

Characterizing variation in Northwest Atlantic fish-stock abundance

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Catch-per-tow indices obtained by research vessels for the years 1963–2009 from NAFO statistical areas 4W, 4X, 5Y, and 5Z were studied to determine how fish “apparent abundance” in the decade 2000–2009 differed from the long-term time-series. Cluster analysis of normalized catch-per-tow data indicated that the abundance and species composition of stocks in each statistical area changed dramatically over the 50-year period. There were decreases in thorny skate, ocean pout, cusk, witch flounder, and monkfish and increases in herring, haddock, northern shrimp, and spiny dogfish. Cluster analysis suggested that these decreases and increases were not gradual, but abrupt, and that these abrupt decreases and increases were concentrated in the decade of the 1980s. Observations of abrupt change were supported by regression-tree analysis of individual stocks. Examination of the interrelationship among abundance indices from different stocks by Bonferroni-adjusted correlation coefficients showed that the abundance trajectories of most stocks were uncorrelated. It appears that the set of population transitions during the decade of the 1980s was a dominant event in the statistical time-series.

Keywords: fish-stock abundance, regime shift, variation.

Introduction

A coherent synthesis of long-term fish-stock variability on the Northwest Atlantic continental shelf is not yet available. Some studies focus on one or a few species of fish, others on relatively small areas. Here, we found major increases and decreases in fish abundance that appeared to be concentrated in the decade of the 1980s. Various authors give differing views on the causes of variation in fish-stock abundance in the Northwest Atlantic. For example, many focus on cod (*Gadus morhua*) and attribute its decline to fishing (e.g. Myers *et al.*, 1996). Halliday and Pinhorn (2009) focus on the Canadian NAFO areas and attribute the decline in stocks in the early 1990s not to fishing, but to the North Atlantic Oscillation. Rothschild (2007) examined the entire NAFO area and suggested that the coherent decline in cod, which began in 1985 and culminated in the early 1990s, resulted from a major environmental signal rather than fishing. Frank *et al.* (2005) envisioned the removal of cod by fishing sets in motion a “trophic cascade” of predator–prey interactions that modifies ecosystem structure.

Here, we contribute to a synthesis of long-term variability of fish stocks by focusing on the ca. 50-year time-series of catch per tow or catch per unit of effort (cpue) for areas 4W, 4X, 5Y, and 5Z

(Figure 1). The analysis is intended to characterize the variation in normalized cpue data from US and Canadian research vessels. The main objectives are to (i) determine whether the indices of abundance indicate that stock abundance is changing over the period of concern, (ii) investigate how abundance changes are correlated with each other, and (iii) report on how the long-term dynamics relate to the decade 2000–2009. To accomplish these objectives, the study examines normalized cpue data by characterizing the variability of each individual stock using cluster analysis and regression trees, and the covariability among stocks using correlation and principal component analyses. This characterization will lead hopefully to further analysis of the relationships between stock dynamics, fishing, and the ocean environment, important topics that are beyond the scope of this paper.

Material and methods

Data were obtained from the Canadian Department of Fisheries and Oceans (DFO) maritime’s research-vessel trawl surveys (1970–2009; Clark and Branton, 2007) and the US National Marine Fisheries Service Northeast Fisheries Science Center (NMFS) research bottom-trawl surveys (1963–2008). The DFO data were obtained from OBIS (Ocean Biogeographic

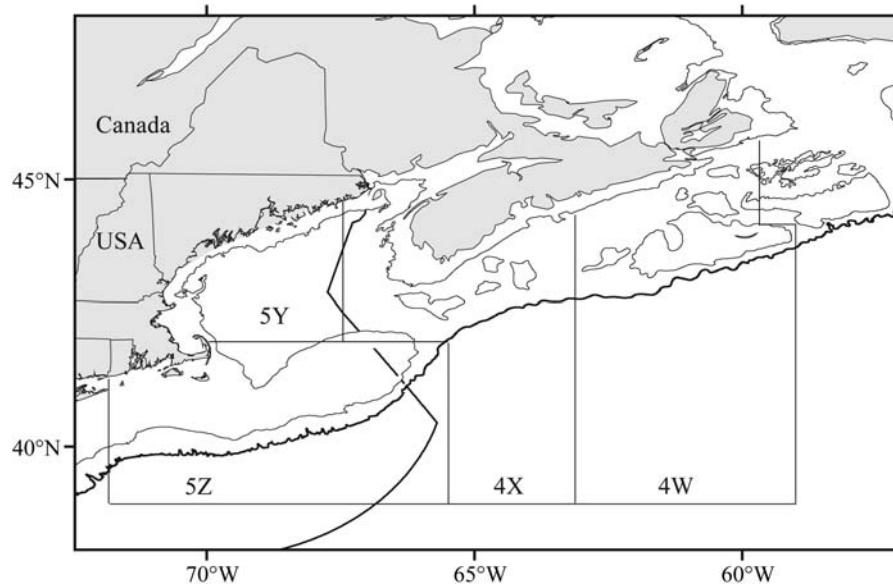


Figure 1. NAFO areas 4W, 4X, 5Y, and 5Z included in this study.

Information System) and the NMFS data from NMFS, along with the calibrating factors used to adjust the data for interannual differences in catchability (Azarovitz, 1981; Despres *et al.*, 1988). To reduce extraneous variance, analysis was limited to the DFO summer series (Ricard *et al.*, 2010) and the NMFS autumn survey. Data were readily available from 4W, 4X, 5Y, and 5Z (data for other areas required further processing and analysis and were beyond the scope of this paper). Areas 4W and 4X yielded 46 104 tows, and areas 5Y and 5Z 120 847 tows.

The basic data are reported in kilogrammes of fish of each species taken per tow. In the datasets, if a species was not caught in a tow, then it was not reported. (This means that the kg-per-tow data for species k are the average abundance per tow, given that a fish of species k is caught in the particular tow.) This problem of species-specific zero-catch tows has been addressed in various ways. In some studies, zero-catch tows are ignored. Other studies use the “delta distribution” (e.g. Smith, 1988). Here, to obtain a catch-per-tow index averaged over all tows, the delta distribution was approximated by first estimating the maximum number of tows for each area and year, then dividing the total catch taken by survey vessels by the maximum number of tows made each year, in each area, to give the annual average relative abundance for each stock.

