

Evaluating changes in marine communities that provide ecosystem services through comparative assessments of community indicators

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Abstract

Fisheries provide critical provisioning services, especially given increasing human population. Understanding where marine communities are declining provides an indication of ecosystems of concern and highlights potential conflicts between seafood provisioning from wild fisheries and other ecosystem services. Here we use the nonparametric statistic, Kendall's tau, to assess trends in biomass of exploited marine species across a range of ecosystems. The proportion of 'Non-Declining Exploited Species' (NDES) is compared among ecosystems and to three community-level indicators that provide a gauge of the ability of a marine ecosystem to function both in provisioning and as a regulating service: survey-based mean trophic level, proportion of predatory fish, and mean life span. In some ecosystems, NDES corresponds to states and temporal trajectories of the community indicators, indicating deteriorating conditions in both the exploited community and in the overall community. However differences illustrate the necessity of using multiple ecological indicators to reflect the state of the ecosystem. For each ecosystem, we discuss patterns in NDES with respect to the community-level indicators and present results in the context of ecosystem-specific drivers. We conclude that using the NDES requires context-specific supporting information in order to provide guidance within a management framework.

Keywords: ecological indicator; comparative approach; community metric; IndiSeas; fishing impacts

Introduction

Oceans provide important ecosystem services for human well-being, including provisioning services (e.g., procurement of seafood and medicinal products), regulating services (e.g., moderation of climate fluctuations and protection against flooding and erosion), cultural services (e.g., aesthetic and spiritual benefits, and recreation), and supporting services (e.g., nutrient cycling, carbon storage, and trophic stability) (Worm et al. 2006, Daniel et al. 2012). The provision of seafood from wild capture fisheries is one of the most critical benefits that humans derive from the ocean and as such, the regulation of commercial harvests of fish stocks has become a priority. Additionally, there has been a concerted effort to measure and regulate other ecosystem services that may have negative impacts on fisheries (e.g., balancing conservation objectives underlying ecotourism) through marine spatial planning (Foley et al. 2010), better valuation (Börger et al. 2014) and analyses of the synergies and trade-offs (Halpern et al. 2012) of marine ecosystem services. However, while declines in some fisheries have been halted or some fish stocks have recovered due to precautionary fisheries management or reduced exploitation rates (Worm et al. 2009), many exploited stocks around the world are in decline due to a combination of stressors such as overfishing, pollution, habitat degradation, and climate change. These stock declines result in fisheries yields, which are less than optimal and ultimately can lead to stock collapse. This is of growing concern due to the direct impacts on food security for over three billion people who rely on fisheries to supply a significant portion of their animal protein (FAO 2014). Fishing represents one of the most significant human impacts on marine ecosystems and has led to many changes including alterations of the trophic structure, declines in the abundance of top predators, biodiversity, and overall resilience and biomass of some ecosystems (Pauly et al. 1998, Jackson et al. 2001, Christensen et al. 2003, Perry et al. 2010, Jackson et al. 2011). Additionally, the spatial footprint of fishing has continued to increase as fisheries have expanded offshore (Coll et al. 2008a, Swartz et al. 2010) and into deeper waters (Morato et al. 2006). These expansions have often been facilitated by the use of increasingly sophisticated fishing technology (Pauly et al. 2002). These remarkable technological improvements have resulted in fleets that are more efficient (Pauly & Palomares 2010) and more powerful (Anticamara et al. 2011) than at any time in the past. However, this has not led to increased catches but rather a stagnation or even slow decline in the overall global catch (FAO 2014), threatening the delivery of this critical ecosystem service.

Traditionally, fish stocks have been assessed and managed as single units, with little consideration for the linkages with other components of the ecosystem. However, there is a growing push to manage fish stocks cohesively as one aspect of an ecosystem-based approach to marine management (Link et al. 2002, Garcia 2009). This is in line with the objectives of several international conventions such as the Convention on Biological Diversity (CBD 2010) and regional legislations such as the European Marine Strategy Framework Directive (EU Directive 2008/56/EC) or the EU Common Fisheries Policy (European Commission 2013). An ecosystem approach to management requires the development of indicators and robust methods to

gauge changes in marine ecosystems. This requires indicators of ecosystem change that are easy to interpret in order to measure the impacts of fishing, climate change, and other factors across ecosystems and to provide management guidance at an ecosystem level.

However, the development of robust and reliable marine indicators is still in its infancy, and multiple indicators may be necessary to capture changes in different components of the community and to provide a more complete understanding of ecosystem status (Shin et al. 2010b, Bundy et al. 2012). For example, trophic level indicators calculated for different portions of the ecosystem (e.g., surveyed biomass vs. landings) can provide differing views of the status of the ecosystem (Shannon et al. 2014) and highlight places where trophic instability may be affecting the delivery of provisioning and/or regulating ecosystem services. The need to interpret multiple ecosystem indicators to obtain a more complete understanding of the status of the system is particularly important in an ecosystem services framework since the majority of ecosystem indicators currently available are not comprehensive and are often inadequate to characterize ecosystem services when used alone (Liquete et al. 2013, Piroddi et al. In Review).

Here we test an indicator, which has been proposed as a 'simple community analysis' (Lynam et al. 2010), and which can be interpreted in terms of trends and correlations of multiple species at the community-level, for use as a gauge of the ability of an ecosystem to deliver provisioning services. This measure was originally developed and demonstrated using fish survey and phytoplankton count data from waters off the west coast of Ireland (Lynam et al. 2010). The indicator is based on a nonparametric test statistic, Kendall's tau (Kendall & Gibbons 1990), which is used to determine the strength of declining or non-declining trends in a set of time series of species biomass from the comparison of theoretical and observed distributions of the statistic. We also assess the proportion of non-declining species across several ecosystems.

Similar to Lynam et al. (2010), we use this statistic in a simple community analysis approach to explore biomass trends for exploited species within ecosystems and to estimate the proportion of non-declining exploited species biomass, the 'Non-Declining Exploited Species' (NDES) indicator. The rationale for exploring non-declining trends, rather than the proportion of declining trends, is to have an indicator that should have a lower value at higher levels of fishing pressure (i.e., more declining biomass trends with higher exploitation rates), in line with other ecological indicator formulations selected for comparing the effects of fishing across ecosystems (Shin et al. 2010b). Cross-ecosystem comparisons of the NDES indicator are possible because it accounts for the distinct number of species and differing length of the time series data available in each ecosystem. First, we illustrate, based on the full set of single exploited species trends for each ecosystem, the proportion of non-declining species and compare the indicator values between ecosystems. Second, in order to understand the patterns in NDES, which provides information specific to the exploited portion of the community, we compare NDES to three

community-level indicators that provide a gauge of the ability of a marine ecosystem to function both in a provisioning role and as a regulating service (i.e., through maintenance of biodiversity, trophic stability, and reproductive potential): proportion of predatory fish (PPF), survey-based mean trophic level (TL_{sc}), and mean life span (mLS), which were described by Shin et al. (2010b). In particular, the utility of trophic level indicators for capturing the health and status of different components of the marine community has been explored in detail by Shannon et al. (2014). We use these indicators to determine whether exploited species biomass is associated with other ecosystem-level changes. These particular indicators were selected because (a) data to compute the indicators for each ecosystem were available, (b) they are more integrative as they include all survey species as opposed to looking only at the exploited portion of the community, and (c) they are species-based like the NDES, but also account for different functional traits within the greater community. Each of these indicators is also formulated such that greater fishing pressures results in lower indicator scores.

Methodology

Ecosystems

We analyze 22 marine ecosystems spanning upwelling, high-latitude, temperate, and tropical marine habitats across the world's oceans (Table 1). They comprise the Barents Sea, the Bay of Biscay, the central Baltic Sea, the eastern Bering Sea, the eastern Scotian Shelf, the English Channel, the Guinean Shelf, the Gulf of Cadiz, the Irish Sea, the north Aegean Sea, the northern Humboldt Current, the north Ionian Sea, north-central Adriatic, the northeast U.S., the North Sea, the Portuguese coast, the south Catalan Sea, the southern Benguela, the Scottish west coast, the U.S. west coast, the west coast of Vancouver Island (hereafter referred to as Vancouver Island), and the western Scotian Shelf. The 22 ecosystems assessed here have been selected because multiple trends of species biomass from biological surveys or stock assessments are available through the IndiSeas international initiative (Shin et al. 2012; www.indiseas.org). The majority of these ecosystems were described and explored in a series of papers resulting from the IndiSeas project (Coll et al. 2010b, Shin et al. 2010b, Bundy et al. 2012). The number of species with biomass time series available for analysis and the average timespan over which the biological surveys and stock assessments were conducted vary greatly between ecosystems (Table 1). The northeast U.S. shelf has both the greatest number of available biomass time series (124) and the longest survey duration (47 years). Conversely, the north Ionian Sea has the fewest number of time series (5) and the north Aegean Sea has the shortest survey duration (4 years). The full list of species assessed in each ecosystem, length of time series, Kendall's tau correlation coefficient of exploited species biomass time series, and the relative proportional contribution of each species' average biomass to the overall average exploited biomass available in each ecosystem is presented in Table S1 in the Supplementary Information.

Calculating the Non-Declining Exploited Species (NDES) indicator

Lynam et al. (2010) used the Kendall's tau correlation coefficient to quantify the degree of association between the species biomass as measured from a biological survey (X variable) and the time series of years over which the survey was conducted (Y variable). Kendall's tau is a measure of the strength of the tendency of these two variables, X and Y to move in the same (or opposite) direction. That is, the estimates of tau in a set of species provide a probability of having a monotonic temporal trend in the biological data. Lynam et al. (2010) noted that one of the strengths of such a rank-based method over other parametric methods (e.g., Pearson's product moment correlation coefficient) is that the relationship between the measured variables does not have to be linear and does not rely on any assumption about the distribution of the variables.

