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Testing candidate indicators to support ecosystem-based management: the power of monitoring surveys to detect temporal trends in fish community metrics

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Community metrics describe aspects of community structure and are often calculated from species-size-abundance data collected during fish stock monitoring surveys. Several community metrics have been proposed as indicators to support ecosystem-based fishery management. These metrics should be sensitive to fishing impacts and respond rapidly to management action, so that managers can assess whether changes in the fish community are a desirable or undesirable response to management. It should also be possible to estimate metrics with sufficient precision so that changes in the community can be detected on management time scales of a year to a few years. Here, we test the power of a large-scale annual trawl survey (North Sea International Bottom Trawl Survey, IBTS) to detect trends in six community metrics: mean length, mean weight, mean maximum length, mean maximum weight, slope of the biomass size spectrum, and mean trophic level. Our analyses show that the power of the trawl survey to detect trends is generally poor. While community metrics do provide good long-term indicators of changes in fish community structure, they are unlikely to provide an appropriate tool to support short-term management decisions. If fish community metrics are to provide effective support for ecosystem-based management, and management time scales cannot be extended, then the power of many surveys to detect trends in fish community structure will need to be improved by increased replication and standardization.

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[⌖]Mike Nicholson died on 6 June 2003, shortly after this paper was submitted. He is greatly missed.

Introduction

Long-term monitoring of fish communities has provided unique insights into the effects of fishing and the environment on marine ecosystems (Overholtz and Tyler, 1985; Duplisea and Kerr, 1995; Greenstreet and Hall, 1996; Fogarty and Murawski, 1998; Bianchi et al., 2000). Changes in fish communities have typically been described using metrics of size-structure, diversity, or trophic structure (Rice, 2000; Rochet and Trenkel, 2003; Trenkel and Rochet, 2003).

The principal effects of fishing on the size and species composition of communities are well known. As size-selective mortality rates rise, the mean size of individuals in the community falls, and species with larger body sizes form a smaller proportion of community biomass (reviews: Jennings and Kaiser, 1998; Gislason and Sinclair, 2000; Greenstreet and

Rogers, 2000). Changes in the size composition of communities have been described using mean or mean maximum size (Jennings et al., 1999) and the slopes of biomass size spectra (Pope et al., 1988; Murawski and Idoine, 1992; Bianchi et al., 2000). Mean and mean maximum size fall in response to increased fishing mortality, while the slopes of size spectra (relationships between biomass of individuals by body size class (y) and body size (x)) become increasingly negative (Rice and Gislason, 1996; Gislason and Rice, 1998).

Changes in the size structure of communities reflect the direct and indirect effects of fishing, including (i) the differential vulnerability of larger species, (ii) within-population changes in mean body size and life history, (iii) genetic changes in life history, (iv) predator—prey relationships in the community, and (v) competition or competitive release. Since body size is loosely correlated with trophic level, the

trophic level of the community also falls in response to fishing (Pauly *et al.*, 1998; Pinnegar *et al.*, 2002). However, the response of trophic level to fishing is less consistent than the response of body size (Jennings *et al.*, 2002).

While many community metrics are reliable indicators of the long-term effects of fishing, and an understanding of their response to fishing is grounded in theory and practice, this understanding is based on retrospective analyses of long time-series. In recent years, several community metrics have been proposed as indicators to support ecosystem-based fishery management (NCM, 1999; Link, 2002). The indicators would be used to establish the status of fish communities relative to reference levels and to set management targets (ICES, 2001). The use of metrics as indicators to support management is a significant departure from their use in retrospective analysis. This is because managers typically make decisions and assess the success of management on time scales of one to a few years rather than the time scales of decades over which trends in metrics have hitherto been described.

While indicators are intended to provide a simple description of temporal trends in community structure, the trend will not be the only signal present in the data. There will also be random changes due to both sampling and year-to-year variation (Fryer and Nicholson, 1993). Fryer and Nicholson (1993) discussed statistical tests for linear trends and incidents in the presence of random year-to-year variation, and also evaluated the power of a monitoring programme to detect them. Power is defined as the probability that a particular trend will be detected. Formulating expressions for the power allows us to quantify the type and magnitude of change in a metric that is likely to be detected, or vice versa, the number of years of monitoring data needed (Gerrodette, 1987; Fairweather, 1991; Nicholson and Fryer, 1992; Fox, 2001).

