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QLSPA Estimates of Greenland Halibut Stock Size

by

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Abstract

SPA's for Greenland Halibut in NAFO Divisions 2J and 3K are presented. These SPA's are intended to be illustrative only because of uncertainties about stock structure and the magnitude of the historical commercial catch that has been reported for this stock. Nonetheless, the illustrative SPA's presented in this paper should give some indication of the size of the Greenland Halibut stock, and the problems associated with using SPA as an assessment tool for this stock. A series of SPA's are presented, starting with a simple model structure. For each SPA in the series only a few modelling assumptions are changed, and the effect of the changes are illustrated. The final SPA is fairly consistent with the stock size indices used for estimation, although the modelling assumptions required to produce this consistency are tenuous. This SPA suggests the 2000 stock biomass for ages 5-17 is 220 000 tonnes, which is the highest observed since 1975. The next highest biomass estimates is 210 000 tonnes in 1991.

1 Introduction

In this paper SPA's for Greenland Halibut in NAFO Divisions 2J and 3K are presented. These SPA's are intended to be illustrative only. This is because there are considerable uncertainties about stock structure and the magnitude of historical commercial catches reported for this stock. Another problem is that the survey indices used for estimation cover different sub-components of the stock, and are therefore difficult to interpret. Nonetheless, the illustrative SPA's presented in this paper should give some indication of the size of the Greenland Halibut stock, and the problems associated with using SPA as an assessment tool for this stock.

QLSPA (Cadigan, 1998) is used for estimating SPA parameters. The SPA part of QLSPA is based on the assumption that the commercial catches are removed at the middle of each year. Let N_{ay} denote the unknown beginning of year stocks numbers at age a in year y, and let C_{ay} denote the fraction of N_{ay} caught by the commercial fishery each year. These catches are assumed to be known exactly. The cohort model used in QLSPA is

$$N_{a+1\,y+1} = N_{ay}e^{-M_{ay}} - C_{ay}e^{-M_{ay}/2}, \quad (1)$$

where M_{ay} is the natural mortality which is also assumed to be known or estimated from other information. Model (1) is commonly used in fisheries, and provides very reasonable results even if the fishery is prosecuted at times other than the mid-year (see Mertz and Myers, 1996). If estimates of the stock numbers-at-age in the last year (survivors) plus the stock numbers at the oldest age in the SPA are available then (1) can be used to reconstruct the complete stock size for all ages and years given the C_{ay}'s and M_{ay}'s.

The survivors and the numbers at the oldest age can be estimated when indices of stock abundance are available, although a common approach is to use an approximation for the numbers at the oldest age (see **Section 2.2**). Let R_{say} denote the value of the sth index for age a and year y. The basic relationship we consider is $R_{say} \approx q_{sa}N_{ay}$. The q_{sa} term is referred to as the catchability of the index, and is typically unknown but nominally assumed to be the same from year to year. If an index is measured at a fraction t since the beginning of the year then the index is compared with stock numbers at the same time; that is $R_{say} \approx q_{sa}N_{ay}(t)$, where

$$N_{ay}(t) = N_{ay}^{1-t} N_{a+1\,y+1}^{t}.$$

Stock numbers-at-age and catchabilities are commonly estimated (e.g. Gavaris, 1988; Myers and Cadigan, 1995) using nonlinear least squares with (1) and a stochastic observation model

$$\log(R_{say}) = \log(q_{sa}) + \log\{N_{ay}(t)\} + \varepsilon_{say}, \tag{2}$$

where ε_{say} is a random error term with mean zero and constant, but unknown, variance. The variance term includes both measurement variability in the indices and process error in (1). QLSPA involves even more general estimation procedures than does the approach based on (2). QLSPA is described in the next section.

2 Quasi-likelihood estimators of stock abundance

The QL part of QLSPA stands for quasi-likelihood, and is the method used for estimation and inference. Quasi-likelihood methods allow more arbitrary models for the variance of the indices than are implied by (2). The variance function can easily be specified to accommodate Normal, Poisson, and Gamma/Lognormal types of variation. Quasi-likelihood methods are semi-parametric in that they do not require completely specified stochastic models for the relative abundance indices used in estimation. Lee and Nelder (1999) concluded that when the sample size is small and the exact form of the probability distribution of the data is unknown and accurate estimates of the third and fourth order moments (i.e. $E(R^3)$ and $E(R^4)$) are not available then Quasi-likelihood estimation is the most practical choice. Also, these estimators possess certain optimality properties that suggest they should provide reasonable SPA inference. In this section a brief review of quasi-likelihood estimation theory is first presented, followed by specific procedures for estimating stock abundance using SPA's.

2.1 Overview of quasi-likelihood theory

Quasi-likelihood estimators are based only on assumptions about the mean and variance of a random variable. The mean and variance functions we assume for stock abundance indices are

$$\begin{aligned} E(R_{say}) &= \mu_{say} = q_{say}N_{ay}(t), \\ Var(R_{say}) &= \phi_s v(\mu_{say}, \theta), \end{aligned} \tag{3}$$

where ϕ_s is a dispersion parameter. The variance function $v(\mu, \theta)$ depends on μ and θ, and θ may be known or unknown. A wide variety of data can be efficiently analyzed using this model. For example, normally distributed indices can be analyzed by taking $v(\mu, \theta) = \mu^{\theta}$ with $\theta = 0$; Poisson distributed indices can be analyzed with the same v and $\theta = 1$; gamma or lognormally distributed indices can be analyzed with $\theta = 2$. The latter specification for θ leads to a constant coefficient of variation model and is commonly used for fisheries data. In practise θ is often chosen through trial and error with the aid of residual plots. It is possible to estimate θ, and this will be used with the Greenland Halibut stock.

Quasi-likelihood estimators are defined in terms of an estimating equation from which a fit function, or quasi-likelihood, can often be developed. For independent random variables a quasi-likelihood can always be constructed, which is the case in this paper. The quasi-likelihood has many of the same properties that a regular likelihood function has. When the variance function is different for some parts of the data then the quasi-likelihood can be used to combine information from the different parts of the data. We show how to do this at the end of this section.

The estimating equation for the sth index is

$$\sum_{a,y} \frac{r_{ay} - \mu_{ay}}{\phi v(\mu_{ay}, \theta)} \dot{\mu}_{ay}, \tag{4}$$

where $\dot{\mu}_{ay}$ is the derivative of μ_{ay} with respect to the unknown parameters. The lower case r denotes an observed index. The unknown N_{ay}'s in (1) and the q's in (3) are estimated as the solution of setting (4) equal to zero. Equation (4) is optimal among all equations that are linear in r (see McCullagh and Nelder, 1989). The quasi-likelihood function associated with this model is

$$Q(r, \mu) = \int_r^\mu \frac{r - t}{\phi v(t, \theta)} dt.$$

The deviance function

$$D(r, \mu) = -2\phi Q(r, \mu)$$

is a measure of the discrepancy between r and μ.

The deviance for the power of the mean variance model ($v(\mu, \theta) = \mu^\theta$; see Nelder and Pregibon, 1987) is

$$D(r, \mu) = \begin{cases} 2[r \log(r/\mu) - (r - \mu)], & \text{if } \theta = 1, \\ 2[r/\mu - \log(r/\mu) - 1], & \text{if } \theta = 2, \\ 2\left[\frac{r^{2-\theta} - (2-\theta) r \mu^{1-\theta} + (1-\theta)\mu^{2-\theta}}{(1-\theta)(2-\theta)}\right], & \text{if } \theta \neq 1, 2. \end{cases} \tag{5}$$

Note that when $\theta \geq 2$ then $D(r, \mu)$ is not defined for $r = 0$.

Another useful variance model is $v(\mu, \theta) = \theta\mu + (1 - \theta)\mu^2$, where we constrain $\theta \in [0, 1]$ so that ϕ is identifiable. Several empirical examples of fisheries data exhibit variability that follows this quadratic variance model. The advantage of this model is that when μ is large then the coefficient of variation is approximately constant, which is often suitable for biological data. Prior to the collapse of many fish stocks off the east-coast of Canada μ was relatively large for all ages and years, and a constant coefficient of variation model was suitable. This may be why (2) was widely used by stock assessment scientists (i.e. it is suitable for constant coefficient of variation models). On the other hand when μ is very small then $v(\mu, \theta)$ is approximately linear in μ which also often appears suitable for biological data. The deviance for the quadratic variance model is given by

$$D(r, \mu) = 2 \log \left\{ \frac{\theta + (1 - \theta)\mu}{\theta + (1 - \theta) r} \right\} \left\{ \frac{r}{\theta} + \frac{1}{1 - \theta} \right\} - \frac{2r}{\theta} \log \left(\frac{\mu}{r} \right).$$

This deviance is defined for all $r \geq 0$. The total deviance for all ages and years is $D = \sum_{a,y} D(r_{ay}, \mu_{ay})$.

