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Predicting Spawning Stock Biomass for Georges Bank and Gulf of Maine Atlantic Cod Stocks with Research Vessel Survey Data

by

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This report is a product of the 21st Northeast Regional Stock Assessment Workshop (21st SAW). Proceedings and products of the 21st SAW are scheduled to be documented and released as subissues (denoted by a lower case letter) of *Northeast Fisheries Science Center Reference Document* 96-05 (*e.g.*, 96-05a) . Tentative titles for the 21st SAW are:

An index-based assessment of winter flounder populations in the Gulf of Maine

Assessment of winter flounder in Southern New England and the Mid-Atlantic

Influence of temperature and depth on the distribution and catches of yellowtail flounder, Atlantic cod, and haddock in the NEFSC bottom trawl survey

Predicting spawning stock biomass for Georges Bank and Gulf of Maine Atlantic cod stocks with research vessel survey data

Preliminary results of a spatial analysis of haddock distribution applying a generalized additive model

Report of the 21st Northeast Regional Stock Assessment Workshop (21st SAW): Public Review Workshop

Report of the 21st Northeast Regional Stock Assessment Workshop (21st SAW): Stock Assessment Review Committee (SARC) consensus summary of assessments

Stock assessment of northern shortfin squid in the Northwest Atlantic during 1993

The Lorenz curve method applied to NEFSC bottom trawl survey data

ABSTRACT

Indices of mature biomass, derived from spring and autumn NEFSC research vessel bottom trawl surveys, were used to derive long-term trends in spawning stock biomass (SSB) for stocks of Gulf of Maine and Georges Bank cod for years before VPA-based estimates were available. The relationship between survey mature biomass indices and VPA-derived estimates of SSB were determined by linear least squares regression with the survey index as the dependent variable. Both variables were transformed to logarithms and the survey indices were smoothed by an integrated moving average procedure before performing the regressions. To obtain estimates of SSB in years prior to VPA estimates, the linear equations were rearranged to predict the independent variable (SSB) from the smoothed survey indices. Regressions were jackknifed to estimate extrinsic prediction limits.

For Georges Bank cod, predicted survey values from the time series smoothing exhibited stronger relationships with SSB than unfitted indices. The log transformation linearized the relationships, homogenized residual variance, and improved overall fit, suggesting a lognormal error structure. Both surveys predicted SSB with an extrinsic error of 18-21%. Overall, SSB for Georges Bank cod was estimated to have declined from 100,000-140,000 mt during the 1970s to 40,000-50,000 mt in 1993 and 1994. Results for Gulf of Maine cod were less conclusive as the relationship between SSB and the survey indices of mature biomass was not well defined.

INTRODUCTION

To rebuild depleted stocks of Atlantic cod, haddock, and yellowtail flounder, total allowable fishing on most groundfish stocks will be restricted to a fraction of current levels when Amendment 7 of the Northeast Multispecies Fishery Management Plan is implemented (NEFMC 1995). Therefore, virtual population analysis (VPA) may not be applicable due to reduced data availability and decreased fishing mortality rates, which may be less than natural mortality. Alternate methods of assessing the current status of these stocks and for monitoring fishery trends will be required.

The management approach of Amendment 7 is to reduce fishing mortality to a low level to promote stock recovery above specific spawning stock biomass (SSB) threshold levels within specified time periods. Progress toward achieving these SSB objectives will need to be monitored during the rebuilding process. It is likely that fishery managers will be relying more heavily on research vessel bottom trawl survey results because fishery-based indicators such as catch-per-unit-effort are not likely to reflect stock abundance under such management measures as restrictive total allowable catches or severe limitations on effort.

The purpose of the present study was to develop methods to estimate SSB from bottom trawl survey data. The general approach was to estimate mean weight per tow of mature fish from Northeast Fisheries Science Center (NEFSC) surveys, reduce sampling error through time series modeling, and quantify the relationship between survey observations and VPA estimates. Data for two stocks of Atlantic cod were used to explore possible methods.

METHODS

Virtual population analysis has been used to estimate Atlantic cod spawning stock biomass for the Georges Bank stock, 1978-1994 (Serchuk *et al.* 1994), and the Gulf of Maine stock, 1982-1994 (Mayo 1995). Results from spring and autumn NEFSC bottom trawl surveys were used to indicate relative abundance at age for VPA calibration in both stock assessments. Therefore, SSB estimates from VPA are not completely independent from age-aggregated survey indices.

Indices of mature biomass were computed for Gulf of Maine and Georges Bank cod from spring 1968-1995 and autumn 1963-1994 NEFSC bottom trawl survey data. Biomass indices (stratified mean weight per tow; Cochran 1977) of mature cod were derived by calculating the proportion of mature cod at length from fitted logistic equations taken from O'Brien *et al.* (1993) as follows:

$$P = \frac{e^{[a+(bL)]}}{1+e^{[a+(bL)]}}$$

where P = proportion mature, L = length (cm), and a and b are intercept and shape parameters, respectively from the fitted logistic regression. For Georges Bank cod the logistic parameters were: a = -4.932 and b = 0.127. Parameters for Gulf of Maine cod were: a = -5.500 and b = 0.171 (O'Brien *et al.* 1993).

Stratified mean number of mature fish per tow was computed by applying the logistic equation at the strata set level to the stratified mean number of fish per tow at length. Mean numbers per tow at length were converted to mean weight per tow at length by applying an exponential length-weight equation (Serchuk *et al.* 1994) to each length.

The equation used for converting length to weight was:

$$W = aL^b$$

where W = weight (kg), L = length (cm), and a and b are intercept and slope parameters, respectively, from the fitted regression. For both cod stocks, the length-weight parameters were: a = 0.000008104 and b = 3.052. Stratified mean weight per tow of all fish was then obtained by summing over all lengths.

Predictive relationships between VPA estimates of SSB and survey indices of mature biomass were developed using linear least squares regressions. In all regressions, survey indices were assumed to be dependent on SSB, as estimated by VPA (Cook 1995). Initial predictive models regressed untransformed indices on SSB and log transformed indices on Log SSB.

Fogarty *et al.* (1986) improved the correspondence between survey indices and VPA estimates of biomass for six northeast stocks by reducing survey estimation error through time series modelling. Pennington (1985, 1986) found that integrated moving average models reduced measurement error in survey time series by using the autocorrelation of serial observations. Accordingly, integrated moving average models have been used to develop time series fitted indices for many northeast fish stocks (NEFC 1988, NEFSC 1992). A moving average process is one in which current observations are influenced by past events. Autocorrelation was expected for survey indices of SSB, because cohorts contribute to SSB over several years. The moving average impacts on sequential observations of SSB may result from the effect of large year classes on subsequent SSB estimates. Observations were log transformed to homogenize variance and linearize relationships, and were first order differenced to remove negative trends (Fogarty 1989). Autocorrelation of transformed survey estimates of SSB was investigated to specify time series models. Specifications were made *a priori* for series with inconclusive empirical diagnostics (Pennington 1985, 1986; Fogarty *et al.* 1986; Pennington and Godø 1995). Adequacy of *a priori* model specification was checked by autocorrelation analysis of residuals (Pennington 1986).

Relationships between integrated moving average indices and log SSB from VPA were examined using linear least squares. Linear equations were rearranged to predict stock biomass as the independent variable: $X=(Y-a)/b$ (Sokal and Rohlf 1981). Regressions were jackknifed (Efron and Gong 1981) to estimate extrinsic prediction accuracy and assess stability of parameter estimates.

RESULTS

Georges Bank Cod

VPA estimates and survey indices of Georges Bank cod SSB are presented in Figure 1. The linear bivariate relationships between survey indices and VPA estimates of SSB were weak, curvilinear, and exhibited increasing residual variance (Figure 2). Log transformation improved fit, linearized relationships and homogenized residual variance, suggesting lognormal error structure.

Time series models were developed for spring and autumn survey indices of mature Georges Bank cod (Appendix 1). Significant autocorrelation at a lag of one year and gradually decaying partial autocorrelation from a one year lag suggested first order moving average models. Conditional least square estimates of moving average parameters (θ) were 0.58 for both surveys, which is within the range of θ estimated for NEFSC survey indices of other fish stocks (Table 1). Parameter estimates were significantly positive, and residuals were not autocorrelated. Similarity in autocorrelation structure and parameter estimates between the spring and autumn survey time series analyses suggests that Georges Bank cod SSB had a characteristic moving average process.

Predicted values from time series models had stronger relationships with SSB than did unfitted survey indices (Figures 3a and 4a). Results are given in Table 2. Residual analysis did not reveal significant outliers, curvilinearity, or heteroscedasticity. Jackknifed estimates of parameter standard error (SE) were consistently lower than analytical estimates of SE. Although 95% confidence intervals of predicted SSB showed considerable uncertainty in survey predictions, the two surveys produced very similar estimates (Figure 3b and 4b). The spring and autumn surveys predicted SSB with 16% and 18% error, respectively; corresponding extrinsic prediction errors of jackknifed observations increased to 18% and 21%. Both surveys overestimated SSB from 1984 to 1986 and underestimated SSB from 1987 to 1992.

