Marine ecosystem assessment in a fisheries management context

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Abstract: We examined a suite of abiotic, biotic, and human metrics for the northeast U.S. continental shelf ecosystem at the aggregate, community, and system level (>30 different metrics) over three decades. Our primary goals were to describe ecosystem status, to improve understanding of the relationships between key ecosystem processes, and to evaluate potential reference points for ecosystem-based fisheries management (EBFM). To this end, empirical indicators of ecosystem status were examined and standard multivariate statistical methods were applied to describe changes in the system. We found that (*i*) a suite of metrics is required to accurately characterize ecosystem status and, conversely, that focusing on a few metrics may be misleading; (*ii*) assessment of ecosystem status is feasible for marine ecosystems; (*iii*) multivariate points of reference can be determined for EBFM; and (*iv*) the concept of reference directions could provide an ecosystem level analog to single-species reference points.

Résumé : Nous avons étudié une série de >30 métriques abiotiques, biotiques et humaines de l'écosystème de la plate-forme continentale du nord-est des É.-U. à l'échelle de l'association, de la communauté et du système couvrant plus d'une trentaine d'années. Nos objectifs principaux étaient de décrire l'état de l'écosystème, d'améliorer la compréhension des relations entre les processus principaux de l'écosystème et d'évaluer des valeurs de référence potentielles à utiliser dans une approche écosystémique de gestion de la pêche (EBFM, « ecosystem-based fisheries management »). Pour ce faire, nous avons examiné les indicateurs empiriques de l'état de l'écosystème et nous avons utilisé les méthodes multidimensionnelles courantes pour décrire les changements dans le système. Nous avons trouvé que (*i*) il faut une série de métriques pour caractériser de façon précise l'état de l'écosystème et, inversement, la concentration sur un petit nombre de métriques peut induire en erreur; (*ii*) il est possible d'évaluer l'état des écosystèmes marins; (*iii*) on peut déterminer des valeurs de références multidimensionnelles pour usage dans l'EBFM; et (*iv*) le concept de direction de repérage peut fournir à l'échelle de l'écosystème un analogue aux valeurs de référence utilisées dans le cas d'une seule espèce.

[Traduit par la Rédaction]

Introduction

There is considerable interest in ecosystem-based fisheries management, as evinced by several recent reports, articles, and books (discussed in Link 2002). The current relevance and awareness of an ecosystem approach has been attributed to conflicting stakeholders or legislation (i.e., allocation of biomass issues), debate over the most important processes in an ecosystem, limitations of single-species management, or simply the use of an ecosystem perspective to justify a wide variety of positions.

Considering factors that impact marine resource populations in a context beyond just the species level has a long and noted history in fisheries science. Multispecies, trophodynamic, environmental, and ecosystem considerations are certainly not novel (e.g., Baird 1873; Lankester 1884). Several approaches were developed in the 1970s and 1980s to extend single-species models by incorporating some of these broader considerations in a fisheries management context (e.g., May et al. 1979; Mercer 1982; Daan and Sissenwine 1991). Yet despite the attention given to this problem during the past century and a half, many basic issues remain unaddressed. The implementation of broader ecosystem considerations has not yet become widespread in fisheries management (particularly in large, marine ecosystems), although it has been recently advocated and even mandated.

Several metrics exist that can indicate ecosystem status independent of specific objectives (e.g., Rice 2000; Brodziak and Link 2002). These "emergent" metrics may be at the multispecies (= community), food web (= important trophic links), aggregate (= groupings of related taxa), or whole system (= entire open ecosystem) level. We view any attempt to ascertain and understand the status of an ecosystem as sequential, involving multiple metrics and the interdisci-

Received 7 February 2002. Accepted 28 June 2002. Published on the NRC Research Press Web site at http://cjfas.nrc.ca on 10 September 2002.
J16754

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 DOI: 10.1139/F02-115

Table 1. Metrics examined in this study and the extent of these time series.

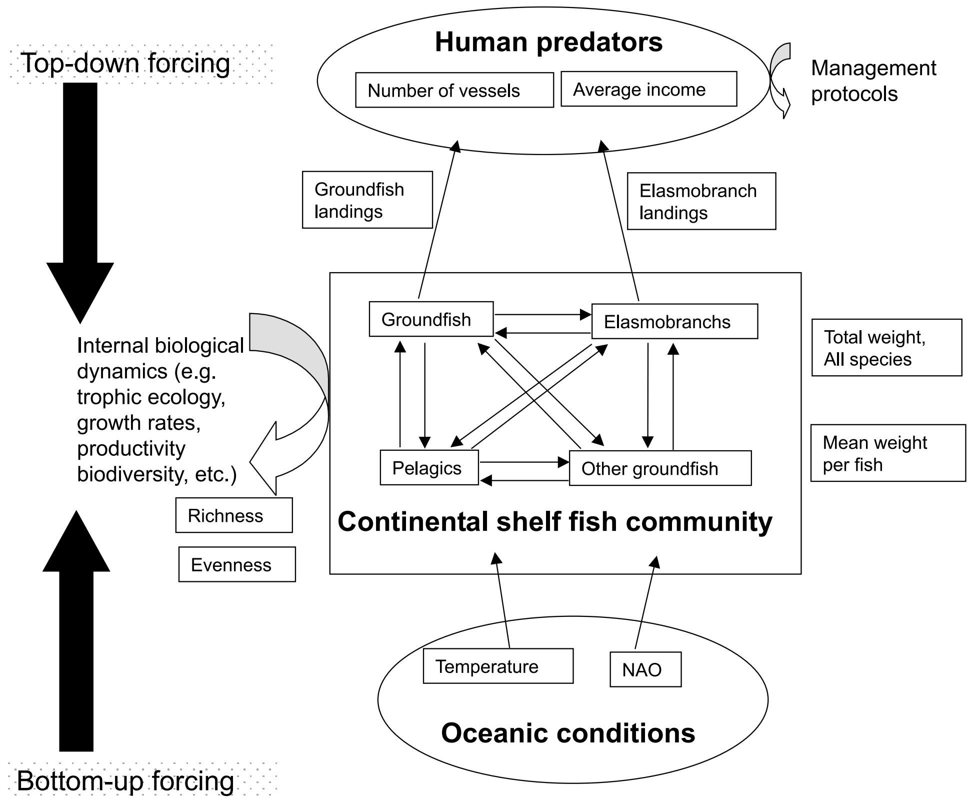
Metric	Start year	End year	Time range	Source	In models	Indexes: process
Biotic metrics						
Resource dynamics						
Total biomass index	1963	2000	37	BTS	N (Fig. 2*a*)	System production
Relative abundance of NE species groups	1963	1999	36	BTS	N	Aggregate production, biomass allocation
Principal groundfish abundance	1963	1999	36	BTS	Y (Fig. 2*c*)	Aggregate production
Elasmobranch abundance	1968	1999	31	BTS	Y (Fig. 2*b*)	Aggregate production
Other groundfish abundance	1963	1999	36	BTS	Y (Fig. 2*c*)	Aggregate production
Principal pelagics abundance	1968	1994	31	BTS	Y (Fig. 2*c*)	Aggregate production
Georges Bank cephalopod abundance	1963	1999	36	BTS	N	Aggregate production
Gulf of Maine total species richness	1963	2000	37	BTS	N (Fig. 3*b*)	Diversity, biomass allocation
Gulf of Maine species evenness	1963	2000	37	BTS	N	Diversity, biomass allocation
Georges Bank total species richness	1963	2000	37	BTS	Y (Fig. 3*b*)	Diversity, biomass allocation
Georges Bank species evenness	1963	2000	37	BTS	Y	Diversity, biomass allocation
Mid-Atlantic Bight total species richness	1963	2000	37	BTS	N (Fig. 3*b*)	Diversity, biomass allocation
Mid-Atlantic Bight species evenness	1963	2000	37	BTS	N	Diversity, biomass allocation
Internal dynamics						
Mean animal length on Georges Bank	1963	2000	37	BTS	N (Fig 2*d*)	Allometric dynamics
Mean animal weight, shelf-wide	1963	2000	37	BTS	Y	Allometric dynamics
Silver Hake linkage density	1973	1999	26	FH	N (Fig. 3*a*)	Trophic dynamics, energy flow
Percentage cannibalism of Gadids	1973	1998	25	FH	N	Trophic dynamics
Percent of fish mature at age-1 and age-2 for Georges Bank haddock and cod	1963	1997	34	BTS	N	Population dynamics, allometric dynamics
Consumption of pelagic species by major predators	1977	1997	20	FH, BTS	N	Biomass allocation, energy flow, trophic dynamics
Abiotic metrics						
Shelf-wide surface and bottom water temperature anomalies	1963	2000	37	BTS	N	Forcing physics
5-year average of NAO index	1823	2000	177	OCE	N	Long-term forcing
NAO index	1960	2000	41	OCE	Y (Fig. 3*c*)	Long-term forcing
Bottom temperature anomalies in the Gulf of Maine	1963	2000	37	BTS	Y (Fig. 3*d*)	Forcing physics
Bottom temperature anomalies on Georges Bank	1963	2000	37	BTS	Y	Forcing physics
Bottom temperature anomalies in the northern Mid-Atlantic Bight	1963	2000	37	BTS	Y	Forcing physics
Bottom temperature anomalies in the southern Mid-Atlantic Bight	1963	2000	37	BTS	Y (Fig. 3*d*)	Forcing physics
Human metrics						
Otter trawl landings by species	1964	2000	36	OBS	Y (Fig. 4*a*)	Humans as predators
Otter trawl revenue by species	1964	2000	36	OBS	Y (Fig. 4*b*)	Humans as predators
Number of otter trawl vessels by size class	1964	2000	36	OBS	Y (Fig. 4*c*)	Humans as predators
Otter trawl income in year 2000 value	1964	2000	36	OBS	N	Humans as predators
Average otter trawl income in year 2000 value	1964	2000	36	OBS	Y (Fig. 4*d*)	Humans as predators