An assessment of the power of surveys to detect trends in candidate indicators is important. If the power of the survey is low and it takes many years of monitoring to detect a relevant trend, then the monitoring programme and/or indicator may need to be modified to provide useful information for managers. Here, we test the power of a large-scale long-term monitoring survey to detect trends in six community metrics: mean length, mean weight, mean maximum length, mean maximum weight, slope of the biomass size spectrum, and mean trophic level. The analyses show that these metrics are unlikely to be appropriate tools for underpinning short-term management decisions and we suggest that surveys or management methods may need to be modified to support more effective ecosystem-based management.

Methods

Community metrics were calculated for the fish community sampled on the North Sea International Bottom Trawl survey (IBTS) from 1982 to 2000. In this survey, between 117 and 173 ICES rectangles (boxes of 0.5° latitude and 1° longitude: area of one rectangle 3720 km² at 53°N) were fished annually with a Grande Ouverture Verticale (GOV) trawl. We conducted two analyses, one for all rectangles sampled and one for those rectangles sampled in every year ($n = 107$). The first approach provided higher replication within years, but space and time effects contribute to the variance in metrics among years. With the second approach, replication is lower, but time rather than space effects contribute to variance. Metrics were calculated from species-size-abundance data for each rectangle in each year, based on a standard tow duration of 1 h. Mean values of the metrics were then calculated among rectangles within years.

The following metrics were calculated from the species-size-abundance data for each haul in each year. All bottom dwelling (demersal) fishes of > 8 cm total length were used to calculate weight and length based indicators and mean trophic level.

Mean length was calculated as

$$\overline{L} = \sum L/N$$

where L is the length of an individual and N is the total number of individuals. *Mean weight* was calculated as

$$\overline{W} = \sum W/N$$

where W is the body mass of an individual. *Mean maximum length* was calculated as

$$\overline{L}_{max} = \sum (L_{max\,j} N_j)/N$$

where $L_{max\,j}$ is the maximum length obtained by species j, as reported by Jennings *et al.* (2002) and by CEFAS (unpublished), and N_j is the number of individuals of species j. *Mean maximum weight* was calculated as

$$\overline{W}_{max} = \sum (W_{max\,j} N_j)/N$$

where $W_{max\,j}$ is the maximum body mass attained by species j, as reported by Jennings *et al.* (2002) and by CEFAS (unpublished), and N_j is the number of individuals of species j. *Mean trophic level* was calculated as

$$\overline{TL} = \sum (TL_{ij} W_{ij}) \Big/ \sum W_{ij}$$

where TL is trophic level and W is body mass for individual i of species j. Mean trophic level was calculated following the approach of Jennings *et al.* (2002). Principally, we used species-specific relationships between $\log_{10}$ length and trophic level for the 31 most abundant species, as determined using nitrogen stable isotope analysis, to assign trophic levels to all individuals of these species in all catches. These 31 species accounted for $>98\%$ by weight of total survey catches. Biomass weighted mean trophic level was calculated for catches in each rectangle in each year.

The *slopes and intercepts of biomass size spectra* were calculated for the fish communities sampled in each year of the IBTS. Fish > 8 g body mass were assigned to $\log_2$ body mass classes, and cumulative biomass by $\log_2$ body mass was calculated. The linear relationship between $\log_2$ body mass (x) and $\log_{10}$ biomass (y) was described as $y = bx + a$, where b is the slope, and a is the intercept of the size spectrum.