Here, we take the same approach, calculating the Kendall's tau coefficient for each exploited species in an ecosystem with time series of biomass data (Table 1). The rationale is to build an indicator which would be simple to estimate, and easy to communicate, reflecting what proportion of exploited species have their biomass increasing or decreasing in each ecosystem, potentially as a result of fishing. Each tau is calculated by examining the difference between consecutive years and the corresponding consecutive biomass values (Lynam et al. 2010). If the differences are both positive, then this demonstrates an increase in biomass. By looking at all pairs in a time series within an ecosystem, one can determine whether the biomass over the time series is generally increasing or decreasing. The higher the proportion of concordant or discordant pairs, the stronger the increase or decrease, respectively. This procedure results in a measure of the probability of an increasing biomass trend (tau) for each exploited species from biological surveys or stock assessments in an ecosystem. A histogram of the resulting distribution of all Kendall's tau coefficients within an ecosystem allows a comparison of the observed distribution of tau with the theoretical expected distribution to assess whether there is a significant monotonic trend. An observed distribution of the statistic tau that is shifted to the left of the expected theoretical distribution indicates an ecosystem with more species with declining biomass than expected by chance alone. The converse is true for an observed distribution shifted to the right of the expected theoretical distribution.

Because we are interested in determining whether the NDES indicator is significantly high (i.e., more non-declining trends) or low (i.e., more declining trends), we formally test whether the observed distribution of the statistic tau is shifted to the right or left of the theoretical expected distribution with a two-tailed nonparametric Kolmogorov-Smirnov (KS) single-sample goodness-of-fit test. The null hypothesis tested is that there is no difference between the observed distribution and the expected distribution. The KS significance test takes into account the number of species and the differing length of the time series in the calculation of the theoretical expected distribution (red line in Figure 1). An ecosystem with few species trends, but a long time series will have a more leptokurtic distribution than an ecosystem with few species trends with short time

series. The proportion of non-declining biomass of exploited species out of the total number of exploited species biomass trends in an ecosystem (as determined from this method) is taken to be the state indicator we call ‘Non-Declining Exploited Species’ (NDES).

Kendall’s tau and associated analyses were conducted in R version 3.0.2 (R Core Team 2013) using the packages ‘stats’, and ‘SuppDists’ (Wheeler 2009).

Supplemental community-based indicators

We conducted several analyses to compare the NDES indicator directly with the status and trends of three other community indicators including proportion of predatory fish (PPF), average trophic level of the surveyed community (TLsc), and mean lifespan (mLS). These indicators were selected from the set of IndiSeas indicators chosen according to a carefully defined set of criteria (Shin et al. 2012) because they were available for the majority of the ecosystems presented here. Additionally, they are important indicators of ecosystem status and trend and have been noted to be effective at capturing different aspects of ecosystem functioning such as the state of turnover processes, predator-prey dynamics, and trophic composition (Shin et al. 2010b, Shin & Shannon 2010, Bundy et al. 2012, Shannon et al. 2014). The PPF is calculated as the ratio of the biomass of predatory fish species surveyed to the total biomass surveyed and TLsc is calculated as the biomass-weighted average trophic level of the total surveyed community. The PPF and TLsc are designed to capture the effect of fishing on larger and higher trophic level species in the ecosystem. The mLS is calculated as:

$$\sum_s (age_{MAX,s} \cdot B_s) / \sum_s B_s$$

where B_s is the survey biomass estimate for a given species s and $age_{MAX,s}$ is the maximum longevity of the species. This indicator is used as an inverse proxy for turnover rate and conveys the idea that fishing favors the emergence of species with a short lifespan (Shin et al. 2010b). The three indicators hence reflect changes in different facets of functional diversity (Bundy et al. 2010) and capture more of the ability of the ecosystem to act in a regulating role through the maintenance of biodiversity, trophic stability, and reproductive potential.

In contrast to the NDES indicator, which looks specifically at the biomass of the exploited component of the ecosystem, mLS, PPF, and TLsc, are calculated on the full suite of surveyed species biomass (i.e., surveyed biomass of exploited and non-exploited species) in a given ecosystem (Shin et al. 2010b). Because the indicators were designed to capture different components of the state of the ecosystem, we do not necessarily expect to find correlations between the indicators, but we illustrate similarities and differences between the indicators and provide some context for the patterns observed in each ecosystem.

First, for each ecosystem we compare the NDES indicator with the current state of each of the community indicators (PPF, TLsc, and mLS) using petal plots. The state for each of the three community indicators is calculated as the average of the most recent five years for which data were available (for most systems this was 2006-2010). Thus, the 'current state' of the ecosystem with regard to these three community indicators is compared directly with the NDES indicator (i.e., the proportion of exploited species with non-declining biomass in each ecosystem). For each of the 22 ecosystems the values for the four indicators are rescaled between 0 (worse state) and 1 (better state) in order to allow for comparison between indicators and between ecosystems. Each of the indicators used in the analyses presented here are designed such that higher fishing pressure should result in a lower indicator score (Shin et al. 2010b).

Next, for each ecosystem, we also evaluate the correlation over time of the three ecosystem indicators (PPF, TLsc, and mLS) with the biomass time series for each exploited species that were used to calculate the NDES. We perform this comparison again using the Kendall's tau correlation coefficient to quantify the degree of association between the times series of exploited species biomass from the survey (X variable) and each time series of ecosystem indicator values (Y variable). These comparisons are calculated for all years in which both biomass values and ecosystem indicator values exist. Here, in contrast to the Kendall's tau calculated for the NDES indicator, we used a two-tailed binomial test to assess the significance of the hypothesis that there are more positive or negative correlations between the biomass trends and the three community indicator values than would be expected by chance. Because we are looking at pairwise changes in the community indicator values and the biomass of an exploited species, we are assessing the trajectories of the time series, rather than correlating linear trends (i.e., slopes). A positive correlation indicates that the exploited biomass trends are following the same trajectory as the community indicator trends (i.e., increasing or decreasing). We present the proportion of positively correlated trends per ecosystem and term proportions greater than 0.5 'positively correlated' (i.e., more similar trajectories) and proportions less than 0.5 'negatively correlated' (i.e., more opposing trajectories). In order to determine whether the community indicators are positively or negatively correlated to biomass trends (i.e., decreasing/increasing community indicator associated with decreasing/increasing biomass trends), we calculate the slopes of each of the community indicators based on the complete time series of normalized indicator values (i.e., standardized by subtracting the mean and dividing by the standard deviation) for each ecosystem using generalized least-squares models with autoregressive errors following Blanchard et al. (2010). These slopes are used to further investigate the relationships between the trends in exploited species biomass and the community indicators.

Finally, in order to better understand the state and trend patterns in the NDES indicator and the three community indicators, we examine the biomass trends of the exploited species within an ecosystem with respect to the species trophic level (local

values provided by IndiSeas experts or determined from FishBase, www.fishbase.org, see Table 1S). The rationale for this exploration is to evaluate whether there is a greater proportion and number of declining trends for lower or higher trophic level species. Thus, we compute the biomass-weighted average trophic level of the exploited species with declining biomass and compare that to the biomass-weighted average trophic level of the exploited species with non-declining biomass in a given ecosystem. Because each ecosystem will have a different composition of species with varying trophic levels that is related to factors specific to the particular ecosystem (e.g., levels of primary productivity, exploitation history, oceanography, etc.), we define 'lower' or 'higher' trophic levels on a relative basis within an ecosystem, and we do not compare these values between ecosystems. However, we explore whether ecosystems with a higher proportion of declines of higher trophic level exploited species tend to have lower scores for the ecosystem indicators.

Results & Discussion

The Non-Declining Exploited Species (NDES) Indicator

Histograms of Kendall's tau statistic indicate the distribution of negatively (decreasing; white portion of histogram bars) and positively (increasing; grey portion of histogram bars) correlated biomass trends for the exploited species in each ecosystem (Figure 1). Based on the proportion of non-declining trends (i.e., the NDES indicator), we find that in 10 out of the 22 ecosystems, more than half of the exploited species trends are significantly non-declining (Table 1; $NDES > 0.5$, p -value < 0.05). Most biomass trends are not declining for exploited species (i.e., higher NDES values) in the English Channel, the south Catalan Sea, the eastern Bering Sea, the southern Benguela, the western Scotian Shelf, the North Sea, the northeast U.S., Vancouver Island, the Portuguese coast, and the Barents Sea (ordered from lower to higher NDES values). We find that the observed values of the tau statistic in these ecosystems are shifted to the right of the expected theoretical distributions (red lines), indicating that there are fewer species declining in biomass than should be expected by chance alone.

Nine ecosystems have significantly more species that show declining biomass trends (Table 1; $NDES < 0.5$, p -value < 0.5), including the Guinean Shelf, the north Ionian Sea, the Gulf of Cadiz, the Bay of Biscay, the north-central Adriatic, the eastern Scotian Shelf, the Irish Sea, the U.S. west coast, and the north Aegean Sea (ordered from lower to higher NDES values). We find that the observed values of the tau statistic in these ecosystems are shifted to the left of the expected theoretical distributions (red lines), indicating that there are more species with a declining biomass than should be expected by chance alone. Note that the U.S. west coast and the north Aegean Sea ecosystems have relatively short time series (8 and 4 years, respectively), which results in expected theoretical distributions of the tau statistic that are broader and flatter compared with the rest of the ecosystems. It is expected

that the variance of the expected distributions of the tau statistic should increase as the length of the time series of biomass decreases, which is a weakness of the indicator. The NDES indicator is non-significant in the central Baltic Sea, the northern Humboldt Current, and the Scottish west coast.