Therefore, for each area, the abundance index (kg tow^{-1}) of species k in year t is estimated from

$$\text{cpue}_k(t) = \frac{1}{\max_{s \in S(n_s(t))}} \sum_{i=1}^{n_k(t)} x_{k,i}(t),$$

where x is the observed weight (kg tow^{-1}) of tow i , n the number of tows in year t , and S is the most frequently observed species analysed.

For example, in area 5Z in 2008, dogfish was the most frequently observed, in 149 tows. Therefore, to obtain an average cpue for all tows, the observed weight of each species taken in 2008 in area 5Z was divided by 149.

There are some 190 species in areas 4W and 4X, and ~ 300 species in 5Y and 5Z. It was impractical to consider all ca. 500 species, so the analysis concentrated on the 35 most frequently

observed in 4W and 4X and the 35 most frequently observed in 5Y and 5Z. The 35 most frequently observed species in 4W and 4X or 5Y and 5Z sum to a total of 46 species, 24 of which are found in all four areas (Table 1).

For the purposes of this paper, we refer to any fish such as cod as a species and any species in a specific statistical area as a stock. In other words, in our nomenclature, there are 4W, 4X, 5Y, and 5Z stocks of the species cod. This nomenclature is developed for the convenience of this analysis and is not intended to replace the definitions used for stock assessment.

As there are 140 stocks, each year is represented by up to 140 catch-per-tow statistics. Each catch-per-tow statistic is based on averaging a large number of observations (~ 50 tows for 4W and 4X, 80 for 5Y, and 100 for 5Z). Because of the large number of catch-per-tow statistics and the fact that each is based on an arithmetic mean, the averages can be considered to have an approximately normal distribution.

The catches-per-tow, or cpue, statistics are assumed to reflect changes in relative abundance within each stock. However, it is difficult to make comparisons between or among stocks because, in general, catchability coefficients are not available for each stock. To deal with this problem, we have normalized by subtracting the mean and dividing by the standard deviation (s.d.) of the cpue statistics so that comparisons among stocks are possible by comparing the normalized data on the same scale. The unknown catchability for each stock is assumed to be constant for the particular stock under consideration.

The study of variability was initiated by subjecting the normalized cpue data to standard methods used in k -means cluster; regression tree, correlation, and principal components analysis.

Results

The normalized indices plotted in Figure 2, which reflect the composite variability for all 140 stocks, have a mean of zero and an s.d. of about ± 3 units. The average normalized cpue of the ensemble of stocks is constant and close to zero over the 50-year study period.

Table 1. The species analysed, and the abbreviations being used in Figures 3 and 7 and in Table 3, where the symbol “_..” indicates the areas _4W, _4X, _5Y, or _5Z.

Species	Scientific name	Area	Abbreviation
Acadian redfish	<i>Sebastes fasciatus</i>	5YZ	REDFISH_..
Alewife	<i>Alosa pseudoharengus</i>	4XY, 5YZ	ALEWIFE_..
Alligatorfish	<i>Aspidophoroides monopterygius</i>	4XY	ALLGFISH_..
American lobster	<i>Homarus americanus</i>	5YZ	LOBSTER_..
American plaice	<i>Hippoglossoides platessoides</i>	4XY, 5YZ	PLAICE_..
Atlantic cod	<i>Gadus morhua</i>	4XY, 5YZ	COD_..
Atlantic halibut	<i>Hippoglossus hippoglossus</i>	4XY	AHALIBUT_..
Atlantic herring	<i>Clupea harengus</i>	4XY, 5YZ	HERRING_..
Atlantic mackerel	<i>Scomber scombrus</i>	4XY, 5YZ	MACKEREL_..
Atlantic rock crab	<i>Cancer irroratus</i>	5YZ	ROCKCRAB_..
Atlantic wolffish	<i>Anarhichas lupus</i>	4XY	WOLFFISH_..
Butterfish	<i>Peprilus triacanthus</i>	5YZ	BTFISH_..
Capelin	<i>Mallotus villosus</i>	4XY	CAPELIN_..
Cusk (tusk)	<i>Brosme brosme</i>	4XY	CUSK_..
Fourspot flounder	<i>Paralichthys oblongus</i>	5YZ	FSPOT_FL_..
Greater argentine (herring smelt)	<i>Argentina silus</i>	4XY	HSMELT_..
Greenland halibut (turbot)	<i>Reinhardtius hippoglossoides</i>	4XY	GHALIBUT_..
Gulf stream flounder	<i>Citharichthys arctifrons</i>	5YZ	GULSTR_FL_..
Haddock	<i>Melanogrammus aeglefinus</i>	4XY, 5YZ	HADDOCK_..
Jonah crab	<i>Cancer borealis</i>	5YZ	JNCRAB_..
Little skate	<i>Leucoraja erinacea</i>	4XY, 5YZ	LTSKATE_..
Longfin hake	<i>Phycis chisteri</i>	4XY	LFHAKE_..
Longfin squid	<i>Loligo pealeii</i>	5YZ	LFSQUID_..
Longhorn sculpin	<i>Myoxocephalus octodecemspinosus</i>	4XY, 5YZ	LSCULPIN_..
Monkfish (goosefish)	<i>Lophius americanus</i>	4XY, 5YZ	MONKFISH_..
Moustache sculpin	<i>Triglops murrayi</i>	4XY	SCULPIN_..
Northern sand lance	<i>Ammodytes dubius</i>	4XY	NSLANCE_..
Northern shortfin squid	<i>Illex illecebrosus</i>	4XY, 5YZ	NSSQUID_..
Northern shrimp	<i>Pandalus borealis</i>	5YZ	NSHRIMP_..
Ocean pout	<i>Zoarces americanus</i>	4XY, 5YZ	OCNPOUT_..
Pollock (saithe)	<i>Pollachius virens</i>	4XY, 5YZ	POLLOCK_..
Red hake (squirrel hake)	<i>Urophycis chuss</i>	4XY, 5YZ	REDHAKE_..
Rockfish and rosefish	<i>Sebastes</i>	4XY	ROCKFISH_..
Sea raven	<i>Hemitripterus americanus</i>	4XY, 5YZ	SEARAVEN_..
Sea scallop	<i>Placopecten magellanicus</i>	5YZ	SCALLOP_..
Shrimp uncl	Crustacea, shrimp	5YZ	SHRUNCL_..
Silver hake	<i>Merluccius bilinearis</i>	4XY, 5YZ	SILVEHAKE_..
Smooth skate	<i>Malacoraja senta</i>	4XY, 5YZ	SM_SKATE_..
Spiny dogfish	<i>Squalus acanthias</i>	4XY, 5YZ	DOGFISH_..
Thorny skate	<i>Amblyraja radiata</i>	4XY, 5YZ	TH_SKATE_..
White hake	<i>Urophycis tenuis</i>	4XY, 5YZ	WH_HAKE_..
Windowpane flounder	<i>Scophthalmus aquosus</i>	4XY, 5YZ	WINDOW_FL_..
Winter flounder	<i>Pseudopleuronectes americanus</i>	4XY, 5YZ	WINTER_FL_..
Winter skate	<i>Leucoraja ocellata</i>	4XY, 5YZ	WTSKATE_..
Witch flounder	<i>Glyptocephalus cynoglossus</i>	4XY, 5YZ	WITCH_FL_..
Yellowtail flounder	<i>Limanda ferruginea</i>	4XY, 5YZ	YELLOWTL_..