If the variance functions for indices differ, as will often be the case, then the deviances can no longer be added together. For example, variance functions may differ if we use stock size indices from different surveys and we do not wish to assume that the dispersion parameters (ϕ_s's) are the same for each survey. In this case we use a df-adjusted extended quasi-likelihood function (Nelder and Pregibon, 1987):

$$Q^+(r_s, \mu) = -\frac{1}{2} \log \{2\pi\phi_s v_s(r_s, \theta_s)\} - \frac{1}{2} D_s(r_s, \mu)/\phi_s. \tag{6}$$

The combined extended quasi-likelihood for all sets of indices is $Q^+ = \sum_s \sum_{a,y} Q^+(r_{say}, \mu_{say})$. The fit function used for stock size inferences is

$$\Lambda = -2Q^+. \tag{7}$$

The standard errors produced by QLSPA come from the approximation

$$Cov(\hat{\beta}) = \frac{1}{2} \frac{\partial^2 \Lambda(\beta)}{\partial\beta\partial\beta'}\bigg|_{\beta=\hat{\beta}}, \tag{8}$$

where β is a vector of all the SPA parameters that are estimated. It is my experience that confidence intervals (CI's) based on these standard errors have better accuracy when the CI's are based on the ln parameterization; that is, when β is actually the $\ln(\cdot)$ of the SPA parameters. For example, if $N_{1Y} = \exp(\beta_1)$ then a $(1-\alpha)100\%$ confidence interval for N_{1Y} is better approximated as

$$\exp\left\{\hat{\beta}_1 \pm Z_{1-\alpha/2} \times s.e.(\hat{\beta}_1)\right\}.$$

In all of the runs presented below the ln of parameters were estimated, and the ln standard errors are reported as CV's. This is because the standard error of $\hat{\beta}$ is the CV of $\exp(\hat{\beta})$.

2.2 Parameter constraints

In practise many of the unknown parameters in (1) and (3) are removed using constraints. Usually the q_{say}'s are constrained to be equal for all years. In QLSPA the q's are merely assumed to be equal for d_s disjoint sets of ages and years, denoted as $C_{s1}, ..., C_{sd_s}$. The unknown numbers at the oldest age (N_{Ay}) in the SPA are also constrained as follows. Define the fishing mortality for N_{ay} as

$$F_{ay} = \log(\frac{N_{ay}}{N_{a+1\,y+1}}) - M_{ay}. \tag{9}$$

When F is small then $F \doteq C/N$. The N_{Ay}'s are constrained so that their fishing mortalities are proportional to the average for some range of younger ages. In effect,

$$N_{Ay} = \alpha_y \frac{C_{Ay} e^{M_{Ay}/2}}{1 - e^{-F_{\text{ave}\ y}}}.$$

Note that $F_{\text{ave}\ y}$ is a function of $N_{a\,y+1}$'s, so the result of the F constraint is that N_{Ay}'s are constrained to be functions of α_y's and unknown survivors. Hence, the only unknown parameters in the cohort model are the survivors and the α_y's. There are potentially as many α_y's as there are N_{Ay}'s; however, it is often reasonable to constrain the α_y's. In many assessments the α_y's are all assumed to be equal to a constant (usually one), although in QLSPA it is possible to estimate the α_y's.

3 SPA runs

In this section a sequence of SPA's are presented. The sequence starts with the QLSPA that is most similar to the ADAPT approach commonly used in the assessment of fish stock off the east-coast of Canada. Other QLSPA's are then presented in which a small number of assumptions are relaxed and/or changed to make them more realistic. First we present the common assumptions used in most of the SPA's.

3.1 Cohort model

The SPA is based on total catch of Greenland Halibut for ages $a = 5, ..., 17$ during years $y = 1975, ..., 1998$ in NAFO Divisions 2J and 3K. The cohort model was run to age 2 by approximating the commercial catches at ages 2-4 as zeros.

1. Natural mortality (M_{ay}) was assumed to be 0.2 for all a and y.
2. Fishing mortalities (F's) on age 17 in 1975-1999 were set equal to the average F's for ages 14 to 16.
3. No "plus" age class.

The α_y's used with the F constraints are constrained to be equal over four time periods: 1975-1985, 1986-1990, 1991-1995, and 1996-1998. The α's were also constrained so that $0.9 \leq \alpha \leq 1.1$. The rationale for this constraint is that we feel it is unrealistic that the fishery selectivity at age 17 can vary substantially from the average over ages 14-16. At these ages we feel the fishery selectivity should change only slowly with age, which is what our boundary constraints on the α's imply.

3.2 Stock size indices

Two indices of stock size (R_{ay}) were used for estimation purposes. They are:

1. Canadian RV survey of 2J3K ($R_{1ay};\ a = 2, ..., 17,\ y = 1978 - 1999$),
2. EU survey of the Flemish Cap, ($R_{2ay};\ a = 2, ..., 12,\ y = 1991 - 1999$).

Each index is assumed to be proportional to stock size at some time within a year. The catchability models for the survey indices are:

1. $E(R_{1ay}) = q_{1a}N_{ay}(t),\ t = 0.83;$
2. $E(R_{2ay}) = q_{2a}N_{ay}(t),\ t = 0.83.$

The variance model used in each run usually is

$$Var(R_{say}; \theta) = \phi_s \left\{ \theta_s \mu_{ay} + (1 - \theta_s)\mu_{ay}^2 \right\}.$$

The dispersion parameter ϕ is estimated separately for each index, which is called self-weighting. A lower bound on the ϕ_s parameter is used (i.e. $\phi_s \geq 0.3$) so that one survey cannot get a relatively large "weight" in estimation. The variance parameter θ is also estimated separately for each index.

3.3 Run1: No year effects

The Canadian RV indices for ages 13-17 are difficult to model because Halibut at these ages are caught infrequently in the survey. Nonetheless, this information should not be ignored. We use a constant variance model (i.e. $Var(R) = \phi$) for the Canadian RV age 13-17 indices because there are many zeros in the data during the 1990's and a relative error variance model is problematic because it only affects the non-zero indices. The age 13-17 Canadian RV indices are treated as a separate survey, and are weighted separately from the 5-12 Canadian indices. The rationale for this is that many people argue that the "error" in the indices for older age fish is greater than the error in the indices for younger age fish.

Parameter estimates are presented in Table 1. Unfortunately the $\frac{1}{2}$ in equation (8) was omitted from the variance calculation by mistake. Hence, the CV's in Table 1 should be multiplied by $\sqrt{1/2}$. This is the same for all other runs considered (Tables 2-3). Abundance and biomass estimates are given in Figure 1. The goodness-of-fit plot in Figure 2 suggests there are mis-specifications in the model however.

3.4 Run2: Year effects

Figure 2 suggests rather consistent annual discrepancies between the SPA and stock size indices. These discrepancies are auto-correlated. A possible mechanism for this is that the catchability of the stock by the two surveys has changed gradually over the years. This could be explained by a gradual migration of Greenland Halibut out of the survey regions. In this run we account for this by introducing years effects to the catchability model. The year effects are assumed to vary only slowly over time. This is in contrast to Cadigan and Myers (1995), who modelled year effects as random variables having no relationship between years (i.e. independent).

The survey catchability model in this run is

$$E(R_{say}) = \tau_y q_{sa} N_{ay}(t_s).$$

We set $\tau_{1998} = 1$ so that the other τ's can be uniquely estimated. There are many ways to constrain the τ's to vary smoothly over time. We choose a simple approach in which we add a penalty term to (7). This penalty term increases as the between year variation in τ increases.

The penalized extended quasi-likelihood fit function we use to estimate year effects and the other SPA parameters is

$$\Lambda_p = -2\sum_s \sum_{a,y} Q^+(r_{say}, \mu_{say}) + \gamma \sum_{y=2}^{Y} (\tau_y - \tau_{y-1})^2/(Y-1).$$

The γ term is fixed, and controls the strength of the penalty term. If $\gamma = 0$ then the penalty term has no effect, and the τ's are estimated freely. Note that if all the τ's are equal then the penalty term is also zero. There are criteria for choosing good values for γ; however, we simply choose a value small enough to remove the discrepancies between the stock size indices and the SPA. We also investigate the sensitivity of our results to the choice of γ.

The standard errors are tentatively based on the Hessian of Λ_p and may not be reliable. This is not the standard approach when using an estimating equation that is not the score function of a likelihood or quasi-likelihood, and $\partial\Lambda_p(\beta)/\partial\beta$ is not such a function. Inferences based on the penalized fit function are difficult, and further research about how to do this is required. All I can say is that the standard errors are almost surely larger than those presented in Tables 2-3 (when multiplied by $\sqrt{1/2}$).

Through trial and error we found that $\gamma = 1000$ gave reasonable results. Parameter estimates are presented in Table 2. Comparisons of the stock size estimates from this run and from **Run1** are presented in Figure 3. Discrepancies between the SPA and aggregate indices are shown in Figure 4. The year effects run resulted in lower estimates of young fish in recent years. The results in Table 2 suggest that the Canadian RV indices for ages 13-17 have received the most weight in estimation. A better approach for modelling these indices may be to aggregate them (i.e. sum over age). This can reduce the effect of aging errors.

3.5 Run3: Aggregate Can RV 13+, year effects

In this run we treat the Canadian RV indices for ages 13-17 as an aggregate. The catchability model is

$$E(R_{sy}) = \tau_y q_s \sum_a w_{ay} N_{ay}(t_s).$$

We use the same variance model and ϕ with the 13+ indices as with the 2-12 indices. All of the QLSPA results are presented in Table 3. Various plots of the SPA output are presented in Figure 5-16. The estimated year effects are shown in Figure 7. They suggest a decline in Greenland Halibut catchability starting in 1985. Catchability appears to have been increasing since 1992. There are systematic residual patterns (see Figure 12 and Figure 16) that suggest the SPA formulation is still mis-specified.

4 Discussion and Conclusions

The year effects run (**Run3**) is simply an interpretation of the reported commercial catch for 2J3K Greenland Halibut that is more consistent with the research surveys indices and the CPUE indices than the run without year effects that we presented.