Statistical methods

Statistical power was defined as the probability that a specified effect achieves statistical significance using a specified test applied to data collected under a specified sampling scheme. We followed Nicholson and Fryer (2002) and considered the power to detect a future short-term trend in a community metric. We considered a time-series of observations y_t, $t = 1...T$ which can be written as

$$y_t = \mu_t + \varepsilon_t$$

where

$$\varepsilon_t \sim N(0, \sigma^2)$$

$$\mu_t = g(t) \quad t = 1982-2000$$

$$\mu_t = \alpha + \beta t \quad t = 2001-(2000 + T)$$

and g(t) is an unspecified smooth function of t.

Hence the overall trend consisted of some non-specified smooth trend for the period 1982–2000, followed by a short-term linear trend beginning in 2001 and lasting for T years.

As well as the magnitude and pattern of trend, statistical test, and sampling scheme, the power depends on the significance level of the test (which we set at 5% with a two-tailed test) and on the magnitude of the residual variance, σ^2. We estimated the variance for each metric following Fryer and Nicholson (1993), using a loess smoother to estimate g(t) and the residual sum of squares from the fitted smoother as the basis for estimating σ^2. However, since this approach may give biased estimates of σ^2 if the amount of smoothing is inappropriate, we modified their approach and adopted a simple difference-based variance estimation method recommended by Gasser *et al.* (1986). This has the form

$$\hat{\sigma}^2 = \frac{2}{3(T-2)} \sum_{i=3}^{T} (0.5y_{t-2} - y_{t-1} + 0.5y_t)^2$$

for a time-series with equally spaced observations. Although this estimator is asymptotically inefficient, it provides a good balance between bias and precision with small values of T (Dette *et al.*, 1998).

The estimated variance was used to derive the power of detecting the projected short-term linear trend using a modified linear regression which focuses on the period from 2001, but uses all data from 1982 to estimate the residual variance.

Our approach assumed that residual variance was constant over time, and ignored any information about within-year variation. However, residual variance could vary from year to year due to fluctuating sample sizes or variation in the spatial distributions of the metrics. An alternative approach would be to partition the total variance into a constant between-year variance and a fluctuating within-year variance.

Results

In the period 1982–2000, the mean weight and length, mean maximum weight and mean maximum length, and trophic level of the sampled fish community all decreased, while the slope of the size spectrum became steeper and the intercept increased. The patterns were similar for all rectangles and for the fixed rectangles (sites) that were sampled in every year of the survey (Figure 1). The rate of change in metrics was generally faster in the period 1982–1990 than 1991–2000, and this is captured by the smoother.

The estimated variance of each metric was used to calculate the power of predicting a projected short-term linear trend in the time-series after 2001. Figure 2 shows the power of detecting a projected linear trend over $T = 10$ years as a function of the slope of the short-term trend. There was no consistent benefit from basing metrics on all rectangles or fixed rectangles, suggesting that any observed benefit was simply due to the uncertainty in the estimate of σ^2.