Cluster membership for each statistical area (4W, 4X, 5Y, and 5Z) is shown in Figure 3. The analysis was constructed to identify two clusters for each area. Each panel in Figure 3 gives the mean normalized value for each cluster for each of the two clusters for the 15 species that are most highly differentiated by the cluster analysis (available space precludes plotting all 35 stocks for each area). Each cluster is characterized by a combination of relatively high or relatively low abundance for each stock. For example, in area 4W, cluster 1 contains relatively abundant thorny skate, ocean pout, wolffish, plaice, witch flounder, cusk, smooth skate, and monkfish, and relatively fewer herring, haddock, etc. Also clear in Figure 3 is that cluster 2 contains relatively more-abundant herring and haddock and relatively less-abundant skate, ocean pout, wolffish, etc. In area 4X, cluster 1 contains relatively abundant thorny

skate and cusk and relatively less-abundant herring, winter flounder, little skate, etc. In area 5Y, cluster 1 is characterized by relatively abundant witch flounder, thorny skate, pollock, and cod and relatively less-abundant northern shrimp, etc. In area 5Z, cluster 1 is characterized by abundant witch flounder, monkfish, cod, yellowtail flounder, and white hake, and relatively less-abundant spiny dogfish and rock crab.

Note that the degree of differentiation between the clusters is ranked from left to right (based on the *F*-statistic) so that for area 4W, for example, the greatest discrimination between clusters 1 and 2 is given by thorny skate, the second greatest by ocean pout, the third by wolffish, etc.

The ranking of intensity of discrimination from left to right depicts the stocks on the left changing more than those on the

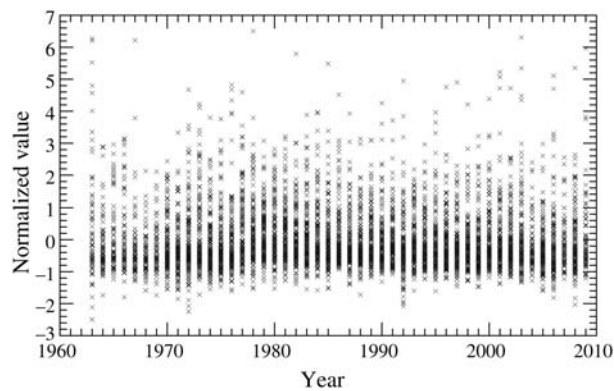


Figure 2. The composite variability of normalized cpue data (small crosses). The time-series of stocks in 4W and 4X are from 1970 to 2009, and those of stocks in 5Y and 5Z are from 1963 to 2008. There are 96 stocks in all (24 common species in the four areas).

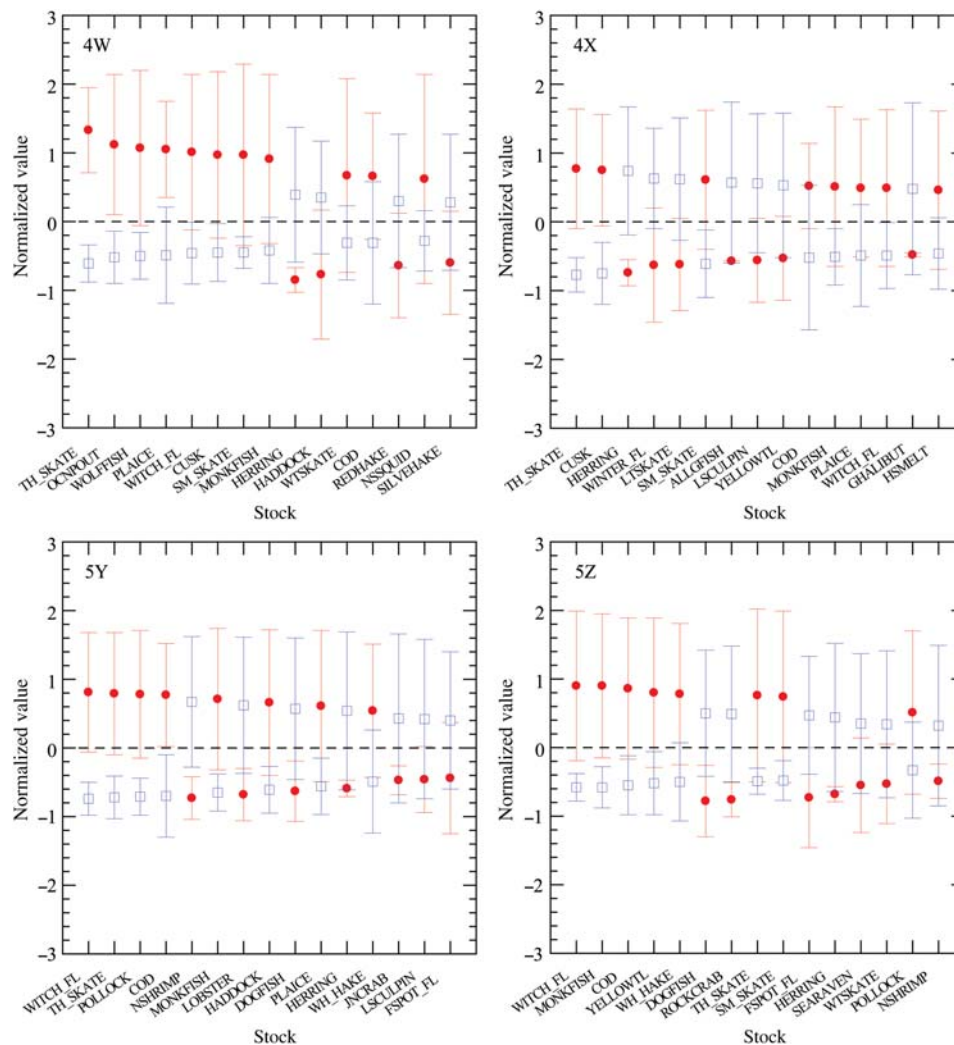


Figure 3. Cluster profile plots of the 15 most differentiated or statistically volatile stocks for each area. The abundance indices time-series are partitioned into two clusters: cluster 1 refers to the first part of the time-series (red), and cluster 2 (blue) to the second part of the time-series. The horizontal dashed lines at zero indicate the grand mean across all data. A stock mean within each cluster is marked by a dot (for cluster 1) or an open square (for cluster 2). The vertical lines indicate 1 s.d. above or below the mean (see Table 1 for a full list of species names).