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5 Appendix: Tables

Table 1. QLSPA parameter estimates from **Run 1**.

```
CAN_RV_13+     index for years 1978 to 1999 , and ages 13 to 17. Var =  exp^0
CAN_RV_2-12    index for years 1978 to 1999 , and ages  2 to 12. Var =  Quadratic
EU_RV          index for years 1991 to 1999 , and ages  2 to 12. Var =  Quadratic
-------------------------------------------------------------------------

Extended Deviance =  3499.2 , df =  403 , #Parms =   48

Penalty =    0.00

Var scale =  CAN_RV_13+      0.300
             CAN_RV_2-12     3.426
             EU_RV          15.379
```

Quadratic Var Const	Estimate	Std. Err	95% L	95% U
CAN_RV_2-12	0.919	0.019	0.886	0.954
EU_RV	0.979	0.010	0.959	0.998

Age	Survivors	CV	95% L	95% U
2	154283.1	0.29	88146.16	270043.4
3	157876.4	0.21	105469.5	236323.8
4	255236.0	0.17	181734.1	358465.4
5	226029.7	0.15	167060.7	305813.6
6	105312.1	0.13	80841.55	137189.7
7	42110.89	0.13	32394.14	54742.22
8	21115.77	0.15	15642.02	28505.00
9	8676.80	0.23	5554.98	13553.02
10	1702.67	0.25	1042.24	2781.59
11	766.96	0.32	408.49	1440.02
12	361.66	0.12	283.34	461.63
13	160.29	0.04	149.55	171.80
14	97.26	.	.	.
15	48.63	.	.	.
16	14.37	.	.	.

Year Effect Constraint	Effect	CV	95% L	95% U
.	1.00	.	1.00	1.00

F Constraint	Estimate	CV	95% L	95% U
F17_X_1975-85	0.900	.	.	.
F17_X_1986-90	0.900	.	.	.
F17_X_1991-95	1.100	.	.	.
F17_X_1996-99	1.100	.	.	.

Q_CONST	Estm (x1000)	CV	95% L	95% L
CAN_RV_02	1.4680	0.09	1.2335	1.7470
CAN_RV_03	1.8710	0.09	1.5818	2.2130
CAN_RV_04	1.6026	0.08	1.3603	1.8880
CAN_RV_05	1.4744	0.09	1.2482	1.7418
CAN_RV_06	1.4041	0.09	1.1826	1.6671
CAN_RV_07	1.5859	0.09	1.3219	1.9025
CAN_RV_08	1.5630	0.11	1.2617	1.9361
CAN_RV_09	1.3537	0.15	1.0181	1.7999
CAN_RV_10	1.3645	0.19	0.9399	1.9808
CAN_RV_11	1.7359	0.22	1.1196	2.6915
CAN_RV_12	2.3250	0.26	1.3938	3.8782
CAN_RV_13	2.3617	0.13	1.8287	3.0499
CAN_RV_14	4.3988	0.16	3.2276	5.9949
CAN_RV_15	6.7438	0.25	4.1309	11.0094
CAN_RV_16	5.9088	0.50	2.2197	15.7290
CAN_RV_17	3.8119	1.15	0.3977	36.5374
EU_RV_02	6.9738	0.15	5.2002	9.3522
EU_RV_03	11.4174	0.15	8.5304	15.2815
EU_RV_04	23.8589	0.14	18.0426	31.5501
EU_RV_05	50.3254	0.14	38.3511	66.0385
EU_RV_06	117.641	0.14	90.0538	153.681
EU_RV_07	179.182	0.14	137.210	233.993
EU_RV_08	206.043	0.14	157.392	269.732
EU_RV_09	207.904	0.14	157.779	273.953
EU_RV_10	125.022	0.15	92.6852	168.641
EU_RV_11	65.5660	0.17	46.9002	91.6608
EU_RV_12	55.8937	0.22	36.5944	85.3713

Table 2. QLSPA parameter estimates from **Run 2**.

CAN_RV_13+	index for years 1978 to 1999 , and ages 13 to 17. Var =	exp^0
CAN_RV_2-12	index for years 1978 to 1999 , and ages 2 to 12. Var =	Quadratic
EU_RV	index for years 1991 to 1999 , and ages 2 to 12. Var =	Quadratic

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Extended Deviance = 3369.4 , df = 381 , #Parms = 70

Penalty = 14.52

Var scale =		
	CAN_RV_13+	0.300
	CAN_RV_2-12	1.514
	EU_RV	27.907

Quadratic Var Const	Estimate	Std. Err	95% L	95% U
CAN_RV_2-12	0.718	0.062	0.636	0.811
EU_RV	0.995	0.003	0.990	1.000

Age	Survivors	CV	95% L	95% U
2	58838.40	0.43	25567.94	135402.3
3	85615.07	0.34	44070.99	166321.2
4	155317.7	0.28	88954.94	271188.9
5	151382.5	0.24	94805.31	241723.4
6	67775.50	0.22	44205.93	103911.8
7	29353.63	0.20	19734.99	43660.32
8	14283.50	0.24	8851.55	23048.89
9	4071.73	0.41	1833.50	9042.25
10	1112.50	0.24	688.42	1797.83
11	491.61	0.34	252.66	956.56
12	347.11	0.05	313.91	383.82
13	160.25	.	.	.
14	97.26	.	.	.
15	48.63	.	.	.
16	14.37	.	.	.

Year Effect Constraint	Effect	CV	95% L	95% U
1978_YE	1.42	0.22	0.93	2.16
1979_YE	1.30	0.24	0.82	2.08
1980_YE	1.23	0.25	0.75	2.02
1981_YE	1.22	0.25	0.75	1.99
1982_YE	1.37	0.20	0.92	2.02
1983_YE	1.35	0.20	0.92	1.98
1984_YE	1.26	0.20	0.86	1.86
1985_YE	1.08	0.22	0.70	1.66
1986_YE	0.92	0.23	0.58	1.46

1987_YE	0.79	0.24	0.50	1.25
1988_YE	0.60	0.27	0.36	1.02
1989_YE	0.49	0.26	0.29	0.82
1990_YE	0.41	0.25	0.25	0.67
1991_YE	0.26	0.27	0.15	0.44
1992_YE	0.38	0.26	0.23	0.64
1993_YE	0.56	0.23	0.36	0.89
1994_YE	0.68	0.21	0.46	1.02
1995_YE	0.83	0.17	0.59	1.15
1996_YE	0.83	0.15	0.62	1.13
1997_YE	0.97	0.11	0.79	1.20
1998_YE	1.03	0.07	0.89	1.20
1999_YE	1.00	.	.	.

F Constraint	Estimate	CV	95% L	95% U
F17_X_1975-85	0.900	.	.	.
F17_X_1986-90	0.900	.	.	.
F17_X_1991-95	0.900	.	.	.
F17_X_1996-99	1.100	.	.	.

Q_CONST	Estm (x1000)	CV	95% L	95% L
CAN_RV_02	2.4840	0.32	1.3335	4.6271
CAN_RV_03	3.0402	0.29	1.7290	5.3458
CAN_RV_04	2.5471	0.26	1.5277	4.2467
CAN_RV_05	2.0621	0.25	1.2654	3.3604
CAN_RV_06	1.8085	0.24	1.1214	2.9164
CAN_RV_07	1.8770	0.24	1.1670	3.0190
CAN_RV_08	1.6625	0.24	1.0434	2.6489
CAN_RV_09	1.5101	0.25	0.9324	2.4458
CAN_RV_10	1.6152	0.25	0.9839	2.6517
CAN_RV_11	2.1347	0.26	1.2774	3.5674
CAN_RV_12	2.7997	0.27	1.6508	4.7482
CAN_RV_13	4.3788	0.23	2.8049	6.8358
CAN_RV_14	5.8245	0.25	3.5984	9.4278
CAN_RV_15	6.5707	0.32	3.5048	12.3187
CAN_RV_16	4.4603	0.55	1.5036	13.2312
CAN_RV_17	2.7061	1.21	0.2536	28.8734
EU_RV_02	15.0962	0.35	7.6197	29.9086
EU_RV_03	21.8389	0.31	11.8255	40.3313
EU_RV_04	44.5718	0.28	25.9710	76.4949
EU_RV_05	89.0972	0.25	54.4293	145.846
EU_RV_06	183.875	0.23	116.855	289.334
EU_RV_07	283.884	0.23	180.647	446.119
EU_RV_08	312.121	0.23	198.942	489.687
EU_RV_09	317.528	0.23	201.689	499.899
EU_RV_10	211.489	0.24	132.553	337.433
EU_RV_11	119.847	0.26	71.8098	200.019
EU_RV_12	92.9561	0.30	52.1344	165.742

Table 3. QLSPA parameter estimates from **Run 3**.

```
CAN_RV        index for years 1978 to 1999 , and ages  2 to 12. Var =  Quadratic
EU_RV         index for years 1991 to 1999 , and ages  2 to 12. Var =  Quadratic
```

Extended Deviance = 3319.1 , df = 297 , #Parms = 66

Penalty = 13.95

Var scale =		
	CAN_RV	1.559
	EU_RV	25.083

Quadratic Var Const	Estimate	Std. Err	95% L	95% U
CAN_RV	0.753	0.055	0.677	0.838
EU_RV	0.994	0.003	0.988	1.000