Note: For the source, BTS = bottom trawl survey, FH = food habits, OBS = observer and port agent commercial landings database, OCE = oceanographic database, REG = regulations implemented. Whether or not the metric was used in the multivariate statistical models is denoted (Y/N), and if appropriate, the corresponding figure is noted. The general process indexed by each metric is also listed.

plinary integration, synthesis, and interpretation of these ecosystem metrics. The metrics need to be sensitive to change, directional, general enough to be useful, feasible to measure, and able to incorporate uncertainty. It takes multiple time series of metrics and associated monitoring to assess the status of a system to interpret these metrics in any sort of meaningful management context.

Our goals were to examine some common ecosystem metrics to assess the status of the U.S. northwest Atlantic continental shelf ecosystem and to determine whether any of these metrics, or a combination thereof, could serve as useful ecosystem reference points analogous to single-species reference points and control rules common in fisheries management. We present example metrics representative of the major processes in this ecosystem. Additionally, we present multivariate analyses of ecosystem status and evaluate their

Fig. 1. Conceptual model of major ecosystem processes. All metrics in the solid boxes were used in the principal components and canonical correlation analyses.



utility as ecosystem-level reference points. We view this as an initial step in the iterative process of developing an approach for ecosystem-based fisheries management.

Methods

Data sources—empirical indicators

We used existing databases and analyses to estimate a suite of metrics, including human, abiotic, and biotic factors (Table 1). The majority of these databases are associated with the Northeast Fisheries Science Center's (NEFSC's) long-standing bottom trawl surveys. As such we will preclude a detailed discussion of the methodology involved with collecting these data and estimation of the various parameters. For more details on most biotic metrics, see Azarovitz (1981) and NEFSC (1999). For the community diversity metrics, we used what was captured by the survey trawl gear. We grouped the groundfish into major groundfish (haddock (*Melanogrammus aegelfinus*), cod (*Gadus morhua*), and yellowtail flounder (*Limanda ferruginea*)) and others. For more details about trophic metrics, see Link and Almeida (2000) and Overholtz et al. (2000). For more details about physical oceanographic metrics, see Mountain (1989), Taylor and Bascuñán (2001), and Brodziak and Link (2002). For landings, commerical fisheries information, and related human parameters, see NEFSC (1999), Brodziak and Link (2002), and S.F. Edwards (NMFS, Woods Hole, MA 02543, U.S.A., unpublished data).

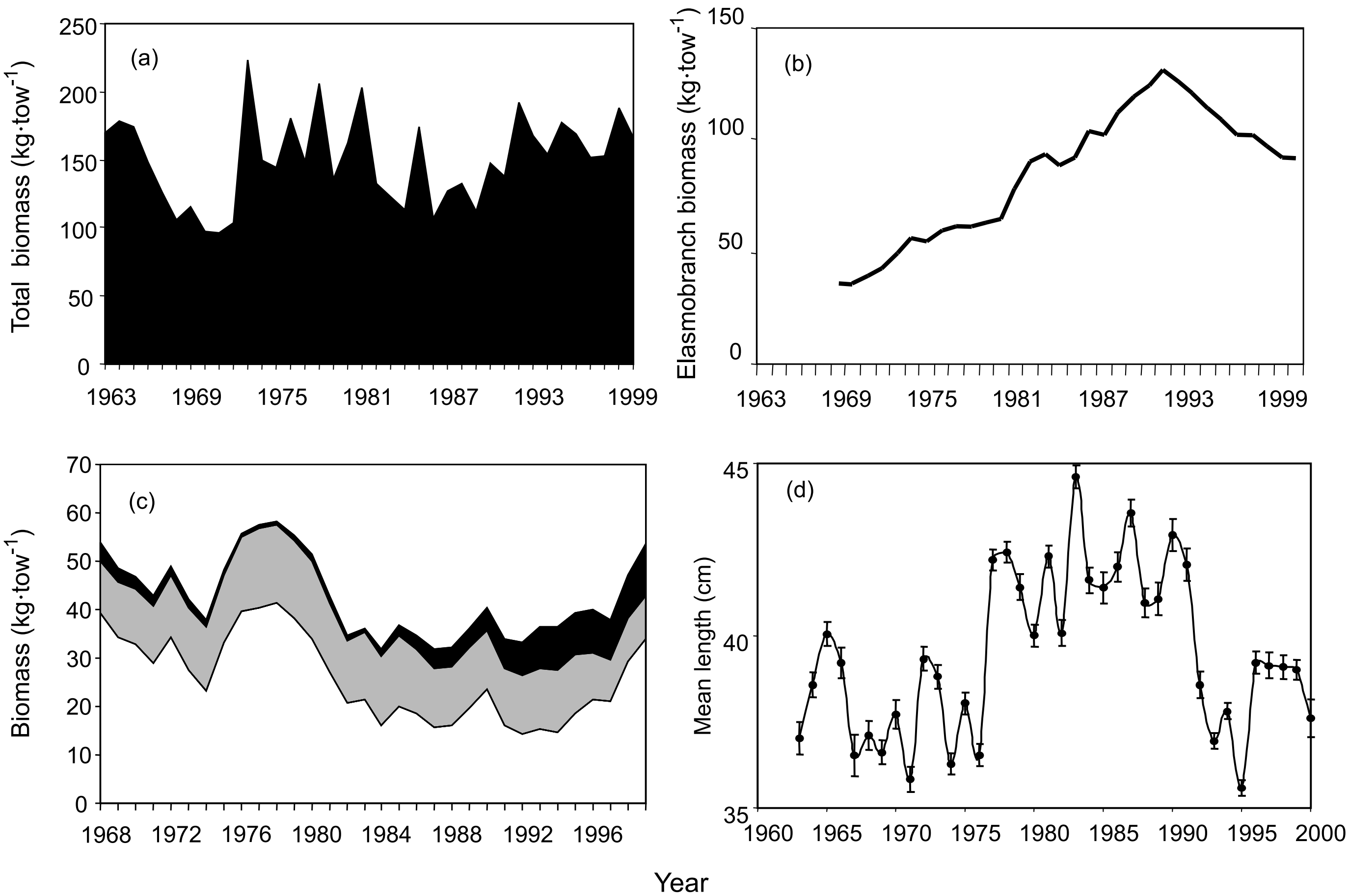
We selected various human, abiotic, and biotic metrics from a suite of many possible (Table 1) that correspond to the major processes in the northwest Atlantic ecosystem (Fig. 1). We recognize that the other metrics not selected may similarly quantify major processes within this ecosystem. The selected metrics are not meant to be exhaustive, but rather representative of the major components of this ecosystem. The metrics are also useful as proxies for various activities and processes within the ecosystem, for example, the number of vessels can serve as an indicator of the overall fishing effort potentially occurring in the system. For a broader selection and discussion of metrics for this ecosystem, see Link and Brodziak (2002).