right (Figure 3), indicating that the change for each area can be thought of as arising in stocks that are highly variable (stocks 1–15) and in stocks that are relatively stable (stocks 16–35, which are not plotted).

Cluster membership was anticipated to be random with respect to time. However, it turned out that cluster membership was temporally coherent. The time of shift from cluster 1 to cluster 2 is 1981/1982 in 4W, 1988/1989 in 4X, 1984/1985 in 5Y, and 1980/1981 in 5Z. In other words, for the ensemble of species, the cluster analysis showed that the 1980s represented a time of transition from an assemblage of species characteristic of cluster 1 to an assemblage characteristic of cluster 2.

The coherent shift from cluster 1 to cluster 2 suggested a value in examining whether similar breakpoints existed within each individual species. Regression-tree analysis allowed the identification of a single breakpoint for each stock (see Figure 4 for examples). The summary of the regression-tree analysis is shown for each area in Table 2. The number of stocks showing increases (positive)

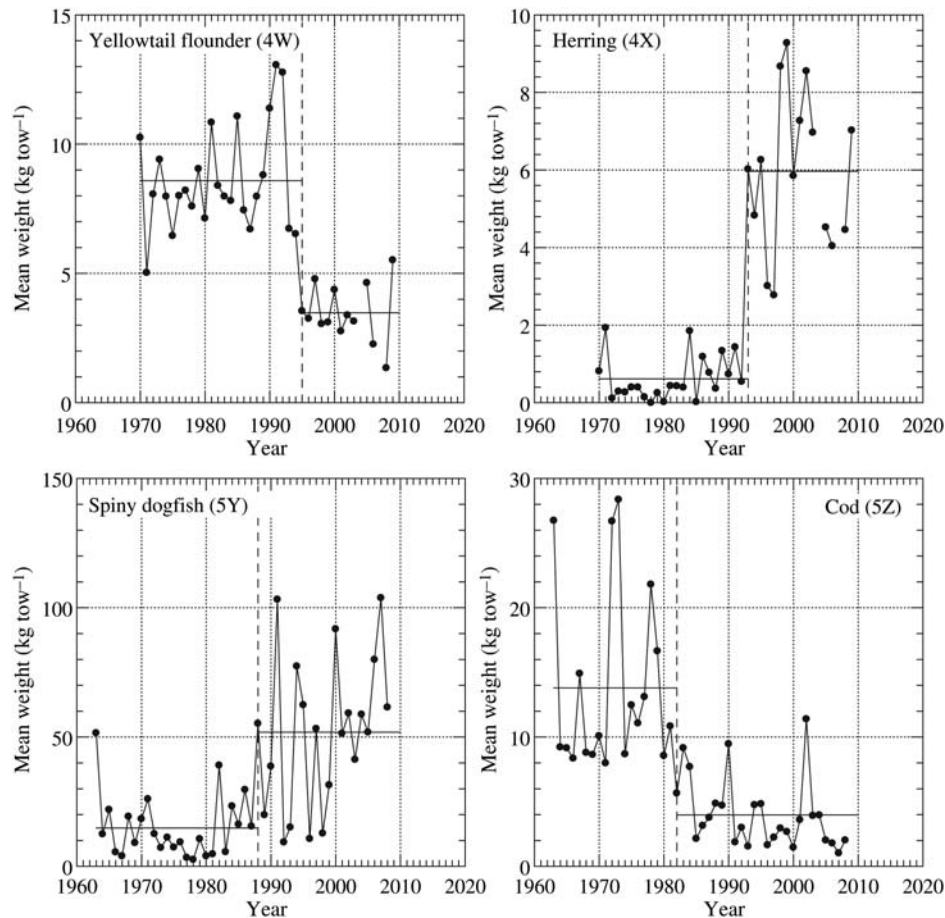


Figure 4. Examples of regression-tree analysis for the decreasing 4W yellowtail flounder and 5Z cod stocks, and the increasing 4X herring and 5Y spiny dogfish stocks. The break-year derived by the regression-tree models is indicated by the vertical dashed line and the mean cpue of before-and-after data by a horizontal line. Note that the kg-per-tow values are not normalized. This does not change the breakpoint and facilitates the calculation of the before-and-after ratio, which for yellowtail flounder is 2.5, for herring is 9.7, for spiny dogfish is 3.5, and for the cod stock is 3.5.

Table 2. Statistics derived from the regression-tree model, giving the average break-year, the proportional reduction in error, and the ratio of pre- to post-break-year cpue.

Statistics of significantly split stocks									
Area	Number of stocks	Number of stocks		Break-year		Proportional reduction of error		Ratio	
		Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
4W	35	12	19	1989	1984	0.37	0.44	6.7	4.2
4X	35	13	12	1991	1991	0.41	0.36	9.7	3.3
5Y	35	19	10	1986	1985	0.29	0.47	8.0	3.3
5Z	35	15	17	1986	1978	0.28	0.36	6.2	3.6

For a few of the increasing stocks (two in 4W, three in 4X, and one in 5Y), the cluster mean cpue values before the break-year are zero, resulting in an invalid ratio, so these ratios are not counted in calculating the average ratio.

and decreases (negative) in 4X and 5Z was about equal, whereas 4W had more decreases than increases, and 5Y more increases than decreases. The average break-year for increases was in the late 1980s or the early 1990s, and the average break-year for decreases also in the late 1980s and the early 1990s, except for area 5Z, which had its average break-year in 1978. The proportional reduction in error resulting from the regression-tree

partitioning for increasing stocks amounted to $\sim 30\%$, and that for the decreasing stocks to $\sim 40\%$.