Age	Survivors	CV	95% L	95% U
2	73283.73	0.45	30157.57	178081.5
3	101492.5	0.37	49579.18	207763.2
4	178179.6	0.31	97086.91	327005.7
5	169384.4	0.26	101308.9	283203.9
6	75359.54	0.24	47075.84	120636.4
7	32152.36	0.22	20771.13	49769.76
8	15783.35	0.26	9438.40	26393.68
9	4948.32	0.45	2028.94	12068.30
10	1228.64	0.28	705.35	2140.17
11	547.56	0.38	257.50	1164.33
12	348.51	0.06	310.63	391.00
13	168.46	0.15	125.06	226.91
14	97.30	0.03	91.10	103.93
15	49.73	0.34	25.51	96.95
16	14.37	0.16	10.58	19.53

Year Effect Constraint	Effect	CV	95% L	95% U
1978_YE	1.35	0.25	0.82	2.23
1979_YE	1.23	0.29	0.70	2.17
1980_YE	1.19	0.30	0.66	2.14
1981_YE	1.24	0.28	0.72	2.13
1982_YE	1.35	0.23	0.85	2.14
1983_YE	1.35	0.23	0.87	2.10
1984_YE	1.30	0.23	0.83	2.01
1985_YE	1.15	0.24	0.72	1.86
1986_YE	1.02	0.25	0.62	1.68
1987_YE	0.88	0.26	0.53	1.47

1988_YE	0.70	0.29	0.39	1.25
1989_YE	0.61	0.28	0.35	1.05
1990_YE	0.49	0.27	0.29	0.84
1991_YE	0.31	0.31	0.17	0.56
1992_YE	0.45	0.28	0.26	0.78
1993_YE	0.66	0.24	0.41	1.05
1994_YE	0.77	0.21	0.51	1.18
1995_YE	0.91	0.17	0.64	1.27
1996_YE	0.90	0.16	0.66	1.22
1997_YE	1.02	0.11	0.82	1.26
1998_YE	1.05	0.07	0.91	1.22
1999_YE	1.00	.	.	.

F Constraint	Estimate	CV	95% L	95% U
F17_X_1975-85	0.900	.	.	.
F17_X_1986-90	0.900	.	.	.
F17_X_1991-95	0.900	.	.	.
F17_X_1996-99	1.100	.	.	.

Q_CONST	Estm (x1000)	CV	95% L	95% L
CAN_RV_02	2.1197	0.34	1.0812	4.1558
CAN_RV_03	2.6187	0.31	1.4176	4.8375
CAN_RV_04	2.2214	0.28	1.2755	3.8689
CAN_RV_05	1.8361	0.27	1.0788	3.1251
CAN_RV_06	1.6321	0.27	0.9683	2.7509
CAN_RV_07	1.7166	0.27	1.0201	2.8886
CAN_RV_08	1.5645	0.26	0.9355	2.6166
CAN_RV_09	1.4324	0.27	0.8416	2.4378
CAN_RV_10	1.5350	0.28	0.8891	2.6501
CAN_RV_11	2.0310	0.29	1.1580	3.5620
CAN_RV_12	2.6533	0.29	1.4943	4.7112
CAN_RV_13+	4.3017	0.28	2.4839	7.4497
EU_RV_02	12.3790	0.38	5.8738	26.0885
EU_RV_03	18.3438	0.34	9.4230	35.7099
EU_RV_04	38.2399	0.30	21.1949	68.9927
EU_RV_05	77.3883	0.27	45.2125	132.462
EU_RV_06	161.912	0.25	99.0145	264.763
EU_RV_07	250.492	0.25	153.330	409.226
EU_RV_08	275.928	0.25	170.057	447.710
EU_RV_09	280.018	0.24	173.525	451.867
EU_RV_10	186.355	0.26	113.037	307.226
EU_RV_11	105.341	0.27	61.7754	179.632
EU_RV_12	82.5544	0.30	46.1026	147.827

Population Numbers at age

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	2+
1975	124E3	107E3	66220	52349	31960	23600	14840	9250	4118	1849	638	680	438	181	68	105	436860
1976	83854	101E3	87375	54217	42558	23616	14119	7665	3989	1844	878	400	304	236	90	17	422556
1977	86618	68654	83015	71537	44373	34292	16412	6662	2865	1271	759	484	236	220	176	72	417646
1978	83655	70917	56209	67967	58086	31795	18305	6790	2801	1429	841	504	291	166	161	121	400038
1979	63863	68491	58062	46020	52948	39943	17915	8132	2967	992	516	357	212	140	84	84	360725
1980	78387	52287	56075	47537	35519	35454	21099	9115	5600	1994	552	288	163	90	39	14	344213
1981	102E3	64177	42809	45911	38731	27193	20748	8516	2579	1121	716	336	188	121	66	30	355012
1982	105E3	83323	52544	35049	36808	27623	13391	6626	3075	1306	686	457	236	127	80	41	366792
1983	103E3	86311	68219	43019	28452	28055	16898	5749	2220	994	530	330	227	121	47	35	384518
1984	114E3	84583	70665	55853	34587	20076	14102	7036	2630	1191	625	365	175	109	38	31	406286
1985	123E3	93516	69250	57856	44912	26215	11149	4595	2063	1014	607	382	203	90	20	5	434607
1986	135E3	1E5	76565	56697	45574	31967	16112	5961	2513	1225	687	407	234	123	55	3	473378
1987	151E3	11E4	82268	62686	46167	35286	20372	8585	3551	1632	783	435	270	141	67	24	523315
1988	124E3	123E3	90339	67356	51199	36077	18933	8594	4464	2136	988	386	153	69	20	3	528386
1989	102E3	102E3	101E3	73963	54878	39035	22176	11538	5871	3234	1567	714	220	69	9	5	517633
1990	86188	83166	83308	82710	60392	43132	25191	14289	8105	4113	2251	1041	454	135	38	6	494521
1991	82488	70565	68091	68206	66720	43330	23883	13787	8015	4200	2278	1042	460	180	30	19	453295
1992	71639	67536	57774	55748	53253	47608	23575	9785	4823	3195	1751	765	349	131	35	9	397976
1993	83383	58653	55294	47301	41860	33717	20303	8258	4092	2354	1700	766	269	92	25	7	358074
1994	105E3	68268	48021	45271	30068	19860	11575	5839	2561	1689	973	520	264	118	34	2	339593
1995	175E3	85582	55893	39316	22135	10307	6178	3379	1993	1099	649	415	136	71	56	20	402144
1996	309E3	143E3	70069	45761	30966	16003	5542	3131	1696	1143	587	284	112	34	8	3	627189
1997	266E3	253E3	117E3	57368	35965	20650	7323	2806	1699	933	541	270	103	38	9	1	763460
1998	124E3	218E3	207E3	95995	45247	25673	10081	3087	1267	842	384	221	97	33	10	0	731416
1999	73284	101E3	178E3	169E3	75360	32152	15783	4948	1229	548	349	168	97	50	14	6	653044
2000	134E3	60000	83095	146E3	137E3	56609	18533	9490	2550	442	138	8	7	0	1	0	647651

Fishing Mortalities

	5	6	7	8	9	10	11	12	13	14	15	16	17
1975	0.007	0.103	0.314	0.461	0.641	0.603	0.544	0.266	0.604	0.420	0.504	1.206	0.639
1976	0.000	0.016	0.164	0.551	0.784	0.944	0.687	0.396	0.327	0.124	0.093	0.012	0.069
1977	0.008	0.133	0.428	0.683	0.667	0.495	0.212	0.210	0.308	0.151	0.111	0.171	0.130
1978	0.050	0.174	0.374	0.611	0.628	0.838	0.819	0.658	0.667	0.534	0.477	0.451	0.439
1979	0.059	0.201	0.438	0.476	0.173	0.197	0.385	0.384	0.585	0.654	1.069	1.599	0.996
1980	0.005	0.067	0.336	0.707	1.063	1.408	0.824	0.296	0.228	0.100	0.117	0.058	0.082
1981	0.021	0.138	0.508	0.941	0.819	0.480	0.291	0.248	0.152	0.187	0.214	0.268	0.201
1982	0.009	0.072	0.291	0.646	0.894	0.929	0.702	0.531	0.500	0.468	0.791	0.612	0.561
1983	0.018	0.149	0.488	0.676	0.582	0.422	0.264	0.173	0.438	0.534	0.968	0.236	0.521
1984	0.018	0.077	0.388	0.921	1.027	0.753	0.474	0.292	0.387	0.458	1.517	1.897	1.162
1985	0.039	0.140	0.287	0.426	0.403	0.321	0.190	0.199	0.290	0.303	0.297	1.563	0.649
1986	0.005	0.056	0.251	0.430	0.318	0.232	0.249	0.255	0.211	0.307	0.405	0.620	0.400
1987	0.002	0.047	0.423	0.663	0.454	0.308	0.301	0.506	0.847	1.162	1.776	2.798	1.721
1988	0.005	0.071	0.287	0.295	0.181	0.122	0.110	0.125	0.365	0.594	1.873	1.134	1.080

