Evaluating Catch Mean Trophic Level as an Indicator of Ecosystem Change

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Abstract

The mean trophic level (MTL) of catch has been proposed to track changes in marine ecosystems resulting from fishing. Despite the ongoing debate surrounding its validity, catch MTL is a key indicator for measuring progress toward global biodiversity goals. Evaluations of catch MTL have found no linear correlation between trends in the indicator and the ecosystem state. I use simulation models and a method common in epidemiology to evaluate catch MTL as a strategic indicator for ecosystem changes even though it is not linearly related. The performance of catch MTL was 'fair' when applied globally, but varied considerably across individual simulated ecosystems. Catch MTL performed most reliably when the composition of the catch reflected the ecosystem and fishing pressure was constant over time. The inconsistent performance of catch MTL suggests it is not a reliable indicator of ecological change, but it may provide useful information about fisheries catch over time.

Keywords: Catch mean trophic level; ecosystem indicators; ROC curves; fisheries

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Introduction

Fishing and Its Impacts

Fish and seafood are a major source of food and a substantial global industry. Fish account for approximately 17% of the global population's intake of animal protein, and provide more than 3 billion people with 20% of their animal protein (FAO, 2012). Additionally, fisheries stimulate economic activity through revenue and employment. Global marine capture fisheries produced between 77 and 84 million tonnes annually for the past 15 years, with an estimated annual first-sale value of almost US$100 billion. Capture fisheries directly employs approximately 40 million people, and the entire fish and seafood industry provides 180 million jobs annually (FAO, 2012).

Fishing pressure can have direct and indirect consequences on marine ecosystems. The most immediate results of fishing pressure on a targeted population are decreased average size and abundance, and exploitation is the most common cause (55%) of marine extinctions (Dulvy et al. 2003; Hall, 1999; Myers et al. 2007; Russ, 1991). Fishing pressure also impacts the genetic diversity of a population, especially when fishing activity is highly selective (Kenchington, 2003; Smith et al. 1991). Consequently, heritable life history characteristics can change within a population, including reproductive capacity, which determines the ability of a population to sustain itself under conditions of high mortality (Kenchington, 2003). By changing the average size and abundance of targeted species, fishing pressure can also alter the size structure and diversity within a marine community (Bianchi et al. 2000; Hall 1999; Stevens et al. 2000). Indirect ecological consequences of fishing include mesopredator release due to decreased abundance of apex predators, although the magnitude of the compensatory response may differ among ecosystems (Jennings & Kaiser, 1998; Daan et al. 2003; Dulvy et al. 2004). Fishing can also indirectly affect the composition of the marine ecosystem through the removal of targeted species and the subsequent

competitive release of less abundant species (Dulvy et al. 2000; Jennings & Kaiser, 1998; Stevens et al. 2000). These indirect effects of fishing are likely substantial and impact multiple levels of the food chain, although the consequences may be different for ecosystems with top-down control and those with bottom-up control (Blaber et al. 2000; Greenstreet & Rogers, 2000; Myers et al. 2007; Stevens et al. 2000; Travers et al. 2010).

The current rate of global fishing is unprecedented. Currently, 57% of fish stocks monitored by the Food and Agriculture Organization of the United Nations (FAO) are estimated to be fully exploited, meaning the current catches are at maximum sustainable yield. Another 30% of monitored stocks are overexploited or depleted, producing less than their maximum potential yield. Only 13% of fish stocks are considered under exploited or moderately exploited, and could potentially yield more than their current catch (FAO, 2012). The percentages of fully exploited, overexploited, and depleted stocks are the highest in the entire time series considered by the FAO, which is generating increasing concern (Garcia & de Leiva Moreno, 2003; Hilborn et al. 2003; Myers & Worm, 2003; FAO, 2012).

Ecosystem Indicators

At this time, fisheries managers are uncertain how to monitor changes caused by fishing in the marine ecosystem. Scientists have explored a number of ecological and socio-economic indicators to help sustainably manage fish stocks from an ecosystem-based perspective (Bowen & Riley, 2003; Cury et al. 2005; Cury & Christensen, 2005).

Ecological indicators track specific aspects of the marine community as representations of the state of the ecosystem. Based on theoretical and empirical evidence, decreases in size-based indicators such as mean length or weight of a marine community generally indicate negative effects of fishing on the marine community (Jennings & Dulvy, 2005; Rochet & Trenkel, 2003; Shin et al. 2005; Piet & Jennings, 2005). Similarly, a decline in biomass or biomass ratios (such as pelagic:demersal) of a

population, community, or ecosystem reflects a loss of species abundance or a shift in size dynamics within an ecosystem (Fulton et al. 2005; Rochet & Trenkel, 2003). Size spectra, which combine measures of organisms' sizes with their abundance or biomass in the ecosystem, also reveal disproportionate changes among various size-groups within a community (Duplisea & Castonguay, 2006; Piet & Jennings, 2005; Rochet & Trenkel, 2003). An increase in size spectra may indicate increased abundance of large predatory species or a loss of small prey organisms. Diversity indices capture the number and relative abundances of species or size classes within an ecosystem, with a decline in the index suggesting loss, or impending loss of biodiversity (Fulton et al. 2005; Piet & Jennings, 2005; Rice, 2003; Rochet & Trenkel, 2003; Shin et al. 2005).

Socio-economic indicators measure some aspect of human interaction with the marine environment to provide an understanding of ecosystem state. For example, the economic performance of a fishing fleet, characterized mainly by profitability and economic efficiency, can provide clues regarding ecosystem changes (Gasalla et al. 2010) with declining economic performance suggesting decreasing abundance or availability of target groups. The relationship between seafood price and trophic level may also provide insight to ecosystem changes, with a rise in market price potentially reflecting reduced local availability of a species relative to demand, so that a comprehensive price index may reveal trends in a particular ecosystem (Pinnegar et al. 2002; 2006). The economic attributes of a particular taxon, including price and size as a representation of potential profitability, may be even more important indicators of fishing activity and key to identifying populations susceptible to fishery expansion (Sethi et al. 2010).

While some of these indicators have shown promising results, there are often trade-offs associated with obtaining or using indicators. Size-based and abundance-based indicators are straightforward to calculate and communicate, and can reflect the state and functioning of ecosystems because many ecological and fishing processes are size dependent (Fulton et al. 2005; Shin et al. 2005). Likewise, the biomass of marine populations or communities can serve as a robust indicator of ecosystem attributes, especially when measured for sensitive groups found at the top of the food web or those

targeted by fisheries (Fulton et al. 2005). However, size-based and biomass-based indices require extensive data collection from species or the ecosystem as a whole, including organisms not targeted commercially. The data are often based on fisheries-independent trawl surveys, which can be expensive and labor-intensive, and the indicators are often sensitive to gear, timing, and location of sampling (Shin et al. 2005). Diversity indices perform less consistently as indicators of the ecosystem state than size-based or abundance-based indicators, presenting no clear trends in response to ecological changes (Piet & Jennings, Shin et al. 2005). Diversity indices also require extensive fishery-independent sampling, and can be difficult to communicate due to various measures and definitions of diversity (Fulton et al. 2005; Hill, 1973; Spellerberg & Fedor, 2003).

Socio-economic indicators can be quite sensitive to factors such as spatial scale and consumer preferences, and therefore may not accurately track changes in the ecosystem. Encompassing data from a larger area or multiple fishing fleets may alter trends seen in socio-economic indicators (Gasalla et al. 2010; Pinnegar et al. 2006), and the globalization of seafood production and consumption masks local supply and demand trends (Pinnegar et al. 2006). Government subsidies, increasing aquaculture production, and changes in consumer preferences due to marketing also create high variability in socio-economic indicators (Gasalla et al. 2010; Pinnegar et al. 2006). These factors are difficult to incorporate into regional socio-economic indicators and add to the difficulty of differentiating between change in the ecological system and change in the social system.

Catch Mean Trophic Level

The mean trophic level (MTL) of fisheries catch was proposed as a tool to evaluate changes in fisheries landings on a global scale (Pauly et al. 1998). Trophic level represents an ecological function, rather than a particular group of species, and characterizes energy flow in an ecosystem. A change in energy flow will likely impact the population structure, but not necessarily vice versa, allowing trophic structure to account

for the natural resilience found in many marine ecosystems (Lindeman, 1942; Levine, 1980).

Pauly et al. (1998) estimated global catch MTL each year since 1950 based on FAO catch statistics and trophic level estimates for 220 groups of fish and invertebrates, and suggested the observed decline is due to systematically removing top predators from marine ecosystems, or “fishing down the food web”. In other words, fishermen are no longer catching high trophic-level species such as sharks and tuna because few remain, and this loss of high trophic-level species presumably impacts the composition and functioning of the ecosystem. The authors showed similar declines for marine and inland areas, and varying trends in catch MTL for different regions around the world. However, the “fishing down the food web” theory suggests that catch MTL should decrease as fisheries landings increase, which was not the case in three of four regions evaluated. The authors attributed the surprising results to large unreported catches, discards, and possibly indirect effects of fishing on trophic dynamics of the ecosystems.

The ability to assess fishing impacts on a global scale was both novel and desirable, but Caddy et al. (1998) quickly expressed concern that landings may not truly reflect the abundance of organisms in an ecosystem. Additionally, assuming a decline in catch MTL is a result of “fishing down the food web” oversimplifies the effects of fishing on global stocks, and does not consider other events that may cause declines in catch MTL such as coastal eutrophication or deliberate targeting of particular taxa. Finally, assigning a trophic level to each component of the landings is difficult given the taxonomic resolution of most catch data, and an estimated decline in catch MTL is difficult to statistically substantiate (Caddy et al. 1998).

Catch Mean Trophic Level as an Ecosystem Indicator

Despite the concerns regarding the interpretation of declines in catch MTL, scientists began to consider catch MTL as an ecosystem indicator to measure changes in biodiversity (Pauly & Watson, 2005). The indicator, termed “Mean Trophic Index”

(MTI) is appealing because it can be calculated from existing catch data around the world, trends are obvious and easily quantified, and the data can be aggregated into various spatial and taxonomic configurations. More important than the actual value of the indicator is the trend in MTI over time, with a downward trend suggesting a change in the structure of the underlying ecosystem and an unsustainable fishery (Pauly & Watson, 2005). MTI was declared one of the key indicators used by the Convention on Biological Diversity (CBD) in 2004 to measure progress toward global biodiversity goals (CBD, 2004). In an updated strategic plan, the MTI is still listed as an indicator for 3 of the 20 biodiversity targets established by the convention (CBD, 2010).

Since the introduction of the catch MTL as an indicator of ecosystem change, several studies have supported its use. Changes in catch MTL were an accurate indicator of fishing impacts in a small, isolated, freshwater area (Kantoussan et al. 2010), and downward MTI trends in rapidly developing fisheries in the Gulf of Thailand corresponded to changes in the abundance of multiple species and the composition of the ecosystem (Pauly & Chuenpagdee, 2003). In areas experiencing population growth and economic development, declines in catch MTL often corresponded to higher total fisheries catches and increased marine pollution and habitat loss, reflecting ecological changes due to increased anthropogenic activity (Clausen & York, 2008). However, in some cases the indicator must be used with caution; the signal from 'Fishing Down the Food Web' can be masked if the catch data is over-aggregated. While some argue that choosing the appropriate spatial scale and taxonomic grouping, as well as omitting more variable low trophic level groups from analyses will allow the indicator to more accurately detect ecosystem changes (Pauly & Palomares, 2005; Pauly & Watson, 2005), data availability does not always allow for the comparative analysis of multiple levels of aggregation (Caddy et al. 1998, Fulton et al. 2005). Further exploration of the meaning of particular MTL values may allow the indicator to be used as a policy-activation tool, wherein a given change in catch MTL over time would elicit a precautionary management strategy or more detailed research (Pauly & Watson, 2005; Powers, 2010).