We calculated quintiles of the empirical distribution for the representative metrics. By color coding various quintiles, we obtain a perspective of recent years relative to the overall average for each metric (Halliday et al. 2001; Brodziak and Link 2002; Caddy 2002). For example, if a metric exhibits values in the highest quintile during the most recent year or set of years, we would code that year as black, indicative that this metric value was one of the highest (i.e., positive) values observed. By examining the full suite of metrics, one can visualize the status of an ecosystem relative to historical levels. We assigned the highest quintiles black, the second dark gray, the third cross-hatched, the fourth vertically lined, and the lowest white. This approach differs from the typical "traffic light" approaches (Halliday et al. 2001; Caddy 2002) in that we did not assign a value judgement (i.e., good or bad) to any particular quintile.

Data analysis—statistical models

We used principal components analysis (PCA; Legendre and Legendre (1998) or Jongman et al. (1999); on the corre-

Fig. 2. (*a*) Total fish biomass of the entire northeast shelf ecosystem as estimated from the Northeast Fisheries Science Center bottom trawl surveys. These estimates include all finfish species. (*b*) Major trends in aggregate biomass for the elasmobranchs. (*c*) Major trends in biomass for principal groundfish (open), other groundfish (shaded), and principal pelagics (solid). (*d*) Mean length (± standard error) of all fish species on Georges Bank.



lation matrix) on the selected metrics to reduce the number of multivariate dimensions to a smaller set of linear combinations that explained the most variance, provided some delineation of key processes (e.g., biotic tradeoffs, abiotic forcing functions, human intervention, etc.) effecting the ecosystem, and tracked major trends across the time series. The conceptual model that we used for the PCA included abiotic and human factors that can influence the biotic metrics as well as other biotic metrics that index internal regulatory biological processes (Fig. 1).

In addition to the simple descriptive PCA model, we used canonical correlation analysis (CanCorr; Jongman et al. (1999) or Legendre and Legendre (1998)) to examine the linear relationships between multivariate response (biotic) and explanatory (human and abiotic) metrics. Although the general conceptual model that we used was the same as in the PCA analysis, the CanCorr provided an evaluation of possible dependance among metrics. CanCorr is a multivariate equivalent to multiple linear regression that used the biotic metrics as response variables.

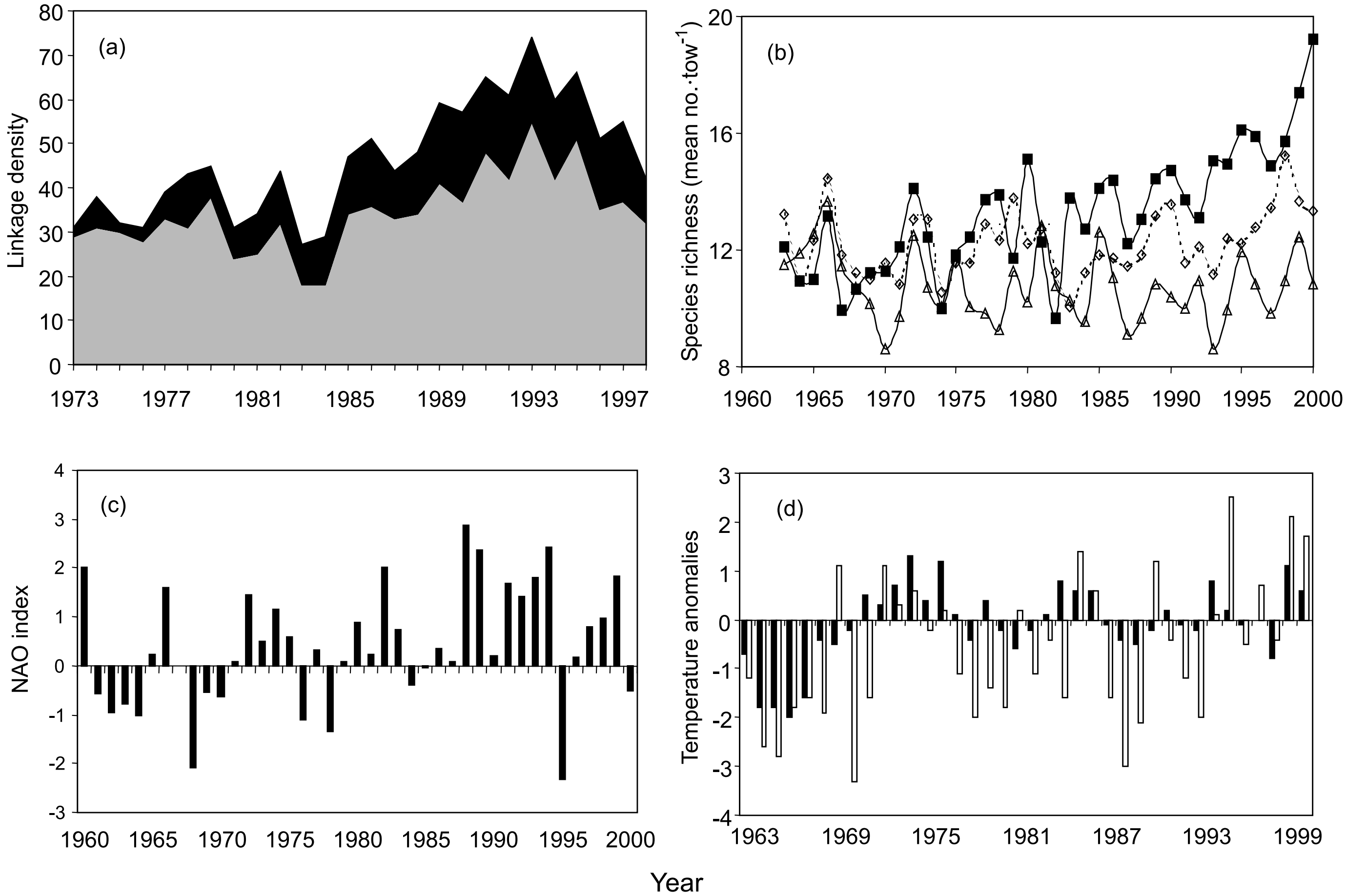
The PCA and CanCorr results were further explored to determine if the first two principal component weights or the first two canonical axes could be used to describe ecosystem status as a multivariate analogue to single-species reference points. From the PCA, we grouped annual scores plotted in phase–space into related quadrats to represent major "regimes" or "stanzas" of this ecosystem. We then examined the multivariate trajectory and potential dependent relationships among the ecosystem metrics using the CanCorr results. By examining the results from both methods, we could then ascertain ecosystem status relative to some desirable state in multivariate space. For example, if there was a strong relationship between the first canonical axes from the CanCorr analysis, we could use that relationship to suggest possible manipulations in the explanatory axis (and composite metrics) that would result in changes to the response axis corresponding to a desirable locale in the phase–space plot from the PCA.