Comparison of the NDES indicator with community status indicators

The current status for the three community indicators and the NDES indicator vary greatly among ecosystems (Figure 2). In some ecosystems, the scores for all four indicators are relatively high (e.g., the eastern Bering Sea, the northeast U.S. and Vancouver Island) suggesting these ecosystems have a better ecosystem state overall. In other cases, the scores are all relatively low (e.g., the central Baltic Sea, the Gulf of Cadiz, the Irish Sea, the north Ionian Sea, the north Aegean Sea, and the northern Humboldt Current), suggesting a worse ecosystem state on average. For other ecosystems the NDES indicator contrasts with the results of the community-level indicators (e.g., the Bay of Biscay) suggesting that patterns in the exploited portion of the community are not reflected in the whole community.

The composition of the trophic levels of the species that are declining within an ecosystem can provide some insight as to why the NDES scores might be higher or lower than the status of the community indicators (Figure 3) and can help illustrate the similarities between the patterns in the exploited species versus the whole community. For example, the north-central Adriatic receives a high score for TLsc. However, the proportion of non-declining species is 29%, resulting in a low NDES score. This discrepancy can be explained by the fact that the biomass-weighted average trophic level of the declining species is lower (~ 3.1) relative to the biomass-weighted average trophic level of the species that are not decreasing (~ 3.75), indicating that lower trophic level species in the system are the ones declining and resulting in a higher TLsc. However, the fact that the average trophic level of these species is less than 4 suggests that large predatory fish are not abundant in the north-central Adriatic, which may point to why the scores for PPF and mLS are also lower (Coll et al. 2009, Coll et al. 2010a). Similar trophic level patterns are found for the Bay of Biscay, which is strongly over-exploited (Gu nette & Gascuel 2012) and where the PPF status is high relative to the lower scores for the NDES indicator. These discrepancies can be explained by the fact that the biomass of lower trophic level species is declining.

The north Ionian Sea has the lowest status scores (i.e., 0) for the three community indicators and the NDES indicator. In this ecosystem, there are few exploited biomass trends, which are used to calculate the NDES indicator and all are declining according to the Kendall's tau statistic (Figure 1, Table 1). Additionally, the average trophic level of the exploited biomass is around 3.2, which is relatively low. This ecosystem, like many regions in the Mediterranean (e.g., south Catalan Sea: Coll et al. 2008b), is dominated by lower trophic level organisms (especially invertebrates and small pelagic fish) due to historic and current heavy fishing pressure (Piroddi et al. 2010). This situation also occurs in other heavily exploited Atlantic ecosystems, for

example in the Gulf of Cadiz (Torres et al. 2013). The reduction in the trophic level of the overall ecosystem is reflected in the low status of the community indicators.

The Barents Sea provides an example of a higher score for the NDES indicator and a lower score for the community indicators. In the Barents Sea, nine out of 11 biomass trends are non-declining and the biomass-weighted average trophic level of the declining exploited species is lower. In this case, the NDES indicator does not reflect what is happening in the overall system. However, the Barents Sea is an ecosystem where stocks of short-lived small capelin (*Mallotus villosus*) and transient stocks of young herring (*Clupea harengus*, 0-4 years old) are major drivers for the top predators (Hjermann et al. 2010, Johannesen et al. 2012). These stocks show large natural fluctuations over relatively short time periods. During the 38 years of survey data analyzed here, capelin has fluctuated between very low biomass levels (Gjøsæter et al. 2009) and the highest peak in history (within the last 10 years) followed by natural declines one to two years after each peak. This pattern is likely causing a temporary reduction in the TLsc even if the long-lived, top predator species show a concurrent increase over the same period. Similar to the Barents Sea, the NDES scores for the Portuguese coast, southern Benguela, and the south Catalan Sea are also higher than the status of the community indicators, with fewer declining species trends. However, in these cases there are fewer declining exploited biomass trends, and it is mainly biomass of higher trophic level fish that is decreasing (Figure 3), corresponding to the lower scores for TLsc, PPF, and mLS, and in line with independent observations (e.g., the south Catalan Sea: Coll et al. 2008b).

For the English Channel and the western Scotian Shelf, there are more exploited species biomass trends that are not declining, but there is still a relatively large number of declining species compared to other ecosystems. In both ecosystems, the declining species have a lower average trophic level. For the western Scotian Shelf, the average trophic level of the species that are not declining is > 4 , corresponding to a higher TLsc, which is at odds with the low scores for PPF and mLS. This is because Atlantic herring (*Clupea harengus*), a declining, exploited species with a relatively low trophic level, constitutes a large part of the surveyed biomass (~68%, Table S1). Conversely, for the English Channel, the PPF score is very high, especially given the fact that the average trophic level of the declining and non-declining species is lower and quite similar (~3.5 versus ~3.75). The fact that the average trophic levels of the declining and non-declining species are lower corresponds with the lower mLS and TLsc. Additionally, the English Channel is characterized by a regime shift that affected the fish community in mid-1990s, which was illustrated both by a declining biomass of small forage fish and an increasing biomass of large demersal fish (Auber et al. Submitted).

In some cases, the trophic level of the declining species does not adequately explain the discrepancy between the NDES indicator scores and the three community indicators. For example, on the U.S. west Coast, the biomass-weighted average trophic level of the declining species is close to that of non-declining species.

However, declining trends in biomass and mean trophic level of the surveyed species have been attributed to climate variability and attenuating mortality of a strong 1999 year class for multiple species targeted by the groundfish fishery (Keller et al. 2012, Tolimieri et al. 2013). Because overfishing is not the main driver of the trends in biomass, it is not surprising that the four indicators do not show perfect correlations. The score for mLS is very high due to long-lived rockfish species. In contrast the scores for the NDES, PPF, and TLsc indicators are lower compared to other ecosystems. Lower PPF and TLsc scores are due in part to the three most abundant species in the survey: Pacific hake (*Merluccius productus*), Dover sole (*Microstomus pacificus*), and longspine thornyhead (*Sebastolobus altivelis*). The diet of Pacific hake is dominated by euphausiids (Robinson 2000), while Dover sole and longspine thornyhead consume primarily benthic invertebrates (Gabriel & Pearcy 1981, Rooper & Martin 2009)—none of these species are considered predatory by the PPF index. For the Guinea Shelf, the scores for PPF are higher than the other indicators, although the scores across all indicators are quite low. The low score for the NDES indicator is a result of declines in all 20 biomass trends available. The biomass-weighted average trophic level of these declining species is just under 3.5, which corresponds to the low TLsc and mLS scores, but suggests that the PPF score should be lower.

There are three ecosystems for which the NDES indicator is not significant: the central Baltic Sea, the northern Humboldt Current, and the Scottish west coast. The NDES indicator for each of these ecosystems is close to 0.5, indicating that the proportions of increasing and decreasing exploited species are relatively even. In the central Baltic Sea and the northern Humboldt Current, the NDES indicator has a higher status than the community indicators. In the central Baltic Sea, lower trophic level clupeids (sprat and herring) are the dominant species in the system in terms of overall abundance (Eero 2012). In contrast, there is only one abundant higher trophic level predatory marine fish (Atlantic cod, *Gadus morhua*), which is also the most valuable and therefore heavily exploited species in the Baltic, and moreover subject to climate-related fluctuations (Eero et al. 2011). A possible explanation for the lower PPF and TLsc scores in the central Baltic is the climate-initiated regime shift in this ecosystem at the end of the 1980s, which resulted in a strong decrease in the cod population and a substantial increase in the abundance of clupeids likely due to reduced predation by cod (e.g., Möllmann et al. 2009, Eero 2012, Tomczak et al. 2013).

Similarly, for the Northern Humboldt, the decrease in mLS and TLsc during the study period responds to the recovery of the short-lived anchoveta (*Engraulis ringens*) after El Niño 1997-98. Because of the dominance of this species in this upwelling ecosystem, a reduction of mLS and TLsc likely corresponds to an increase in ecosystem health, highlighting the need for a context-specific approach to interpreting these indicators. In contrast, on the Scottish west coast, no regime shift has been identified, but large demersal fish (haddock: *Melanogrammus aeglefinus*, pollack: *Pollachius pollachius*, squids: *Lophius* species, flatfishes: Pleuronectiformes) and predators (rays and skates) have also shown an increase in the late 1990s

(Bailey et al. 2011, Alexander et al. In Press). These increases occurred in the absence of large declines in important small forage fish species such as herring and mackerel (*Scomber scombrus* and *Trachurus trachurus*), although sprat (*Sprattus sprattus*) and sandeels (*Ammodytes tobianus*) have declined.

Comparison of the NDES indicator with community indicator trends

Comparing the exploited single species biomass trends directly with the trends in the three ecosystem indicators, i.e., PPF (Figure 4), TLsc (Figure 5), mLs (Figure 6) we obtain insights as to which ecosystem indicators are positively or negatively correlated with the NDES indicator. An understanding of the direction of the correlation between the community indicators and the exploited species biomass trends allows us to determine whether the patterns in the exploited community are reflected in the overall community (i.e., a positive correlation). When there are negative correlations between the NDES and the community indicators, this may be an indication that different pressures or drivers (e.g., climate change) may be affecting different segments of the community. We explore this possibility in the context of the trophic structure of the exploited community (i.e., Figure 3). Additionally, we explore the overall significance of the temporal trend in each of the community indicators for each ecosystem. When we see significant trends in the indicator time series, we can directly infer the relationship between correlations in the exploited species biomass time series and the ecosystem indicator of interest, i.e., whether patterns in the exploited community are also picked up in the overall community.