Examining the temporal distribution of break-years derived from regression-tree analysis, it appears that the decade of the 1980s was the most volatile in the sense that most increases or decreases were during the 1980s. This is consistent with the *k*-means analysis from which the conclusion, as reported above,

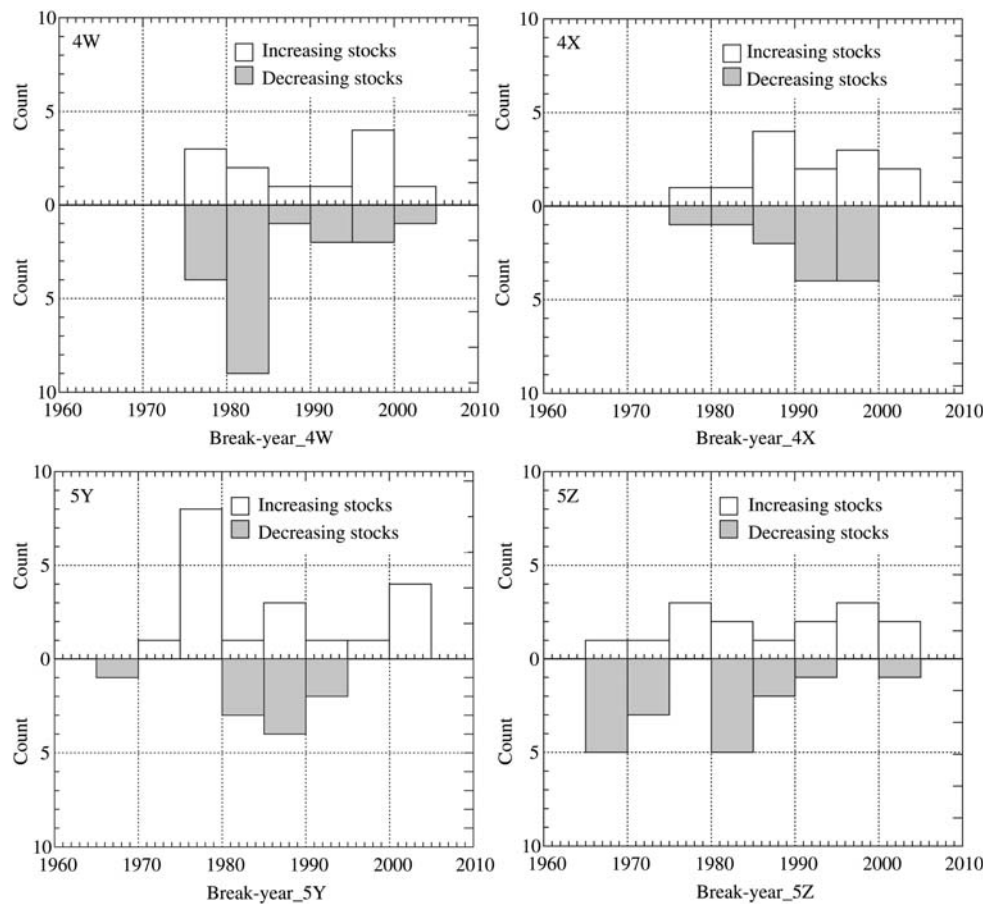


Figure 5. Histogram of the break-year (5-year bin) estimated by the regression-tree model.

was that the greatest changes in stock abundance were during the 1980s (Figure 5). Excluding pre-1975 data, the number of decreasing stocks for each 5-year bin was 5 for 1975–1980, 19 for 1980–1985, 9 for 1985–1990, and 6 for 1995–2000. The number of increasing stocks for each 5-year bin was 5 for 1975–1980, 15 for 1980–1985, 9 for 1985–1990, and 8 for 1995–2000.

The increase in the index of abundance at the break-year resulting from regression-tree partition amounted to an increase by a factor of 7 or 8, whereas the decreases amounted to a factor of 3 or 4. The temporal distribution of increases and decreases is shown in Figure 6. (Note that the factors of increases or decreases are calculated using the raw or non-normalized statistics.)

Bonferroni-adjusted correlations among the 9730 possible pairs of species yielded just 141 statistically significant correlations, 131 positively and 10 negatively correlated. Therefore, ~10% of the stocks are correlated, and of these, only a negligible percentage is correlated negatively. Specific pairs of correlated stocks are listed in Table 3.

The correlation matrix was decomposed onto its principal components. The first two principal components accounted for just 35% of the total variation but where the principal component analysis was based on each statistical area, the percentage variability increased to ~45%. For the composite of the four areas, some species increased, some decreased, some remained stable, and some had a hump-like or oscillatory distribution (Figure 7). Declining stocks included cod, monkfish, plaice, smooth skate, thorny skate, and witch flounder, increasing stocks included

dogfish and herring, stable stocks included longhorn sculpin, mackerel, and northern shortfin squid, and oscillating stocks included pollock and white hake.

Discussion

The analysis revealed a major change in stock composition in the 1980s. Examination of the cluster assignments was consistent with the notion that the assemblage of species in each area changed over the 50-year period from one group of species to another. Basically, cod, monkfish, plaice, smooth skate, thorny skate, and witch flounder were “replaced” by dogfish and herring. Note that the populations of harp and grey seals began to increase in the 1970s (see 2011–2015 Integrated Fisheries Management Plan for Atlantic Seals; DFO Canada), showing that some predators are replacing others, complicating the idea that the removal of predators by fishing (e.g. on cod) results in lower trophic-level fauna. The analysis reveals that the transitory dynamics involved many, rather than a few, species.

It is reasonable to think that the trends and correlations in research-vessel-survey cpue lend insight into ecosystem structure, although the temporal-spatial abundance of the larger fish and invertebrates typically sampled by research-vessel surveys represent a rather narrow view of the ecosystem.