Conversely, a number of scientists have questioned the specificity of catch MTL as an indicator of ecological change due to fishing. In other words, a change in the

indicator value may in fact be informing users of changes due to other factors, such as expansion of the fishery, policy changes, or increased ability to harvest certain species (Rice, 2003).For example, contrary to the downward trend in catch MTL found by Pauly et al. (1998), catch MTL significantly increased by 3% since 1970 in a review of biodiversity indicators by Butchart et al. (2010), due to the spatial expansion of fisheries over that time period. Catch MTL declines can also reflect the addition (rather than replacement) of low trophic level species to the suite of targeted species, and the decline in catch MTL caused by this pattern of fishery expansion does not signify the change in ecosystem structure theorized by "fishing down the food web" (Butchart et al. 2010; Essington et al. 2006). The indicator can also reflect deliberate policy decisions that may change the composition of the catch (Caddy et al. 1998; de Mutsert et al. 2008; Powers & Monk 2010), as seen in a 60 year analysis of fisheries in Florida where economic and regulatory conditions largely determined the trophic structure of landings (Munyandorero & Guenther, 2010). Technological advances also influence catch MTL (Butchart et al. 2010), as the increased accessibility to low trophic level fish and harvesting capabilities of the fishery were likely responsible for declining catch MTL values over the last 50 years (Caddy & Garibaldi, 2000). Clear relationships between the each of these factors and catch MTL are difficult to quantify, but there is ample evidence that changes in catch MTL may not be specific to changes in the underlying ecosystem.

Examining Catch Mean Trophic Level as a Strategic Ecosystem Indicator

The use of catch MTL as an indicator most importantly relies on the assumption that a change in catch MTL actually reflects a change in ecosystem MTL, and studies that explicitly evaluated this relationship found that changes in the indicator and ecosystem were not correlated and the relationship was inconsistent (Branch et al. 2010; Fulton et al. 2005; Piet & Jennings, 2005; Travers et al. 2010). Thus far, evaluations and applications of catch MTL have assumed a linear relationship between indicator and change in the ecosystem. Under this assumption, which is not necessary for an indicator to be useful, fisheries managers have sought to use catch MTL as a *tactical* indicator

with clear actions linked to reference points, and the severity of management response is linked to the severity of change in the indicator (Bowen & Riley, 2003; Cury and Christensen, 2005; Fulton et al. 2005; Livingston et al. 2005; Pauly & Watson, 2005; Powers, 2010). As a tactical indicator, increasingly large changes in catch MTL would trigger the implementation of increasingly stringent management strategies.

However, consider a fire alarm which goes off when a certain amount of smoke is detected in the house. The alarm does not ring more loudly for a large fire than a small fire; it is simply a notification of a fire. Further assessment of the situation usually reveals the cause and, consequently, the appropriate response. In the same way, catch MTL may be able to act as a *strategic* indicator for ecosystem changes, simply indicating whether or not the ecosystem is changing beyond a given threshold. This type of alarm neither suggests the cause of ecosystem MTL decline nor prescribes a solution, but simply warns managers that an ecosystem change has occurred, stimulating further investigation to determine the appropriate management response.

This study uses a methodology common in epidemiology to determine whether catch MTL can be used as a reliable strategic indicator for changes in ecosystem MTL. In order for catch MTL to be a reliable strategic alarm, changes in the indicator must accurately reflect a change in the ecosystem, as well as reflect no change when the ecosystem has not changed. Catch MTL must avoid setting off a false alarm, indicating an ecosystem change when one has not occurred, or failing to detect a change when an actual change has occurred. This research evaluates the probability of detection errors in different scenarios to determine whether catch MTL can be a reliable indicator for ecosystem change without the condition of a linear relationship between catch MTL and ecosystem MTL.

Methods

Data

The data used in this simulation study is based upon the data used to challenge the assumption of a direct correlation between changes in catch MTL and changes in ecosystem MTL (Branch et al. 2010). Twenty-six ecosystems around the world were reconstructed in Ecopath with EcoSim (Pauly et al. 2000) using catch data and fisheries-independent survey data.

Each ecosystem was projected for 100 years under conditions of no fishing to achieve an 'unfished' state, and then harvested for an additional 100 years under one of eight fishing scenarios (Table 1) (Branch et al. 2010). The eight fishing scenarios aim to encompass many of the debates surrounding different drivers of changes in catch MTL mentioned previously. For example, 'Fishing Down the Food Web' applied fishing pressure in a manner representative of the original hypothesis from Pauly et al. (1998), where the top trophic level is fished first to a particular level of depletion, then the next highest trophic level is fished to a particular level of depletion and so on. The different fishing scenarios represent actual fishing practices that occur across a range of economic development and data availability, and are all included to determine the response of the ecosystem to each schedule of fishing pressure. For example, 'Based on Availability' applies fishing pressure to the most abundant nearshore taxa first, then gradually adds less abundant, less accessible groups as the more easily available taxa become depleted. This fishing scenario represents a fishery typical in a developing nation with little existing ecological data. "Fishing at MMSY", or applying pressure to each trophic group based on the multispecies maximum sustainable yield of the ecosystem, represents an ecosystem-based fishing pressure in a data-rich region.

For each year *k* of simulation under a fishing scenario, the MTL of the catch and the MTL of the ecosystem were calculated using Equation 1 where Y_i is the landings (for catch MTL computation) or biomass (for ecosystem MTL computation) of a trophic group and TL_i is the trophic level of that group.

Equation 1.

The output from the simulations, consisting of 20,800 values (26 ecosystems, 8 fishing scenarios, 100 years of each combination) of ecosystem MTL and corresponding catch MTL removed from that ecosystem, was provided by Elizabeth Fulton (Commonwealth Scientific and Industrial Research Organisation). I conducted all analyses for this study using the statistical software R, version 2.12.1 (2010).

Analysis

For the purpose of this study, I divided the data into 10-year time intervals, a time length long enough to observe a meaningful trend in data (Nicholson & Jennings, 2004), but short enough to be useful in a management context. For each 10-year time interval, I used the 'rlm' function in R (2010) to fit a robust regression to the log of the catch MTL and the ecosystem MTL, separately, in order to quantify the trend for each. The robust regression produced an estimated fit that reduced the influence of outliers and was more statistically sound than a simple regression for time-series data, which often violates of the assumption of uncorrelated residual values (Rousseuw & Leroy, 2003).

The percent change in MTL over a ten year period was the metric for 'change' in the catch and the ecosystem. I calculated the percent change in catch MTL and ecosystem MTL separately over each decade using Equation 2, where *m* is the estimated slope of the corresponding robust regression.

Equation 2.

The percent change in ecosystem MTL was considered the 'true' ecological response due only to fishing pressure because the data were simulated. In total, the analyses utilized 2080 sets of 'true' change in ecosystem MTL and the corresponding percent change in MTL of the catch removed from that ecosystem over the same 10-year period to test how often different magnitudes of change in catch MTL correctly indicated a particular magnitude and direction of change in the ecosystem.

To conduct such a test, I evaluated each pair of ecosystem MTL and catch MTL percent change values in accordance to a pair of threshold values. The threshold value for ecosystem MTL represented the magnitude considered a 'true' change in the ecosystem for which a manager might have concern. For example, if a manager wants to be able to detect a decline in ecosystem MTL greater than 1%, the ecosystem MTL threshold would be -1. Any instance in which the percent change in ecosystem MTL is steeper than a 1% decline is classified as a true decline, while a percent change in ecosystem MTL less steep than a 1% decline or increasing represents no ecosystem decline. For this particular ecosystem threshold value, an ecosystem that has experienced a change in MTL of -1.5% would be classified as 'truly declining' while an ecosystem that has changed by -0.7% would be considered 'not declining'. The observed true declines over ten years, and thus the ecosystem thresholds evaluated in this study ranged from 0% to 3%. Observed true declines larger than 3% were rare, as were increases in ecosystem MTL, preventing the assessment of whether catch MTL is a reliable indicator for ecosystem recovery.

For a given threshold of 'true' decline in the ecosystem, I tested a range of threshold values for catch MTL, which represent the sensitivity of the indicator 'alarm'. A high, positive catch MTL threshold value such as +20% catch MTL represents a sensitive alarm which is triggered often because the change in catch MTL was generally more negative than this threshold. This is equivalent to a car alarm that is activated by someone walking too close to the vehicle. A very low negative catch MTL threshold value such as -20% would represent an insensitive alarm that is set off infrequently because the change in catch MTL was rarely more negative than this value. This alarm setting is similar to a car alarm that is only activated when the window is shattered. By

testing a range of catch threshold values, I accounted for the possibility that a 5% or greater decline in catch MTL, for example, could be a reliable signal that a 2% or greater decline has occurred in the ecosystem MTL. The direction and magnitude of the change in catch MTL do not have to be equivalent to the direction and magnitude of the change in ecosystem MTL in order to be a reliable indicator of ecosystem decline. To account for the range of percent change in catch MTL observed in the data, I evaluated catch thresholds as insensitive as -50% and as sensitive as +50% by 0.5% increments for a total of 201 thresholds.

When each pair of ecosystem MTL and catch MTL percent change values calculated from the data was compared to the test thresholds, there were four possible outcomes (Table 2). A true positive (TP) occurred when the change in catch correctly signalled a decline in the ecosystem, which resulted when both ecosystem MTL and catch MTL surpassed the specified thresholds. A false negative (FN) occurred when the catch failed to detect a true decline in the ecosystem, which resulted when the ecosystem MTL exceeded the threshold, but catch MTL did not. A false negative can be quite costly on a short time scale if the loss of a resource goes undetected. A true negative (TN) occurred when the catch correctly indicated that the ecosystem did not decline, which resulted when neither the ecosystem MTL nor the catch MTL exceeded the thresholds. Finally, a false positive (FP), or false alarm, occurred when the catch erroneously indicated a decline in a non-declining ecosystem, which resulted when the ecosystem MTL did not exceed the threshold but catch MTL did. A false positive can result in the unnecessary implementation of management action, and frequent false positive results can lead to the mistrust of scientific evidence by decision-makers. In order for catch MTL to be a reliable indicator, situations must exist in which correct results (true negatives or true positives) were common and detection errors (false negatives and false positives) were few.

For each pair of ecosystem and catch thresholds, I determined the number of TP, FN, TN, and FP results across all 2080 simulations. I then calculated the true positive rate and false positive rate using Equation 3 and Equation 4, respectively. The true positive rate is the proportion of times there was a TP result when there was an actual

change in ecosystem MTL, and the false positive rate is the proportion of times there was a FP result when there had not been a change in ecosystem MTL.

$$\text{TP rate} = TP / (TP + FN) \qquad \text{Equation 3.}$$

$$\text{FP rate} = FP / (FP + TN) \qquad \text{Equation 4.}$$

A situation in which ecosystem declines are frequently detected and there are few false alarms would result in a high TP rate and a low FP rate, indicating a reliable alarm. If declines are rarely detected and false positives frequently occur, the TP rate would be low and the FP rate would be high, indicating an uninformative and unreliable alarm.