The PPF is significantly positively correlated with the majority (i.e., more than half) of exploited species biomass trends in 16 ecosystems (Table 2, Figure 4). This suggests that the trajectory of exploited species biomass corresponds to the trajectory of the proportion of predatory fish in these ecosystems. These positive correlations occur in the Barents Sea, the eastern Bering Sea, the eastern Scotian Shelf, the English Channel, the Gulf of Cadiz, the Irish Sea, the north Aegean Sea, the northern Humboldt Current, the north Ionian Sea, the north-central Adriatic, the North Sea, the southern Benguela, the south Catalan Sea, the U.S. west coast, Vancouver Island, and the western Scotian Shelf. For three of these ecosystems, the Barents Sea, the English Channel, and the western Scotian Shelf, the trend in PPF is significantly increasing (Figure 7) and most of the exploited biomass trends are also increasing (Table 1, NDES: 0.82, 0.55 and 0.60 for the Barents Sea, the English Channel, and the western Scotian Shelf, respectively). Similarly, for the eastern Scotian Shelf, the northern Humboldt Current, the Gulf of Cadiz, and the north Ionian Sea, less than half of the exploited species biomass trends are declining (Table 1, NDES: 0.37, 0.40, 0.08, and 0, respectively). For the southern Benguela and the south Catalan Sea, the linear trend in PPF is significantly decreasing (Figure 7), but the majority of exploited species have positive biomass trends (Figure 1). This discrepancy is better explained by the fact that the exploited species with declining biomass in these ecosystems have higher average trophic levels than the non-declining exploited species (Figure 3). For ecosystems with a significant trend in the

NDES indicator based on the p -value of the Kendall's tau statistic (Table 1), but without a significant relationship in the PPF trend (the eastern Bering Sea, the Gulf of Cadiz, Irish Sea, north Aegean, and U.S. west coast), a signal may be present in the exploited portion of the community that is masked in the overall community. For example, in the eastern Bering Sea, changes in climatic patterns that have influenced summer bottom temperatures have been associated with declines in commercially exploited Alaska pollock (*Theragra chalcogramma*), and increases in predatory arrowtooth flounder (*Atheresthes stomias*), for which there is little commercial exploitation (Zador et al. 2011, Hunsicker et al. 2013).

Four ecosystems: the Bay of Biscay, the Guinean Shelf, the northeast U.S., and the Scottish west coast, have negative correlations between PPF and the available biomass trends (i.e., less than half of the exploited species biomass trends are positively correlated with PPF; Table 2, Figure 4). This suggests that the trajectory of exploited species biomass contradicts the trajectory of the proportion of predatory fish in these ecosystems. There is a significant decreasing trend in the PPF indicator over time for the northeast U.S. (Figure 7) and more exploited species that are not declining (Table 1, NDES: 0.75). Conversely, there is a significant increasing trend in PPF for the Scottish west coast (Figure 7) and more exploited species that are declining (Table 1, NDES: 0.45). The biomass-weighted average trophic levels corroborate these patterns (Figure 3). For the northeast U.S., although there are fewer species with a declining biomass, the average trophic levels of both the declining and non-declining species are relatively high (~ 4), suggesting that there is a greater proportion of higher trophic level predatory fish are experiencing declines. For the Scottish west coast, the biomass-weighted average trophic level of the declining exploited species is lower than the non-declining species, suggesting that higher trophic level species are being less affected by fishing or other drivers. This is likely due to the introduction of the cod recovery plan in 2004 (EU 2004), which reduced direct fishing mortality on demersal fish in the mixed fishery, although it did not have the intended effect of an increase in the cod stock on the Scottish west coast (Bailey et al. 2011, Alexander et al. In Press).

The trophic level of the surveyed community (TLsc) indicator is significantly and positively correlated with the biomass trends in 9 ecosystems (Table 2, Figure 5): the Bay of Biscay, the eastern Scotian Shelf, the English Channel, the Guinean Shelf, the Irish Sea, the north-central Adriatic, the south Catalan Sea, the U.S. west coast, and Vancouver Island. This suggests that the trajectory of exploited species biomass corresponds to the trajectory of the average trophic level of the surveyed community in these ecosystems. The NDES is higher in the English Channel, the south Catalan Sea, and Vancouver Island (Table 1, NDES: 0.55, 0.56, and 0.77, respectively). However, there are no significant trends in the normalized TLsc time series for these three ecosystems (Figure 7). There are significant negative correlations in the TLsc time series for the eastern Scotian Shelf, the north-central Adriatic, and the U.S. west coast, confirming the positive correlation between exploited species with declining biomass trends and declining TLsc. Additionally, for the eastern Scotian Shelf and the U.S. west coast, the biomass-weighted mean

trophic level of the declining species is slightly higher than the biomass-weighted mean trophic level of the non-declining species (Figure 3).

The TLsc indicator is significantly and negatively correlated with the exploited species biomass trends in eight ecosystems: the eastern Bering Sea, the Gulf of Cadiz, the northern Aegean Sea, the north Ionian Sea, the northeast U.S., the North Sea, the southern Benguela, and the western Scotian Shelf (Table 2, Figure 5). This suggests that the trajectory of exploited species biomass contradicts the trajectory of the average trophic level of the surveyed community in these ecosystems. There are more exploited species with declining trends in the Gulf of Cadiz, the north Aegean Sea, and the north Ionian Sea (Table 1, NDES: 0.08, 0.44, and 0, respectively). The normalized time series trend in TLsc is significantly increasing only for the north Ionian Sea and the western Scotian Shelf. For the western Scotian Shelf, examining the biomass-weighted average trophic level does not provide an explanation for the negative correlation between the exploited biomass trajectories and the TLsc trajectories. In this case the average trophic level of the declining species is lower (Figure 3) due to the high proportion of herring in the biomass, which supports the significant declining slope of the TLsc trend in this ecosystem. There are significant declining trends in the normalized time series of TLsc for the southern Benguela and the North Sea, supporting the negative correlation between the exploited biomass trajectories (Table 1, NDES: 0.59) and the TLsc trajectories. Additionally, the biomass-weighted average trophic level of the declining species is higher than that of the non-declining species in both of these ecosystems, suggesting that the patterns in the exploited species are mirrored in the community indicator.

The mean life span (mLS) indicator is significantly positively correlated with the biomass trends in nine ecosystems (Table 2, Figure 6). This suggests that the trajectory of exploited species biomass corresponds to the trajectory of the mean life span in these ecosystems. In the eastern Scotian Shelf, the Guinean Shelf, the Gulf of Cadiz, the northern Humboldt Current, and the north Ionian Sea ecosystems the NDES indicator is lower (Table 1, NDES: 0.37, 0, 0.08, 0.40, and 0, respectively), and we see significant declines in the slopes of the trends for mLS for all of these systems, with the exception of a non-significant decline for the Guinean Shelf (Figure 7), confirming the positive correlations found with the Kendall's tau analyses. There are more non-declining trends in the English Channel, the northeast U.S., the southern Benguela, and the south Catalan Sea (Table 1, NDES: 0.55, 0.75, 0.59, and 0.56, respectively). In the northeast U.S., there is a lower proportion of declining exploited species (Table 1, NDES: 0.25) and the trend in mLS is increasing significantly (Figure 7), confirming the positive correlations found with the Kendall's tau analyses. However, for the Southern Benguela, there are more non-declining exploited species (Table 1, NDES: 0.60), but a significantly declining mLS trend (Figure 7). A possible explanation is that the exploited species with a declining biomass have higher trophic levels, corresponding to the decline in mLS over time, and possibly reflecting the observed declines in abundance of some K-selected species off South Africa's west coast (Atkinson et al. 2012).

The mLS is negatively correlated with biomass trends in eight ecosystems (Table 2; Figure 6). Six ecosystems have significant negative correlations: the eastern Bering Sea, the Irish Sea, north Aegean Sea, the north-central Adriatic, the North Sea, the Scottish west coast, the U.S. west coast, and the western Scotian Shelf. This suggests that the trajectory of exploited species biomass contradicts the trajectory of the mean life span in these ecosystems. In the eastern Bering Sea, the North Sea, and the western Scotian Shelf, the NDES is higher (Table 1, NDES: 0.59, 0.73, and 0.60, respectively). The linear slopes of the mLS are only significant for the north-central Adriatic, the Scottish west coast, and the western Scotian Shelf (Figure 7), and in each of these cases the slopes are positive. In the case of the western Scotian Shelf, where we have fewer declining exploited biomass trends (Table 1, NDES: 0.60) and a positive linear trend in mLS (Figure 7), we expect a positive correlation from the Kendall's tau analysis. However, the fact that the biomass-weighted average trophic level of the non-declining species is much higher (~4.2 versus ~3.3) could be contributing to longer life spans if higher trophic level species are correlated with higher life spans (Figure 3). For the north-central Adriatic and the Scottish west coast, the proportions of non-declining species are low (Table 1, NDES: 0.29, and 0.45, respectively). Similar to the western Scotian Shelf, the proportion of lower trophic level species is declining, which could be contributing to longer life spans. However, in the case of the Scottish west coast, another explanation is that there has been an increase in higher trophic level species due to reduced fishing (EU 2004).

Conclusions

The NDES allows us to assess the proportion of declining species in an ecosystem and provides a useful measure with which to gauge the ability of a marine ecosystem to sustainably provide wild seafood. Given the importance of seafood to provide critical sustenance for humans is of growing concern (Barrett 2010, Garcia & Rosenberg 2010, Srinivasan et al. 2010, Barange et al. 2014), the NDES may be used as a simple indicator to identify areas where the delivery of this food provisioning ecosystem service is declining or is already in jeopardy. Simple ecosystem indicators such as this have the potential to be used in regions with more robust fisheries management, as well as in regions that are considered to be data-limited and limited in resources and expertise to provide well-founded management advice. In regions with robust fisheries management, ecosystem indicators such as NDES serve an important role in providing a measure of overall ecosystem health, which is critical given that most fisheries management advice continues to be delivered on a single stock basis despite global rhetoric about intentions to adopt ecosystem based management. In regions with less robust fisheries management, the value of NDES cannot be understated. Such a simple indicator, even if calculated with only a limited number of trends, can provide some guidance on status where one may not have been previously available.