Inferring dynamic changes, trends, and correlations in stock biomass depends on the assumption that research-vessel catchability is constant over the entire time-series. The fact that this assumption may not always be valid under circumstances where

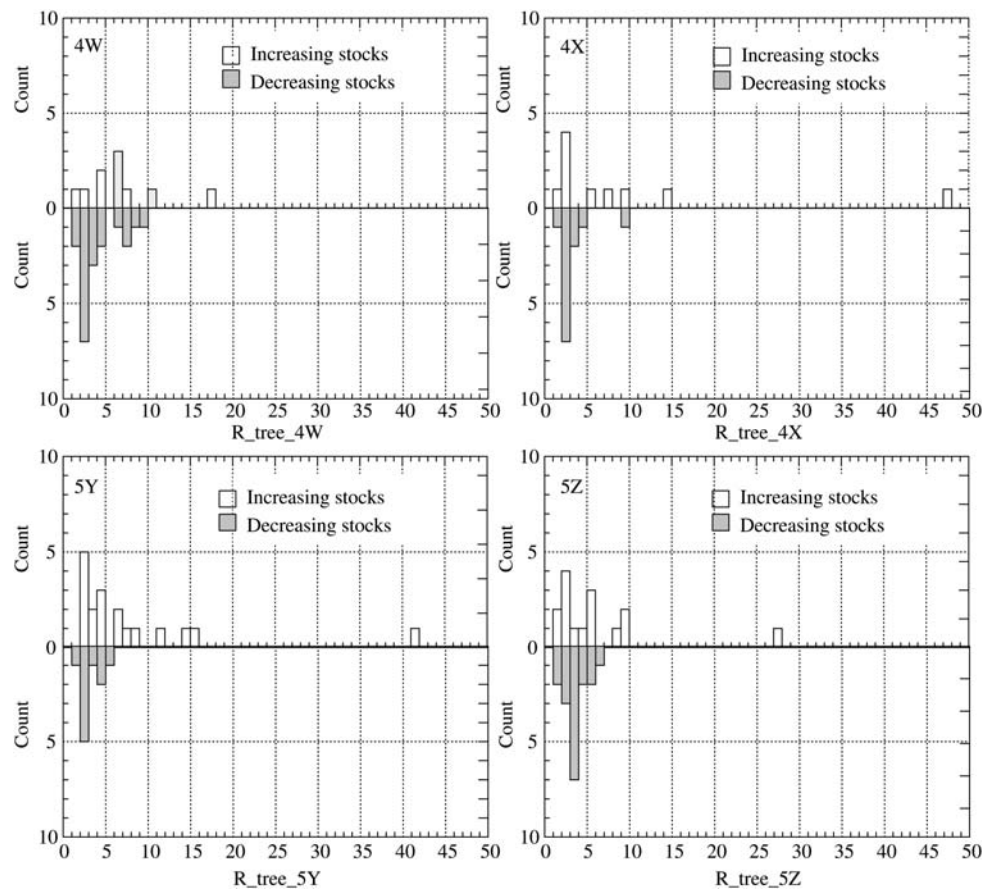


Figure 6. Histogram of the ratio of biomass indices, defined as the pre-break-year mean divided by the post-break-year mean for decreasing stocks and the post-break-year mean divided by the pre-break-year mean for increasing stocks. For a few of the increasing stocks (2 in 4W, 3 in 4X, 1 in 5Y), the cluster mean cpue values before the break-year are zero, resulting in an invalid ratio that is not shown.

fish such as herring change their position in the water column is discussed by McQuinn (2009).

Inferences based on the cpue statistic are further complicated by the research-vessel catchability for each species or stock being generally different. As the catchability coefficients are in general not known, it is difficult to compare the absolute abundance among species, although relative abundance can be compared by normalizing the time-series for each species and stock in s.d. units (see, for example, Rothschild, 2007).

Beyond the observation that the change from one species assemblage to another was abrupt rather than gradual, it also appeared for each statistical area that the transition from one assemblage to another in the 1980s was dominated by a group of statistically volatile species, for which the cluster differentiation was relatively large. This outcome is consonant with the literature. For example, not only have changes in abundance been noted in the decade of the 1980s, rapid changes in growth, condition factor, and mortality rates have also been noted (see, for example, Choi *et al.*, 2004; Rothschild, 2007; Halliday and Pinhorn, 2009).

The most volatile species are not necessarily the species of greatest commercial importance, so their dynamics are not as fully appreciated. For example, thorny skate and ocean pout were the most volatile in 4W, thorny skate and cusk the most volatile in 4X, witch flounder and thorny skate in 5Y, and witch and monkfish in 5Z. Clearly, an analysis of the interrelation of the

ocean environment and fish stocks might focus on thorny skate and witch flounder, stocks that were the most volatile, rather than on stocks that are of large biomass and the focus of major fishing operations. It might be that these highly variable species are better indicators of ecosystem functioning than heavily fished commercial species.

Focusing on the abrupt changes, it has not been generally mentioned that a major component of stock decreases or increases in population abundance over a 50-year period can occur in a very short time (a few years). A decline by a factor of 3 or 4 represents a loss in annual instantaneous units of ~ 1.25 , a very large decline. Increases by a factor of 6–10 are probably indicative of large year classes or recruitment events. One interpretation is that there was a major negative shock to the extant populations in the decade of the 1980s, a shock that caused an instantaneous decline in these extant populations corresponding to an annual instantaneous rate of 1.25. At the same time, another group of species was perhaps responding through large recruitment to replace the original group.

It is of course important to examine how stocks covary. Covariation is important from the perspective of hypotheses regarding top-down and bottom-up control. We found that after correction for excessive statistically significant correlations, the stocks mostly varied independently of each other. Of the relatively few stocks that were correlated, most stocks were correlated

Table 3. Correlation among the studied stocks at the 5% level with respect to Bonferroni-adjusted correlation probability.