Based on the smoothed trends (Figure 1), we estimated maximum predicted rates of change for the community metrics (b_{max}, Table 1) and a more realistic estimate of the likely rates of change under the existing management regime ($b_{max}/4$, Table 2). A more detailed analysis of power (Tables 1, 2) shows that the power of the IBTS to detect trends in all six community metrics was weak on time scales relevant to management. Thus the detection of a short-term trend in the metrics (b_{max}) with a power of 90% after 10 years (b_{10}) required that the rate of trend was greater than the maximum rates previously observed in the time-series. Moreover, after 3, 5, or 10 years of monitoring, it is unlikely that the maximum rates of change in any metric would be detected (T = 3, 5, or 10, Table 1) and almost certain that realistic rates of change would not (Table 2). To increase the probability of detecting a trend in b_{max} to 90% would require between 12 and 30 years of monitoring for the different metrics (Table 1), while for $b_{max}/4$, between 30 and 75 years of monitoring would be required (Table 2).
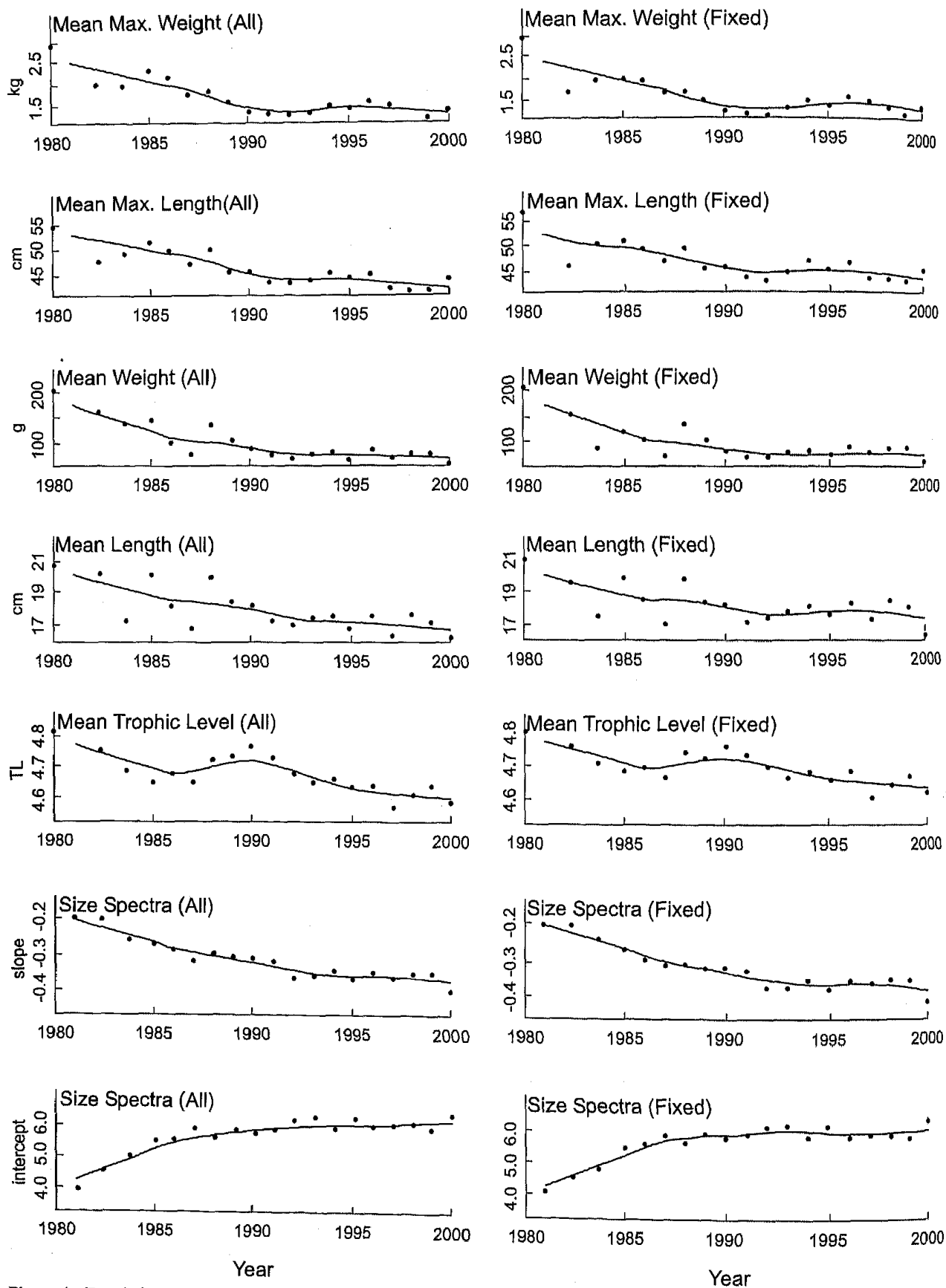
Figure 1. Trends in community metrics for the North Sea fish community based on data for all rectangles and fixed rectangles.