It is important to note that the number and length of available species biomass time series may influence the proposed indicator. The comparisons made here are over

the length of the surveys or assessments that are available in each ecosystem. For the 22 ecosystems presented this represents an average of 27 years, but can be as many as 45 years (northeast U.S.) and as few as four (north Aegean Sea). One of the strengths of Kendall's tau is that the length and number of time series is accounted for in the significance test. However, there may also be situations where biomass trends are variable over the length of the time series. In the Bay of Biscay for example, horse mackerel (*Trachurus trachurus*) declined strongly from the early 1970s to the early 1980s where it remained stable until the early 2000s, when it began to strongly increase. In cases such as these, the determination of a declining trend will come down to the proportion of concordant versus discordant pairs, a result that may not be optimal in cases where there are opposing trends over the time series. Overall, the NDES may not always be an appropriate indicator, given that 1) longer time series data likely have a higher probability of containing opposing trends in species biomass and 2) shorter time series have a larger variance in the tau distribution and trends are more difficult to detect than for longer time series. However, a subset of years from a longer time series can be selected to best reflect the current status of the ecosystem.

Here we illustrate, through a direct comparison of the 'current status' of three community indicators and the NDES indicator, that many declining biomass trends can point to declining TL, lower mLS, and lower PPF (or the converse), highlighting similar patterns in the delivery of both provisioning and regulating services of the ecosystems. This may make intuitive sense if the exploited portion of the ecosystem is tracking what is happening at the community level. However, in some cases, the patterns among these community-level indicators do not agree (e.g., there is a low proportion of species with declining biomass but the mean trophic level of the surveyed community is low). This may be because the NDES indicator is calculated using the full time series available for each exploited species to provide a state indicator, whereas the current status for the community indicators is calculated over the most recent five years and for both exploited and non-exploited species. However, in cases where there is a difference in the status of the community indicators and the NDES indicator, we find it is critical to explore which components of the ecosystem are actually declining. One way to do this is to examine the proportion of declining species in the context of trophic level. Here, we find that in some cases, discrepancies between the directions of the indicators can be explained by looking at the biomass-weighted average trophic level of the declining component of the ecosystem. In general, many declines in higher trophic level exploited species correspond to lower scores for the proportion of predatory fish (PPF) and the trophic level of the surveyed community (TLsc), and to a lesser degree lower mean life span (mLS) suggesting that the pattern captured in the exploited biomass is also observed at the community level. In other cases, in ecosystems driven by lower trophic level fish rather than top-down predation pressure, a high score of NDES may occur with an increase in PPF and a relatively low TLsc (e.g., the north Ionian Sea). In some cases, this happens where lower trophic level species dominate the proportion of exploited species, such as in upwelling systems (e.g., several upwelling systems and many of the Mediterranean systems have low scores

for current state of community indicators). Since the NDES and biomass trends of exploited species are species-weighted whereas mLs, PPF and TLsc are biomass-weighted indicators, we may expect to find some discrepancies in trajectories and seemingly inconsistent correlations.

Additionally, for some regions, stock assessment biomass estimates may provide a better indication of population trends than survey biomass estimates (i.e., some surveys were not designed to sample all species in the community with equal efficiency and some species are assessed using alternate survey data). For example, standard surveys were not conducted in the eastern Bering Sea until a few years after a regime shift. Thus, the survey time series captures the decline from the peak abundance of Alaska pollock that followed the regime shift, whereas the stock assessment, which incorporates alternate survey data, provides a time series of abundance that precedes the regime shift.

Similarly, using the Kendall's tau to examine the correlation between ecosystem indicators and the exploited biomass trends in a system allows one to understand whether patterns in exploited species biomass match trajectories in indicators designed to look at the fuller (exploited and non-exploited) community. Again, ancillary information, such as the average trophic level of the declining exploited species and the direction of significant trends in the ecosystem indicators, can explain what drives the relationships between the NDES indicator and other indicators.

A major finding of our analysis is that the multiple impacts of fishing (and other drivers) on marine ecosystems are difficult to track and assess concomitantly with any single indicator since multiple drivers from fishing to climate and habitat destruction are acting at multiple scales and on multiple processes in ecosystems. Therefore, it is important to explore a suite of indicators and their associations (Blanchard et al. 2010, Shannon et al. 2010, Shin et al. 2010b). The NDES indicator can provide a simple way to focus on exploited species and, through comparisons with community indicators, evaluate the significance of such trends at the community level. Furthermore, the indicator does not make naive assumptions that all species should be declining or increasing but compares the proportion declining against the overall pattern. In developing the NDES, we have included the assumption that in an 'healthy' ecosystem the number of species showing biomass declines should on average be balanced by species showing increases (over the relevant timeframe). It is also imperative to identify which key abiotic conditions and biological groups in the ecosystem are changing to determine the potential impact of the change on the food web. The use here of the community-level indicators provides information on the ability of the ecosystems to deliver regulating services such as maintenance of biodiversity, trophic stability, and reproductive capability. These results illustrate the need to understand the exploitation strategy and long-term dynamics of marine ecosystems and ocean and climate forcing and variability when interpreting such ecosystem indicators. This

has been illustrated with trophic level-based indicators (Shannon et al. 2014, Gascuel et al. In press).

The ecological status of marine exploited resources is affected by fishing activity; it can also be strongly dependent on the environment. IndiSeas has collated information on several environmental and climate indicators, such as sea surface temperature (SST) and chlorophyll-a densities, which can help clarify the roles that climate and the environment play on the ecological status of marine exploited resources (Shin et al. 2012). These indicators are used to reflect the production potential of ecosystems and thus may reflect more of the supporting role of ecosystems. Additionally, IndiSeas uses human dimension indicators in order to evaluate the human side of fisheries activities, and benefits to society (Shin et al. 2012). The following are considered: 1) effectiveness of fisheries management and quality of governance; 2) contribution of fisheries to the broader society; and 3) wellbeing and resilience of fishing communities. While the focus here was on the development of a specific indicator to evaluate changes in a provisioning ecosystem service (and comparisons with indicators that capture more of the regulating role of ecosystems), it would be of great interest to explore the broader set of indicators in conjunction with NDES to evaluate the tradeoffs and synergies between other regulating, supporting, or cultural ecosystem services.

When multiple ecosystem indicators are used to evaluate patterns of change, it is important to recognize that some indicators are likely to reflect one aspect of the ecosystem more clearly (e.g. fishing), while others may respond to other processes (e.g., climate change, habitat destruction), and thus proffer confounding assessments (Shin et al. 2010a). In such cases, the use of expert judgment (such as that employed in this project in which local experts provide insights into interpretation of the indicator trends in the context of their ecosystems) to evaluate overall ecosystem health will be beneficial. Conversely, the NDES indicator and its associated histogram of tau scores can provide useful information to understand patterns in other trend-based community-level indicators. For example, if the mean trophic level of a community is increasing, it is useful to know if there is an unexpectedly large proportion of lower trophic level species declining, rather than the inferred increase in higher trophic level species. This has been already observed in ecosystems with a high exploitation level of small pelagic fish and invertebrates, such as in the Mediterranean Sea and the southern Benguela (Coll et al. 2010b, Piroddi et al. 2010, Shannon et al. 2010). Therefore, we conclude that using ecological indicators, including the NDES indicator, requires context-specific supporting information in order to provide guidance within a management setting, but that it can provide a valuable and relatively easy to understand indicator. Given its utility to measure the ability of the ecosystem to deliver seafood, further work will be necessary to explore this indicator in relation to the social, economic, governance, environmental, and other ecological attributes of exploited marine ecosystems to provide a more holistic analysis of their overall health and functioning.

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Tables

Table 1. Description of ecosystems used in the Non-declining Exploited Species (NDES) analysis, including the number of exploited species biomass trends and average length of the time series used to calculate the NDES in each ecosystem. Additionally, the significance of Kendall's tau statistic as determined by a two-sided p -value (bolded if significant), and proportion of non-declining species derived from the NDES indicator are provided. A significant Kendall's tau indicates more declining or increasing trends than could be expected by chance.

Ecosystem	Geographic area	Type of ecosystem	Number of biomass trends	Average time series length	Two-sided p-value of Kendall's tau	Proportion of non-declining species (NDES)
Barents Sea	NE Atlantic	High latitude	11	33	0.006	0.82
Bay of Biscay	NE Atlantic	Temperate	9	23	0.009	0.22
Central Baltic Sea	NE Atlantic	Brackish temperate	6	25	0.441	0.50
Eastern Bering Sea	NE Pacific	High latitude	22	29	0.003	0.59
Eastern Scotian Shelf	NW Atlantic	Temperate	30	41	<0.001	0.37
English Channel	NE Atlantic	Temperate	31	23	0.001	0.55
Guinean Shelf	East-central Atlantic	Upwelling	20	25	<0.001	0.00
Gulf of Cadiz	NE Atlantic	Temperate	13	18	<0.001	0.08
Irish Sea	NE Atlantic	Temperate	15	18	0.009	0.40
North Aegean Sea	NE Mediterranean	Temperate	57	4	<0.001	0.44
North Ionian Sea	NE Mediterranean	Temperate	5	45	0.013	0.00
North Sea	NE Atlantic	Temperate	30	28	<0.001	0.73
North-central Adriatic	Central Mediterranean	Temperate	17	25	<0.001	0.29
Northeast U.S.	NW Atlantic	Temperate	122	47	<0.001	0.75
Northern Humboldt Current	SE Pacific	Upwelling	10	19	0.055	0.40
Portuguese coast	NE Atlantic	Upwelling	10	26	0.003	0.80
Scottish west coast	NE Atlantic	Temperate	11	24	0.076	0.45
South Catalan Sea	NW Mediterranean	Temperate	16	34	0.037	0.56
Southern Benguela	SE Atlantic	Upwelling	59	29	<0.001	0.59
U.S. west coast	NE Pacific	Temperate	29	8	<0.001	0.41
Vancouver Island	NE Pacific	Temperate	22	31	<0.001	0.77
Western Scotian Shelf	NW Atlantic	Temperate	30	41	<0.001	0.60

Table 2. Correlation over time between the biomass time series of each exploited species and the three community indicators (proportion of predatory fish—PPF, and the average trophic level of the surveyed community—TLsc, and mean life span—mLS) for each ecosystem. The proportions of correlations greater than 0.5 are termed ‘positively correlated’ and proportions less than 0.5 are termed ‘negatively correlated’, referring to the preponderance of species-level biomass trends that are positively or negatively correlated with the particular community indicator. The proportions are bolded if the Kendall’s tau is significant (i.e., based on the *p*-values).