Stocks	Correlated stocks
TH_SKATE_4W (14+, 1-)	TH_SKATE_4X+, TH_SKATE_5Z+, WITCH_FL_4W+, MONKFISH_5Y+, MONKFISH_5Z+, COD_5Z+, SM_SKATE_4W+, SM_SKATE_4X+, PLAICE_4W+, POLLOCK_5Y+, OCNPOUT_4W+, CUSK_4W+, CUSK_4X+, WOLFFISH_4W+, WINTER_FL_4X-
TH_SKATE_4X (11+)	TH_SKATE_5Z+, WITCH_FL_4W+, MONKFISH_4W+, MONKFISH_4X+, MONKFISH_5Z+, COD_5Z+, SM_SKATE_4X+, OCNPOUT_4W+, CUSK_4W+, CUSK_4X+, WOLFFISH_4W+
TH_SKATE_5Y (7+)	WITCH_FL_5Y+, WITCH_FL_5Z+, MONKFISH_5Y+, MONKFISH_5Z+, COD_5Y+, WH_HAKE_5Z+, HADDOCK_5Y+
TH_SKATE_5Z (8+)	MONKFISH_5Z+, COD_5Z+, SM_SKATE_5Z+, PLAICE_4W+, PLAICE_5Z+, HADDOCK_5Y+, OCNPOUT_4W+, SILVEHAKE_5Z+
WITCH_FL_4W (6+)	WITCH_FL_4X+, WITCH_FL_5Z+, MONKFISH_4W+, COD_5Z+, OCNPOUT_4W+, CUSK_4W+
WITCH_FL_4X (1+)	MONKFISH_4W+
WITCH_FL_5Y (8+)	MONKFISH_5Y+, MONKFISH_5Z+, COD_5Y+, SM_SKATE_5Y+, PLAICE_5Y+, WH_HAKE_5Z+, HADDOCK_5Y+, POLLOCK_5Y+
WITCH_FL_5Z (3+)	MONKFISH_5Z+, COD_5Z+, OCNPOUT_4W+
MONKFISH_4W (1+)	CUSK_4W+
MONKFISH_4X (1+)	CUSK_4W+
MONKFISH_5Y (7+)	MONKFISH_5Z+, SM_SKATE_4W+, SM_SKATE_5Y+, PLAICE_5Y+, WH_HAKE_5Y+, WH_HAKE_5Z+, POLLOCK_5Y+
MONKFISH_5Z (8+)	COD_5Y+, COD_5Z+, SM_SKATE_5Z+, HADDOCK_5Y+, POLLOCK_5Y+, OCNPOUT_4W+, OCNPOUT_5Z+, WOLFFISH_4W+
COD_4W (2+, 2-)	WH_HAKE_5Y+, WH_HAKE_5Z+, HERRING_4W-, HERRING_4X-
COD_5Y (1+, 1-)	HADDOCK_5Y+, NSHRIMP_5Y-
COD_5Z (4+)	SM_SKATE_5Z+, POLLOCK_5Y+, OCNPOUT_4W+, WOLFFISH_4W+
HERRING_4W (2+, 2-)	HERRING_4X+, GHALIBUT_4W+, WH_HAKE_5Y-, CUSK_4X-
HERRING_4X (2+, 2-)	GHALIBUT_4W+, GHALIBUT_4X+, YELLOWTL_4W-, CUSK_4X-
SM_SKATE_4W (6+)	SM_SKATE_4X+, PLAICE_5Y+, WH_HAKE_5Z+, HADDOCK_5Y+, POLLOCK_5Y+, OCNPOUT_4W+
SM_SKATE_4X (1+)	CUSK_4W+
SM_SKATE_5Y (1+)	SM_SKATE_5Z+
SM_SKATE_5Z (4+)	PLAICE_5Z+, HADDOCK_5Y+, OCNPOUT_4W+, SILVEHAKE_5Z+
PLAICE_4W (2+, 1-)	OCNPOUT_4W+, CUSK_4X+, WINTER_FL_4X-
PLAICE_5Y (1+)	HADDOCK_5Y+
PLAICE_5Z (2+)	HADDOCK_5Y+, SILVEHAKE_5Z+
WH_HAKE_4W (1+)	WH_HAKE_4X+
WH_HAKE_5Y (1+)	OCNPOUT_4W+
WH_HAKE_5Z (1+)	OCNPOUT_4W+
HADDOCK_4W (3+)	WTSKATE_5Z+, SEARAVEN_5Y+, REDHAKE_4W+
HADDOCK_5Y (2+)	HADDOCK_5Z+, OCNPOUT_5Z+
YELLOWTL_4W (1-)	GHALIBUT_4W-
WTSKATE_4W (1+)	CUSK_4W+
WTSKATE_5Y (1+)	SILVEHAKE_5Z+
POLLOCK_5Y (1+)	OCNPOUT_4W+
POLLOCK_5Z (2+)	NSSQUID_4W+, NSSQUID_5Z+
OCNPOUT_4W (1+)	WOLFFISH_4W+
MACKEREL_4X (1+)	CAPELIN_4W+
MACKEREL_5Y (1+)	REDFISH_5Z+
LSCULPIN_5Y (1+)	NSLANCE_4X+
NSSQUID_4W (2+)	NSSQUID_4X+, NSSQUID_5Z+
NSSQUID_5Y (1+)	NSSQUID_5Z+
LTSKATE_5Z (1+)	REDFISH_5Z+
CUSK_4W (1+)	WOLFFISH_4W+
ALLGFISH_4W (1+)	SCULPIN_4W+
LOBSTER_5Y (1+)	JNCRAB_5Y+
SHRUNCL_5Y (1+)	SHRUNCL_5Z+
JNCRAB_5Y (2+)	SCALLOP_5Y+, SCALLOP_5Z+
NSLANCE_4W (1+)	REDFISH_5Z+

Numbers in parentheses indicate the total number of correlated stocks, positive correlations are denoted by "+", and negative correlations by "-". See Table 1 for full list of species names.

positively. This does not support predator-prey-related hypotheses as driving the structural change in the ecosystem, nor does it lend support for ecosystem management, because if all species operate independently, then each would have to be managed independently, a daunting task.

The analysis here provides a provisional representation of the dynamics of fish over a part of the Northwest Atlantic shelf. Over the past half century, the most obvious change was in the species assemblage. Cod, monkfish, and plaice tended to be "replaced" by seals, spiny dogfish, and herring. The transition from one set