Results

Empirical indicators

The average total fish biomass of the ecosystem (Fig. 2*a*), after the initial years of the survey, has effectively shown no trend, within a range of variation, across the time series. However, allocation of fish biomass across different groups has varied (Figs. 2*b*, 2*c*). In more recent years, the planktivore guild has become much more dominant (i.e., increases in juvenile dogfish and small pelagics such as herring and mackerel). This observation simply suggests that within the

Fig. 3. (*a*) Linkage density (number of predators, solid; number of prey, shaded) for silver hake (*Merluccius bilinearis*). (*b*) A measure of diversity (species richness) for the Gulf of Maine (solid squares), Georges Bank (open diamonds), and the Mid-Atlantic Bight (open triangles). (*c*) The North Atlantic Oscillation (NAO) index (adapted from Brodziak and Link 2002). (*d*) Temperature anomalies for two regions of the ecosystem, the Gulf of Maine (solid) and the southern Mid-Atlantic Bight (open) (adapted from Mountain 1989; Taylor and Bascuñán 2001).



limitations of thermodynamics, differential effects of fishing or the environment alter the internal dynamics (e.g., trophic dynamics, community structure, productivity, etc.) of the ecosystem, ultimately regulating the allocation of biomass within the ecosystem.

Most metrics exhibit a change across the time series. Mean length (Fig. 2*d*), number of silver hake species interactions (Fig. 3*a*), Gulf of Maine and Mid-Atlantic Bight species richness (Fig. 3*b*), the North Atlantic Oscillation (NAO; Fig. 3*c*), temperature (Fig. *3d*), and most species landings and associated fisheries income (Fig. 4) have generally changed to values very different in the 1990s vs. the 1980s, suggestive of broad-scale changes in this ecosystem. The consistent peak in many metrics during the late 1970s to early 1980s (Figs. 2–4) is also interesting; this peak occurred for 17 out of the 35 metrics that we examined, and conversely a depressed series of values occurred for 10 others during the same time. This peak may represent some form of cyclicity in the biotic components of the ecosystem, similar to the abiotic features (e.g., temperature, NAO; Figs. 3*c*, *3d*), or a shift to a new steady state. No one metric best described the status of the ecosystem, even though many of the metrics demonstrated similar trends and many of the metrics similarly captured the directionality of key processes and relationships. Examining just one or a few (e.g., pelagic biomass, elasmobranch biomass, silver hake linkage density, species richness in just one region) may be misleading. Given the consistent change in multiple metrics from this time period, there was likely a large event or series of events perturbing the system during the late 1970s to early 1980s.

The quintile approach demonstrates that conditions have changed across the time series (Table 2). Metrics such as pelagic species biomass, the NAO, southern Mid-Atlantic Bight temperatures, and elasmobranch landings are more positive in recent years than most of the other metrics. The previously described peaks during the early 1980s are also apparent. This approach does not present any new information, but packages the information into one simple, intuitive graphic that can be readily digested by multiple stakeholders (Schiller et al. 2001; Halliday et al. 2001; Caddy 2002).

Obviously, many of these metrics are correlated. There are numerous similarities (or inversions) in the directionality and relative magnitude in the major trends observed for most metrics. However, the strength and interdependence of the relationships among the metrics are unknown.