Ecosystem	Proportion predatory fish (PPF)		Survey trophic level (TLsc)		Mean life span (mLS)	
	Two-sided p - value of Kendall’s tau	Proportion positively correlated trends	Two-sided p -value of Kendall’s tau	Proportion positively correlated trends	Two-sided p - value of Kendall’s tau	Proportion positively correlated trends
Barents Sea	0.023	0.73	0.076	0.45	0.076	0.55
Bay of Biscay	0.037	0.33	0.037	0.78	--	--
Central Baltic Sea	0.441	0.50	--	--	0.441	0.50
Eastern Bering Sea	0.001	0.64	<0.001	0.27	<0.001	0.27
Eastern Scotian Shelf	<0.001	0.70	<0.001	0.67	<0.001	0.63
English Channel	<0.001	0.61	<0.001	0.74	<0.001	0.61
Guinean Shelf	<0.001	0.05	<0.001	0.90	<0.001	0.95
Gulf of Cadiz	0.015	0.62	0.015	0.38	<0.001	0.85
Irish Sea	0.028	0.67	0.028	0.53	0.028	0.47
North Aegean Sea	<0.001	0.51	<0.001	0.49	<0.001	0.32
Northern Humboldt Current	0.015	0.70	0.055	0.60	0.015	0.70
North Ionian Sea	0.013	1.00	0.013	0.00	0.013	1.00
North-central Adriatic	0.046	0.53	0.046	0.53	<0.001	0.29
Northeast U.S.	<0.001	0.25	<0.001	0.34	<0.001	0.60
North Sea	<0.001	0.57	<0.001	0.40	<0.001	0.40
Portuguese coast	0.055	0.70	0.055	0.40	0.055	0.60
Southern Benguela	<0.001	0.61	<0.001	0.46	<0.001	0.59
South Catalan Sea	0.013	0.56	0.013	0.56	0.004	0.63
Scottish west coast	0.023	0.36	0.076	0.64	0.023	0.36
U.S. west coast	0.001	0.48	<0.001	0.59	<0.001	0.28
Vancouver Island	0.001	0.64	0.003	0.55	0.008	0.50
Western Scotian Shelf	<0.001	0.53	<0.001	0.47	<0.001	0.40

Figures

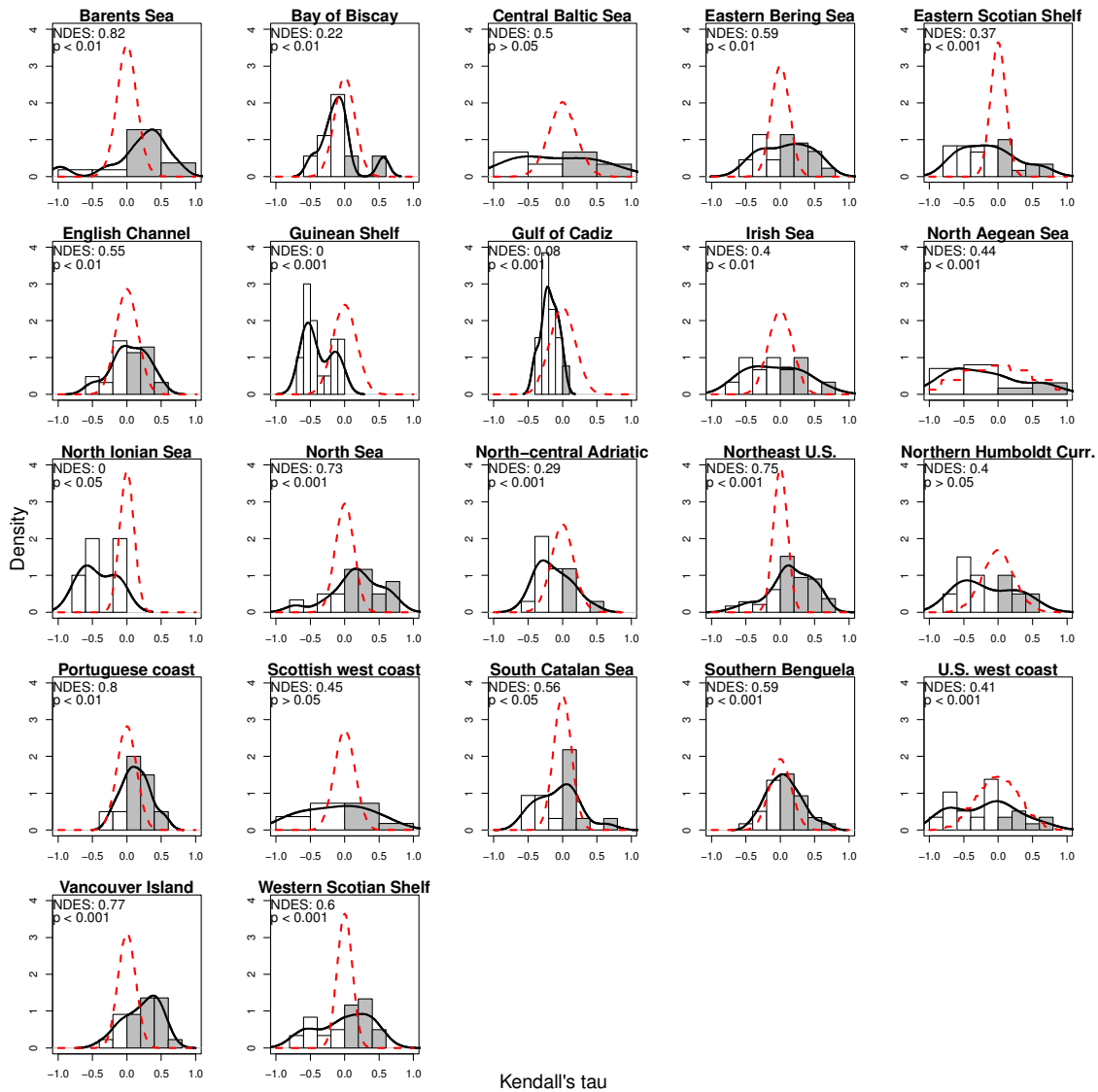


Figure 1. True histograms (bars) of Kendall rank coefficients (tau) by ecosystem with Kernel density smooth functions (solid black lines) contrasted with the theoretical expected distribution of tau by ecosystem (red dashed lines). Shifts in the solid line to the left or right of the dashed line, or histogram bars to the left or right of zero that are taller than the red line, indicate more temporal decreases or increases in the biomass of exploited fish species in the community than would be expected by chance (two-tailed p-value categories are listed in the top left corner of each graph). The white area in the histograms (negative correlations, Kendall's tau < 0) illustrated the proportion of declining exploited species and the grey area in the histograms (positive correlations, Kendall's tau > 0) illustrates the proportion of non-declining exploited species in each ecosystem. The number of non-declining exploited species out of the total is the indicator we call the 'Non-declining Exploited Species' indicator (NDES). NDES values are listed in the top left corner of the graphs with the associated significance level of the indicator (two-tailed p-value categories) for each ecosystem.



Figure 2. Petal plot of current state for each of the NDES indicator and the three community indicators (mean life span—mLS, proportion of predatory fish—PPF, and the average trophic level of the surveyed community—TLsc) for each ecosystem. Each indicator is scaled from zero to one, with a score of one indicating a ‘better’ status. A larger petal corresponds to a higher score. Note that the blank plot for the north Ionian Sea ecosystem reflects the fact that all indicator scores were the lowest in comparison to the other ecosystems.