Receiver Operating Characteristic Curves

Receiver Operating Characteristic (ROC) curves are a common tool in epidemiology to compare the reliability of medical tests to detect a disease (Hanley & McNeil, 1982). For example, a complete blood count (CBC) reveals the number of red blood cells and platelets in a patient's blood, either of which can provide doctors with evidence regarding whether or not the patient has leukemia. If the number of red blood cells is below a certain threshold value, there is a high probability that the patient has leukemia. Given this detection threshold, however, there will be instances in which a patient without the disease is diagnosed with leukemia and patients with the disease do not have low enough red blood cell counts to be correctly diagnosed. The probability of these false positive and false negative results would be different if the detection threshold were increased or decreased. The same applies to an analysis of platelet levels to detect the same disease. An ROC curve determines the probability of correctly diagnosing leukemia (a true positive) and incorrectly diagnosing leukemia in patients who do not have the disease (a false positive) over a range of detection thresholds for each test. By comparing the ROC curve for red blood cell counts and the ROC curve from platelet counts, one can determine which test provides the most reliable evidence of leukemia over all possible detection thresholds.

To construct an ROC curve, the TP rate and FP rate of the test in question is determined for each possible detection threshold, which is represented by a different point along the curve (Figure 1). Detection thresholds at which the test never indicates the presence of disease (TP rate = 0 and FP rate = 0) and detection thresholds at which the test always indicates the presence of disease (TP rate = 1 and FP rate = 1), although not useful in practice, must be evaluated in order to complete an ROC curve. A test that is perfectly accurate at every detection threshold between the two extremes will produce a single point at TP rate = 1 and FP rate = 0. If patients with leukemia have stronger evidence of the disease only 50% of the time more than patients without the disease, the ROC curve will be a diagonal line beginning at the origin (Figure 1). This signifies an unreliable and uninformative test, or one that is equivalent to a coin flip.

Generally, an ROC curve lies somewhere between the diagonal line (an uninformative test) and the horizontal line at TP rate = 1 (a test that correctly detects the disease in every person who has it). The area under the ROC curve (AUC) is a quantitative representation of the strength of association between the test result and the true state, and is calculated to compare reliability between tests (Hanley & McNeil, 1982). In other words, the AUC is the probability of correctly identifying “signal plus noise” from strictly “noise” (Green & Swets, 1966). When comparing AUC values between tests, a greater AUC value indicates a more reliable test. If the red blood cell test for leukemia resulted in an AUC of 0.86 and the platelet count test resulted in an AUC of 0.74, doctors would want to rely more on the results of the red blood cell count for their diagnoses because the association between the number of red blood cells and the presence of leukemia is stronger than the association between the number of platelets and the presence of leukemia, regardless of the specific threhold used. In this study, only one test is being evaluated, so a simplified rating scale is used to interpret AUC values in regards to indicator reliability (Table 3). Although there is some subjectivity in the interpretation of AUC values, an AUC between 0.90 and 1.0 generally represents a very strong association between the indicator and the true status of the test subject, while an AUC near 0.5 suggests little to no association (Children’s Mercy Hospital, 2012; Kaiser Permanente, 2009). Any test that produces an ROC curve with an

AUC less than 0.7 is generally considered untrustworthy, and should be avoided if possible (Hanley & McNeil, 1982).

I employed the ROC methodology to evaluate the use of catch MTL as a strategic indicator of ecosystem change. For a specified ecosystem decline threshold, I calculated the TP rates and FP rates for the entire range of catch MTL threshold values using all simulations available. I then created ROC curves by plotting the resulting TP and FP rates, and calculated the AUC using the trapezoid function in R (Hanley & McNeil, 1982; R, 2010). Here, the AUC represents the probability that an ecosystem that has truly declined experiences a greater decline in catch MTL than an ecosystem that has not declined, and provides a metric of how reliably the percent change in catch MTL indicates a decline in ecosystem MTL.

When the true theshold one is trying to detect occurs very rarely, the AUC value can be deceptively high. For example, in the event that 99 people do not have leukemia and one person does, but 100 test results are always negative, the resulting AUC will be quite high because the test was correct 99% of the time. However, the test failed in the situation of most importance, and could therefore be considered an unreliable test. Similarly, if an ecosystem decline occurred rarely and catch MTL never indicated a decline, the resulting AUC value will be quite high, and thus misleading about the performance of catch MTL as an indicator. To avoid misinterpretation of high AUC values in the case of rare events, any scenario in which fewer than10% of the cases did not qualify as a 'true' ecosystem change was eliminated from the analysis.

I created ROC curves and calculated AUC values for different configurations of the simulated data to determine whether there were scenarios in which catch MTL worked as a reliable indicator of ecosystem change. The first step was to determine whether catch MTL was a reliable indicator globally and across all fishing pressures, using all available simulations. The second step was to test the responsiveness of the indicator by examining how well it detected past or future ecosystem changes. By comparing the catch data from one decade to the ecosystem change that occurred in the following decade, I evaluated the reliability of the indicator as a predictor of future ecosystem change. By comparing the catch data from one decade to the ecosystem

change that occurred in the previous decade, I was able to determine whether catch MTL can reliably reflect ecosystem change that previously occurred. Offsetting the catch data first backward then forward by one decade allowed me to determine whether there was a time lag affecting the indicator. Third, to compare whether the accuracy of catch MTL varies by ecosystem, I created an ROC curve and calculated the respective AUC for each individual ecosystem modelled. Fourth, I grouped ecosystems by marine eco-region (Spalding et al. 2007) to test whether catch MTL is a more reliable indicator in any particular climatic region than others. Fifth, I evaluated whether the type of fishing pressure exerted on the ecosystem (Table 1) influences the reliability of catch MTL as an indicator of ecosystem MTL change. Sixth, I explored whether the complexity of the modeled ecosystem influenced the ability of catch MTL to act as a reliable indicator of ecosystem change by comparing the number of trophic taxa included in each Ecopath with EcoSim model to its calculated AUC value.

Error Rates

The probabilities of committing a FP or FN error over the range of detection thresholds for catch MTL illustrated the difficulty of using of catch MTL as a strategic indicator. As a final exploratory step, I calculated the FP rate using Equation 3 and the FN rate using Equation 5 across a range of catch MTL detection thresholds (Figure 2).

$$\text{FN rate} = \text{FN} / (\text{TP} + \text{FN}) \qquad \text{Equation 5.}$$

This method allowed for the identification of specific catch MTL threshold at which the total probability of committing an error was minimized, as well as an estimate of the total probability of committing an error at that threshold value. Using Figure 2 as an example, if the management goal was to minimize detection errors, the reference point for catch MTL would be set at -2%, the threshold with the lowest combined probability of triggering a false alarm or failing to detect a true decline. Additionally, calculating error rates provided a clear visualization of tradeoffs between various potential ‘reference points’ for the indicator. Failing to detect a decline may be more

costly and have greater ecological consequences than implementing unnecessary restrictions on a fishery, thus a FN may be more important to detect than a FP. Minimizing a FN error requires managers to accept a higher probability of FP, and this method allows for explicit evaluation of tradeoffs given different management objectives.

Results

Global Performance

Overall, the change in catch MTL was a ‘fair’ indicator of ecosystem MTL decline when all the data were considered (Figure 3). When detecting a true ecosystem decline greater than 0%, decreases in catch MTL were greater in an ecosystem that was truly declining than in a non-declining ecosystem only 71% of the time. Increasing the ecosystem decline threshold to greater than 0.5% or greater than 1% resulted in similar ROC curves and corresponding AUC values (0.70 and 0.73, respectively). Although AUC values increased slightly as ecosystem decline thresholds increased from 0% to 1%, there was no meaningful increase of the reliability of the indicator (Figure 4). The indicator consistently performed as a ‘fair’ indicator across the range of ecosystem decline thresholds for which a sufficient number of true ecosystem declines permitted analysis.

Catch MTL was a ‘poor’ indicator when used to predict ecosystem MTL changes in the following decade (Figure 5). There was only a 65% probability that the indicator experienced a greater decline in an ecosystem that truly declined in the following decade than one that did not, and performance did not improve when detecting true ecosystem declines greater than 0.5%.

Similarly, catch MTL was a ‘poor’ reflection of past ecosystem declines (Figure 5). An AUC of 0.66 revealed a weak association between the indicator and the state of the ecosystem in the previous decade. When the previous decade’s detection threshold was increased to 0.5%, indicator performance did not improve with a resulting AUC of 0.63.

Ecosystems

In an analysis of catch MTL performance in individual ecosystems, the results varied widely (Table 4). For example, in the simulated New Zealand ecosystem, the indicator failed at detecting a difference between a declining and non-declining ecosystem with an AUC value of 0.55. However, in the simulated Southeast Alaska ecosystem catch MTL was a 'good' indicator of any decline in the ecosystem, resulting in an AUC value of 0.88 which signifies a very strong association between the indicator and the trend in the ecosystem. The variability in AUC values across ecosystems remained large regardless of the definition of 'true' ecosystem decline (0%, 1%, 2% or 3%).

The general reliability of catch MTL as an indicator improved as the definition of a true ecosystem decline increased (Table 5). Approximately half of AUC values signified that catch MTL was a 'good' or 'fair' indicator when detecting an ecosystem MTL decline greater than 0%, while the other half revealed 'poor' or 'failing' performance. The indicator's reliability slightly improved when the definition of decline was increased to 1% or greater, with 'good' or 'fair' performance in two-thirds of the ecosystems analyzed. In the event of a true ecosystem decline greater than 2%, catch MTL was an 'excellent' or 'good' indicator in five of six ecosystems. Only two ecosystems experienced ecosystem MTL declines greater than 3%. Catch MTL was a 'good' indicator of decline in one scenario but a 'poor' indicator in the other.

Catch MTL was a 'fair' indicator in all marine eco-regions evaluated (Table 6). AUC values resulting from an analysis of the simulated Central Indo-Pacific ecosystems (n = 3) were 0.71 for detecting true ecosystem declines greater than 0% and greater than 0.5%. The simulated ecosystems in the temperate North Pacific eco-region (n = 6) revealed similar ROC curves (Appendix A), with AUC values of 0.70 and 0.68 for declines greater than 0% and 0.5%, respectively. In the temperate North Atlantic eco-region, where the largest number of simulated ecosystems in this study were located (n = 9), catch MTL produced AUC values ranging from 0.71 to 0.77 for ecosystem decline thresholds from 0% to 1% (Table 6). Catch MTL was not a more reliable indicator in any one region than another.

Fishing Scenarios

The type of fishing scenario applied to an ecosystem appears to influence whether catch MTL was a reliable indicator of ecosystem decline (Table 7). While there is still a lot of variability in indicator performance across fishing scenarios, catch MTL performs consistently within each scenario.

Catch MTL was a consistently 'good' indicator of ecosystem MTL changes over a range of true decline thresholds in the Fishing Down the Food Web, Fishing at MSY, and Fishing at 20% scenarios. When the Fishing Down the Food Web scenario was applied, catch MTL resulted in AUC values of 0.8 or greater in three of four ecosystem decline levels tested. For the Fishing at MSY and Fishing at 20% scenarios, ROC curves also yielded AUC values of 0.8 or greater for all ecosystem declines tested. The AUC values increased as true ecosystem decline thresholds increased for both Fishing Down the Food Web and Fishing at 20%, although the increased AUC values only reclassified the indicator in Fishing Down the Food Web.