Gulf of Maine cod

Survey indices and VPA estimates of SSB for Gulf of Maine cod are presented in Figure 5. Relationships between SSB and survey indices were weak (Figure 6).

Time series models were developed for spring and autumn indices of mature Gulf of Maine cod (Appendix 2). A first order integrated moving average model was specified for the autumn time series because differenced observations had significant autocorrelation at the one year lag. An *a priori* first order moving average model was specified for the spring series because observations were not significantly autocorrelated. Moving average parameters, estimated as 0.52 and 0.33, were significantly positive and produced residuals with no autocorrelation.

The relationship between the time series fitted spring index and SSB was not statistically significant, and the regression for the autumn series was weak (Table 3; Figure 7a). Confidence limits of estimated SSB were not plotted because of their wide range. Although the autumn regressions were significant, and predicted SSB provides some indication of previous levels of SSB, it appears that survey indices of mature biomass cannot predict SSB of Gulf of Maine cod with sufficient precision to assess current conditions relative to desired SSB thresholds.

DISCUSSION

Although it is possible to scale survey estimates of spawning stock using a simple log-log regression with VPA as the independent variable (Cook 1995), VPA does not estimate SSB without error. Both survey indices and VPA estimates are dependent on actual levels of SSB. To check if survey indices and VPA estimates were both proportional to the true population, Pennington and Godø (1995) regressed survey indices on VPA estimates because VPA estimates appear more precise. Bootstrapped estimates of precision for cod VPAs (which may be optimistic because catch at age is assumed to be without error) suggest a low coefficient of variation (CV) for estimates of SSB (10% for Georges Bank, Serchuk *et al.* 1994, and 9% for Gulf of Maine, Mayo 1995), whereas CVs of survey indices estimated by the present integrated moving average models were greater than 25%. Although both variables are measured with error, model I regression is the proper method for a predictive model (Sokal and Rohlf 1981). Jackknifed parameter estimates suggest that the present regression estimates are robust to statistical violations.

The relationship between the VPA-based SSB estimates and the survey index of mature biomass is out of phase for Gulf of Maine cod, particularly in the spring. The VPA SSB series for this stock is rather short (1982-1994) and features a major recruitment event driven by the 1987 year class. However, the increase in SSB resulting from the growth and maturation of this year class, as indicated by the spring survey, lags the VPA-based estimates by several years. Further investigation of the distribution of cod in the spring survey is warranted before any definitive conclusions can be drawn from this data set.

ADAPT calibration (Gavaris 1988) iteratively estimated abundance and SSB by optimizing predictions of survey observations, as a product of population abundance and estimated catchability (q). The linear equations used to predict SSB from survey indices in the present analysis may viewed as estimating catchability (b=q) and a threshold SSB ($e^{-a/b}$ mt) below which the survey does not catch mature fish. Linear regression through the origin would eliminate the need to justify a SSB threshold. More complicated functional models may fit the present relationships better, but would imply variable survey catchability (Pennington and Godø 1995). For example, quadratic regression of mature biomass indices on SSB would imply that q is linearly related to SSB. Allowing q to vary for the purpose of scaling mature biomass indices to units of SSB would link contradictory models because the independent estimates of SSB were calibrated assuming constant q.

Size and age at maturity of Georges Bank and Gulf of Maine cod has decreased within cohorts from the 1970 year class to the 1991 year class due to declining stock abundance (O'Brien 1990 and 1995). Accordingly, Georges Bank and Gulf of Maine stock assessments included changing maturity at age to estimate SSB (Serchuk *et al.* 1994 and Mayo 1995, respectively). The maturity ogive used in the present study may only represent the period from which it was derived, 1985-1990. These analyses should be considered provisional upon developing more appropriate annual maturity ogives. Predicting SSB with current survey indices of mature biomass may lead to overestimates of SSB if stock abundance and maturity at size increase.

Although SSB predictions may be improved through more accurate estimates of maturity at length, more elaborate models or estimation procedures, these analyses show that time series fitting of survey indices improves relationships with VPA estimates of SSB, and performance of these methods for predicting SSB is survey-specific.

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Table 1. Estimates of integrated moving average parameters (θ) for trawl survey indices of fish stocks in the northeast U.S. and standard error of estimates where reported.

Study	Species	Stock	Survey	Years	Index	θ
Pennington 1985	haddock	GB	spring	16	N	0.62
	"	"	autumn	21	N	0.30
	"	GM	spring	16	N	0.27
	"	"	autumn	21	N	0.34
Pennington 1986	yellowtail flounder	SNE	spring	17	N	0.24
	" "	"	autumn	22	N	0.40
	" "	GB	spring	17	N	0.61
	" "	"	autumn	22	N	0.36
Fogarty et al. 1986	cod	GB	autumn	23	B	0.65
	haddock	GB	autumn	23	B	0.05
	yellowtail flounder	SNE	autumn	23	B	0.15
	" "	GB	autumn	23	B	0.45
	silver hake	SGB	autumn	23	B	0.55
	redfish	GB	autumn	23	B	0.45
NEFSC 1992**	haddock	GB	autumn	29	B	0.00
	"	GM	autumn	29	B	0.25
	red hake	NGB	autumn	29	B	0.50
	yellowtail flounder	GB	autumn	29	B	0.45
	" "	SNE	autumn	29	B	0.30
	" "	MA	autumn	29	B	0.20
	summer flounder	GB-MA	spring	25	B	0.25
	winter flounder	SNE	spring	25	B	0.50
	witch flounder	GM-GB	autumn	29	B	0.50
	American plaice	GM-GB	autumn	29	B	0.30
	redfish	GB	autumn	29	B	0.45
	black sea bass	GM-MA	spring	24	B	0.20
	goosefish	GM-MA	autumn	29	B	0.45
	ocean pout	GM-MA	spring	24	B	0.40
	wolffish	GM-GB	spring	25	B	0.30
	spiny dogfish	NE	spring	25	B	0.55
	lobster	GM-MA	autumn	29	B	0.55
	shrimp	GM	autumn	29	B	0.35
	Illex	GM-MA	autumn	29	B	0.30
Helser & Hayes 1995	wolffish	NE	spring	25	N	0.50
O'Brien 1995	cod	GB	spring	26	B	0.45
	"	"	autumn	26	B	0.60
	"	GM	spring	26	B	0.45
	"	"	autumn	26	B	0.15
Pennington & Godø 1995	haddock	GB	autumn	28	N	0.23
	yellowtail flounder	GB	autumn	28	N	0.44
	" "	SNE	autumn	28	N	0.31
current study	cod	GB	spring	27	SSB	0.58
	"		autumn	32	SSB	0.58
	"	GM	spring	27	SSB	0.52
	"		autumn	32	SSB	0.33

GM: Gulf of Maine
GB: Georges Bank
SNE: southern New England
NGB: northern Georges Bank
SGB: southern Georges Bank
MA: mid Atlantic

N: abundance (#/tow)
B: biomass (kg/tow)
SSB: spawning stock biomass (kg/tow)

** θ estimates from 0.60 to 0.95 were considered excessive and not used

Table 2. Linear least squares statistics from regressions of time series fitted Log transformed mature biomass indices from NEFSC surveys on Georges Bank cod spawning stock biomass from VPA.

Spring Survey

Variance	df	SS	MS	F	sig.
Regression	1	2.8569	2.8569	43.1703	0.0000*
Residual	15	0.9926	0.0662		
Total	16	3.8495			

R^2 0.7421

Parameter	est.	S.E.	t	95% Confidence	
b	1.3153	0.2002	6.5704	0.8887	1.7419
a	-11.9461	2.2189	-5.3837	-16.6747	-7.2175

Autumn Survey

Variance	df	SS	MS	F	sig.
Regression	1	4.2068	4.2068	33.1554	0.0000*
Residual	15	1.9032	0.1269		
Total	16	6.1101			

R^2 0.6885

Parameter	est.	S.E.	t	95% Confidence	
b	1.5961	0.2772	5.7581	1.0054	2.1868
a	-15.9584	3.0725	-5.1939	-22.5060	-9.4109

Table 3. Linear least squares statistics from regressions of time series fitted Log transformed mature biomass indices from NEFSC surveys on Gulf of Maine cod spawning stock biomass from VPA.