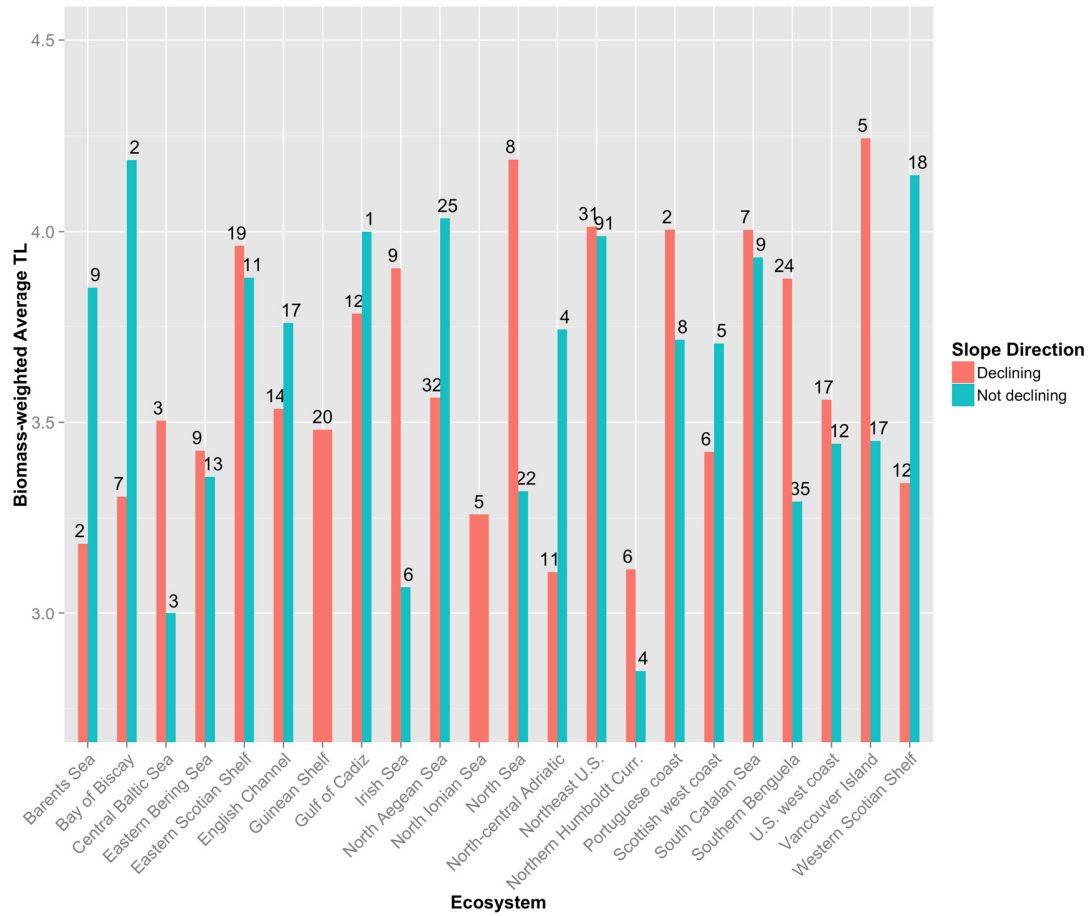


Figure 3. Biomass-weighted average trophic levels of the exploited species trends that are declining (red) and not declining (blue) for each ecosystem. Numbers on the top of each bar correspond to the number of biomass trends of exploited species for each category and ecosystem. Note that the y-axis has a lower truncation at 2.75.

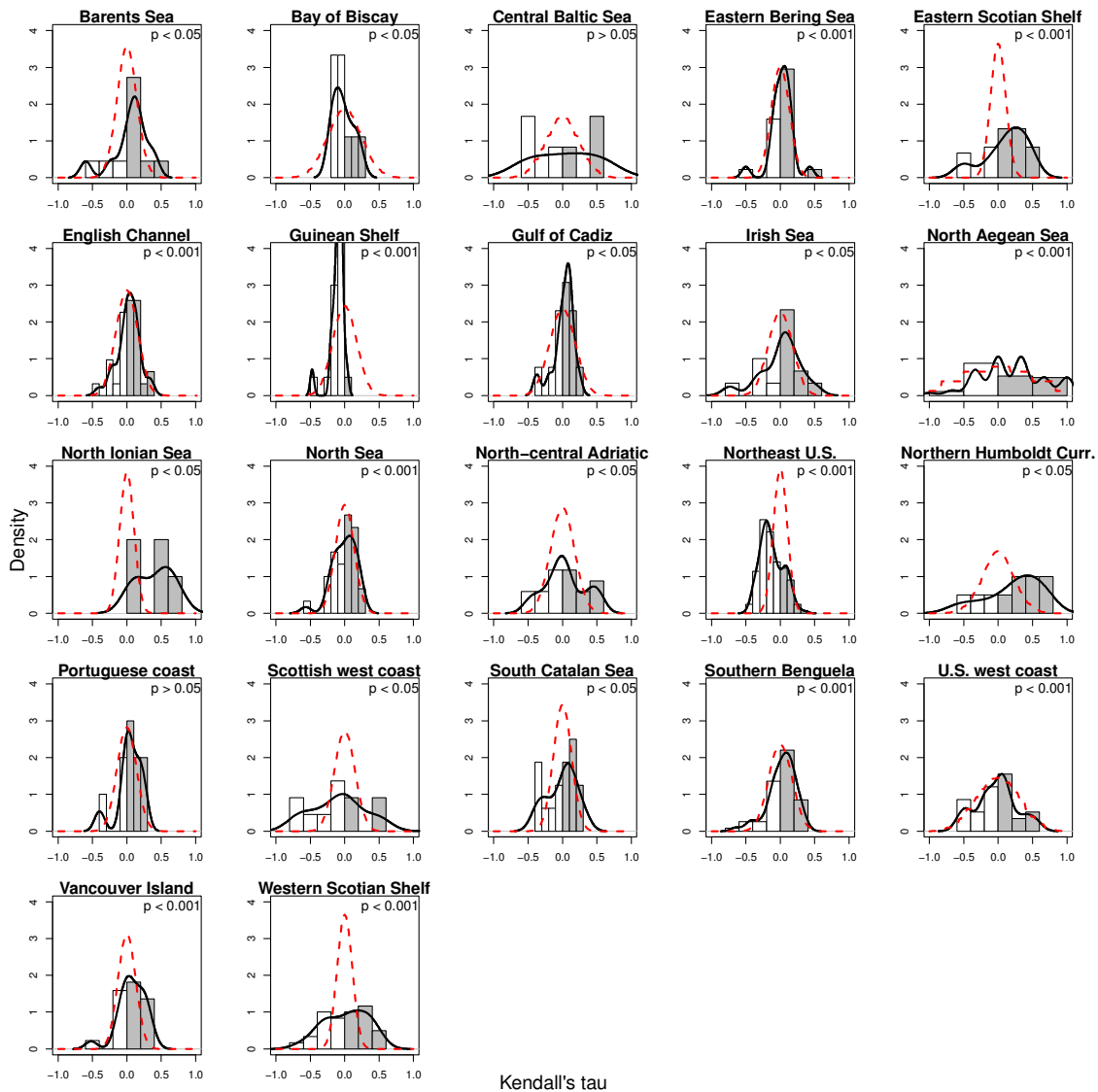


Figure 4. True histograms (bars) of Kendall rank coefficients (τ) by ecosystem indicating the correlation of the exploited species biomass time series with the trend in the community indicator, proportion of predatory fish (PPF), over the whole time series in which both indicators are available. Kernel density smooth functions (solid black lines) are contrasted with the theoretical expected distribution of τ by ecosystem (red dashed lines). A shift in the solid line to the left or right of the dashed line, or histogram bars to the left or right of zero that are taller than the red line, indicates more negative (non-shaded area of histogram) or positive (grey shaded area of histogram) correlations between the PPF and the trends in the exploited species biomass in the community than would be expected by chance (two tailed p-values are listed above each graph).

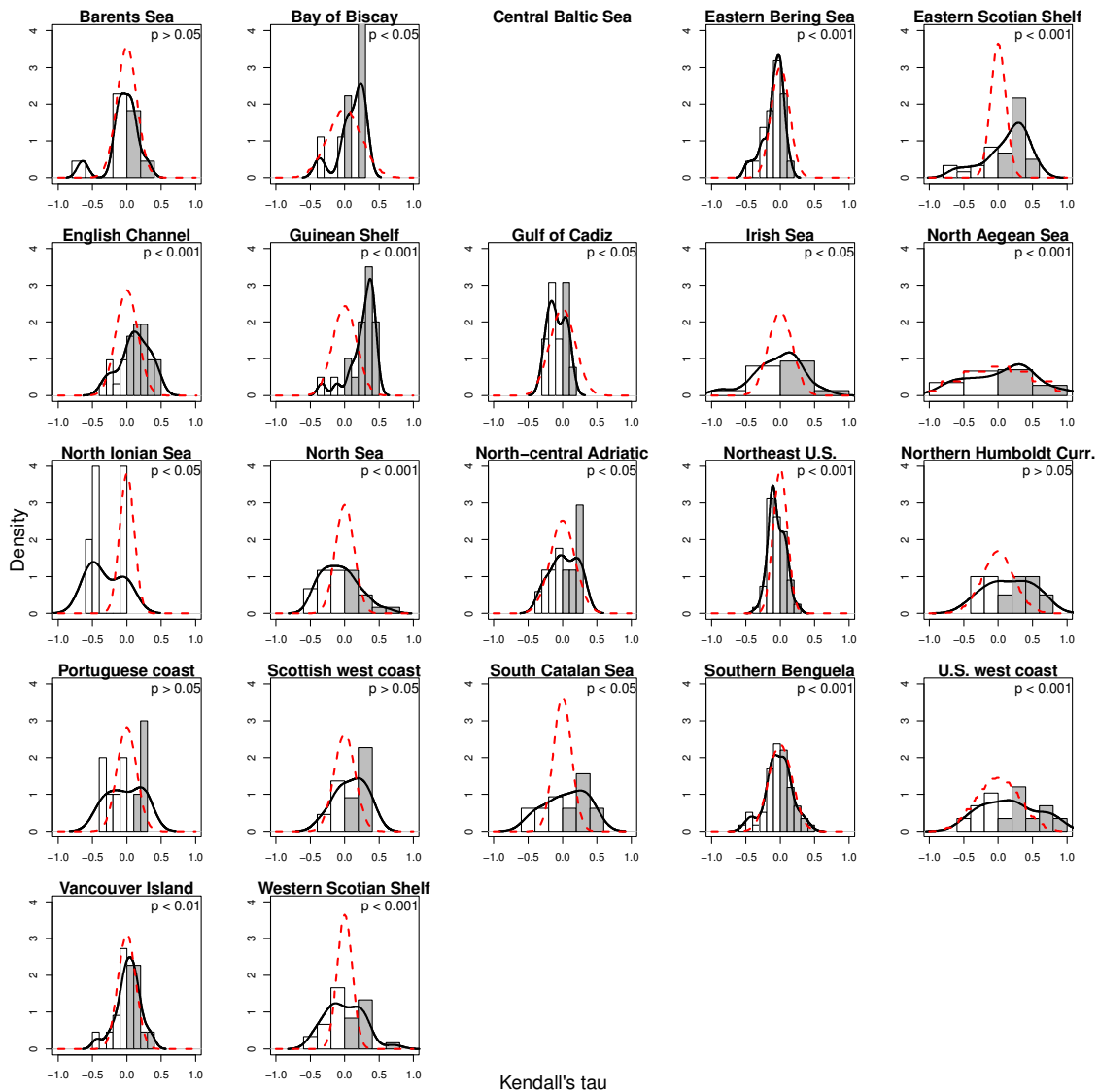


Figure 5. True histograms (bars) of Kendall rank coefficients (τ) by ecosystem indicating the correlation of the exploited species biomass time series with the trend in the community indicator, average trophic level of the surveyed community (TLsc), over the whole time series in which both indicators are available. Kernel density smooth functions (solid black lines) are contrasted with the theoretical expected distribution of τ by ecosystem (red dashed lines). A shift in the solid line to the left or right of the dashed line, or histogram bars to the left or right of zero that are taller than the red line, indicates more negative (non-shaded area of histogram) or positive (grey shaded area of histogram) correlations between the TLsc and the trends in the exploited species biomass in the community than would be expected by chance (two tailed p-values are listed above each graph). The TLsc indicator was not available for the central Baltic Sea ecosystem.

