely involved with the largest portion of the fisheries removals, particularly appropriate for LMEs where foreign extraction is a significant source of fisheries catch. We by no means imply that adopting these EOF measures will be easy or a simple cure-all. Rather, we propose them as an approach as they may be easier to grasp for relatively data-limited situations to help address broader, systemic, LME-wide challenges for these important African fisheries.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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