Under the Fishing Through the Food Web, Fishing Based on Availability, Increase to Overfishing, and Fishing at MMSY scenarios, the resulting AUC values classified catch MTL as a 'poor' or 'failing' indicator of ecosystem MTL declines, with only two total instances of 'fair' performance (Table 7). The AUC values for catch MTL as an indicator under Fishing Through the Food Web were 0.66, 0.73, and 0.67 for detecting ecosystem MTL declines greater than 0%, 0.5%, and 1%, respectively. When Fishing Based on Availability, AUC values were 0.56 or less for all ecosystem decline thresholds evaluated. For the Increase to Overfishing scenario, catch MTL was a 'fair' indicator of true ecosystem decline greater than 0% with an AUC of 0.73, but worsened to a 'poor' indicator for all three increasingly stringent definitions of ecosystem decline. Catch MTL was a 'poor' indicator under the Fishing at MMSY scenario, resulting in an AUC value of 0.65 when detecting true declines greater than 0% and an AUC value of 0.69 when detecting true declines greater than 1%.

The Increase to MSY fishing scenario had inconsistent results, showing catch MTL as a ‘good’ indicator of greater than 0% ecosystem decline, and a ‘fair’ indicator of greater than 0.5% ecosystem decline. To reduce the noise from increasing the fishing pressure over the first 50 years and then maintaining pressure over the final 50 years, I reanalyzed the data simulated under Increase to MSY over the final 50 years only. The resulting AUC value was 0.9 when fishing pressure was held constant, given an ecosystem decline of 0% or greater (Appendix B). The Increase to Overfishing scenario contained similar noise, and when I repeated the analysis using the final 50 years of data simulated under Increase to Overfishing, the resulting AUC increased from 0.75 to 0.8 for an ecosystem decline greater than 0% (Appendix B).

The number of trophic groups accounted for in each modelled ecosystem had no effect on the ability of catch MTL to detect true ecosystem declines of any magnitude evaluated here. Visually there appears to be a trend, but a linear regression revealed no significant relationship at the $\alpha = 0.05$ level (Appendix B).

Error Rates

Plotting the probability of a false negative and a false positive for each catch MTL threshold tested revealed that the catch MTL threshold with the lowest overall probability of committing a detection error is 0%, when all data are considered (Figure 6). In other words, when any decrease greater than zero occurs in catch MTL over 10 years, that is the most accurate indication that the ecosystem is declining more than 0%. At this uninformative best case scenario, there is still a 30% probability of either a false positive or false negative result. As the probability of a false positive error decreases, the probability of a false negative error increases drastically; the reverse is also true (Figure 6).

When a ‘true’ ecosystem decline is defined as a MTL decrease greater than 1%, the catch MTL threshold at which the error rates intersect shifts to -0.02% (Figure 7). At this reference point of minimum total error, the probability of either a false positive or a

false negative remains around 30%.The probability of a false negative when detecting a true ecosystem decline greater than 1% is generally lower than the probability of a false negative when detecting a true ecosystem decline greater than 0%. This means a decrease in catch MTL is more likely to detect a true ecosystem decline greater than 1% than a true ecosystem decline greater than 0%. Catch MTL thresholds ranging from -50% to +50% were evaluated in each analysis, but only the catch MTL range that contains the point of FN and FP intersection is shown in Figures 6 and 7. For most of the catch MTL thresholds tested, the probability of a false positive or a false negative was 90% or greater.

Discussion

Global Performance

Consistently ‘fair’ performance of catch MTL across all ecosystems and fishing scenarios combined suggests the relationship between catch MTL and changes in the ecosystem is weaker than assumed by scientists and organizations currently utilizing the indicator. The results presented here demonstrate that there is only a moderate association between changes in the indicator and changes in the ecosystem state, adding support to other studies that have found no correlation between changes in catch MTL and ecosystem MTL (Branch et al. 2010; Fulton et al. 2005). Given the low accuracy of the indicator when applied globally, catch MTL should not be the primary indicator for changes in global biodiversity, as specified by the Convention on Biological Diversity (CBD, 2004; CBD, 2010).

The poor performance of catch MTL as an indicator of ecosystem change in the following decade and the previous decade suggests catch MTL was most responsive as an indicator of concurrent changes. However, as mentioned previously, this association was still only ‘fair’.

Ecosystems

When the indicator was evaluated for each individual ecosystem, larger declines were more reliably detected, but the indicator still performed inconsistently across ecosystems. The application of catch MTL to “measure the change in mean trophic level of fisheries landings by region and globally” (CBD 2004) in order to assess progress toward biodiversity goals assumes that ecosystems respond in the same way to fishing

pressure, with the response captured equally in all ecosystems. This assumption does not hold true, as shown by the variability in indicator performance across ecosystems. The modeled ecosystems in which catch MTL was a ‘good’ indicator of ecosystem change do not share any obvious characteristics, making it difficult to determine whether the indicator would work for a modeled ecosystem not included in this analysis.

When the data were grouped by eco-region, variability in indicator performance decreased across groups, but catch MTL was only ‘fair’ in all eco-regions evaluated. The indicator did not perform better in any one region than the others. This suggests reliability of the indicator is not dependent on climatic or oceanographic conditions, and more importantly that spatial groupings may mask high variability in indicator performance.

Fishing Scenarios

Catch MTL may be a good indicator of ecosystem decline if the composition of the catch reflects that of the ecosystem. The Fishing at MSY and Fishing at 20% scenarios apply constant fishing pressure to all taxa present, and the fishing pressure applied to each trophic group is based on its abundance. As a result, the composition of the catch reflects the abundance and productivity of taxa in the ecosystem. In both of these scenarios, catch MTL acts as a ‘good’ indicator of ecosystem decline (Table 7). The Increase to Overfishing and Increase to MSY scenarios also applied fishing pressure to all trophic groups based on their abundance, but the indicator did not perform well when the entire time-series was considered (Table 7). Analysing only the years during which the Increase to Overfishing and Increase to MSY fishing scenarios applied fishing pressure across the entire ecosystem and that pressure was held constant improved indicator reliability. This improvement suggests that even when the catch reflects ecosystem abundance, added noise from variable fishing mortality over time can negatively affect the performance of the indicator.

Catch MTL did not reliably detect ecosystem MTL changes when the fishing pressure was selectively applied to specific taxa in the ecosystem. Catch MTL performed poorly as an indicator in the Fishing Through the Food Web, Fishing Based on Availability, and Fishing at MMSY scenarios. In each of these scenarios, the catch MTL was calculated from only the targeted taxa, but the ecosystem MTL was comprised of additional groups including prey for targeted species or relatively inaccessible species. Due to the fact that not all taxa were represented in the catch for these highly selective fishing scenarios, changes in the indicator reflected changes in species targeted rather than the trophic dynamics of the entire ecosystem.

It appears that catch MTL works most reliably as an indicator if the fishing pressure is applied to all ecosystem components based on abundance and productivity, and if the fishing pressure is held constant over time. However, the performance of catch MTL as an indicator in the Fishing Down the Food Web scenario did not fit with this concept. Fishing Down the Food Web applies pressure selectively to the highest trophic level first, then adds the next highest trophic level, and so on, yet catch MTL is a good indicator of ecosystem decline. It is not surprising that catch MTL correctly detects a decline in ecosystem MTL when Fishing Down the Food Web is occurring, because both signatures are strongly forced in this scenario. The challenge is knowing when this scenario is actually occurring; it can be quite difficult to determine when the food web is being fished 'down' and when it is being fished 'through' (Essington et al. 2006). In a Fishing Down the Food Web situation, catch MTL is a 'good' indicator, but performs 'poorly' in a Fishing Through the Food Web scenario (Table 4). If managers are certain that Fishing Down the Food Web is taking place in a region, it is unlikely that an indicator is necessary to provide evidence of the ecosystem response.

The results of this study support the concern presented by Caddy et al. (1998) and the results found by Branch et al. (2010), that catch MTL is not a useful indicator of ecosystem decline if the landings do not reflect the ecosystem. Additionally, the consistency of fishing pressure over time may affect indicator reliability. In the rare event that constant fishing pressure is applied across all ecosystem components based on their abundance and productivity, catch MTL may be able to provide evidence of

ecosystem change as a strategic indicator. However, if the ecosystem is declining by 1% or 2% MTL in a decade, it is likely that there are other metrics simultaneously indicating this change. A decline in catch per unit effort, stock assessments showing decreased abundance, or an expansion of fishing grounds may all provide additional evidence of changes occurring in the ecosystem, as catch MTL is not consistent enough to be used as the sole indicator of ecosystem decline.

Error Rates

A number of studies agree that a good indicator can be used as a possible "policy-triggering" tool with clear reference points tied to management actions. (Bowen & Riley, 2003; Cury and Christensen, 2005; Fulton et al. 2005; Gascuel et al. 2005; Powers 2010; Livingston et al. 2005; Powers & Monk, 2010). However, managers are currently unable to identify the critical threshold values for catch MTL, and no studies have provided promising results in that direction (Link et al. 2010; Powers 2010; Pauly & Watson, 2005; Shin et al. 2010). While ROC curves and AUC values can reveal the situation in which an indicator best discriminates between two states of nature, this method does not specify which detection threshold, or reference point, to use. In other words, an AUC value does not tell us how sensitive our 'alarm' should be in order to minimize incorrect detection of ecosystem decline nor does it consider costs or consequences of a false positive or false negative result, which can be valued quite differently in the context of resource management. A closer look at an indicator's error rates can provide more information regarding these shortcomings.

The tradeoffs between FP or FN errors for different reference points are considerable for catch MTL (Figures 6 and 7). Minimizing one type of error may require managers to accept a very high probability of the other type of error, and any uncertainty surrounding the reference point can result in very high error rates. Additionally, a detection threshold at which total detection error is minimized is visually apparent, but the total error is still quite high for catch MTL. The analysis of error rates reinforces the

difficulty in determining specific reference points for catch MTL as a strategic indicator, and suggests that any further attempt to determine reference points is unwarranted.

The results of this study and several others (Blanchard et al. 2010; Branch et al. 2010; Fulton et al. 2005; Piet & Jennings, 2005) maintain that catch MTL's limited applicability render it an ineffective indicator of global ecosystem change, but that does not mean catch MTL is a useless metric. Catch MTL is relatively easy to measure, and may provide insight to how fisheries develop and expand, or what patterns emerge in the landings before the collapse of a fishery. There is mounting evidence that catch MTL is neither sensitive nor specific to changes in ecosystem MTL, but it still provides information about changes in fisheries landings over time, and may reflect an ecological or socio-economic relationship that has not been explored.

Considerations for Simulation Models

Simulation models can help answer scientific questions by simplifying a relationship or system, isolating a problem, or considering extended time frames, but the nature of the results must carefully be considered before application to the real world. In this simulation study, the indicator response was measured in a variety of modeled ecosystems, representing different types of systems (top-down or upwelling) and complexities (a more hierarchical food chain or a complex food web), and the response was due only to fishing pressure. Additionally, the data used to construct each ecosystem and calculate MTL values were of the finest taxonomic resolution possible given data availability. The simulated results presented here are an exploratory best-case scenario, and can inform users of the performance of catch MTL as an indicator of ecosystem decline, but are not fit for developing management plans for specific real-world ecosystems using catch MTL.