Spring Survey

Variance	df	SS	MS	F	sig.
Regression	1	0.0282	0.0282	0.3840	0.6723
Residual	11	0.8079	0.0734		
Total	12	0.8361			

R^2 0.0337

Parameter	est.	S.E.	t	95% Confidence	
b	-0.1451	0.2344	-0.6190	-0.6446	0.3544
a	2.9650	2.2684	1.3071	-1.8690	7.7990

Autumn Survey

Variance	df	SS	MS	F	sig.
Regression	1	1.7295	1.7295	26.3716	0.0000*
Residual	11	0.7214	0.0656		
Total	12	2.4509			

R^2 0.7057

Parameter	est.	S.E.	t	95% Confidence	
b	1.1375	0.2215	5.1354	0.6655	1.6095
a	-9.5249	2.1435	-4.4436	-14.0927	-4.9571

Appendix 1. Time series analysis of Log transformed NEFSC survey estimates of Georges Bank cod spawning stock biomass.

```
BMDP2T - BOX-JENKINS TIME SERIES ANALYSIS Version: PC90
(1990 IBM PC/MS-DOS)        Date: 10/24/95  at 12:49:50
---------------------------------------------------------

ACF    VAR IS  LNSPRING. DFORDER IS 1. MAXLAG IS 10. /
NO. OF OBS. AFTER DIFFERENCING    =              27
MEAN OF THE (DIFFERENCED) SERIES =         -0.0125
STANDARD ERROR OF THE MEAN        =          0.1193
T-VALUE OF MEAN (AGAINST ZERO)    =         -0.1044

AUTOCORRELATIONS
  1- 10      -.44   .02 -.01 -.12   .19 -.17   .17 -.04 -.16   .16
  ST.E.       .19   .23   .23   .23   .23   .23   .24   .24   .24   .25

PLOT OF AUTOCORRELATIONS
          -1.0 -0.8 -0.6 -0.4 -0.2  0.0  0.2  0.4  0.6  0.8  1.0
LAG    CORR. +----+----+----+----+----+----+----+----+----+----+
                                     I
  1  -0.436             XX+XXXXXXXXI        +
  2   0.020             +          IX         +
  3  -0.007             +          I          +
  4  -0.117             +       XXXI          +
  5   0.193             +          IXXXXX     +
  6  -0.174             +      XXXXI          +
  7   0.173            +           IXXXX       +
  8  -0.040            +          XI           +
  9  -0.163            +       XXXXI           +
 10   0.164            +           IXXXX       +

PACF   VAR IS LNSPRING. DFORDER IS 1. MAXLAG IS 10. /

PARTIAL AUTOCORRELATIONS
  1- 10      -.44 -.21 -.11 -.22   .05 -.11   .09   .08 -.13   0.0
  ST.E.       .19   .19   .19   .19   .19   .19   .19   .19   .19   .19

PLOT OF PARTIAL AUTOCORRELATIONS
          -1.0 -0.8 -0.6 -0.4 -0.2  0.0  0.2  0.4  0.6  0.8  1.0
LAG    CORR. +----+----+----+----+----+----+----+----+----+----+
                                     I
  1  -0.436             XX+XXXXXXXXI        +
  2  -0.210               +   XXXXXI        +
  3  -0.114               +     XXXI        +
  4  -0.216               +   XXXXXI        +
  5   0.047               +        IX       +
  6  -0.108               +     XXXI        +
  7   0.089               +        IXX      +
  8   0.079               +        IXX      +
  9  -0.134               +     XXXI        +
 10   0.005               +        I        +
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Appendix 1 (Continued).

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ARIMA  VAR IS LNSPRING. DFORDER IS 1. MAORDERS ARE '(1)'. /
ESTIMATION METHOD IS CLS. RESID IS RESID_Y2. PCOR. /
ESTIMATION BY CONDITIONAL LEAST SQUARES METHOD
RELATIVE CHANGE IN RESIDUAL SUM OF SQUARES LESS THAN 0.5000E-04

VARIABLE  VAR. TYPE  MEAN      TIME     DIFFERENCES
LNSPRING   RANDOM             6-  33       (1-B^1)

PARAMETER  VARIABLE  TYPE  FACTOR  ORDER  ESTIMATE  ST. ERR.  T-RATIO
        1  LNSPRING   MA        1      1    0.5768    0.1622       3.56

RESIDUAL SUM OF SQUARES  =          7.137047
DEGREES OF FREEDOM       =                26
RESIDUAL MEAN SQUARE     =          0.274502

ACF    VAR IS RESID_Y2. MAXLAG IS 10. /
NO. OF OBS. AFTER DIFFERENCING   =                27
MEAN OF THE (DIFFERENCED) SERIES =           -0.0758
STANDARD ERROR OF THE MEAN       =            0.0997
T-VALUE OF MEAN (AGAINST ZERO)   =           -0.7602

AUTOCORRELATIONS
  1- 10     -.13  .08  .02 -.01  .19 -.04  .16 -.04 -.11  .11
  ST.E.      .19  .20  .20  .20  .20  .20  .20  .21  .21  .21

PLOT OF AUTOCORRELATIONS
          -1.0 -0.8 -0.6 -0.4 -0.2  0.0  0.2  0.4  0.6  0.8  1.0
LAG   CORR. +----+----+----+----+----+----+----+----+----+----+
                                     I
  1  -0.132                 +     XXXI        +
  2   0.077                +         IXX       +
  3   0.022                +         IX        +
  4  -0.014                +         I         +
  5   0.193                +         IXXXXXX   +
  6  -0.042                +        XI         +
  7   0.155                +         IXXXXX    +
  8  -0.043                +        XI         +
  9  -0.108                +      XXXI         +
 10   0.114                +         IXXX      +

PACF   VAR IS RESID_Y2. MAXLAG IS 10. /

PARTIAL AUTOCORRELATIONS
  1- 10     -.13  .06  .04 -.01  .19  .01  .13 -.02 -.14  .05
  ST.E.      .19  .19  .19  .19  .19  .19  .19  .19  .19  .19

PLOT OF PARTIAL AUTOCORRELATIONS
          -1.0 -0.8 -0.6 -0.4 -0.2  0.0  0.2  0.4  0.6  0.8  1.0
LAG   CORR. +----+----+----+----+----+----+----+----+----+----+
                                     I
  1  -0.132                 +     XXXI        +
  2   0.061                 +        IXX      +
  3   0.041                 +        IX       +
  4  -0.011                 +        I        +
  5   0.190                 +        IXXXXXX  +
  6   0.007                 +        I        +
  7   0.132                 +        IXXXX    +
  8  -0.016                 +        I        +
  9  -0.140                 +    XXXXI        +
 10   0.050                 +        IX       +
=================================================================
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Appendix 1 (Continued).

```
================================================================
ACF    VAR IS LNAUTUMN. DFORDER IS 1. MAXLAG IS 10. /
NO. OF OBS. AFTER DIFFERENCING    =            31
MEAN OF THE (DIFFERENCED) SERIES =       -0.0589
STANDARD ERROR OF THE MEAN        =        0.1201
T-VALUE OF MEAN (AGAINST ZERO)    =       -0.4909

AUTOCORRELATIONS
  1- 10    -.57  .09  .17 -.31  .09  .32 -.42  .16  .11 -.36
  ST.E.     .18  .23  .23  .24  .25  .25  .26  .28  .29  .29

PLOT OF AUTOCORRELATIONS
          -1.0 -0.8 -0.6 -0.4 -0.2  0.0  0.2  0.4  0.6  0.8  1.0
LAG   CORR. +----+----+----+----+----+----+----+----+----+----+
                                    I
  1  -0.566           XXXXX+XXXXXXXXI        +
  2   0.094              +          IXX        +
  3   0.172              +          IXXXXX     +
  4  -0.312             +    XXXXXXXXI          +
  5   0.086             +           IXX         +
  6   0.320             +           IXXXXXXXX   +
  7  -0.416            +  XXXXXXXXXXXI           +
  8   0.165           +             IXXXXX        +
  9   0.112           +             IXXX          +
 10  -0.357           +    XXXXXXXXXXI            +

PACF   VAR IS LNAUTUMN. DFORDER IS 1. MAXLAG IS 10. /

PARTIAL AUTOCORRELATIONS
  1- 10    -.57 -.33  .09 -.19 -.31  .32  .05 -.30  .05 -.04
  ST.E.     .18  .18  .18  .18  .18  .18  .18  .18  .18  .18