1989	0.003	0.041	0.238	0.239	0.153	0.156	0.162	0.209	0.254	0.283	0.386	0.136	0.241
1990	0.015	0.132	0.391	0.403	0.378	0.457	0.391	0.570	0.617	0.727	1.296	0.515	0.761
1991	0.047	0.138	0.409	0.692	0.850	0.720	0.675	0.892	0.895	1.054	1.441	0.966	1.038
1992	0.087	0.257	0.652	0.849	0.672	0.517	0.431	0.627	0.846	1.135	1.454	1.438	1.208
1993	0.254	0.546	0.869	1.046	0.971	0.685	0.684	0.985	0.864	0.626	0.781	2.129	1.061
1994	0.516	0.871	0.968	1.031	0.875	0.646	0.757	0.653	1.141	1.118	0.550	0.341	0.602
1995	0.039	0.124	0.420	0.480	0.489	0.356	0.426	0.625	1.106	1.174	1.956	2.723	1.756
1996	0.041	0.205	0.582	0.481	0.412	0.398	0.547	0.577	0.812	0.892	1.123	1.656	1.346
1997	0.037	0.137	0.517	0.664	0.595	0.501	0.688	0.698	0.822	0.941	1.121	3.358	1.987
1998	0.042	0.142	0.287	0.512	0.721	0.639	0.682	0.623	0.618	0.470	0.632	0.399	0.551
1999	0.014	0.086	0.351	0.309	0.463	0.822	1.179	3.519	3.022	7.579	3.806	7.884	7.065

Commercial catch

	5	6	7	8	9	10	11	12	13	14	15	16	17
1975	334.0	2819	5750	4956	3961	1688	702.0	135.0	279.0	136.0	65.00	43.00	45.00
1976	17.00	610.0	3231	5413	3769	2205	829.0	260.0	101.0	32.00	19.00	1.000	1.000
1977	534.0	5012	10798	7346	2933	1013	220.0	130.0	116.0	30.00	21.00	25.00	8.000
1978	2982	8415	8970	7576	2865	1438	723.0	367.0	222.0	109.0	57.00	53.00	39.00
1979	2386	8727	12824	6136	1169	481.0	287.0	149.0	143.0	92.00	83.00	61.00	48.00
1980	209.0	2086	9150	9679	5398	3828	1013	128.0	53.00	14.00	9.000	2.000	1.000
1981	863.0	4517	9806	11451	4307	890.0	256.0	142.0	43.00	29.00	21.00	14.00	5.000
1982	269.0	2299	6319	5763	3542	1684	596.0	256.0	163.0	80.00	63.00	33.00	16.00
1983	701.0	3557	9800	7514	2295	692.0	209.0	76.00	106.0	85.00	68.00	9.000	13.00
1984	902.0	2324	5844	7682	4087	1259	407.0	143.0	106.0	58.00	77.00	29.00	19.00
1985	1983	5309	5913	3500	1380	512.0	159.0	99.00	87.00	48.00	21.00	14.00	2.000
1986	280.0	2240	6411	5091	1469	471.0	244.0	140.0	70.00	56.00	37.00	23.00	1.000
1987	137.0	1902	11004	8935	2835	853.0	384.0	281.0	225.0	168.0	106.0	57.00	18.00
1988	296.0	3186	8136	4380	1288	465.0	201.0	105.0	107.0	62.00	53.00	12.00	2.000
1989	181.0	1988	7480	4273	1482	767.0	438.0	267.0	145.0	49.00	20.00	1.000	1.000
1990	1102	6758	12632	7557	4072	2692	1204	885.0	434.0	212.0	89.00	14.00	3.000
1991	2862	7756	13152	10796	7145	3721	1865	1216	558.0	271.0	124.0	17.00	11.00
1992	4180	10922	20639	12205	4332	1762	1012	738.0	395.0	214.0	91.00	24.00	6.000
1993	9570	15928	17716	11918	4642	1836	1055	964.0	401.0	113.0	45.00	20.00	4.000
1994	16500	15815	11142	6739	3081	1103	811.0	422.0	320.0	161.0	45.00	9.000	1.000
1995	1352	2342	3201	2130	1183	540.0	345.0	273.0	251.0	85.00	55.00	47.00	15.00
1996	1659	5197	6387	1914	956.0	504.0	436.0	233.0	143.0	60.00	21.00	6.000	2.000
1997	1903	4169	7544	3215	1139	606.0	420.0	246.0	137.0	57.00	23.00	8.000	1.000
1998	3575	5407	5787	3653	1435	541.0	377.0	161.0	92.00	33.00	14.00	3.000	0.100
1999	2149	5625	8611	3793	1659	623.0	343.0	306.0	145.0	88.00	44.00	13.00	5.000

Biomass at age

	5	6	7	8	9	10	11	12	13	14	15	16	17	2+
1975	31881	24290	22538	17659	14614	9100	4991	2149	2639	1999	1074	484	831	134249
1976	33018	32344	22553	16802	12111	8816	4978	2960	1552	1388	1396	640	131	138689
1977	43566	33724	32748	19530	10526	6333	3431	2559	1877	1077	1304	1256	572	158502
1978	41392	44145	30364	21783	10728	6189	3859	2835	1956	1328	984	1152	958	167673

1979	28026	40241	38145	21319	12848	6556	2678	1739	1384	966	827	603	664	155997
1980	24434	23407	30809	22154	10483	7056	3130	1497	898	719	455	276	141	125458
1981	17997	23161	21455	20437	10560	4384	2758	2512	1611	1114	971	573	291	107825
1982	18401	25176	24612	15132	9276	5505	3108	2382	2063	1383	959	691	473	109162
1983	17724	17896	24156	19940	9486	4950	2992	2099	1671	1376	886	407	400	103982
1984	21056	20164	16583	15513	10273	5103	3133	2181	1640	1000	747	314	292	97998
1985	32862	33639	24668	13825	7766	4620	2992	2252	1853	1245	647	175	55	126599
1986	19844	26615	25925	17724	9419	5328	3541	2671	2017	1426	938	540	34	116022
1987	22818	27192	29499	23631	13650	7565	4601	2817	2016	1481	941	527	238	136976
1988	24450	29132	29042	22019	14275	9892	6422	3880	1967	948	529	180	38	142774
1989	29585	30787	29940	23994	19118	13133	9692	6051	3513	1317	486	66	50	167733
1990	27956	32974	33039	28189	22977	17613	11738	8400	4884	2633	983	346	63	191795
1991	26123	39498	36007	29329	24968	19724	13899	9434	5559	2959	1423	295	178	209398
1992	23972	30727	37753	29092	17770	11874	9975	6956	3899	2152	938	287	90	175483
1993	17407	22898	27277	24506	14270	9448	7060	6741	3690	1542	659	214	66	135778
1994	14939	15455	15650	13647	9932	5809	5050	3664	2537	1577	874	260	23	89416
1995	14272	11753	8328	7426	5944	4874	3430	2474	2029	809	489	414	182	62426
1996	16474	16753	13315	7050	5639	4204	3598	2265	1408	661	236	65	25	71692
1997	19275	17587	15922	8487	4846	4000	2848	2139	1380	609	249	75	11	77428
1998	35806	24569	20795	12128	5414	2978	2607	1539	1132	572	213	73	2	107828
1999	63180	40920	26043	18987	8679	2889	1695	1398	865	573	321	104	45	165699
2000	54414	74247	45854	22295	16646	5996	1369	553	43	40	0	7	0	221463

Spawner Biomass at age

	10	11	12	13	14	15	16	17	10+
1975	9100	4991	2149	2639	1999	1074	484	831	23267
1976	8816	4978	2960	1552	1388	1396	640	131	21861
1977	6333	3431	2559	1877	1077	1304	1256	572	18408
1978	6189	3859	2835	1956	1328	984	1152	958	19261
1979	6556	2678	1739	1384	966	827	603	664	15418
1980	7056	3130	1497	898	719	455	276	141	14171
1981	4384	2758	2512	1611	1114	971	573	291	14215
1982	5505	3108	2382	2063	1383	959	691	473	16565
1983	4950	2992	2099	1671	1376	886	407	400	14781
1984	5103	3133	2181	1640	1000	747	314	292	14409
1985	4620	2992	2252	1853	1245	647	175	55	13839
1986	5328	3541	2671	2017	1426	938	540	34	16495
1987	7565	4601	2817	2016	1481	941	527	238	20185
1988	9892	6422	3880	1967	948	529	180	38	23856
1989	13133	9692	6051	3513	1317	486	66	50	34309
1990	17613	11738	8400	4884	2633	983	346	63	46659
1991	19724	13899	9434	5559	2959	1423	295	178	53472
1992	11874	9975	6956	3899	2152	938	287	90	36169
1993	9448	7060	6741	3690	1542	659	214	66	29420
1994	5809	5050	3664	2537	1577	874	260	23	19793
1995	4874	3430	2474	2029	809	489	414	182	14702
1996	4204	3598	2265	1408	661	236	65	25	12461
1997	4000	2848	2139	1380	609	249	75	11	11311
1998	2978	2607	1539	1132	572	213	73	2	9115
1999	2889	1695	1398	865	573	321	104	45	7888
2000	5996	1369	553	43	40	0	7	0	8007

6 Appendix: Figures

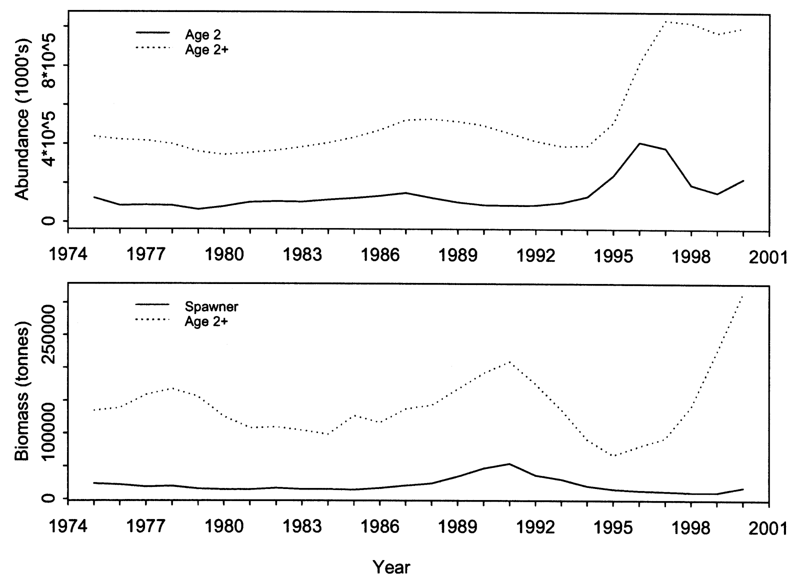

Figure 1: QLSPA abundance and biomass estimates from **Run1**.