Although catch MTL was an accurate indicator of ecosystem change in a few simulated ecosystems, inconsistency and uncertainty prevent its use in management strategies for any particular area. The Ecopath with EcoSim models were based on

current, quality-controlled data and capture a wide range of systems (Branch et al. 2010), but the nature of the simulation disconnects the results from the current state of the ecosystems it was made to represent. After each ecosystem is simulated for 100 years to an 'unfished' state, the subsequent ecosystem response to fishing pressure is informative, but not necessarily representative of the response that has truly occurred in that ecosystem the past or that might occur under that fishing scenario into the future. The disconnection introduces a great deal of uncertainty in the application of the indicator, thus the results presented should not be used as evidence that catch MTL would be a useful indicator in a particular location. However, it's fair performance under even these simulated conditions does signal that it is unlikely to be of much use.

This study investigated the ability of catch MTL to detect a change in ecosystem MTL driven by only one forcing factor: fishing pressure. Even in the absence of other factors that affect marine ecosystems such as climate change, pollution, ocean acidification, and habitat loss, the indicator did not perform reliably or consistently. Removing all forcing factors on the ecosystem except fishing pressure eliminated the question of specificity, and revealed that the indicator was not appropriately sensitive to changes in the ecosystem due to fishing pressure to allow for confident use (Rice, 2003). The indicator's ability to detect an ecosystem decline likely decreases when applied in real-world scenarios due to the additional noise from these factors.

Uncertainty in MTL Calculation

There are a few sources of uncertainty to consider when evaluating catch MTL as an indicator for change in the marine ecosystem. Calculating catch MTL requires the assignment of a trophic level to every taxon in the ecosystem. Sampling or estimation error in trophic levels can be of the same magnitude as natural variations (Shin et al. 2010). For example, adult yellowfin tuna have three different estimated trophic levels, ranging from 4.2 to 4.5, a difference of 0.3 trophic units (FishBase, 2010). In this analysis, I evaluated ecosystem MTL changes as small as 0.5%, or roughly 0.01 to 0.015 trophic level units over a ten-year period. Further research is necessary to

determine whether such large variation in trophic level estimation influences trends in ecosystem or catch MTL. Global trends in catch MTL can be sensitive to the trophic level assigned to key commercial species such as anchoveta (Branch et al. 2010), but this concept requires further sensitivity testing on a regional level.

Similarly, trophic levels may be estimated differently for a species in different regions due to diet composition (FishBase, 2010; Shin et al. 2010), and managers must ensure they are assigning the appropriate trophic level to a species based on location. One area may act as an important nursery for a species, but often the trophic level for a species is calculated from the adult phase (Shin et al. 2010) which would result in falsely elevated ecosystem MTL estimates. Trophic level estimates are often fixed for the entire life span of a species based on limited data availability, which may not accurately capture trophic dynamics in an ecosystem in response to fishing pressure.

Seasonal differences in diet can also alter the trophic level of a species over the course of a year (Karachle & Stergiou, 2008), and scientists must determine whether these differences influence MTL trends over time. Ecological indicators should be sensitive to change in the ecosystem, but it can be problematic if they are too sensitive to uncertainty in calculation (Link et al. 2002). Estimation errors in trophic level assignments for a species, region, life-stage, or season may further complicate the use of catch MTL as an indicator of ecosystem MTL change.

The next step in evaluating ecosystem-based fisheries indicators is connecting various magnitudes of change in ecosystem MTL to ‘health’ or ‘status’ of the ecosystem. In this study, I evaluated a range of possible ecosystem MTL percent declines, but it remains unclear whether a 0.5%, 1%, or 2% ecosystem MTL decline actually alters the structure and composition of the ecosystem or is still within the realm of resilience. Determining the magnitude of ecosystem MTL change that is ecologically significant would enable scientists to evaluate indicator performance when there is actually a functional change in the ecosystem.

Conclusions

Although the cause of fluctuations in catch MTL over time has been heavily debated, this study aims to settle a more specific question: is catch MTL appropriately sensitive to be used as a strategic indicator of change in the ecosystem? On a global scale, catch MTL performed as a 'fair' indicator of changes in ecosystem MTL due to fishing, and did not detect larger changes more reliably than smaller ones. When catch MTL was applied as an indicator of decline in a particular ecosystem, its performance varied from 'poor' to 'excellent'. Within an ecosystem, it appeared that catch MTL could more reliably detect a larger change in ecosystem MTL than a smaller change. However, the results remained quite variable across ecosystems, and an improved association between indicator and ecosystem state did not always equate to a strong one.

If landings were representative of the abundance and productivity of all trophic groups in the ecosystem and fishing pressure was constant over time, catch MTL was a good strategic indicator of ecosystem change. In this limited situation, the indicator may be able to provide managers with an idea of the big picture, but determining the cause of change and the appropriate solution would require further, more specific testing.

In order to be useful for ecosystem-based fisheries management, an indicator must have 'reference points' at which management action is taken or regulations implemented. The overall inconsistent performance and limited applicability of catch MTL as an indicator of ecosystem MTL change does not allow for such reference points to be determined.

Fisheries managers must identify a suite of reliable indicators to monitor ecosystems in order to effectively guide policy development and implementation. Under limited circumstances, catch MTL may provide clues about changes in the ecosystem, but it should not be considered a useful indicator of ecological changes or a method to

monitor global biodiversity changes due to fishing. Although catch MTL is not a reliable indicator of ecological changes due to fishing, the metric is useful for monitoring changes in catch over time and may prove to be a good representation of a yet undiscovered relationship.

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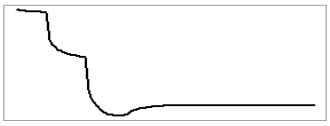
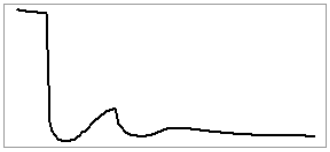
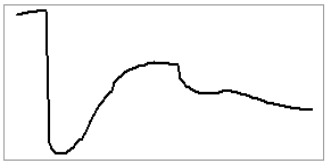
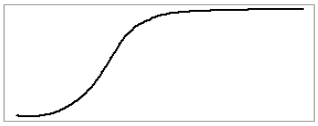
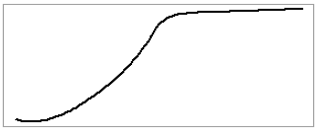
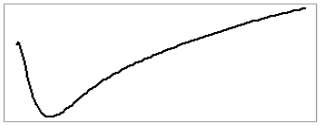
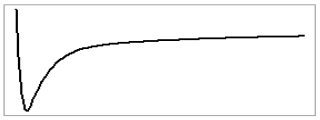
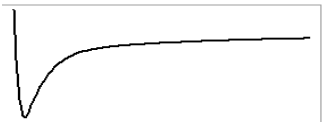
Tables and Figures

Tables

Table 1 Simulated Fishing Scenarios Applied to 'Unfished' Ecosystems

Description	Concept	Example of Change in CatchMTL over 100 Years
Fishing Down Food Web	Remove top trophic level organisms first, then add the next highest trophic level after 15 years, then the next highest, and so on (Pauly et al. 1998).	
Fishing Through Food Web	Half of the highest trophic level is fished at maximum sustainable yield (MSY) for 20 years, then the remainder of that trophic level plus the next lowest trophic level is added. This pattern is repeated for each subsequent trophic level (Essington et al. 2006).	
Based on Availability	The most abundant and accessible trophic levels are removed first. When those become scarce, begin removing next most available trophic level.	
Increase to Overfishing	Gradually increase fishing pressure over the first 50 years until all trophic levels are being overfished. Maintain that fishing pressure for the final 50 years.	
Increase to MSY	Gradually increase fishing pressure over the first 50 years until each trophic level is caught at MSY. Maintain that fishing pressure for the final 50 years.	
Fishing at MSY	Continually fish each trophic level at its MSY.	
Fishing at 20%	Remove 20% of the biomass of each trophic level each year.	
Fishing at MMSY	Fish each trophic level at multi-species maximum sustainable yield (MMSY).	

Note: The right column shows changes in catch MTL that result from each schedule of fishing pressure applied from year 1 to 100, using the Bay of Biscay model as an example. Complete explanations of fishing pressures can be found in the supplementary material from Branch et al. (2010)

Table 2 ***Possible Test Outcomes when Comparing Percent Change in Ecosystem MTL and Catch MTL to Threshold Values***

	Ecosystem decline (eMTL > eThreshold)	**No ecosystem decline** (eMTL ≤ eThreshold)
Alarm triggered (cMTL > cThreshold)	True Positive ✓	False Positive ✗
Alarm not triggered (cMTL ≤ cThreshold)	False Negative ✗	True Negative ✓

Note. The outcome of each test depends on whether the percent change in catch mean trophic level (cMTL) exceeds the catch detection threshold (cThreshold) and whether the observed percent change in ecosystem mean trophic level (eMTL) constitutes a 'true' ecosystem decline (eThreshold).

Table 3 ***Interpretation of Area Under the Curve (AUC) Values***

AUC	Interpretation
0.9 – 1.0	Excellent
0.8 – 0.9	Good
0.7 – 0.8	Fair
0.6 – 0.7	Poor
0.5 – 0.6	Fail
Below 0.5	Possible inverse association

Note: Interpretation of area under the curve (AUC) adapted from Kaiser Permanente (2009) and The Children's Mercy Hospital (2012).

Table 4 ***AUC Values for Individual Ecosystems across Thresholds of True Ecosystem Decline***

Ecosystem	Ecosystem MTL Decline 0%	1%	2%	3%
Aleutians	0.67			
Baltic Sea	0.85	0.8	0.82	0.86
Bay of Biscay	0.7			
Benguela Current	0.79			
Black Sea	0.87			
Calif. Current	0.59	0.82	0.91	
Cent N Pacific	0.65			
E Bering Sea	0.73	0.63		
E Trop Pacific	0.81			
Georges Bank	0.67	0.83	0.88	
Georgia Strait	0.68	0.78		
Great Barrier Reef	0.75	0.86		
Gulf of Mexico	0.58	0.53	0.66	0.63
Gulf of Thailand	0.48	0.53		
Irish Sea	0.57			
Newfoundland-Labrador	0.75			
North Sea (1)	0.65	0.78	0.81	
North Sea (2)	0.73	0.68		
N Gulf of St. Lawrence	0.65	0.76		
NW Australia	0.82			
SE Alaska	0.88			
SE Australia	0.78			
New Zealand	0.55			
W Florida Shelf	0.7			
W Vancouver Island	0.73	0.7	0.81	
W English Channel	0.59			

Note: See Appendix A for ROC curves associated with AUC values.

Table 5 ***Number and Percent of Ecosystems in Each Indicator Rating Category across Thresholds of True Ecosystem Decline***

	Ecosystem MTL Decline							
	0%		1%		2%		3%	
Indicator Rating	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
Excellent					1	16.6		
Good	5	19	4	33	4	66.6	1	50
Fair	9	35	4	33				
Poor/Fail	12	46	4	33	1	16.6	1	50
Total Ecosystems	26		12		6		2	

Table 6 ***AUC Values of Marine Eco-regions of the World across Thresholds of True Ecosystem Decline***

	Ecosystem MTL Decline		
Eco-region	0%	0.5%	1%
Central Indo-Pacific	0.71	0.71	
Temperate N Pacific	0.70	0.68	
Temperate N Atlantic	0.71	0.74	0.77

Note: See Appendix A for ROC curves associated with AUC values.

Table 7 ***AUC Values for Types of Fishing Pressure across Thresholds of True Ecosystem Decline***

Fishing Pressure	Ecosystem MTL Decline 0%	0.5%	1%	1.5%
Fishing Down	0.77	0.80	0.81	0.84
Fishing Through	0.66	0.73	0.67	
Availability	0.54	0.53	0.56	
Inc to Overfishing	0.75	0.68	0.66	0.68
Inc to MSY	0.83	0.72		
At MSY	0.80	0.84		
At 20%	0.80			
At MMSY	0.65	0.69		

Note: See Appendix B for ROC curves associated with AUC values.