PLOT OF PARTIAL AUTOCORRELATIONS
          -1.0 -0.8 -0.6 -0.4 -0.2  0.0  0.2  0.4  0.6  0.8  1.0
LAG   CORR. +----+----+----+----+----+----+----+----+----+----+
                                    I
  1  -0.566           XXXXX+XXXXXXXXI        +
  2  -0.332                +XXXXXXXXI        +
  3   0.091                +        IXX      +
  4  -0.185                +   XXXXXI        +
  5  -0.314                +XXXXXXXXI        +
  6   0.323                +        IXXXXXXXX+
  7   0.050                +        IX       +
  8  -0.296                + XXXXXXXI        +
  9   0.047                +        IX       +
 10  -0.043                +       XI        +
================================================================
```

Appendix 1 (Continued).

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ARIMA  VAR IS LNAUTUMN. DFORDER IS 1. MAORDERS ARE '(1)'. /
ESTIMATION METHOD IS CLS. RESID IS RESID_Y1. PCOR. /
ESTIMATION BY CONDITIONAL LEAST SQUARES METHOD
RELATIVE CHANGE IN RESIDUAL SUM OF SQUARES LESS THAN 0.5000E-04

VARIABLE  VAR. TYPE  MEAN      TIME     DIFFERENCES
LNAUTUMN    RANDOM             1-  32      (1-B^1)

PARAMETER  VARIABLE  TYPE  FACTOR  ORDER  ESTIMATE  ST. ERR.   T-RATIO
        1  LNAUTUMN   MA        1      1    0.5810    0.1481      3.92

RESIDUAL SUM OF SQUARES  =          9.108105
DEGREES OF FREEDOM       =                30
RESIDUAL MEAN SQUARE     =          0.303604

ACF    VAR IS RESID_Y1. MAXLAG IS 10. /
NO. OF OBS. AFTER DIFFERENCING   =             31
MEAN OF THE (DIFFERENCED) SERIES =        -0.1510
STANDARD ERROR OF THE MEAN       =         0.0950
T-VALUE OF MEAN (AGAINST ZERO)   =        -1.5891

AUTOCORRELATIONS
  1- 10     -.22  .07  .12 -.24  .11  .28 -.35  .06  .03 -.29
  ST.E.      .18  .19  .19  .19  .20  .20  .22  .23  .23  .23

PLOT OF AUTOCORRELATIONS
          -1.0 -0.8 -0.6 -0.4 -0.2  0.0  0.2  0.4  0.6  0.8  1.0
LAG   CORR. +----+----+----+----+----+----+----+----+----+----+
                                    I
  1  -0.219               +   XXXXXI        +
  2   0.072               +        IXX      +
  3   0.119               +        IXXX     +
  4  -0.242               +  XXXXXXI        +
  5   0.109              +         IXXX      +
  6   0.284              +         IXXXXXXX  +
  7  -0.355             + XXXXXXXXXI          +
  8   0.062             +          IXX        +
  9   0.032             +          IX         +
 10  -0.287             +   XXXXXXXI          +

PACF   VAR IS RESID_Y1. MAXLAG IS 10. /

PARTIAL AUTOCORRELATIONS
  1- 10     -.22  .03  .15 -.20  0.0  .36 -.26 -.22  .14 -.12
  ST.E.      .18  .18  .18  .18  .18  .18  .18  .18  .18  .18

PLOT OF PARTIAL AUTOCORRELATIONS
          -1.0 -0.8 -0.6 -0.4 -0.2  0.0  0.2  0.4  0.6  0.8  1.0
LAG   CORR. +----+----+----+----+----+----+----+----+----+----+
                                    I
  1  -0.219               +   XXXXXI        +
  2   0.025               +        IX       +
  3   0.147               +        IXXXX    +
  4  -0.202               +   XXXXXI        +
  5   0.004               +        I        +
  6   0.362               +        IXXXXXXXXXX
  7  -0.258               +  XXXXXXI        +
  8  -0.221               +  XXXXXXI        +
  9   0.142               +        IXXXX    +
 10  -0.118               +     XXXI        +
==================================================================
```

Appendix 2. Time series analysis of Log transformed NEFSC survey estimates of Gulf of Maine cod spawning stock biomass.

```
BMDP2T - BOX-JENKINS TIME SERIES ANALYSIS Version: PC90
(1990 IBM PC/MS-DOS)        Date: 10/31/95  at 14:01:44
---------------------------------------------------------

ACF    VAR IS LNSPRING. DFORDER IS 1. MAXLAG IS 10. /
NO. OF OBS. AFTER DIFFERENCING   =              27
MEAN OF THE (DIFFERENCED) SERIES =         -0.0536
STANDARD ERROR OF THE MEAN       =          0.0853
T-VALUE OF MEAN (AGAINST ZERO)   =         -0.6288

AUTOCORRELATIONS
  1- 10     -.25 -.16 -.02  .15 -.16 -.17  0.0  .10  .08 -.09
  ST.E.      .19  .20  .21  .21  .21  .22  .22  .22  .22  .23

PLOT OF AUTOCORRELATIONS
          -1.0 -0.8 -0.6 -0.4 -0.2  0.0  0.2  0.4  0.6  0.8  1.0
LAG    CORR. +----+----+----+----+----+----+----+----+----+----+
                                     I
  1  -0.251                 +  XXXXXXI       +
  2  -0.163                +     XXXXI        +
  3  -0.022                +        XI        +
  4   0.153                +         IXXXX    +
  5  -0.158                +     XXXXI        +
  6  -0.171               +      XXXXI         +
  7   0.005               +          I         +
  8   0.097               +          IXX       +
  9   0.084               +          IXX       +
 10  -0.086               +        XXI         +

PACF   VAR IS LNSPRING. DFORDER IS 1. MAXLAG IS 10. /

PARTIAL AUTOCORRELATIONS
  1- 10     -.25 -.24 -.15  .07 -.13 -.25 -.21 -.12  .05 -.04
  ST.E.      .19  .19  .19  .19  .19  .19  .19  .19  .19  .19

PLOT OF PARTIAL AUTOCORRELATIONS
          -1.0 -0.8 -0.6 -0.4 -0.2  0.0  0.2  0.4  0.6  0.8  1.0
LAG    CORR. +----+----+----+----+----+----+----+----+----+----+
                                     I
  1  -0.251                 +  XXXXXXI       +
  2  -0.241                 +  XXXXXXI       +
  3  -0.151                 +    XXXXI       +
  4   0.070                 +        IXX     +
  5  -0.134                 +     XXXI       +
  6  -0.252                 +  XXXXXXI       +
  7  -0.215                 +   XXXXXI       +
  8  -0.120                 +     XXXI       +
  9   0.047                 +        IX      +
 10  -0.043                 +       XI       +
=================================================================
```

Appendix 2 (Continued).

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ARIMA  VAR IS LNSPRING. DFORDER IS 1. MAORDERS ARE '(1)'. /
ESTIMATION METHOD IS CLS. RESID IS RESID_Y2. PCOR. /
ESTIMATION BY CONDITIONAL LEAST SQUARES METHOD
RELATIVE CHANGE IN RESIDUAL SUM OF SQUARES LESS THAN 0.5000E-04

VARIABLE  VAR. TYPE  MEAN       TIME     DIFFERENCES
LNSPRING   RANDOM               6-  33    (1-B^1)

PARAMETER  VARIABLE  TYPE  FACTOR  ORDER  ESTIMATE  ST. ERR.  T-RATIO
        1  LNSPRING   MA        1      1    0.5201    0.1796      2.90

RESIDUAL SUM OF SQUARES   =         4.596936
DEGREES OF FREEDOM        =               26
RESIDUAL MEAN SQUARE      =         0.176805

ACF    VAR IS RESID_Y2. MAXLAG IS 10. /
NO. OF OBS. AFTER DIFFERENCING   =            27
MEAN OF THE (DIFFERENCED) SERIES =       -0.0870
STANDARD ERROR OF THE MEAN       =        0.0791
T-VALUE OF MEAN (AGAINST ZERO)   =       -1.1001

AUTOCORRELATIONS
  1- 10      .09 -.18 -.09  .04 -.24 -.26 -.05  .12  .09 -.07
  ST.E.      .19  .19  .20  .20  .20  .21  .22  .22  .23  .23

PLOT OF AUTOCORRELATIONS
          -1.0 -0.8 -0.6 -0.4 -0.2  0.0  0.2  0.4  0.6  0.8  1.0
LAG   CORR. +----+----+----+----+----+----+----+----+----+----+
                                     I
  1   0.090                 +        IXX      +
  2  -0.179                +     XXXXI         +
  3  -0.094                +       XXI         +
  4   0.044                +         IX        +
  5  -0.236                +   XXXXXXI         +
  6  -0.262                +  XXXXXXXI         +
  7  -0.048               +         XI          +
  8   0.124               +          IXXX       +
  9   0.089               +          IXX        +
 10  -0.067               +        XXI          +

PACF   VAR IS RESID_Y2. MAXLAG IS 10. /

PARTIAL AUTOCORRELATIONS
  1- 10      .09 -.19 -.06  .03 -.28 -.23 -.12 -.03  .01 -.15
  ST.E.      .19  .19  .19  .19  .19  .19  .19  .19  .19  .19

PLOT OF PARTIAL AUTOCORRELATIONS
          -1.0 -0.8 -0.6 -0.4 -0.2  0.0  0.2  0.4  0.6  0.8  1.0
LAG   CORR. +----+----+----+----+----+----+----+----+----+----+
                                     I
  1   0.090                 +        IXX      +
  2  -0.188                 +   XXXXXI        +
  3  -0.061                 +      XXI        +
  4   0.027                 +        IX       +
  5  -0.285                 + XXXXXXXI        +
  6  -0.233                 +  XXXXXXI        +
  7  -0.120                 +     XXXI        +
  8  -0.025                 +       XI        +
  9   0.011                 +        I        +
 10  -0.150                 +    XXXXI        +
===============================================================
```

Appendix 2 (Continued).