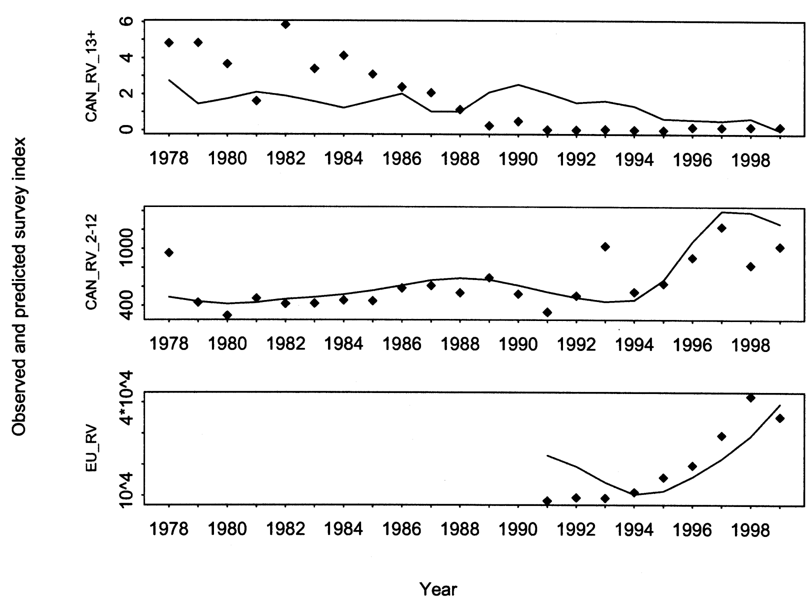

Figure 2. Observer and predicted (summed over age) indices for **Run1**.

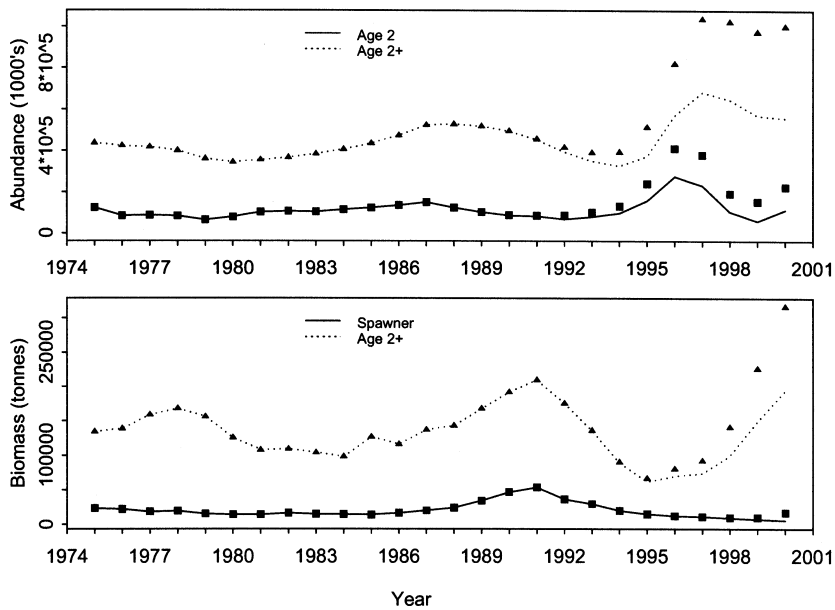

Figure 3: QLSPA abundance and biomass estimates from **Run2**. Plotting symbols mark **Run1** estimates.

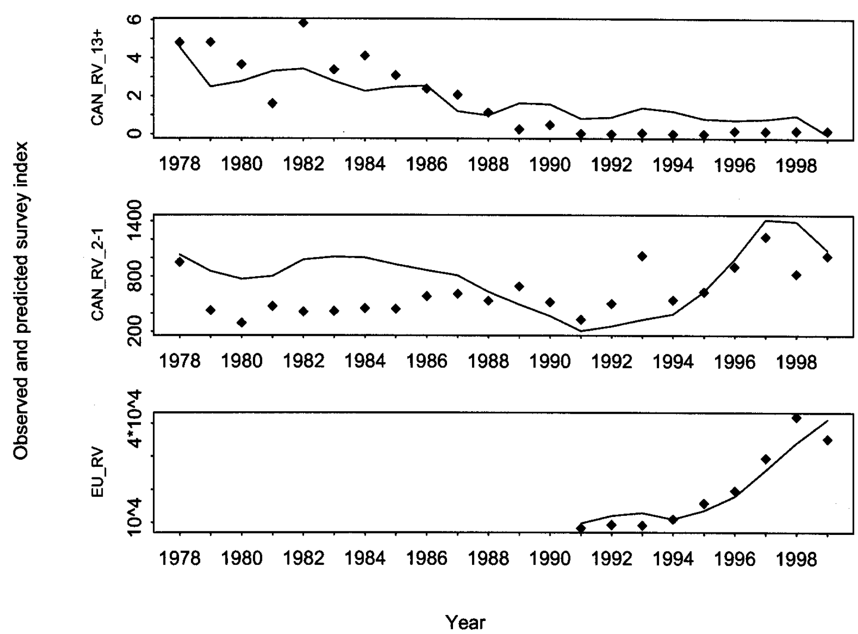

Figure 4: Observed and predicted (summed over age) indices for **Run2**.

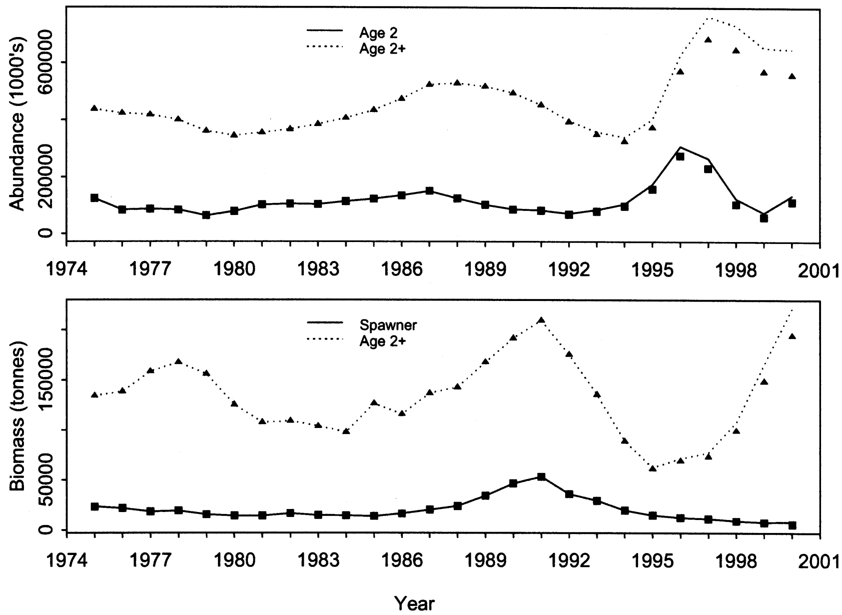

Figure 5: QLSPA abundance and biomass estimates from **Run3**. Plotting symbols mark **Run2** estimates.

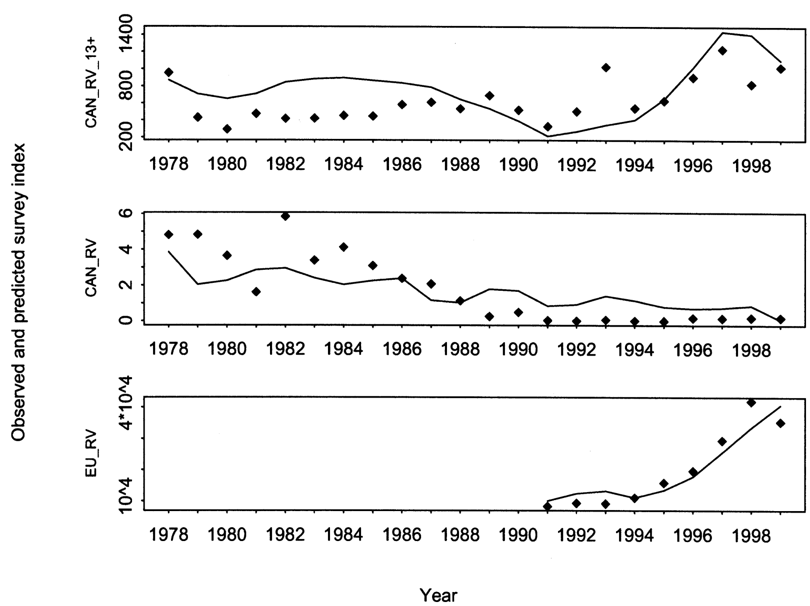

Figure 6: Observed and predicted (summed over age) indices for **Run3**.