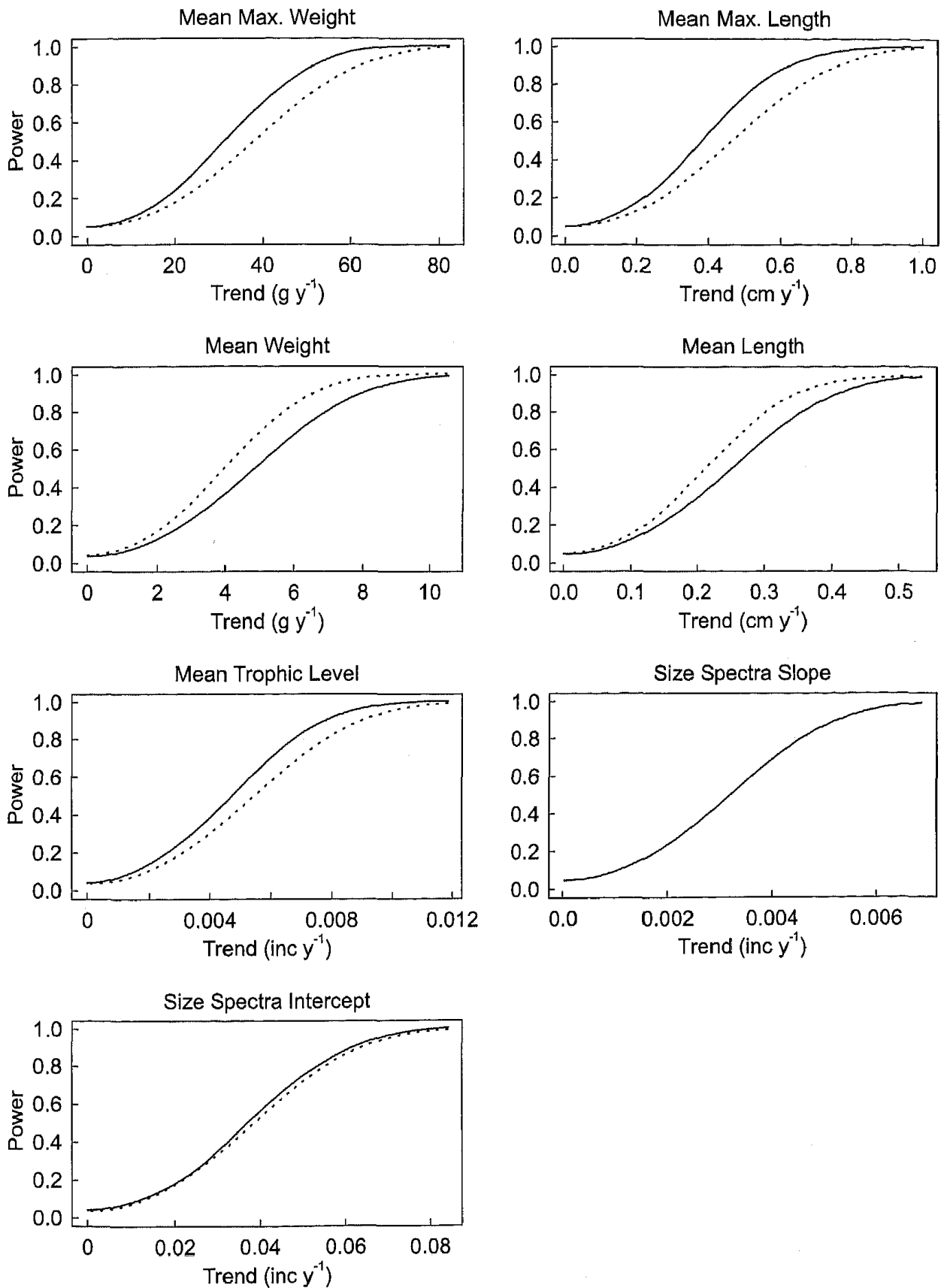Figure 2. The power of detecting a projected linear trend in community metrics over T = 10 years as a function of the slope of the short-term trend. Continuous lines indicate power for all rectangles and broken lines the power for fixed rectangles.