```
=================================================================

ACF    VAR IS LNAUTUMN. DFORDER IS 1. MAXLAG IS 10. /
NO. OF OBS. AFTER DIFFERENCING    =              31
MEAN OF THE (DIFFERENCED) SERIES =          -0.0493
STANDARD ERROR OF THE MEAN       =           0.0787
T-VALUE OF MEAN (AGAINST ZERO)   =          -0.6271

AUTOCORRELATIONS
  1- 10     -.27  .01 -.17 -.19  .05  .09 -.07  .04 -.02  .10
  ST.E.      .18  .19  .19  .20  .20  .20  .20  .21  .21  .21

PLOT OF AUTOCORRELATIONS
          -1.0 -0.8 -0.6 -0.4 -0.2  0.0  0.2  0.4  0.6  0.8  1.0
LAG    CORR. +----+----+----+----+----+----+----+----+----+----+
                                     I
  1  -0.272                + XXXXXXXI        +
  2   0.013                +        I        +
  3  -0.171                +    XXXXI        +
  4  -0.187               +    XXXXXI         +
  5   0.050               +          IX       +
  6   0.091               +          IXX      +
  7  -0.075               +        XXI        +
  8   0.042               +          IX       +
  9  -0.017               +          I        +
 10   0.096               +          IXX      +

PACF   VAR IS LNAUTUMN. DFORDER IS 1. MAXLAG IS 10. /

PARTIAL AUTOCORRELATIONS
  1- 10     -.27 -.07 -.20 -.33 -.17 -.03 -.21 -.17 -.11  .02
  ST.E.      .18  .18  .18  .18  .18  .18  .18  .18  .18  .18

PLOT OF PARTIAL AUTOCORRELATIONS
          -1.0 -0.8 -0.6 -0.4 -0.2  0.0  0.2  0.4  0.6  0.8  1.0
LAG    CORR. +----+----+----+----+----+----+----+----+----+----+
                                     I
  1  -0.272                + XXXXXXXI        +
  2  -0.065                +      XXI        +
  3  -0.200                +   XXXXXI        +
  4  -0.330                +XXXXXXXXI        +
  5  -0.168                +    XXXXI        +
  6  -0.032                +       XI        +
  7  -0.211                +   XXXXXI        +
  8  -0.175                +    XXXXI        +
  9  -0.111                +     XXXI        +
 10   0.020                +        I        +
=================================================================
```

```
=================================================================

ARIMA  VAR IS LNAUTUMN. DFORDER IS 1. MAORDERS ARE '(1)'. /
ESTIMATION METHOD IS CLS. RESID IS RESID_Y1. PCOR. /
ESTIMATION BY CONDITIONAL LEAST SQUARES METHOD
RELATIVE CHANGE IN RESIDUAL SUM OF SQUARES LESS THAN 0.5000E-04

VARIABLE  VAR. TYPE  MEAN      TIME      DIFFERENCES
LNAUTUMN    RANDOM              1-  32    (1-B^1)

PARAMETER  VARIABLE  TYPE  FACTOR  ORDER  ESTIMATE  ST. ERR.  T-RATIO
        1  LNAUTUMN    MA       1      1    0.3314    0.1723     1.92

RESIDUAL SUM OF SQUARES  =          5.396041
DEGREES OF FREEDOM       =                30
RESIDUAL MEAN SQUARE     =          0.179868

ACF    VAR IS RESID_Y1. MAXLAG IS 10. /
NO. OF OBS. AFTER DIFFERENCING   =              31
MEAN OF THE (DIFFERENCED) SERIES =         -0.1107
STANDARD ERROR OF THE MEAN       =          0.0702
T-VALUE OF MEAN (AGAINST ZERO)   =         -1.5771

AUTOCORRELATIONS
  1- 10     -.01 -.05 -.25 -.25 -.01  .07 -.05  .05  .05  .14
  ST.E.      .18  .18  .18  .19  .20  .20  .20  .20  .20  .20

PLOT OF AUTOCORRELATIONS
          -1.0 -0.8 -0.6 -0.4 -0.2  0.0  0.2  0.4  0.6  0.8  1.0
LAG    CORR. +----+----+----+----+----+----+----+----+----+----+
                                     I
  1  -0.006                +         I        +
  2  -0.050                +        XI        +
  3  -0.247                +  XXXXXXI         +
  4  -0.246                +  XXXXXXI         +
  5  -0.010               +          I         +
  6   0.068               +          IXX       +
  7  -0.054               +         XI         +
  8   0.046               +          IX        +
  9   0.048               +          IX        +
 10   0.139               +          IXXX      +

PACF   VAR IS RESID_Y1. MAXLAG IS 10. /

PARTIAL AUTOCORRELATIONS
  1- 10     -.01 -.05 -.25 -.27 -.07 -.04 -.22 -.08  .01  .10
  ST.E.      .18  .18  .18  .18  .18  .18  .18  .18  .18  .18