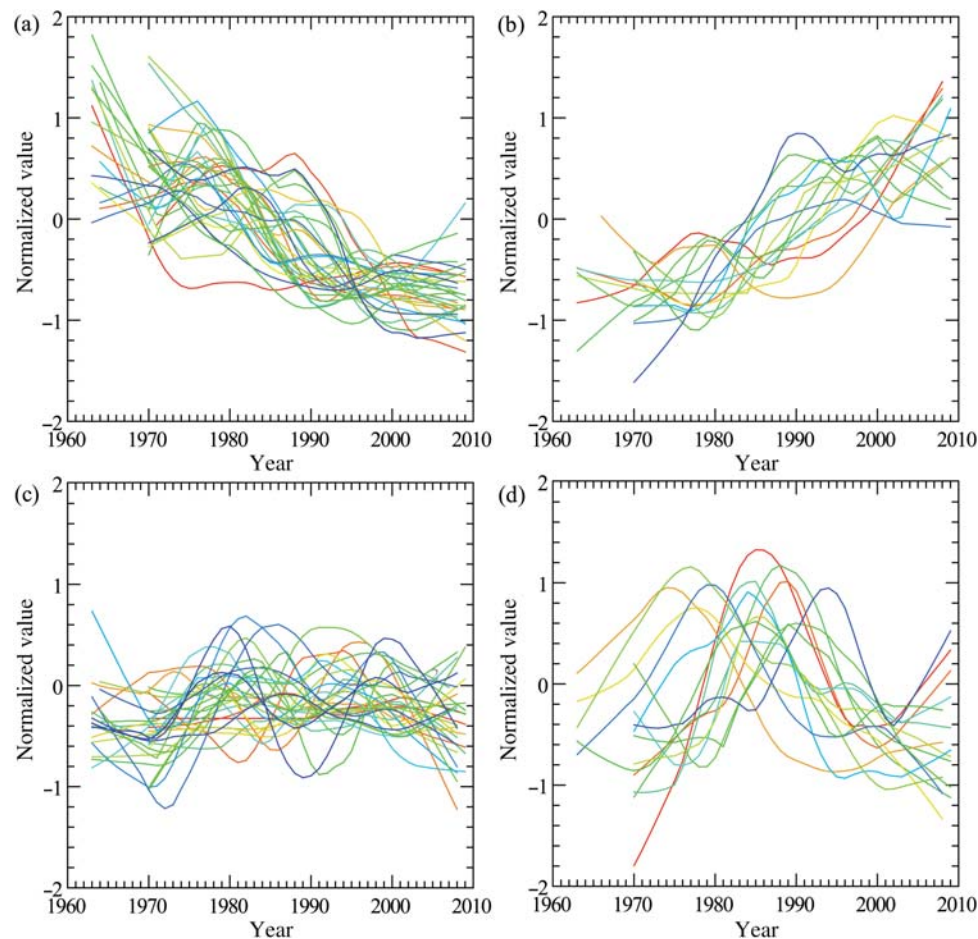


Figure 7. Temporal trajectories for the complexes identified by principal component analyses on 96 stocks (24 species in common in the four areas). Four different trends are distinguished and displayed separately, with LOWESS smoothing curves having tension at 0.35. (a) ALEWIFE_5Z, COD_4W, COD_4X, COD_5Z, HADDOCK_5Y, MONKFISH_4W, MONKFISH_4X, MONKFISH_5Y, MONKFISH_5Z, OCNPOUT_4W, PLAICE_4W, PLAICE_4X, PLAICE_5Y, POLLOCK_5Z, SEARAVEN_4W, SM_SKATE_4W, SM_SKATE_4X, SM_SKATE_5Y, SM_SKATE_5Z, TH_SKATE_4W, TH_SKATE_4X, TH_SKATE_5Y, TH_SKATE_5Z, WH_HAKE_4X, WH_HAKE_5Z, WITCH_FL_4W, WITCH_FL_4X, WITCH_FL_5Y, WITCH_FL_5Z, WTSKATE_4W, YELLOWTL_4W, YELLOWTL_5Z; (b) ALEWIFE_5Y, DOGFISH_4X, DOGFISH_5Y, DOGFISH_5Z, HADDOCK_5Z, HERRING_4W, HERRING_4X, HERRING_5Y, HERRING_5Z, LSCULPIN_4X, LTSKATE_4X, REDHAKE_4X, SEARAVEN_5Z, WINTER_FL_4X, YELLOWTL_4X; (c) ALEWIFE_4W, ALEWIFE_4X, DOGFISH_4W, HADDOCK_4X, LSCULPIN_4W, LSCULPIN_5Y, LSCULPIN_5Z, LTSKATE_4W, LTSKATE_5Y, LTSKATE_5Z, MACKEREL_4X, MACKEREL_5Y, MACKEREL_5Z, NSSQUID_4W, NSSQUID_4X, NSSQUID_5Y, NSSQUID_5Z, OCNPOUT_4X, OCNPOUT_5Y, OCNPOUT_5Z, PLAICE_5Z, REDHAKE_5Y, SEARAVEN_4X, SEARAVEN_5Y, SILVEHAKE_5Y, SILVEHAKE_5Z, WINDOW_FL_4W, WINDOW_FL_5Y, WINTER_FL_5Y, WINTER_FL_5Z, WTSKATE_5Y, YELLOWTL_5Y; (d) HADDOCK_4W, MACKEREL_4W, POLLOCK_4X, POLLOCK_4W, POLLOCK_5Y, REDHAKE_4W, REDHAKE_5Z, SILVEHAKE_4W, SILVEHAKE_4X, WH_HAKE_4W, WH_HAKE_5Y, WINDOW_FL_5Z, WINTER_FL_4W, WTSKATE_4X, WTSKATE_5Z. See Table 1 for a full list of species names.

of stocks to another was characterized by a particular set of volatile species in each statistical area, and changes were not gradual, but abrupt. The downward changes were in the early 1980s, mostly as apparent mortality. Various authors have reported that the declines have been accompanied by decreases in growth rate and condition factor and increases in natural mortality. In contrast, the upward change in the late 1980s was probably recruitment-related and associated with replacement of stocks.

The fact that the transition was over a relatively short period, the decade of the 1980s, is reminiscent of regime change. Although the evidence for many regime shifts is relatively clear, clarity no doubt results from changes in one or a few species. In this case, the possible shift manifests itself as changes over a more diffuse set of years, which of course would be expected

from the non-linear dynamics of fish. As the shift of the composite of species was not at the same point in time, we can think of the observed transient dynamics as a “generalized regime shift”.

In examining the time-series over the half-century period examined here, it appears that the dominant change was in the decade of the 1980s. Hence, a comparison of the decade of the 2000s with long-term variability would suggest that the recent decade is not remarkable or different from the dynamics of the past few decades. The open question, though, relates to whether the new regime will persist or whether it will reverse itself to the skate–cod system.

This study poses many questions for future study. These include the proposition that this perhaps more-detailed characterization of variability might lend greater insight into understanding

the interactions among population abundance, fishing, and the ocean environment. Along these lines, there appear to be some interrelationships among stock dynamics in 4W, 4X, 5Y, and 5Z; in other words, the “stocks” in 4W, 4X, 5Y, and 5Z are not necessarily discrete entities. Exploration of these relationships is an important issue in fishery management because admitting interarea relationships would change stock assessments and optimum yield determinations. The implications of the relative lack of correlations among species are profound. First, correlations may be masked by the high-frequency variability evident in Figure 2. Preliminary analysis leads one to suspect that subjecting the data to a low-pass filter might yield stronger correlative relationships. Without such relationships, it would be difficult to implement ecosystem management, a concept that seems to require interrelationships among species. Also, the abrupt nature of stock dynamics requires the re-examination of production models in the sense that production might need to be estimated for two different periods.

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