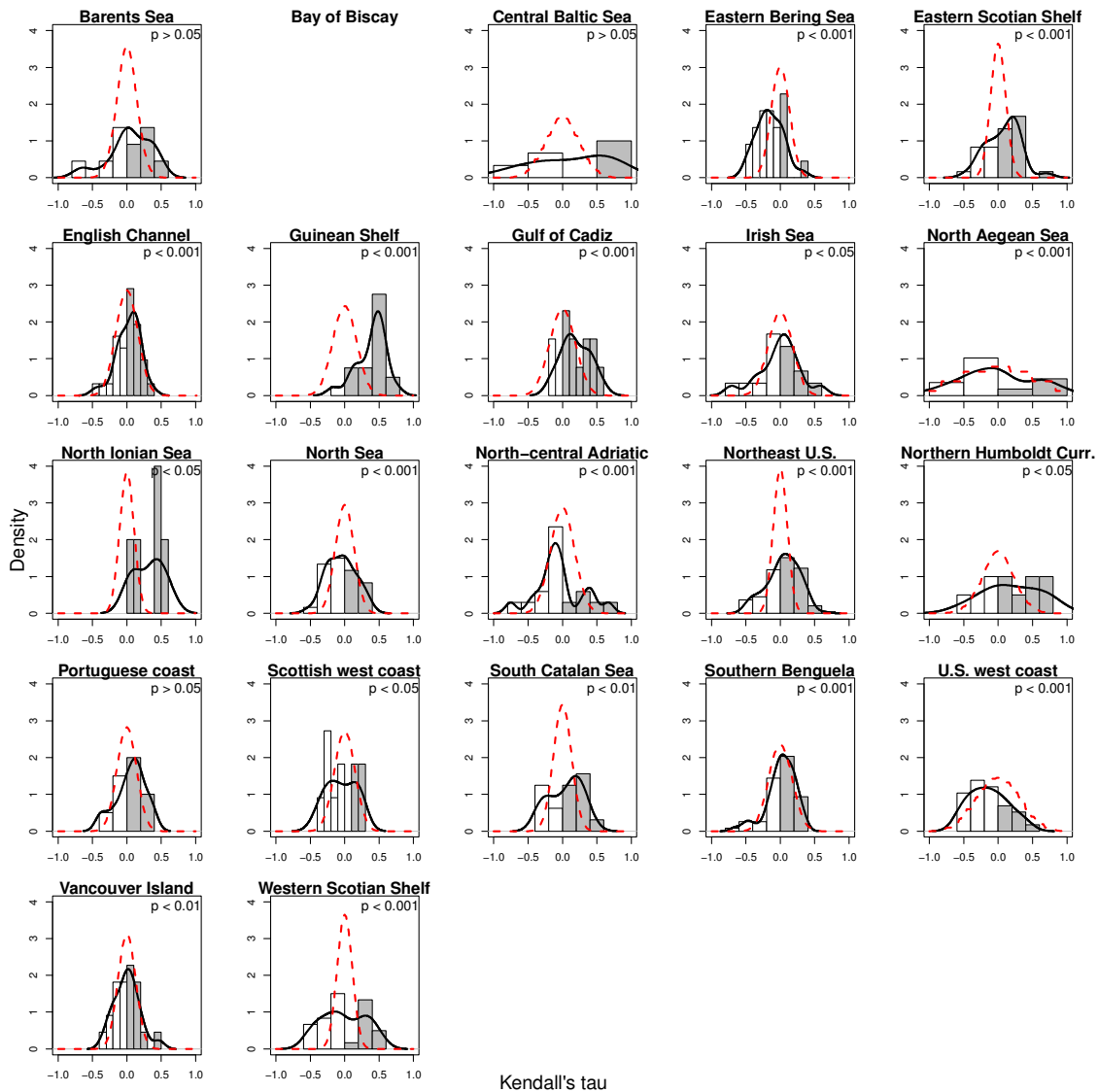


Figure 6. True histograms (bars) of Kendall rank coefficients (τ) by ecosystem indicating the correlation of the exploited species biomass time series with the trend in the community indicator, mean life span (mLS), over the whole time series in which both indicators are available. Kernel density smooth functions (solid black lines) are contrasted with the theoretical expected distribution of τ by ecosystem (red dashed lines). A shift in the solid line to the left or right of the dashed line, or histogram bars to the left or right of zero that are taller than the red line, indicates more negative (non-shaded area of histogram) or positive (grey shaded area of histogram) correlations between the mLS and the trends in the exploited species biomass in the community than would be expected by chance (two tailed p-values are listed above each graph). The mLS indicator was not available for the Bay of Biscay ecosystem.

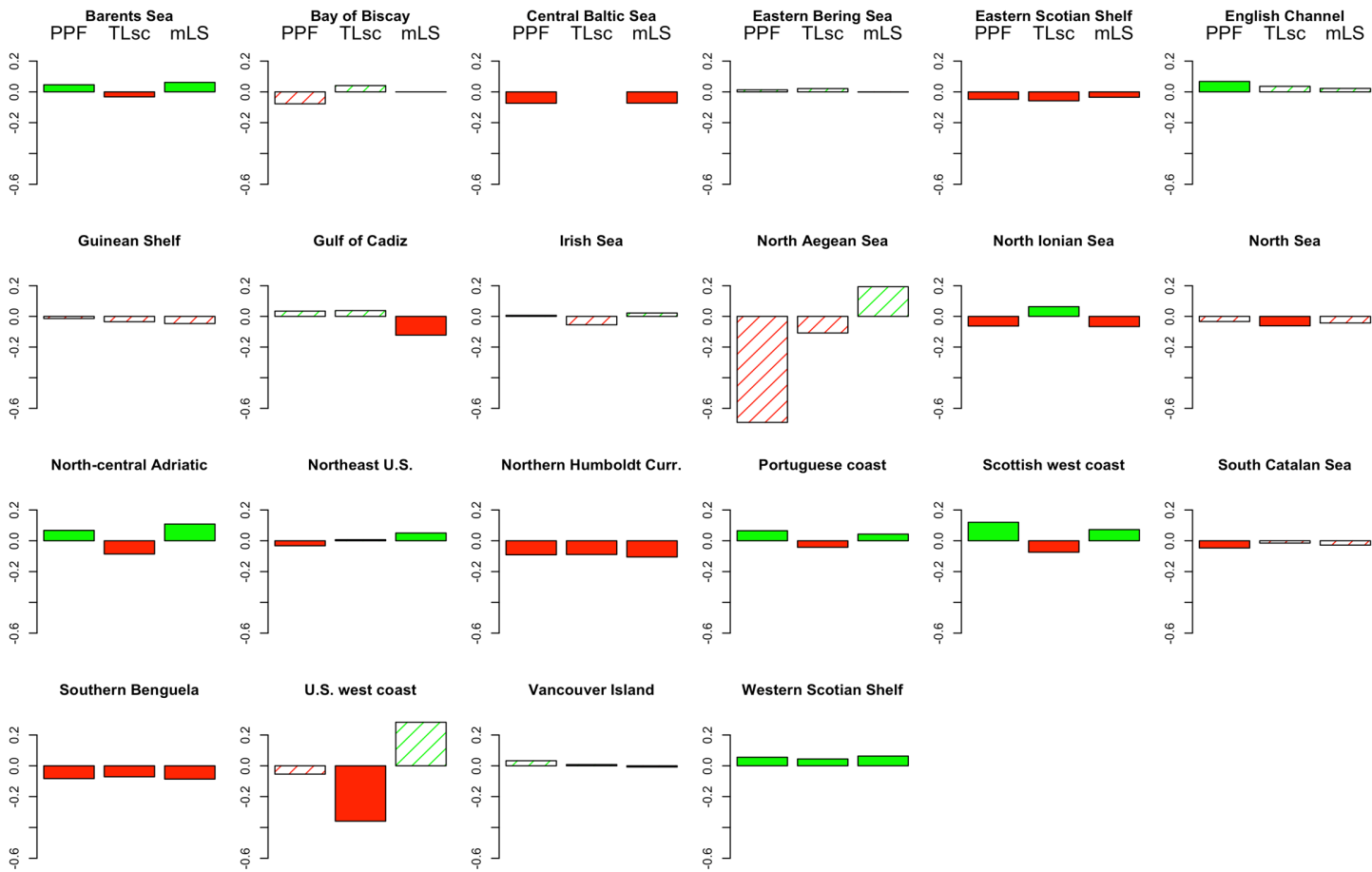


Figure 7. Histograms of slopes of the three independent indicators, proportion of predatory fish (PPF), trophic level of the surveyed community (TLsc), and mean life span (mLS). Solid red indicates a significant decreasing slope and green indicates a significant increasing slope. Striped lines indicate a non-significant trend. These slopes were calculated from standardized time-series using generalized least-squares with autoregressive errors.