Statistical models

The first two axes of the PCA explained 48% of the total

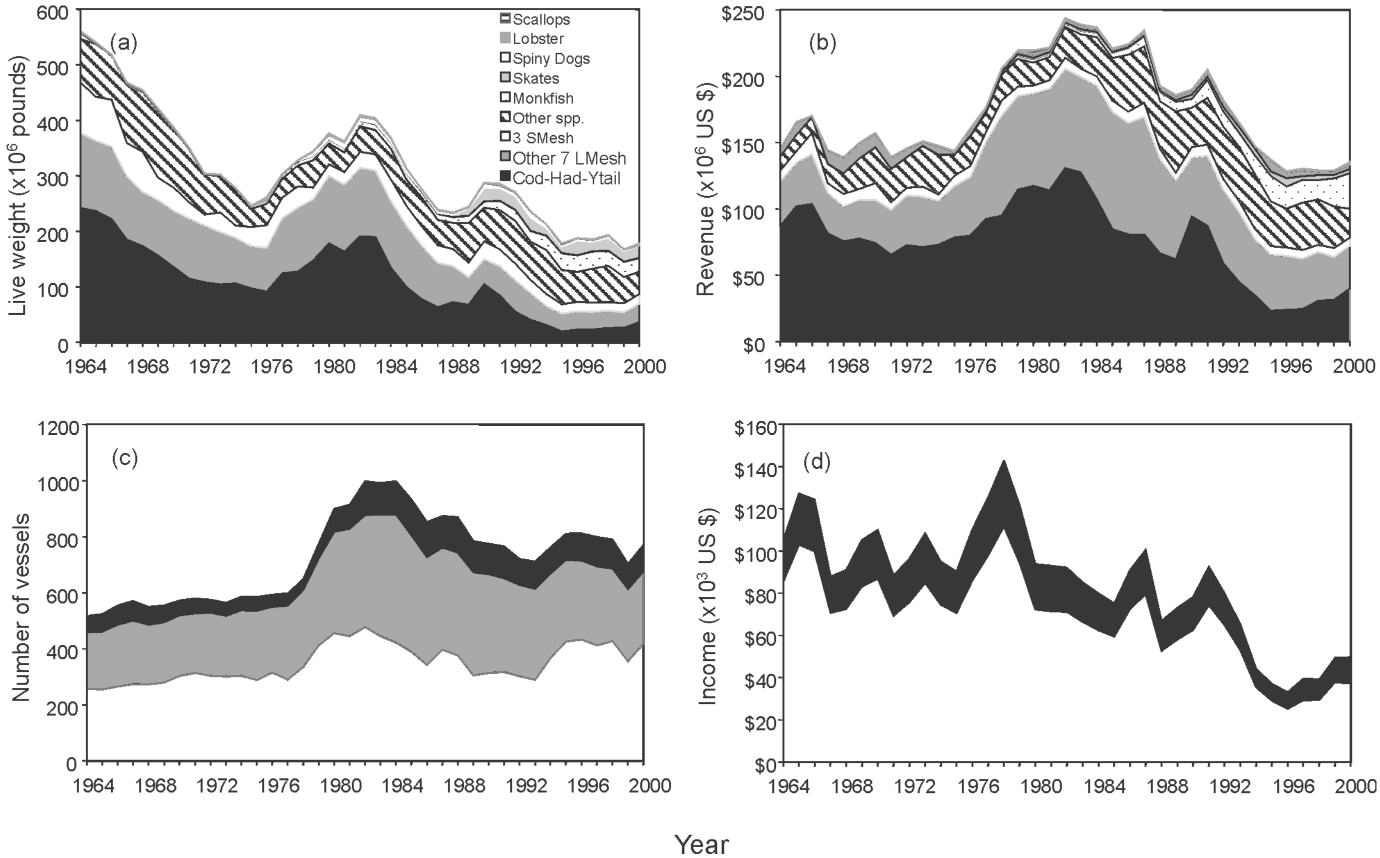


Fig. 4. (*a*) New England otter trawl landings by species or species groups. (*b*) Total otter trawl revenue (adjusted for inflation to year 2000 US$) by species. See the shading legend in Fig. 4*a*. (*c*) Total number of vessels fishing in the otter trawl fleet. Tonnage class 2 (TC2) is open, TC3 is shaded, and TC4 is solid. (*d*) Average otter trawl income (adjusted for inflation to year 2000 US$) per vessel (open) and crew (solid) (all adapted from S.F. Edwards, unpublished data).

variance (Fig. 5), and the first four principal components (PC) explained 70%. Interestingly, no one factor dominated the weightings. The first PC can be thought of as an index of low groundfish biomass and landings, low profits, low species evenness, and small fish at negative scores. Conversely, positive first axis scores corresponded to high skate landings and high elasmobranch and pelagic biomass. The first PC axis scores have generally increased across time, corresponding to increases in elasmobranch biomass–landings, pelagic biomass and declines in groundfish landings, fish size, and income (Figs. 2–4). The second PC can be thought of as an index of temperature and groundfish biomass (positive scores) or conversely total fishing effort (i.e., total number of vessels, landings). The second PC axis scores were lower during the mid-1980s, corresponding to the peak in the number of vessels, groundfish and dogfish landings, cooler temperatures, and declining groundfish biomass (Figs. 2–4).

When the PC scores for the first two axes are plotted throughout time, an interesting trajectory develops (Fig. 6). The pattern generally tracks from the upper left quadrat (I, negative PC1, positive PC2) counter clockwise to the upper right quadrat (IV, positive PC1 and PC2). We categorically group the annual scores into three regions corresponding to conditions noted in Table 2. It is uncertain if the system could even return from the current conditions in the upper right quadrat to the conditions in the upper left.

The first canonical axis of the explanatory variables is primarily defined similar to the second PC axis described above, with positive scores corresponding to high elasmobranch landings, number of vessels, and Mid-Atlantic Bight temperature (Fig. 7*a*). Conversely, negative scores correspond to high groundfish landings. The second explanatory canonical axis effectively is an index of income, the number of vessels, and other groundfish vs. most other species landings. Interestingly, this second axis had neutral scores for various measures of temperature.

The first canonical axis of the response metrics simply contrasts groundfish vs. pelagic biomass (Fig. 7*b*). The second axis contrasts evenness vs. individual fish weight and other groundfish. The univariate statistics show that scores for other groundfish biomass (R^2 = 54.3%, $P < 0.0817$), groundfish biomass (R^2 = 67.5%, $P < 0.0072$), pelagic biomass (R^2 = 72.6%, $P < 0.0019$), and species evenness (R^2 = 69.0%, $P < 0.0050$) are significantly different than 0 for both axes.

The first two axes of the CanCorr analysis explain 81% of the total variance. The first two eigenvalues ($p < 0.003$) and summary statistics are statistically significant (Wilk's λ = 0.00118, df = 88, 88.149, $p < 0.032$). The relationship between the first canonical axes has an R^2 of 93.9% (Fig. 7*c*). Coupled with the PCA trajectory (Fig. 6), this relationship can roughly be interpreted to mean that after a period of high groundfish landings, then low groundfish landings, high elasmobranch landings, high numbers of vessels, and high

Table 2. Summary of 5-year averages of abiotic, biotic, and human metrics to ascertain qualitative status of the north-east shelf ecosystem characteristics. The patterns (see Color code of metric) correspond to the different quintiles that these metrics exhibit with respect to the historical time series. The quadrat and region refer to the location in multivariate space of the PCA (principal component analysis) time trajectory for each period of time (Fig. 6). MAB, Mid-Atlantic Bight; N/A = data not available for that year.

Quadrat		IV	IV	III	II	II	I	I
Multivariate region		C	C	B	B	A	A	A
Metric	Value in 2000	Average 1995-1999	Average 1990-1994	Average 1985-1989	Average 1980-1984	Average 1975-1979	Average 1970-1974	Average 1965-1969
Abiotic metrics								
North Atlantic oscillation	20-0th	60-40th	100-80th	80-60th	80-60th	40-20th	60-40th	40-20th
Gulf of Maine bottom temperature	60-40th	80-60th	60-40th	80-60th	60-40th	60-40th	80-60th	60-40th
Georges Bank bottom temperature	60-40th	80-60th	80-60th	60-40th	60-40th	80-60th	80-60th	20-0th
N MAB bottom temperature	N/A	80-60th	100-80th	60-40th	40-20th	60-40th	60-40th	20-0th
S MAB bottom temperature	N/A	100-80th	60-40th	60-40th	60-40th	60-40th	60-40th	40-20th
Biotic metrics								
Total biomass	N/A	80-60th	80-60th	60-40th	60-40th	80-60th	60-40th	60-40th
Mean weight per fish	N/A	60-40th	60-40th	60-40th	60-40th	60-40th	80-60th	100-80th
Groundfish	N/A	60-40th	20-0th	20-0th	60-40th	80-60th	60-40th	100-80th
Other groundfish	N/A	20-0th	60-40th	80-60th	100-80th	100-80th	60-40th	20-0th
Elasmobranchs	N/A	80-60th	100-80th	100-80th	100-80th	100-80th	20-0th	20-0th
Pelagics	N/A	100-80th	80-60th	60-40th	60-40th	20-0th	60-40th	60-40th
Georges Bank species richness	100-80th	100-80th	60-40th	60-40th	60-40th	80-60th	60-40th	60-40th
Georges Bank species evenness	60-40th	60-40th	60-40th	60-40th	60-40th	80-60th	100-80th	100-80th
Human metrics								
Domestic groundfish landings	20-0th	20-0th	60-40th	60-40th	100-80th	60-40th	60-40th	100-80th
Domestic elasmobranch landings	100-80th	100-80th	100-80th	80-60th	80-60th	100-80th	100-80th	20-0th
Average otter trawl income	20-0th	20-0th	60-40th	60-40th	60-40th	100-80th	80-60th	100-80th
Number of otter trawl vessels	60-40th	80-60th	60-40th	80-60th	100-80th	40-20th	40-20th	20-0th

Color code of metric — Percentiles of empirical distribution: 100-80th (solid black), 80-60th (grey stipple), 60-40th (cross-hatch), 40-20th (vertical lines), 20-0th (white).

Mid-Atlantic Bight temperatures correspond to conditions of low groundfish biomass and high pelagic biomass. The relationship between the second canonical axes has an R^2 of 70.8% (Fig. 7*d*). This relationship can roughly be interpreted to mean that when there is high effort (number of vessels) that switch from groundfish to other species of groundfish and still maintain a profit, then the biomass of other groundfish and the size of all fish begin to decline, altering species evenness for the ecosystem. The fishing fleet is effectively targeting whatever species are abundant in the system to the point that, coupled with environmental change, the targeted species begin to decline. Said another way, these results are a multivariate expression of sequential depletion.