Figures

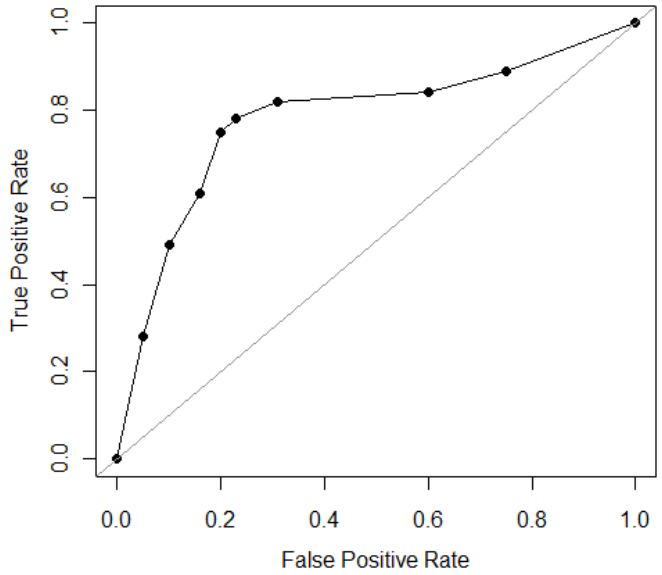


Figure 1. Sample ROC curve

Note: Each point along the ROC curve represents the true positive rate and false positive rate at a different detection threshold for the test administered.

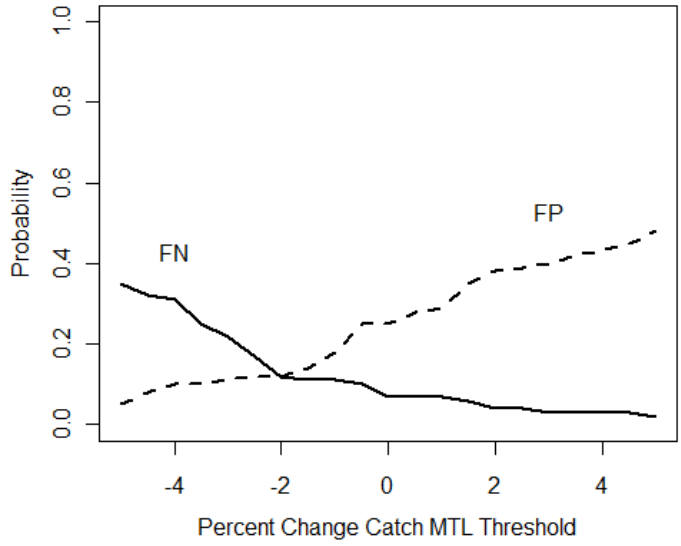


Figure 2 Sample Plot: Probability of a False Positive (FP) or False Negative (FN) Result as a Function of Catch Mean Trophic Level (MTL) Threshold Value

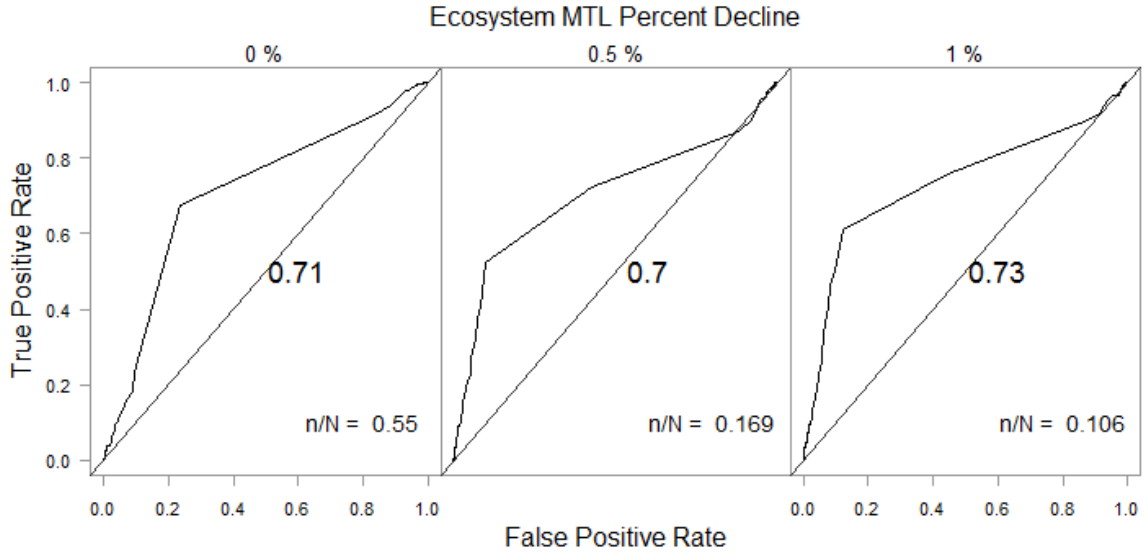


Figure 3 ROC Curves for Catch MTL as a Global Indicator of Ecosystem Decline across Thresholds of True Ecosystem Decline

Note: The AUC of each curve and proportion of total time intervals (n/N) that experienced a decline of each magnitude is indicated.

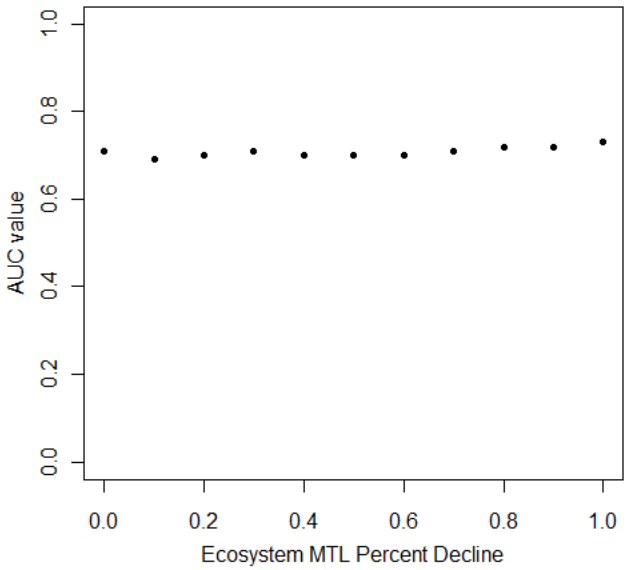


Figure 4. Performance of Catch MTL across a Range of True Ecosystem Decline Thresholds

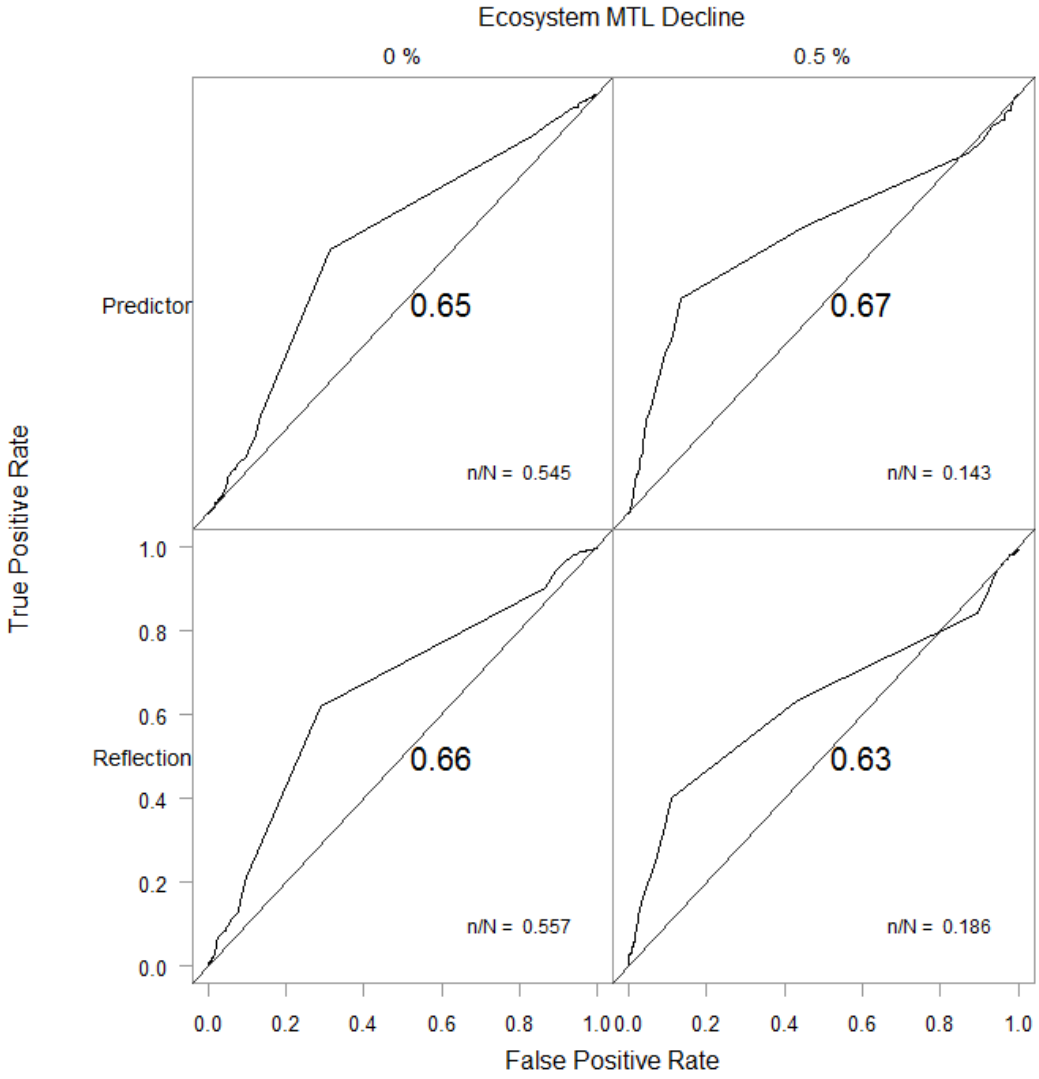


Figure 5. Receiver Operating Characteristic Curves for Catch Mean Trophic Level as a Predictor (top) of Future Ecosystem Change and a Reflection (bottom) of Past Ecosystem Change

Note: The AUC of each curve and proportion of total time intervals (n/N) in which a 'true' ecosystem decline occurred are indicated on each panel.