PLOT OF PARTIAL AUTOCORRELATIONS
          -1.0 -0.8 -0.6 -0.4 -0.2  0.0  0.2  0.4  0.6  0.8  1.0
LAG    CORR. +----+----+----+----+----+----+----+----+----+----+
                                     I
  1  -0.006                +         I        +
  2  -0.050                +        XI        +
  3  -0.248                +  XXXXXXI         +
  4  -0.272                + XXXXXXXI         +
  5  -0.071                +       XXI        +
  6  -0.036                +        XI        +
  7  -0.216                +   XXXXXI         +
  8  -0.082                +       XXI        +
  9   0.010                +         I        +
 10   0.099                +         IXX      +
=================================================================
```

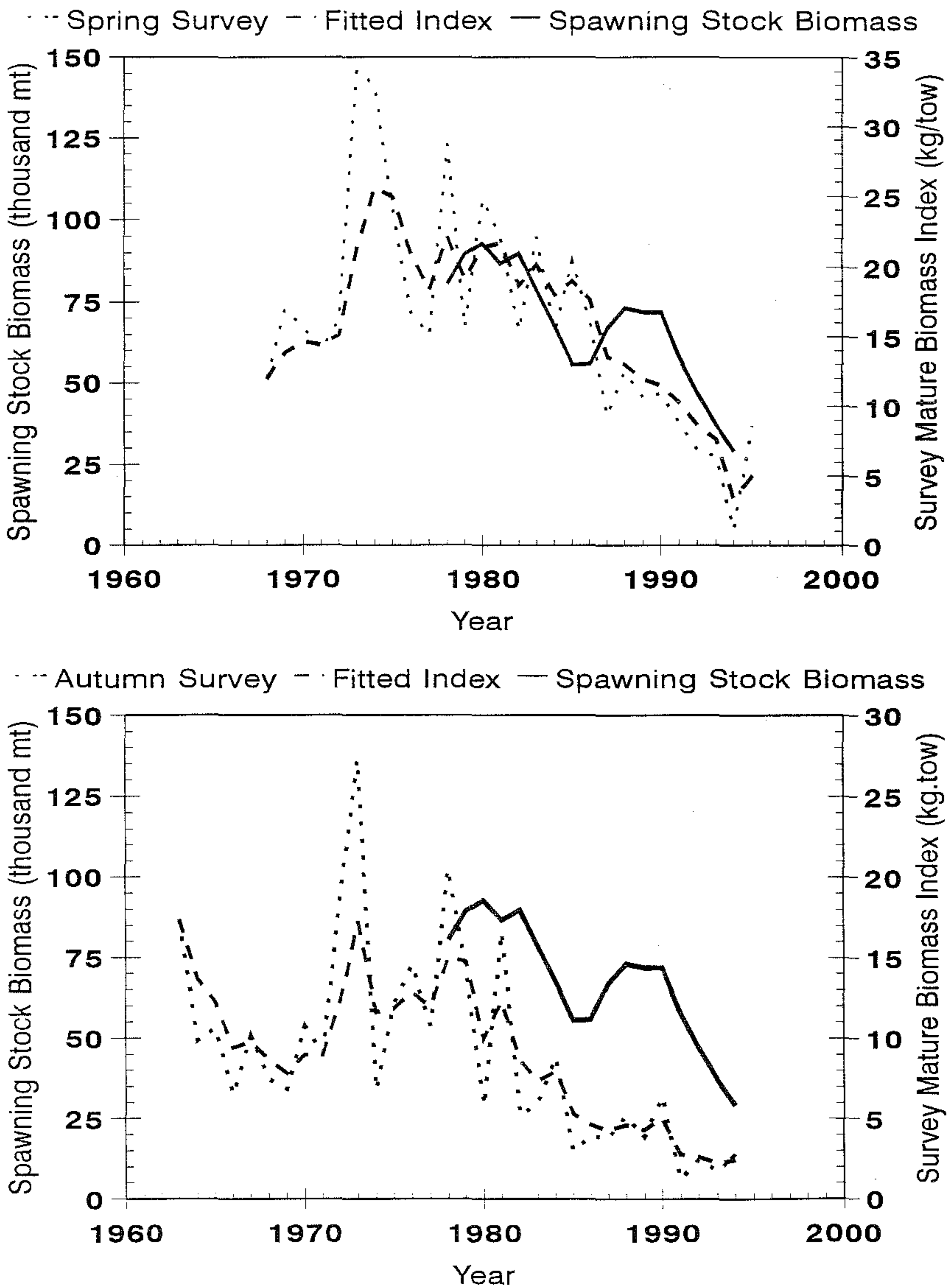


Figure 1. Georges Bank cod spawning stock biomass from VPA and NEFSC survey mature biomass indices.

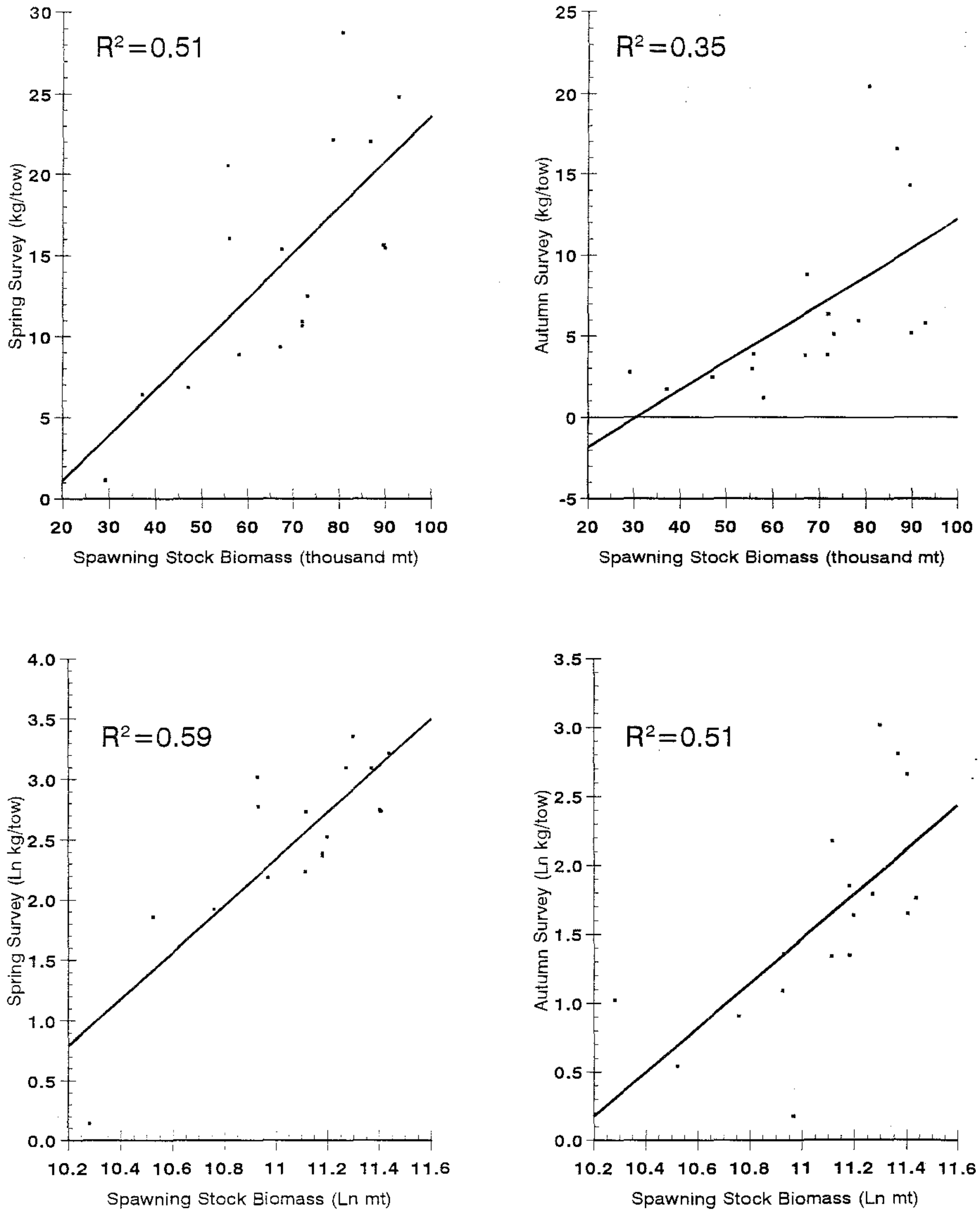


Figure 2. Linear and log-linear relationships between Georges Bank cod spawning stock biomass from VPA (NEFSC 1994a) and NEFSC survey mature biomass indices.

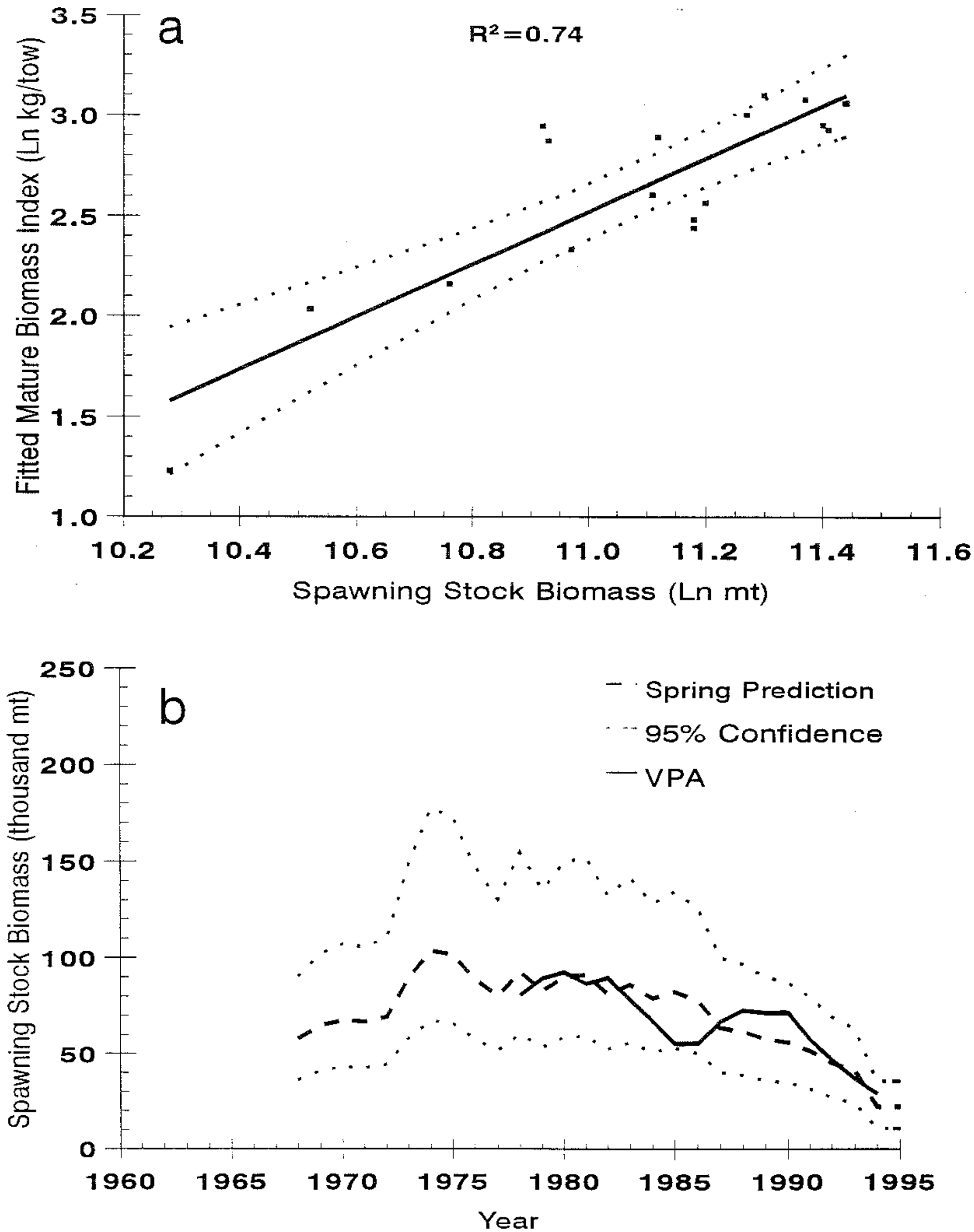


Figure 3. Predicted spawning stock biomass of Georges Bank cod: (a) relationship of SSB and the fitted spring survey mature biomass index with 95% prediction limits, (b) predicted SSB 1968-1995.

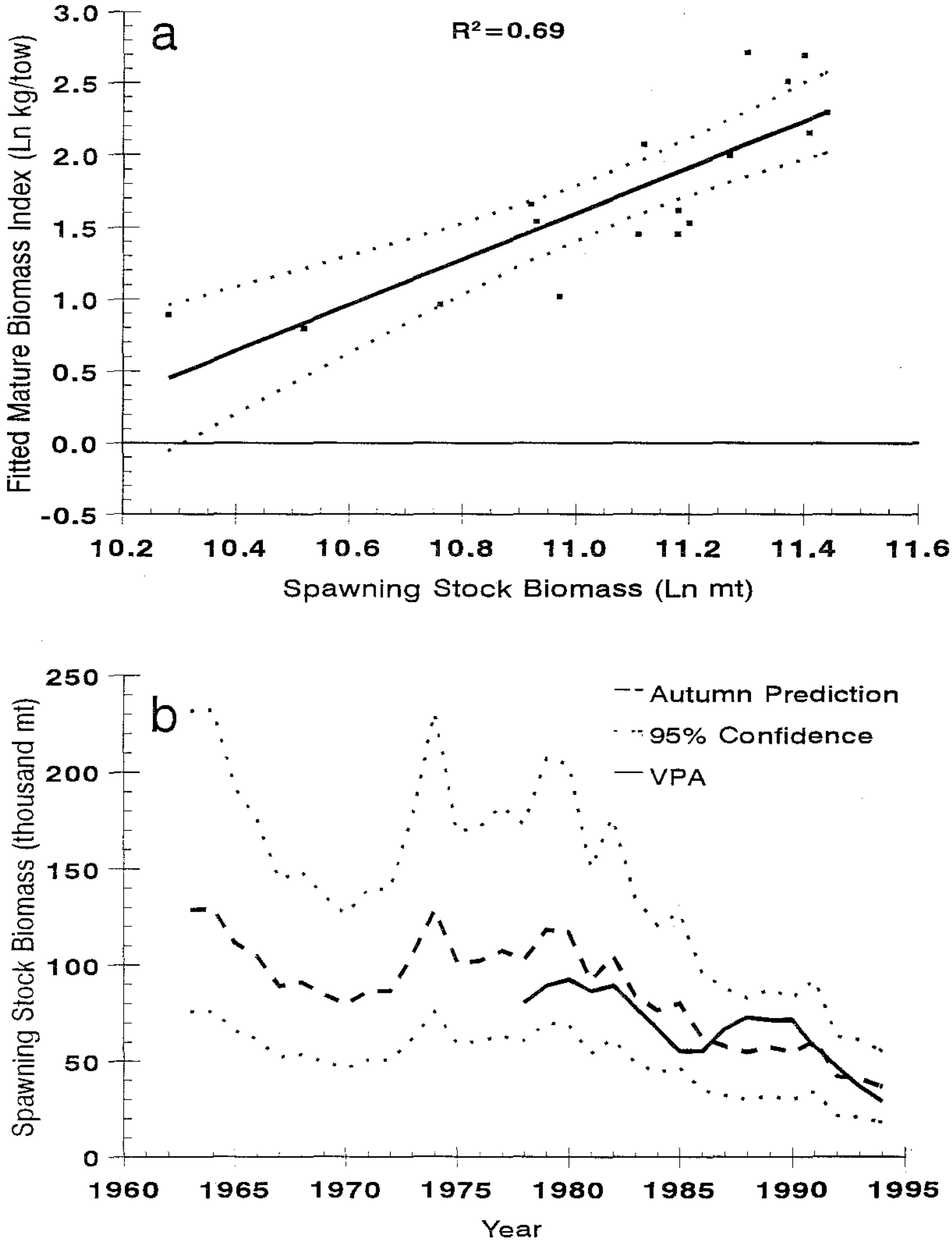
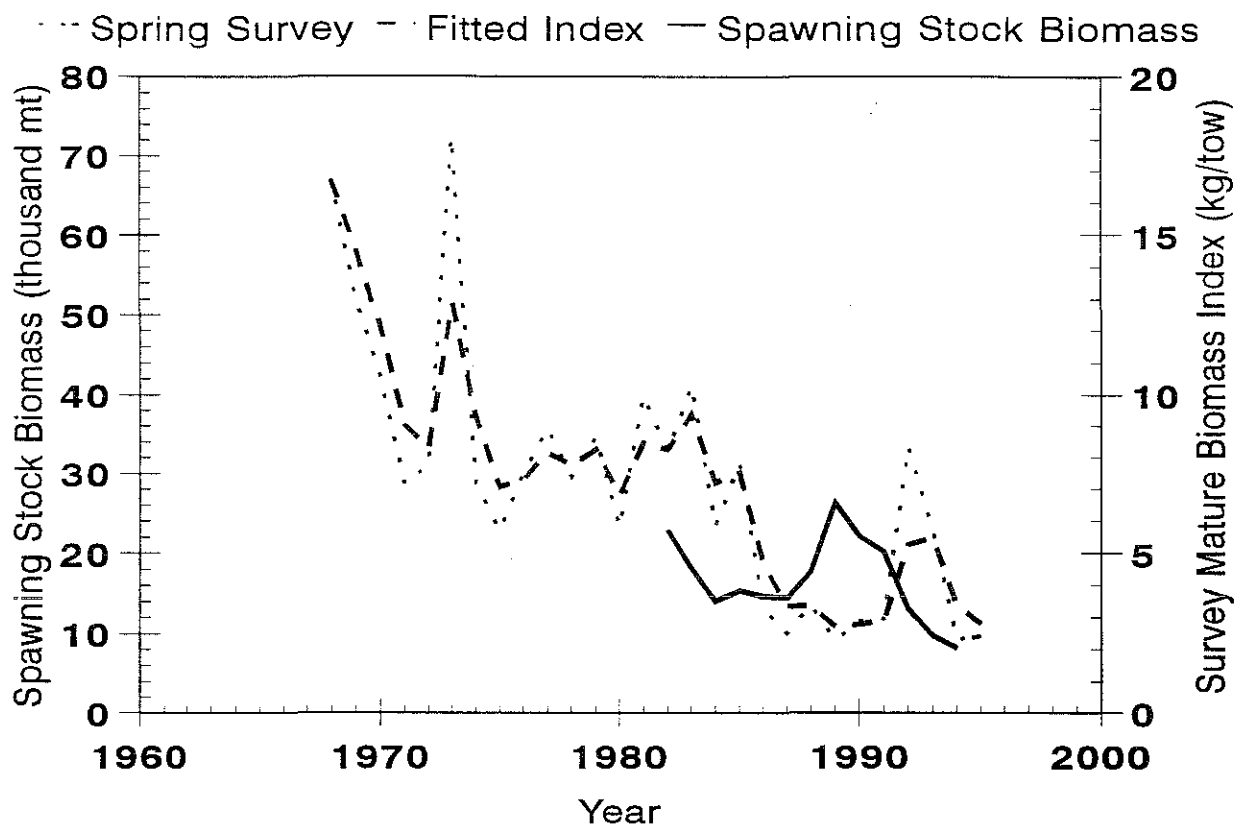