Discussion

Empirical indicators

The status of an ecosystem can be assessed. Assessing ecosystems is not novel for terrestrial, freshwater, or wetlands ecosystems (e.g., Suter 1993; Hall 2001; Schiller et al. 2001). Additionally, it is not novel to assess the status of single-species fish stocks (e.g., Hilborn and Walters 1992; Quinn and Deriso 1999). Yet only a few recent examples have recognized the feasibility of actually assessing major components of marine ecosystems (Boyd and Murray 2001; Eisenack and Kropp 2001; Pitcher and Preikshot 2001). From this assessment of the northwest Atlantic ecosystem, we have an improved picture of the magnitude and relationships within the system. We recognize that there are other components of this ecosystem not included in our analyses (for logistical reasons; e.g., primary or secondary production, whale biomass, etc.), and it would be important to include them in further analyses. Yet the assessment we provide is not trivial given the spatiotemporal scale of our study. Although many marine ecosystems have well-documented, generalized patterns (e.g., water currents, seasonal warming, trophic relationships, etc.), these generalizations can amalgamate and obfuscate real-time changes in an

Fig. 5. The first two principal components with loadings from the various metrics in the model. The first two axes explain approximately 50% of the variation.

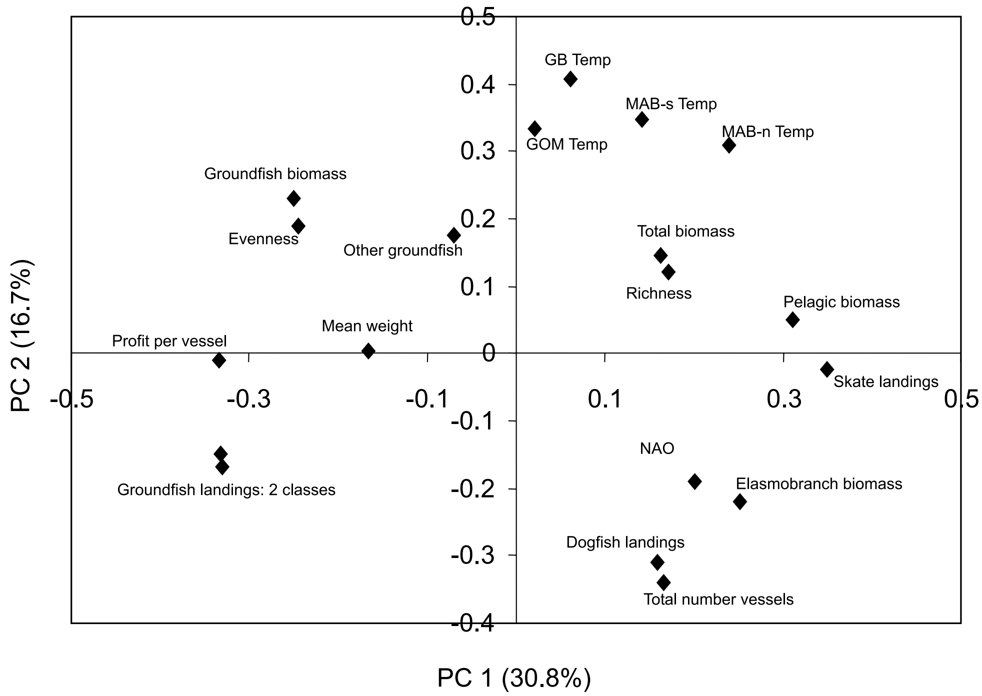
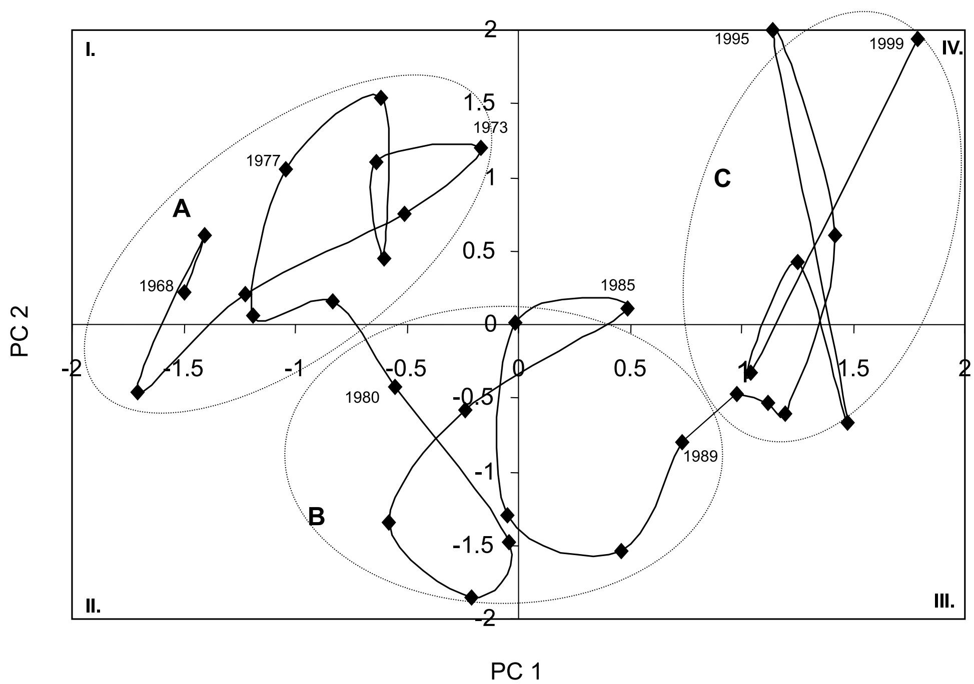