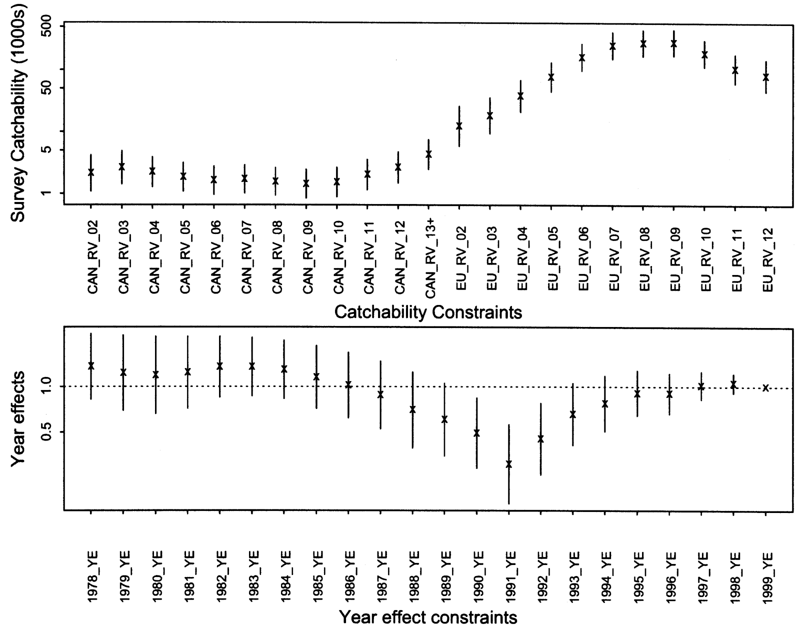

Figure 7: Age catchabilities and year effects for **Run3**.

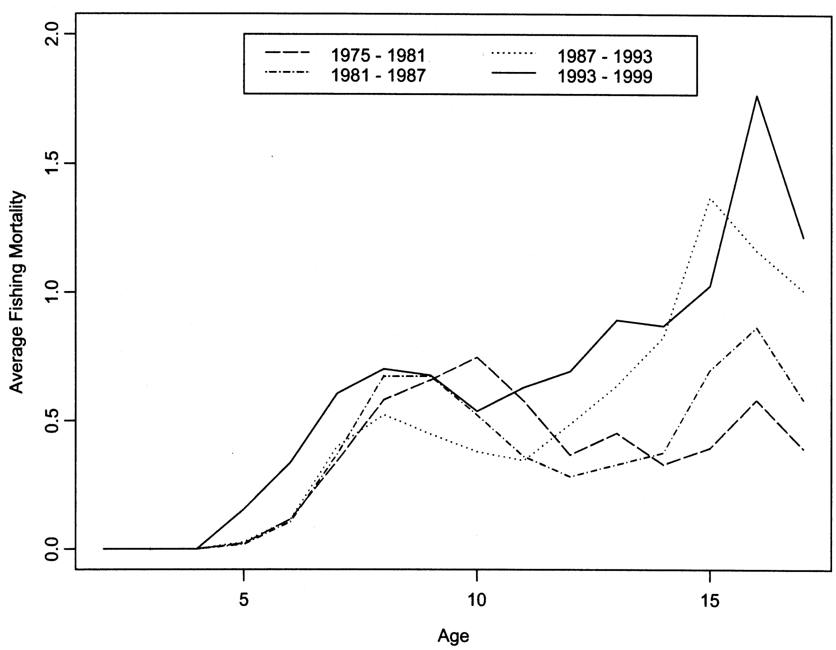

Figure 8: Average fishing mortalities from **Run3**.

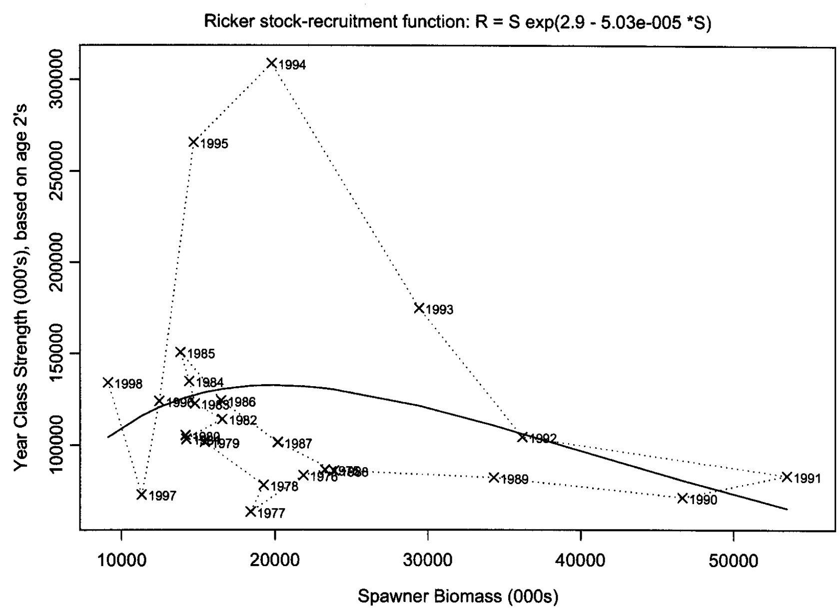

Figure 9: Stock-recruit function from **Run3**.

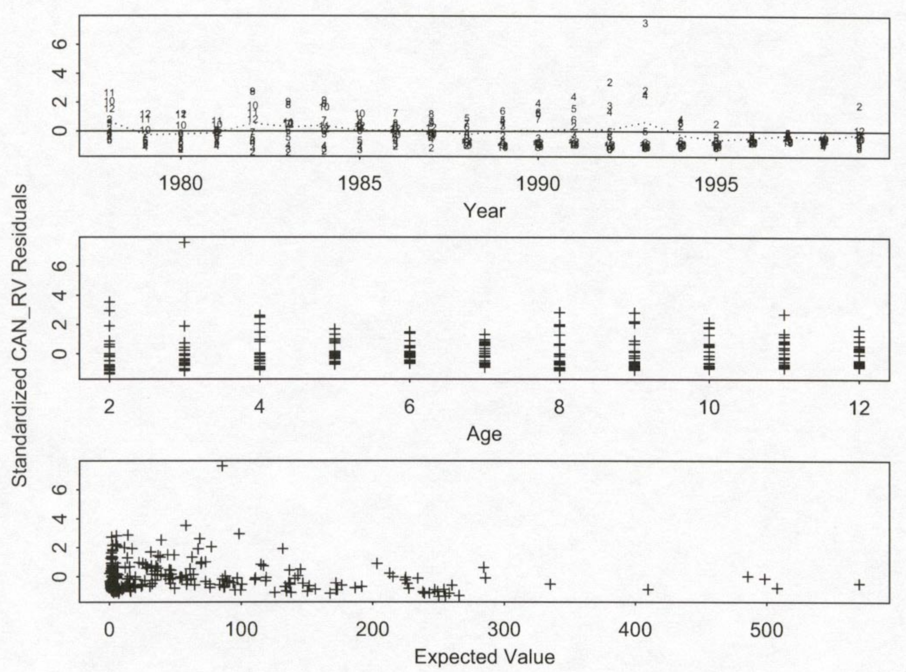

Figure 10: Residuals for the Canadian RV indices at ages 2-12 from **Run3**.

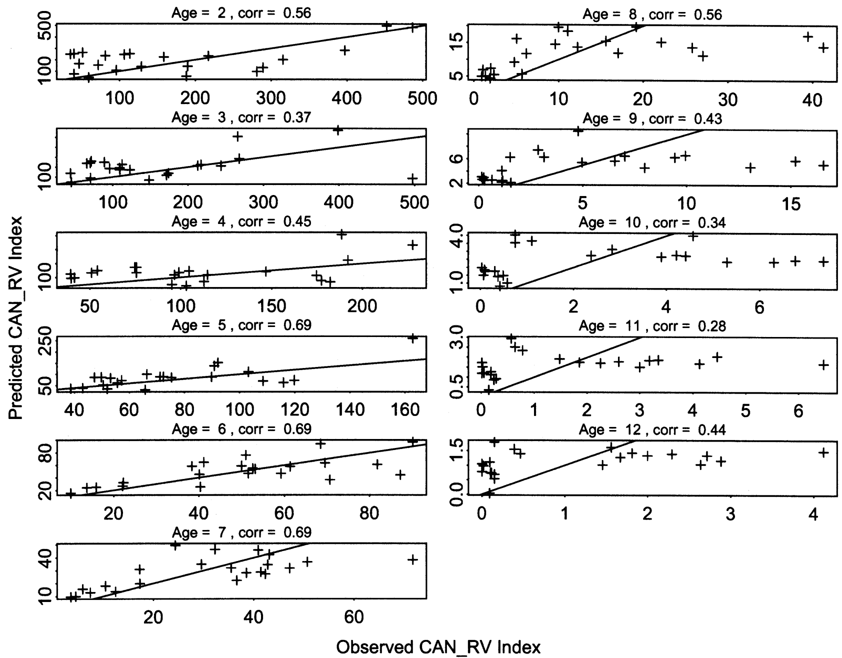

Figure 11: Residuals for the Canadian RV indices at ages 2-12 from **Run3**.