Figure 4. Predicted spawning stock biomass of Georges Bank cod: (a) relationship of SSB and the fitted autumn survey mature biomass index with 95% prediction limits, (b) predicted SSB 1963-1994.



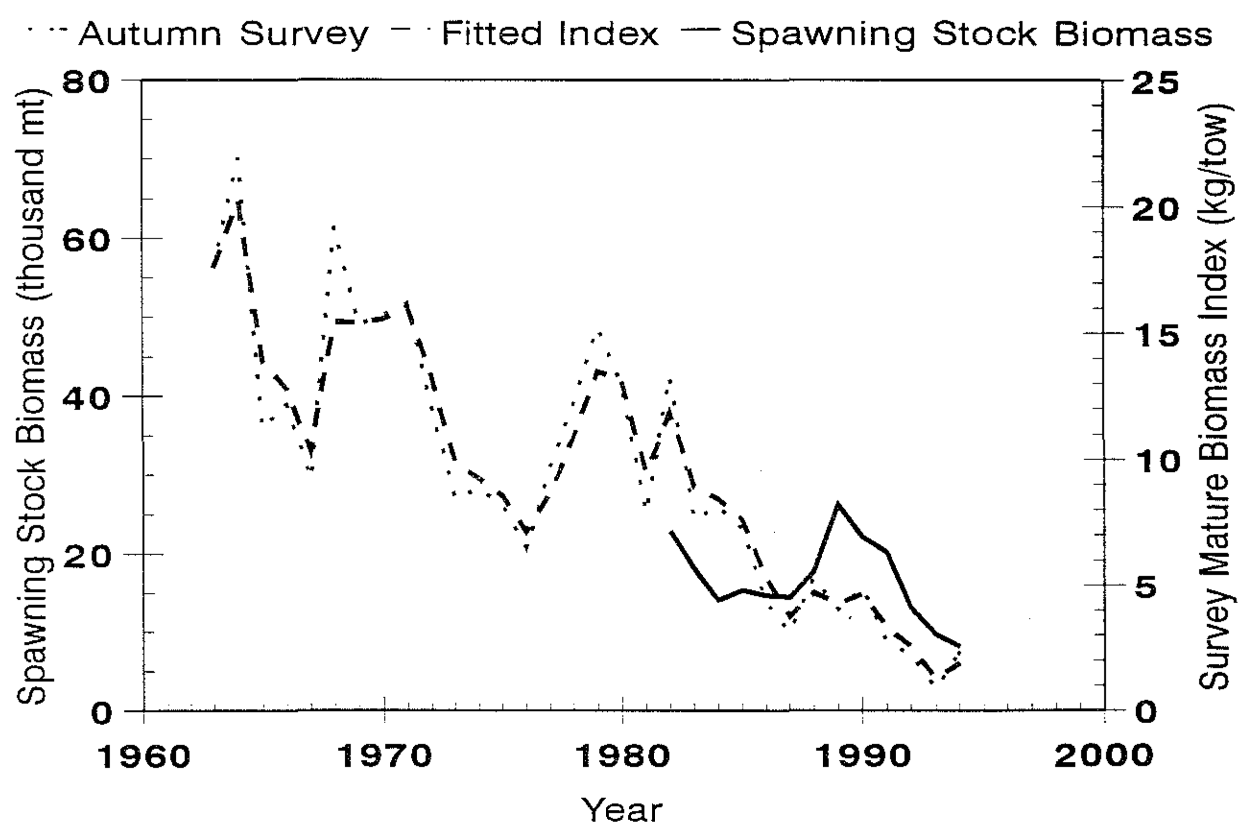


Figure 5. Gulf of Maine cod spawning stock biomass from VPA and NEFSC survey mature biomass indices.

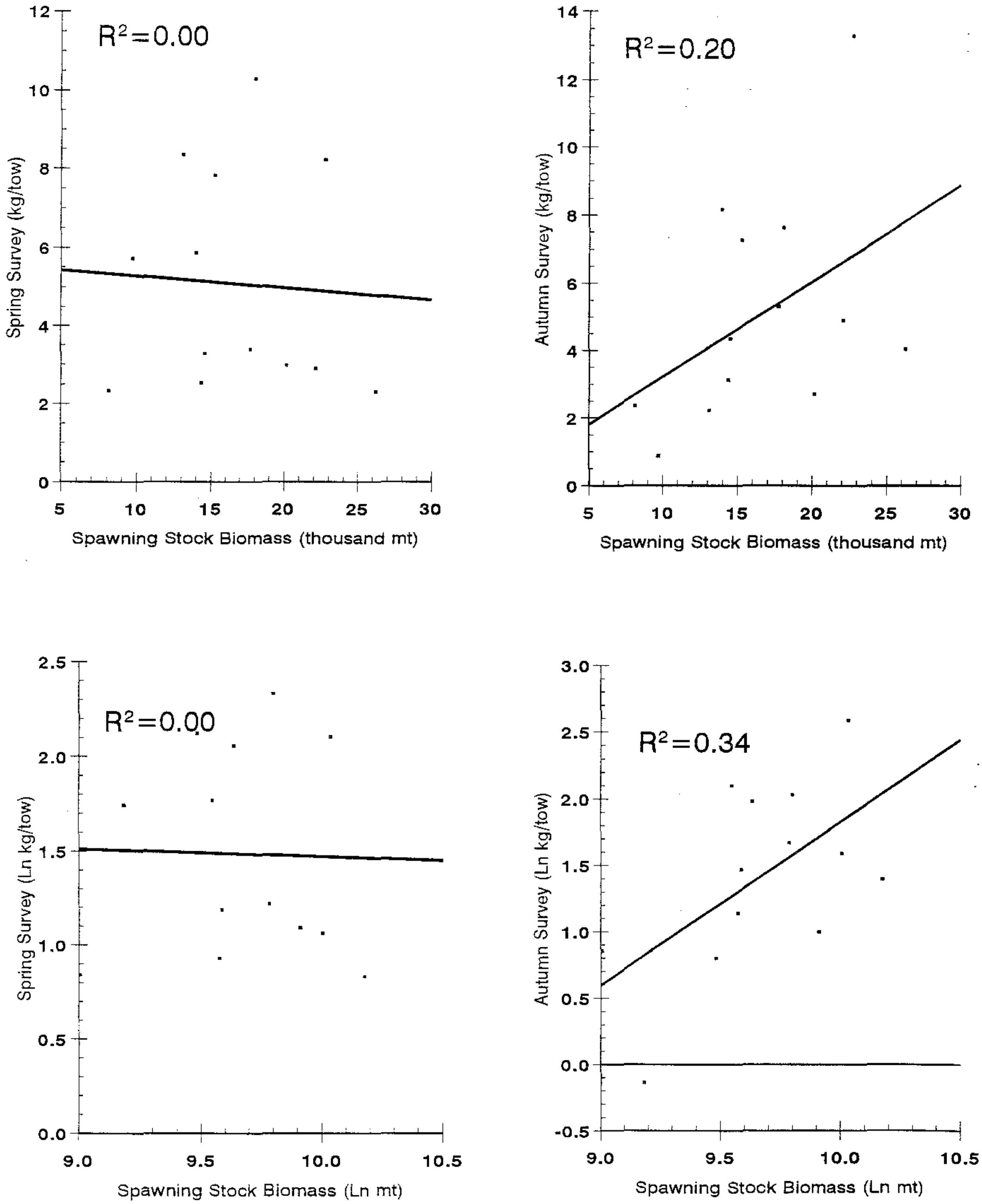


Figure 6. Linear and log-linear relationships between Gulf of Maine cod spawning stock biomass from VPA (NEFSC 1994b) and NEFSC survey mature biomass indices.

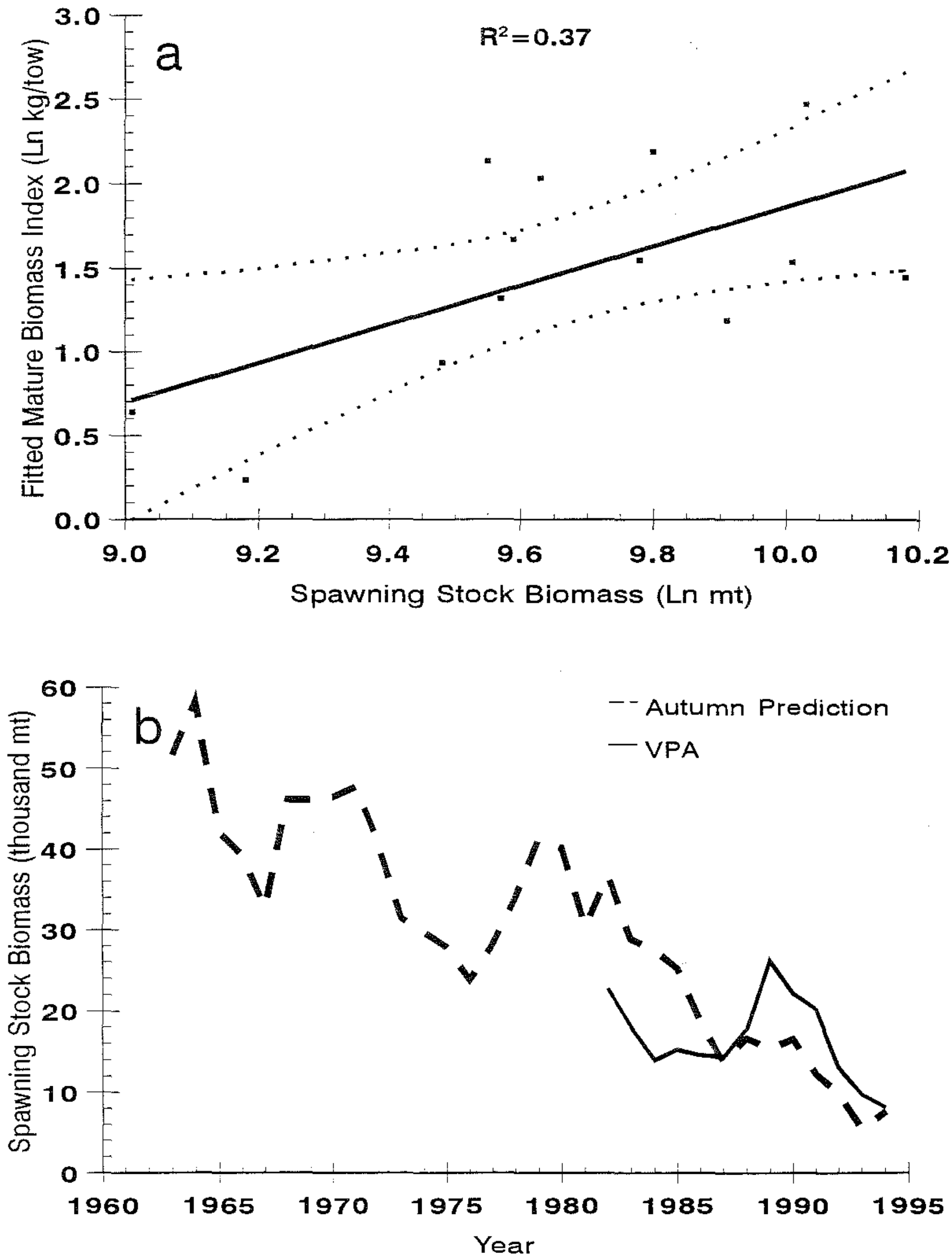


Figure 7. Predicted spawning stock biomass of Gulf of Maine cod: (a) relationship of SSB and the fitted autumn survey mature biomass index with 95% prediction limits, (b) predicted SSB 1963-1994.