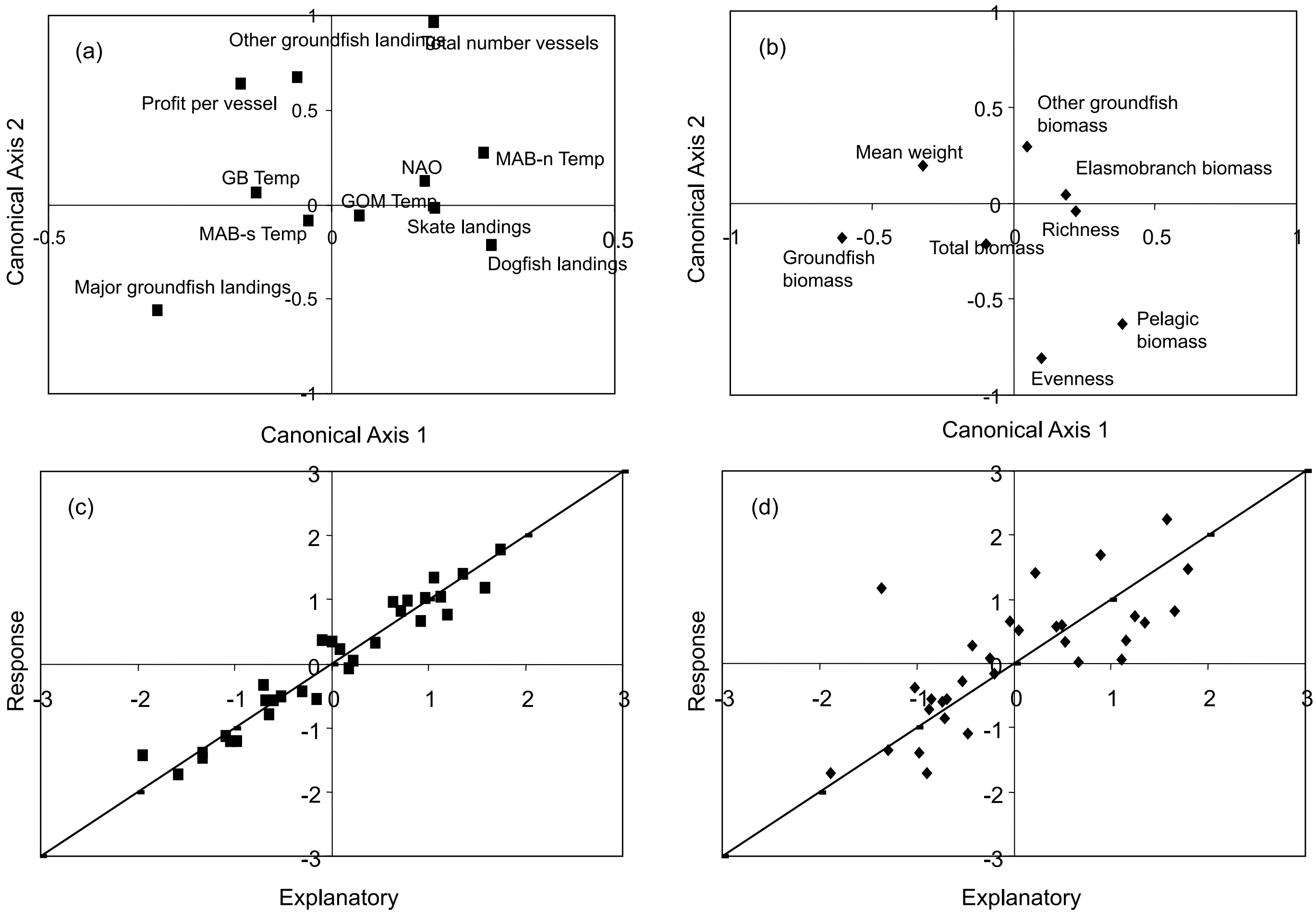
Fig. 6. Scores for each year on the first two principal components, indicating the systemic trajectory. Roman numerals represent quadrat number, and the ellipses represent categorical groupings of similar scores (A, B, and C).



ecosystem. We recommend regularly assessing the status of marine ecosystems much the same as single-species fish stocks are assessed, and we assert that it can be done.

Our results confirm prior studies that focused on specific processes in this ecosystem. For example, we knew that the fish community composition changed drastically (Fogarty and Murawski 1998), that temperature was strongly correlated with the distribution of certain species (Mountain and Murawski 1992), that consumption of key species, energy flows, and related trophic dynamics have altered (Overholtz et al. 2000; Link and Garrison 2002), that diversity changed (Brodziak and Link 2002), and that the size of fish has declined (Murawski and Idoine 1992). The peak observed for many metrics during the late 1970s to early 1980s corresponds to the passage of the first Magnuson–Stevens Fisheries Conservation and Management Act in the late 1970s,

Fig. 7. (*a*) The first two canonical axes for the explanatory metrics, with loadings for said metrics. (*b*) The first two canonical axes for the response metrics, with loadings for said metrics. (*c*) Canonical correlation for between the first axes; R^2 = 93.9%. (*d*) Canonical correlation for between the second axes; R^2 = 70.8%.



which resulted in the expansion of the domestic fleet and a subsequent increase in groundfish landings beyond sustainable levels. Yet this work is distinct from those that focus on a single process in that it integrates all of these considerations at once and attempts to quantitatively determine the importance of numerous processes simultaneously. From that perspective, we view this holistic approach as providing additional (and by all means complementary) information beyond traditional single-species fisheries approaches.

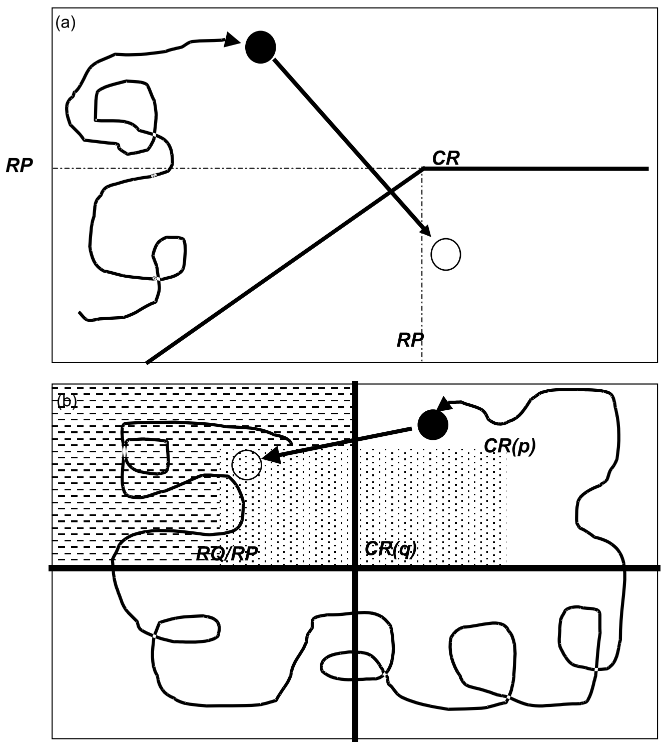
Interpretation of the multivariate relationships identified the relative importance of major processes in this ecosystem. Our results indicate that fishing activities, loosely measured here as landings, profit, or total number of vessels, were the primary factors altering the biotic component of this ecosystem. Yet changes in the environment (e.g., warmer temperatures, long-term climate forcing, etc.) or internal biological processes (i.e., how biomass is allocated among the remaining, noncaptured organisms) can influence the status of the ecosystem. More importantly, now that landings, income, and the number of vessels are declining and management measures have been enacted (e.g., area closures on Georges Bank, mesh size limits, etc.), the abiotic and internal biological processes may become more important factors determining the contemporary status of this ecosystem.

Statistical models

Ecosystem analogs to single-species reference points exist. Other researchers have reached similar conclusions (e.g., Constable 2001; Sainsbury and Sumaila 2001; Schiller et al. 2001). The coefficient weightings in our analyses are consistent with the conceptual model of how this ecosystem functions. One can map current or desired conditions to multivariate phase–space as a way of ascertaining the status of the system relative to some prescribed ecosystem goal. Depending on the value or location of the multivariate score relative to a multivariate ecosystem point of reference, or even reference quadrat, an appropriate action may be then become apparent. The PCA and CanCorr are statistical approaches that can provide reference points and combined may work as ad hoc control rules on an interim basis.

We provide one, admittedly simplistic, approach of how these multivariate analyses could be used in a management context. First, we recommend obtaining values for the multiple metrics for a particular year and (or) situation. Then inserting the values of those metrics into the linear equation combinations derived from the PCA and (or) CanCorr analyses would produce a score for that year. Depending on which reference quadrat (or fraction thereof) the score resides in, appropriate management action could then be taken.

Fig. 8. (*a*) An example of single-species reference points (RP), control rule (CR), and direction (arrow) needed to reach a prescribed goal. The meandering line represents a time series of data, and the circles represent a realized value (solid) and goal (open), respectively. (*b*) An example of an ecosystem-level reference point (RP; the smaller, stippled rectangle) or reference quadrat (RQ; dashed rectangle), control rule (CR), and direction (arrow) needed to reach a prescribed goal. The control rules may be based on either the reference point (CR(p)) or reference quadrat (CR(q)). The meandering line represents a time series of data, and the circles represent a realized value (solid) and goal (open), respectively.