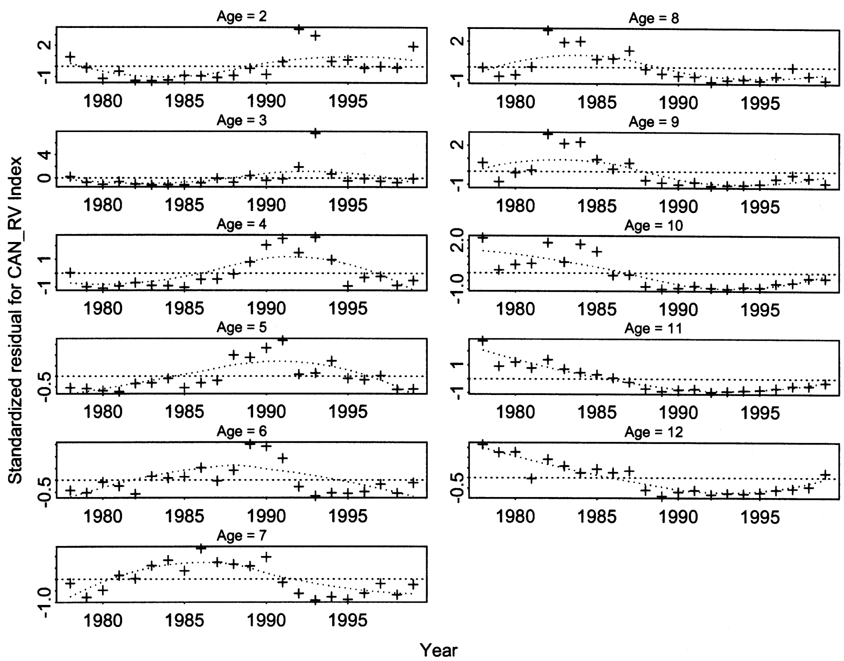

Figure 12: Residuals for the Canadian RV indices at ages 2-12 from **Run3**.

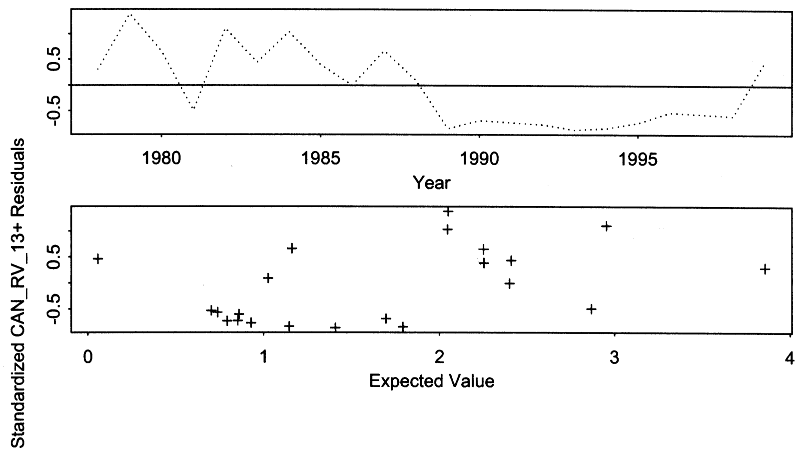

Figure 13: Residuals for the age-aggregated Canadian RV indices at ages 13-17 from **Run3**.

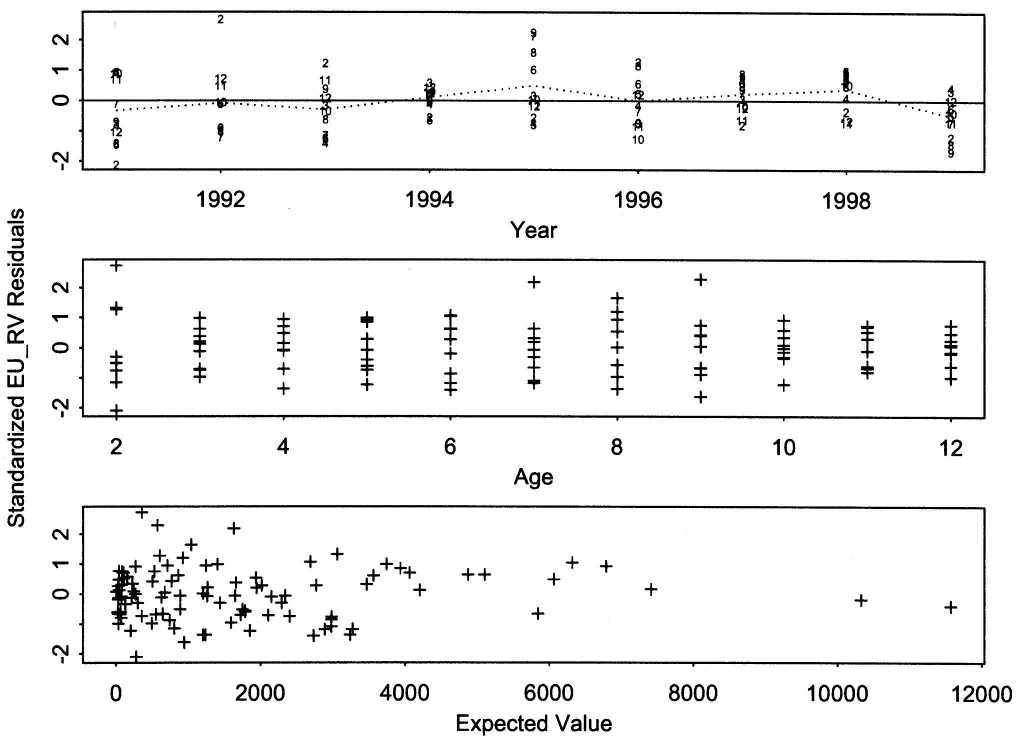

Figure 14: Residuals for the EU RV indices at ages 2-12 from **Run3**.

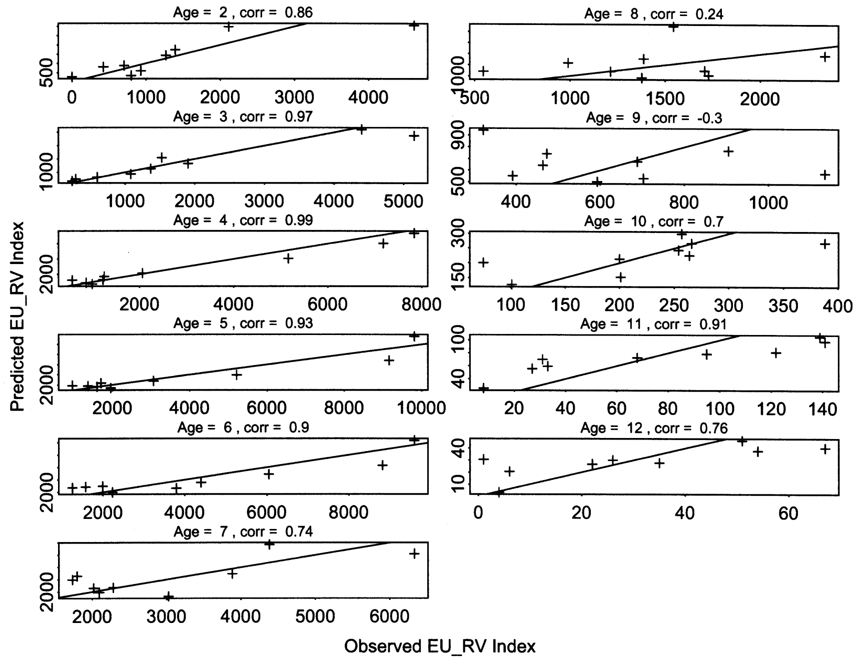

Figure 15: Residuals for the EU RV indices at ages 2-12 from **Run3**.

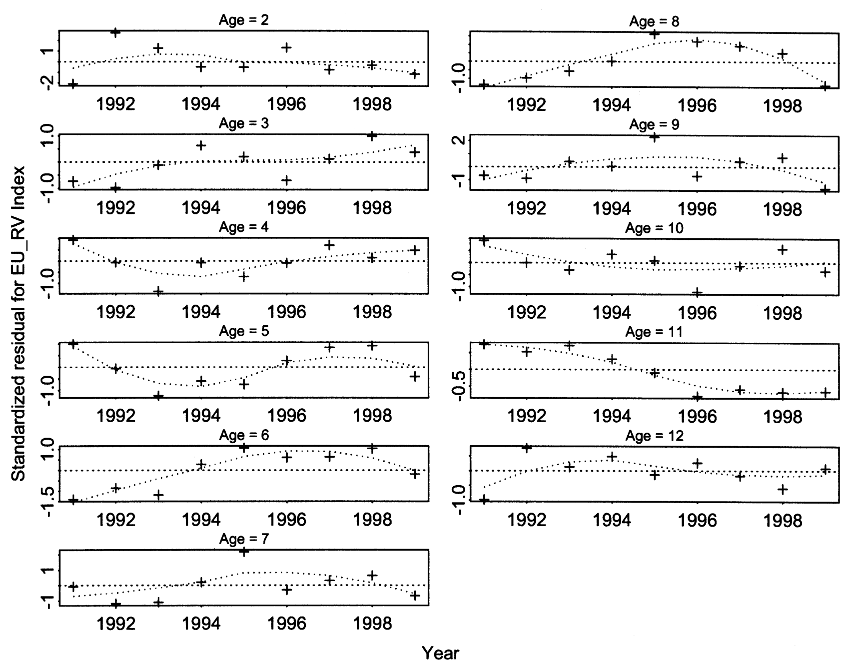

Figure 16: Residuals for the EU RV indices at ages 2-12 from **Run3**.