Table 1. Estimated values of $\hat{\sigma}$ for each metric at *all* and *fixed* rectangles, the short-term trends in each metric (increment per year) that would be detected with a power of 90% after 10 years (b_{10}), estimated maximum predicted rates of change for the community metrics (b_{max}), the power to detect trends in b_{max} after T = 3, 5, and 10 years, and the numbers of years of monitoring that would need to elapse before the powers of detecting b_{max} reached 90%. Code to metrics: Max W, mean maximum weight; Max L, mean maximum length; Mean W, mean weight; Mean L, mean length; MTL, mean trophic level; Slope, size spectra slope; Intercept, size spectra intercept.

Metric		$\hat{\sigma}$	b_{10}	b_{max}	Power			Elapse time
					3 yr	5 yr	10 yr	
Max W	All	139.5	52.1	40	0.07	0.14	0.70	12
	Fixed	168.2	62.8	40	0.06	0.11	0.54	14
Max L	All	1.69	0.63	0.4	0.06	0.11	0.54	14
	Fixed	2.05	0.76	0.4	0.06	0.09	0.40	16
Mean W	All	21.6	8.0	4	0.06	0.09	0.36	16
	Fixed	17.6	6.6	4	0.06	0.10	0.51	14
Mean L	All	1.09	0.41	0.2	0.06	0.08	0.36	16
	Fixed	0.93	0.35	0.2	0.06	0.10	0.46	15
MTL	All	0.021	0.0080	0.004	0.06	0.09	0.37	16
	Fixed	0.024	0.0091	0.004	0.06	0.08	0.30	18
Slope	All	0.014	0.0053	0.001	0.05	0.06	0.09	30
	Fixed	0.014	0.0053	0.001	0.05	0.06	0.09	30
Intercept	All	0.167	0.0622	0.04	0.06	0.11	0.55	14
	Fixed	0.173	0.0645	0.04	0.06	0.11	0.52	14

Discussion

The observed historical trends in community metrics are consistent with those widely reported elsewhere and are largely attributable to the effects of fishing on the size and trophic structure of the North Sea fish community (Rice and Gislason, 1996; Gislason and Rice, 1998; Jennings *et al.*, 1999, 2002). However, the observation that community metrics have historically responded to fishing does not necessarily mean that they can be used as indicators to guide management decisions in the future. This is because managers assess the success of management on time scales of one to a few years rather than the time scales of decades over which links between metrics and fishing effort have been studied.

Our assessment of the power of the IBTS to detect trends in candidate indicators demonstrated that there was a very low probability of detecting meaningful rates of change after less than 10 years of monitoring, even though the IBTS is one of the largest and best resourced trawl surveys

Table 2. Estimated values of $\hat{\sigma}$ for each metric at *all* and *fixed* rectangles, the short-term trends in each metric (increment per year) that would be detected with a power of 90% after 10 years (b_{10}), estimated typical predicted rates of change for the community metrics ($b_{max}/4$), the power to detect trends in $b_{max}/4$ after T = 3, 5, and 10 years and the numbers of years monitoring that would need to elapse before the powers of detecting $b_{max}/4$ reached 90%. Code to metrics: Max W, mean maximum weight; Max L, mean maximum length; Mean W, mean weight; Mean L, mean length; MTL, mean trophic level; Slope, size spectra slope; Intercept, size spectra intercept.

Metric		$\hat{\sigma}$	b_{10}	$b_{max}/4$	Power			Elapse time
					3 yr	5 yr	10 yr	
Max W	All	139.5	52.1	10	0.05	0.06	0.10	30
	Fixed	168.2	62.8	10	0.05	0.05	0.08	34
Max L	All	1.69	0.63	0.1	0.05	0.05	0.08	34
	Fixed	2.05	0.76	0.1	0.05	0.05	0.07	39
Mean W	All	21.6	8.0	1	0.05	0.05	0.07	40
	Fixed	17.6	6.6	1	0.05	0.05	0.08	35
Mean L	All	1.09	0.41	0.05	0.05	0.05	0.07	40
	Fixed	0.93	0.35	0.05	0.05	0.05	0.08	36
MTL	All	0.021	0.0080	0.001	0.05	0.05	0.07	40
	Fixed	0.024	0.0091	0.001	0.05	0.05	0.06	43
Slope	All	0.014	0.0053	0.00025	0.05	0.05	0.05	75
	Fixed	0.014	0.0053	0.00025	0.05	0.05	0.05	75
Intercept	All	0.167	0.0622	0.01	0.05	0.05	0.08	34
	Fixed	0.173	0.0645	0.01	0.05	0.05	0.08	35