The action (i.e., to produce movement from one quadrat to a more desirable quadrat, the vector of which we term the desired reference direction) could be primarily guided by using the canonical relationships established, focusing on those factors that we can control (i.e., human). This assumes the canonical relationships represent some form of dependent relationship among the metrics. For example, if the score were in the upper left quadrat (I) of Fig. 6 and we desired a groundfish-dominated community, the advice would be to not exceed landings of all groundfish beyond a total amount. That is, we would advise keeping the groundfish biomass consistent while maintaining consistent (but not escalating) effort. As another example, if the score were in the lower right quadrat (III) and one desired to remain in that quadrat, then the advice would be to preserve elasmobranch biomass and continue to fish other species groups, recognizing that environmental change may move the score into quadrats II or IV. There are numerous scenarios, and these are just examples of how one might use the reference quadrat and reference direction concepts as a multivariate analogue to single-species reference points and control rules.

The challenges of this approach are that even though it assumes dependent relationships, often the mechanism and specific processes for obtaining particular conditions are complicated or indeterminate. Additionally, even if we do understand specific mechanisms of causality, we may not be able to readily reproduce or manipulate them towards a desired end. For instance, we may have experienced a change of conditions such that the ecosystem is in an alternate steady state. It is possible that despite a clear reference direction, the multivariate trajectory will meander along an infinite combination of possible paths to reach the desired condition. Or it is possible that we may simply not be able to extend our multivariate trajectory in a direction back to the conditions observed in the 1960s to early 1970s without a change in temperature or the NAO. This observation has rather large implications for fisheries management (sensu Beamish 1993).

Another limitation of this approach is that although we may be able to establish multivariate ecosystem reference points or quadrats and determine the general multivariate direction to obtain a desired ecosystem goal, we lack the tools to prescribe the magnitude of how much we would need to change the system. Said another way, we know where the arrow (i.e., reference direction) should point (in multivariate phase–space), we just do not know how big it should be.

We show an example of common single-species reference points and an associated control rule (Fig. 8*a*). As an analogue, the same is shown at the ecosystem level (Fig. 8*b*). Both have points of reference in phase–space, implied limits via the control rules, and a suggested direction (arrows between the circles) to reach the prescribed goal. In the single-species case, if the value of the observed score (solid circle) is outside of the acceptable points of reference (e.g., too high a fishing mortality or effort or catch; too low a biomass or spawning stock biomass or abundance, etc.), then a control rule is invoked based on an agreed-upon set of criteria (e.g., overfishing is deemed to be occurring, the stock is deemed to be overfished, etc.). Appropriate action (e.g., reduce effort) to mitigate the observed condition into a more desirable condition (open circle) is taken, or at least recommended. In the multivariate ecosystem case, the reference points are more arbitrary and could be established as a certain fraction of the PC axes (e.g., less than 0.5 units on PC1, only positive scores on PC2; the smaller stippled rectangle), or could be designated as an entire quadrat (reference quadrat; the dashed rectangle). These could also correspond to something similar to the three different "stanzas" (i.e., ellipses) observed in Fig. 6. As in the single-species example, if the value of the observed score (solid circle) is outside of the acceptable range of the points of reference (or reference quadrat), then a control rule could be invoked to move the score into a more desirable condition (open circle). This particular example demonstrates the desired movement of the observed score in the upper-right quadrat to within the range of conditions bounded by the reference (upper-left) quadrat. The challenges are to develop less arbitrary ecosystem reference points and to develop the most appropriate multivariate action(s) for the control rules associated with these ecosystem reference points.

Recommendations

Although they exist, multivariate ecosystem points of reference do not necessarily suggest appropriate ecosystem control rules. Are ecosystem control rules feasible and practical?

We need to develop mechanistic or analytical models (and associated calculi) for key ecosystem processes. As described earlier, an example of a common single-species reference point and control rule is shown in Fig. 8*a*, whereas Fig. 8*b* shows the same at the ecosystem level. Both have a point of reference in phase–space, implied limits via the control rules, and directions to reach the prescribed goal, but we need a less arbitrary set of control rules for the ecosystem case. The single-species control rule is based on a deterministic understanding of a key underlying process (e.g., stock–recruitment relationships), whereas the ecosystem control rule in this example is entirely empirical. Underlying theoretical mechanisms are available for many of the individual processes in marine ecosystems. For example, ocean circulation models or predation theory or single-species models are reasonably well developed. Linking the various submodels together across disciplines such that we can have a standard, overriding ecosystem model that is less dependent on strict empiricism merits further examination. Using the results of the empirical and statistical approaches may help to conceive and parameterize analytical models (sensu Rigler 1982). However, we need to admit that it may be that we simply will not be able to fully develop an analogous model at the ecosystem level.

Single-species stock assessment (Hilborn and Walters 1992; Quinn and Deriso 1999), environmental impact assessment (Canter 2001), and ecological risk assessment (Suter 1993) have the requisite machinery and tools to provide appropriate management decision criteria. Lessons from these disciplines should be applied for the assessment and management of large marine ecosystems. The distinction between fisheries stock assessment and the environmental assessments is an optimization vs. risk averse set of approaches. Perhaps fisheries science would be wise to give extra consideration to the latter approach. A key challenge for ecosystem based fisheries management is determining how to simultaneously optimize multiple goals when optimization may be a risk-prone perspective.

Additionally, we need to further explore empirical and statistical methods. We propose contrasting predicted quadrat location derived from these multivariate methods with observed values to validate predictions from this approach. This should and can be done for many ecosystems. It should also be done for multiple scenarios within an ecosystem. Pace (2001) notes that even an empirically predictive approach is essential for assessing major environmental concerns. The role of empiricism has been criticized, but it has also demonstrated its value over the long term (Rigler 1982; Peters 1986). Other existing (e.g., redundancy analysis, multidimensional scaling, canonical correspondence analysis, etc.) and yet-to-be-developed multivariate tools should be explored for continuing this approach and to provide even further insight into the interpretation of ecosystem status. We conclude that (*i*) a suite of metrics is required to present the composite picture of the status of an ecosystem, and focusing on just a limited few may be misleading, (*ii*) assessing marine ecosystems is feasible now, (*iii*) multivariate points of reference at the ecosystem level exist, and (*iv*) we may never develop control rules that detail the magnitude of required changes, but the concept of reference directions may be useful for ecosystem-based fisheries management. Empirical and statistical approaches may only be able to give us reference direction, but that may be sufficient for management at the ecosystem level.

Finally, developing the management criteria, theoretical basis, and philosophical acceptance thereof in fisheries sciences remains a key challenge. If fisheries managers and other stakeholders can be more informed of overall ecosystem status and fisheries assessments from a more holistic perspective, then they would be better equipped to choose actions that are more sustainable for the long term (Pitcher 2001; Sainsbury and Sumaila 2001). We hope that the information provided in this work serves as a useful beginning for the difficult task of operationalizing ecosystem-based fisheries management.

Acknowledgements

We thank all the members of the in-house Ecosystem Status Working Group (ESWG) of NEFSC who contributed in various fashions to the development of this and related products. In particular, we acknowledge D. Palka, D. Hart, S. MacLean, J. Boreman, C. Legault, R. Reid, M. Fabrizio, T. Noji, G. Reppucci, D. Dow, K. Lang, J. Olson, J. Kane, and B. Rountree for their encouragement, stimulating comments, and general participation in the working group. This is the third of what we hope are many products from the ESWG. We thank A. Bundy, P. Fanning, and an anonymous reviewer for their kind and constructive comments on earlier versions of this manuscript.

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