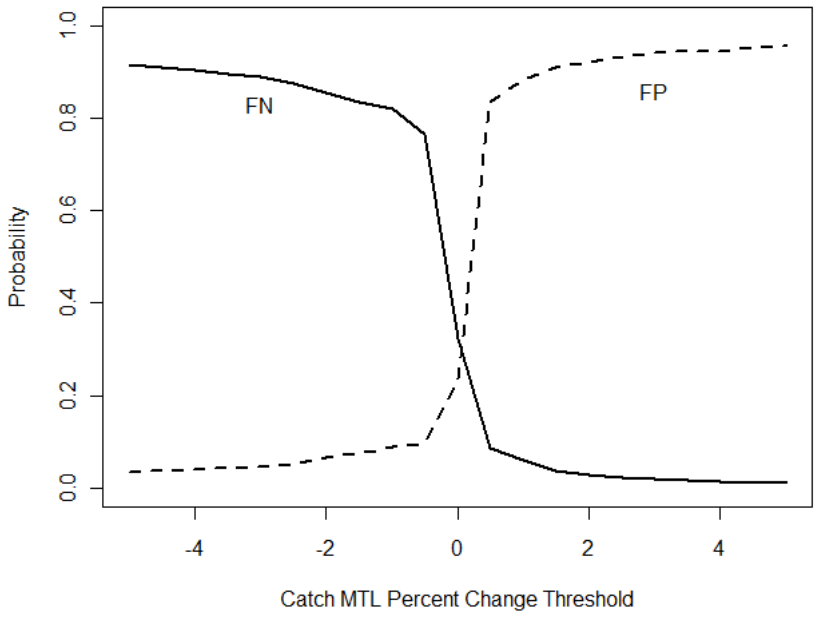


Figure 6. Probability of False Negative (FN) and False Positive (FP) Errors When Detecting an Ecosystem Decline Greater than 0%

Note: The values shown are a sample of all catch MTL thresholds (-50% - 50%) evaluated in this study.

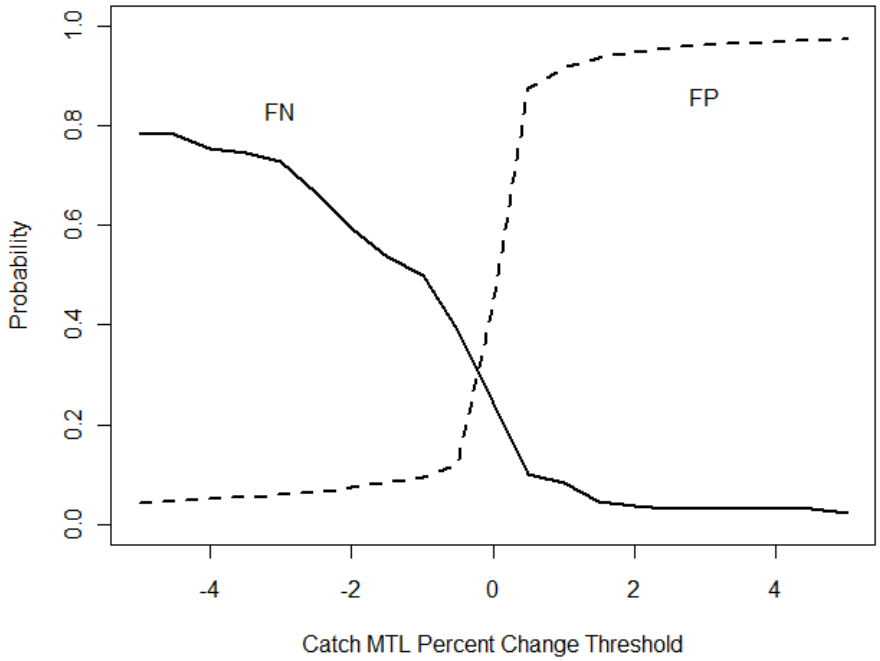


Figure 7. Probability of False Negative (FN) and False Positive (FP) Errors When Detecting an Ecosystem Decline Greater than 1%

Note: The values shown are a sample of all catch MTL thresholds (-50% – 50%) evaluated in this study.

Appendices

Appendix A.

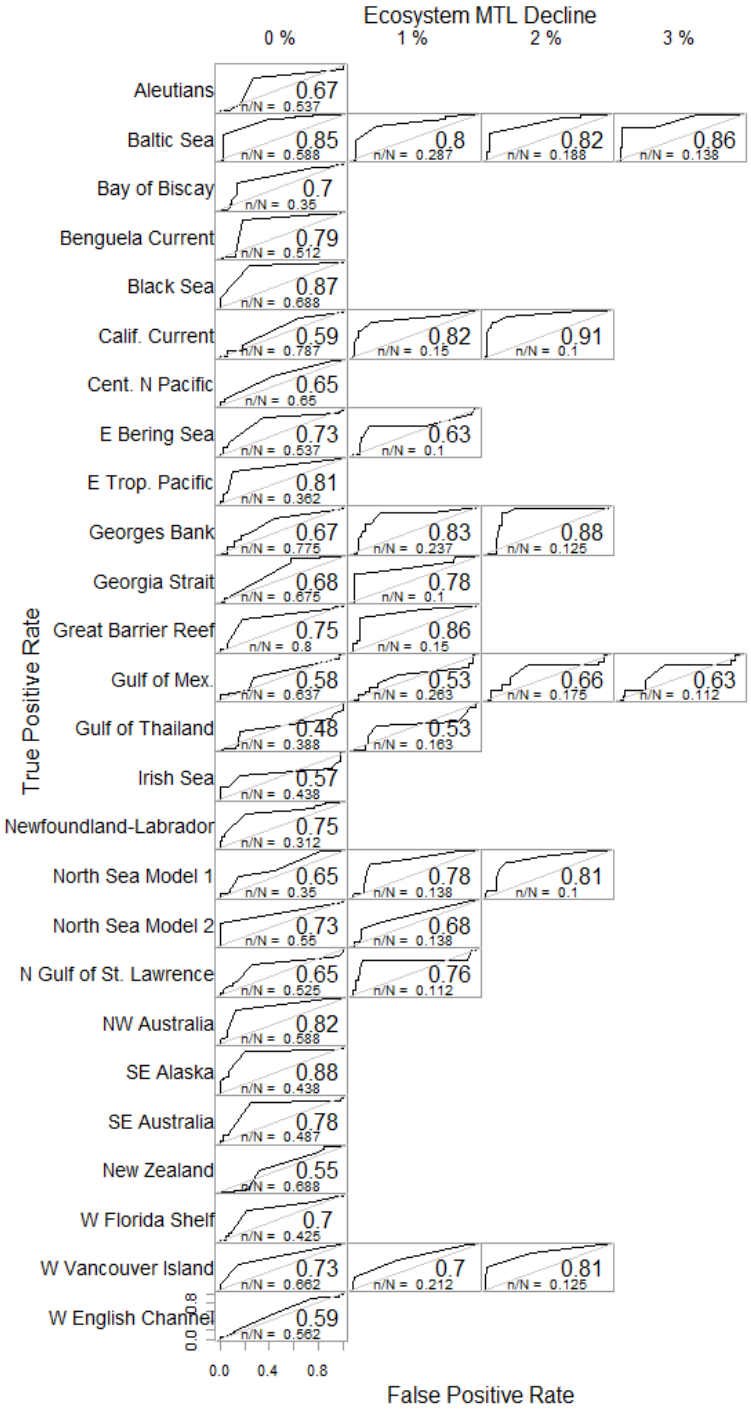


Figure A 1. Receiver Operating Characteristic curves for Catch Mean Trophic Level as an Indicator in Each Ecosystem across Thresholds of True Ecosystem Decline

Note: The AUC of each curve and proportion of total ecosystems (n/N) in which a 'true' ecosystem decline occurred are indicated on each panel.

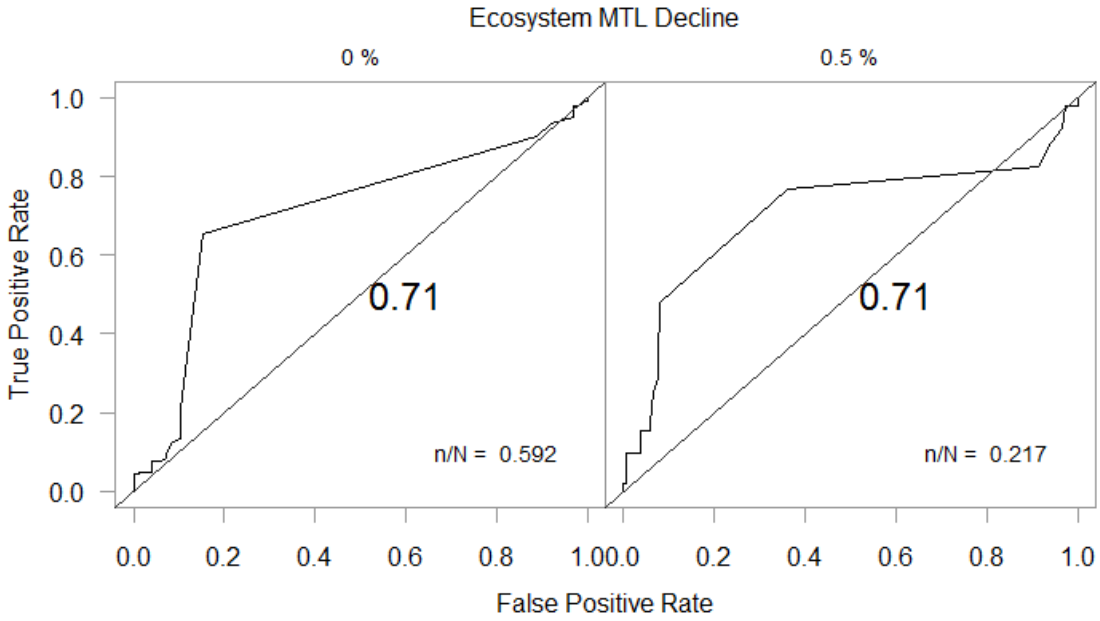


Figure A 2. Receiver Operating Characteristic curves for Catch Mean Trophic Level as an Indicator in the Central Indo-Pacific across Thresholds of True Ecosystem Decline

Note: The AUC of each curve and proportion of total time intervals (n/N) in which a 'true' ecosystem decline occurred are indicated on each panel.

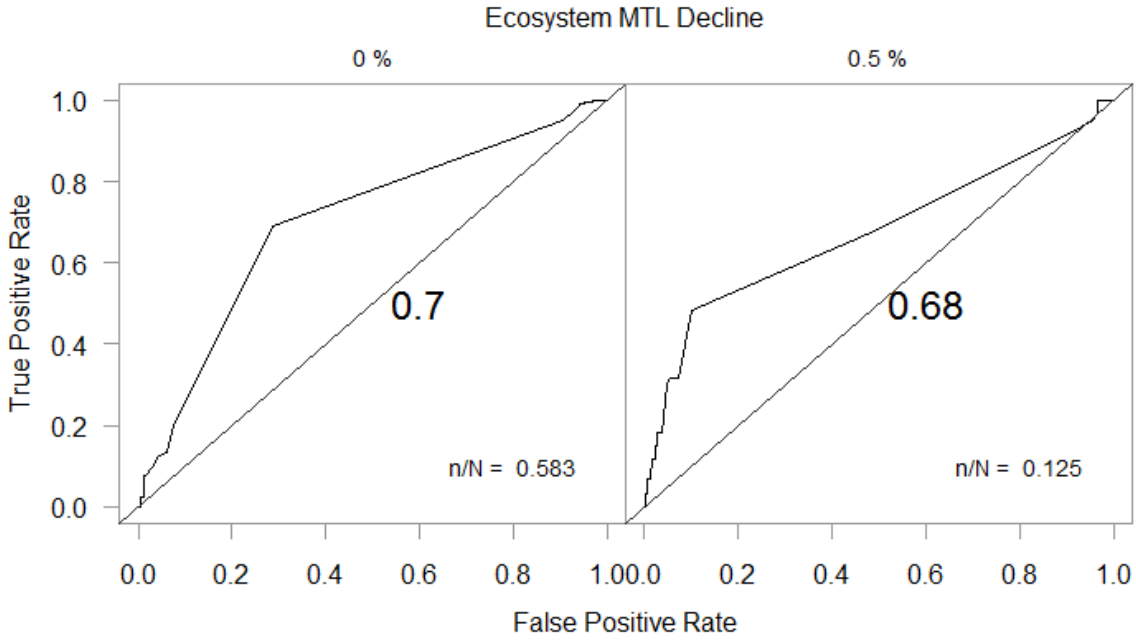


Figure A 3. Receiver Operating Characteristic curves for Catch Mean Trophic Level as an Indicator in the Temperate North Pacific across Thresholds of True Ecosystem Decline

Note: The AUC of each curve and proportion of total time intervals (n/N) in which a 'true' ecosystem decline occurred are indicated on each panel.