in the north east Atlantic. It is also unlikely that there are better candidate indicators of the impacts of fishing on fish communities than the size-based metrics we tested. This is because empirical and theoretical evidence has shown that changes in the size structure of communities are a fundamental response to the size-selective mortality caused by fishing (e.g. Bianchi *et al.*, 2000; Rochet and Trenkel, 2003).

Our approach makes a number of important assumptions which must be considered when interpreting the results. Specifically, (i) that the smoothed trends in metrics from 1982 to 2000 are primarily driven by fishing, (ii) that the fastest rates of change recorded between 1982 and 2000 are typical of the fastest rates of change that would occur following future management action, and (iii) that the impacts of fishing on size-structure are reversible. In relation to (i), the evidence that fishing has the primary influence on the dynamics and size structure of the entire fish community is compelling (e.g. Jennings *et al.*, 1999), even though the environment and fishing are both critical in determining the dynamics of individual species (Daan *et al.*, 1990; Daan and Richardson, 1996). The assessment of predicted rates of change in size-based metrics (ii) and their reversibility (iii) is more problematic. Ideally, rates of change in metrics would be predicted from validated size-based models of the relationships between size structure and size-related fishing mortality. The power of the survey to detect predicted rates of change would then be assessed, allowing for the differential catchability of size classes in the IBTS GOV trawl. While significant progress has been made with size-based modelling (e.g. Gislason and Rice, 1998), validated size-based models for the whole community, and the relevant estimates of catchability, are not available. In the absence of appropriate models and catchability estimates and accepting that rates of change in metrics will not necessarily correspond when fishing mortality is falling rather than rising, historic rates of change in the metrics are the best available predictor of future rates of change. However, the expected inaccuracies in the estimated rates of change are unlikely to influence the main conclusions of this study, since the power of the survey to detect a wide range of plausible rates (from b_{max} to $b_{max}/4$) was always low.

There were no consistent differences in the power to detect short-term linear trends in the candidate indicators when using data for *all* or *fixed* rectangles. Thus the increase in precision at higher levels of replication appears to be offset by greater spatial heterogeneity. This observation cannot be applied to other data sets, since the conclusion is site and survey specific. Indeed, the spatial coverage of many other trawl surveys is much more variable from year to year than that of the North Sea survey, and the surveys are conducted on more heterogeneous habitats (e.g. Celtic Sea survey; Pinnegar *et al.*, 2002).

The candidate indicators we tested provided useful information on historical trends in the structure of fish communities, but our analysis suggested that they would provide little information to help with making short-term management decisions. To improve their utility, the options are (i) to improve the power of the survey, (ii) to accept that community metrics are the best indicators available and to extend the time scale of management to match the time scale at which indicators respond to fishing, or (iii) to avoid the use of community metrics as short-term indicators and to focus on measuring indicators of human activity on the basis of demonstrated links between fishing and fish community structure. Option 1 would be necessary to support the approach to ecosystem-based management proposed for the North Sea (Anon, 2002), but may not be practical because monitoring budgets are already overstretched. If option 1 was practical, then the power of many surveys to detect trends in fish community structure will need to be improved by increased replication and standardization. Option 2 is a possibility, and parallels the development of multi-annual methods in fisheries management, but it would require a significant change from approaches to ecosystem-based management that are currently proposed for the North Sea. Option 3 is pragmatic and presents fewer monitoring difficulties, but managers have already requested that biologically based indicators should be piloted to support ecosystem-based management (Anon, 2002).

We conclude that community metrics do provide good long-term indicators of changes in fish community structure, but they will not guide effective short-term management. If fish community metrics are to underpin ecosystem-based management, and management time scales cannot be extended, then the power of many surveys to detect trends in fish community structure will need to be improved by increased replication and standardization.

Acknowledgements

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