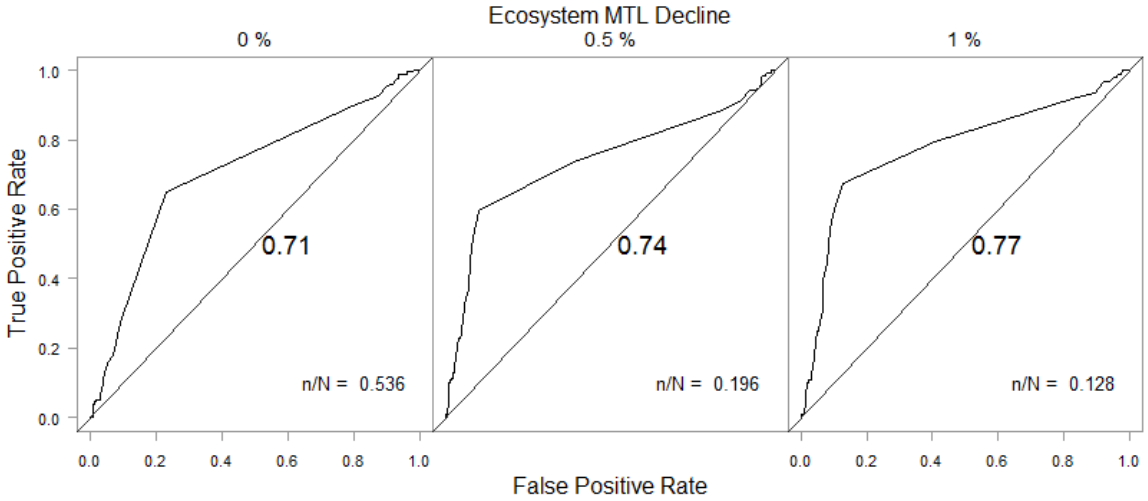


Figure A 4. Receiver Operating Characteristic curves for Catch Mean Trophic Level as an Indicator in the Temperate North Atlantic across Thresholds of True Ecosystem Decline

Note: The AUC of each curve and proportion of total time intervals (n/N) in which a 'true' ecosystem decline occurred are indicated on each panel.

Appendix B.

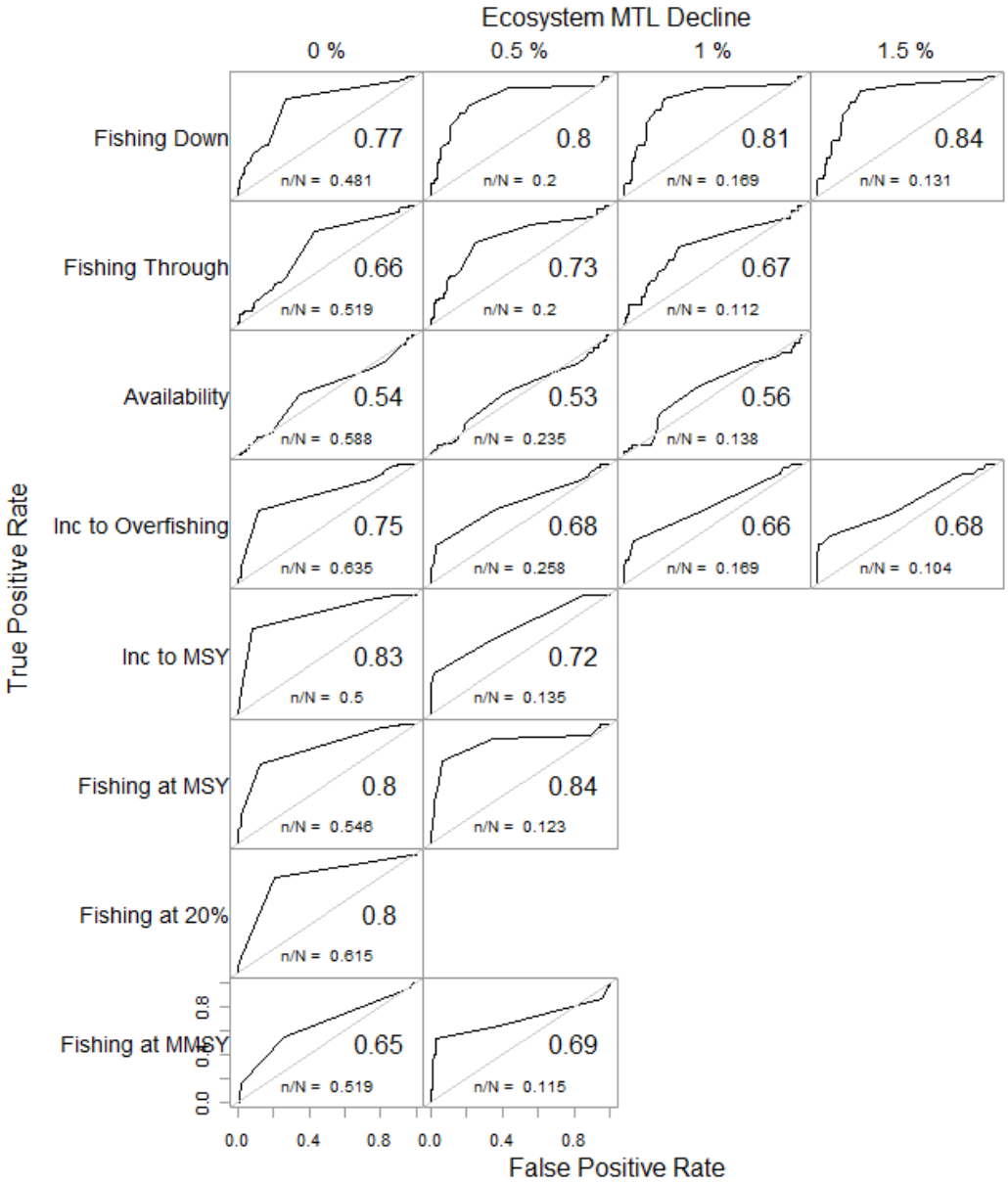


Figure B 1. Receiver Operating Characteristic curves for Catch Mean Trophic Level as an Indicator in each Fishing Scenario across Thresholds of True Ecosystem Decline

Note: The AUC of each curve and proportion of total time intervals (n/N) in which a 'true' ecosystem decline occurred are indicated on each panel.

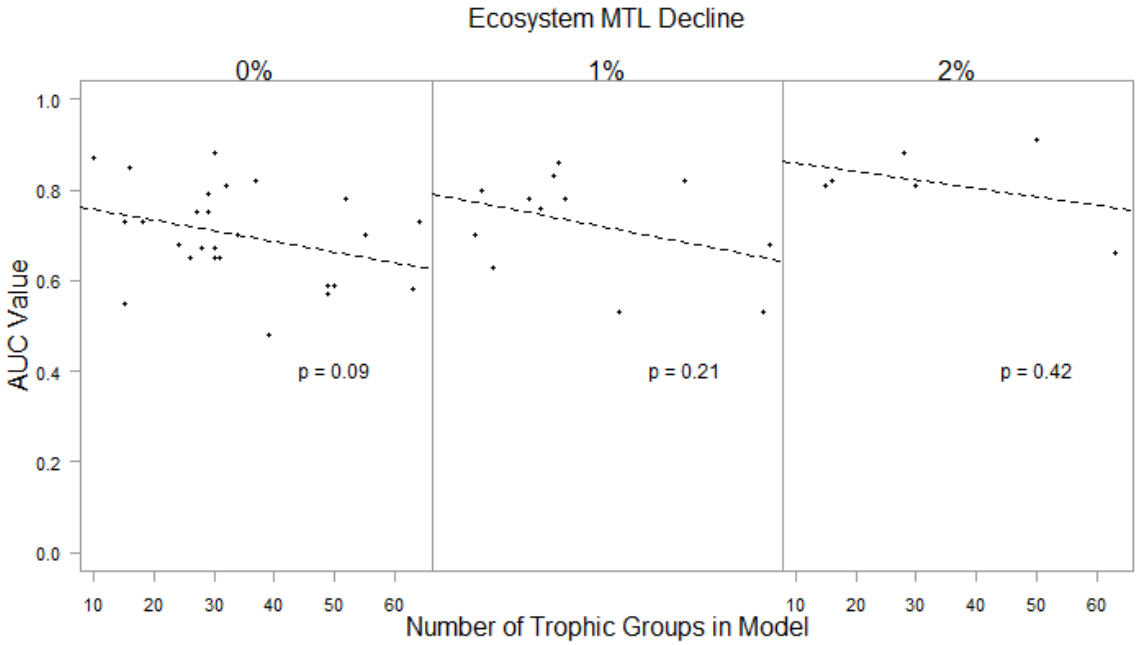


Figure B 2. AUC Values vs. Modeled Complexity of Ecosystems across Thresholds of True Ecosystem Decline

Note: The p-value resulting from a linear regression (dashed line) is shown on each panel.

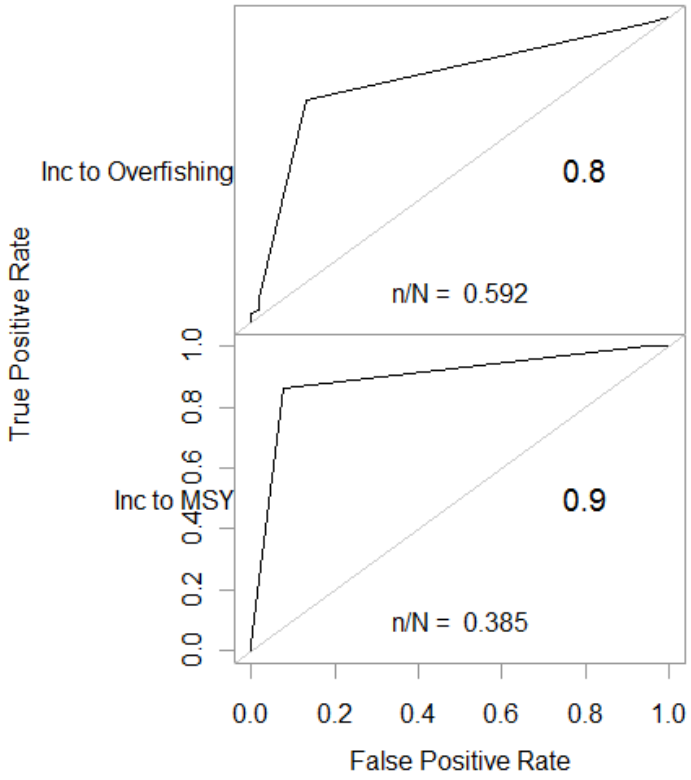


Figure B 3. Receiver Operating Characteristic Curves for Catch Mean Trophic Level Considering Years 51-100 given a True Ecosystem Decline Greater than 0%

Note: The AUC of each curve and proportion of total time intervals (n/N) in which a 'true' ecosystem decline occurred are indicated on each panel.