The following supplement accompanies the article

Spawning stock, egg production and larval survival in relation to small pelagic fish recruitment

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The stock-recruit (SR) relationships of clupeoid stocks

Time series of spawning stock (SSB) and recruitment (R) as well as fishing mortality (F) were extracted from the RAM Legacy database (Ricard et al. 2012) (http://ramlegacy.org/) for small pelagic species belonging to the family Clupeidae and having at least 18 years of data available (Table S1). The RAM Legacy database v3.0 was downloaded on 25/07/2016. We also added two stocks from the Mediterranean (Adriatic Sea [GSA 17 & 18] anchovy and sardine) which have the longest time series of stock assessment data in the basin (outputs of benchmark stock assessments carried out in 2016 by the Working Group on stock assessment of small pelagics in GFCM [General Fisheries Council for the Mediterranean] were used [Anonymous 2015]).

In total, we analyzed time series for 43 stocks including sardines, anchovies, herrings, sprats and menhaden (Table S1). We grouped the herring stocks by area of origin, specifically Northeast (NE) Atlantic, Northwest (NW) Atlantic and Northeast (NE) Pacific, and the remainder stocks (non-herring stocks) into upwelling and non-upwelling areas (Table S1).

All recruitment time series were lagged according to the recruitment age, so that the SSB time series matched the year-class to which it gave birth. Before any analysis, the R, SSB and F time series of each stock were normalized to units of variance for easy comparisons among stocks. We then calculated the ratio of R/SSB, i.e. the recruitment rate, as well as the coefficients of variation (CV, %) of R, SSB and R/SSB. We also examined the autocorrelation in R, SSB, and the recruitment rate (R/SSB) for each stock and extracted the first order autocorrelation values.

In a next step of the analysis, both the Ricker and the Beverton-Holt SR relationships were fitted for each stock:

$R = a \times e^{b \times SSB}$ (Ricker model)

$R = \frac{a \times SSB}{1 + b \times SSB}$ (Beverton-Holt model)

where, *a* is the density-independent and *b* is the density-dependent coefficient. The models were fitted with maximum likelihood estimation assuming log-normal error distribution. The analysis was performed using R (R Core Team 2015) and the *bbmle* package (Bolker & R Development Core Team 2016).

The coefficients of the Beverton-Holt model were significant ($p<0.05$) for only 35% of the stocks (15 stocks, results not shown), compared to 63% of significant Ricker coefficients (26 out of 43 stocks, Table S2). For the stocks with significant Beverton-Holt parameters, the corresponding AIC values were higher or <1 lower that the respective AIC of the Ricker model, except for Herring NAFO 4T spring spawners and Japanese anchovy, with 6.98 and 10.55 lower AIC units for the Beverton-Holt model. Hence, evidence supporting that the Beverton-Holt model was better than the respective Ricker (AIC difference >10 (Burnham and Anderson [2002]) could only be found for the Japanese anchovy. Finally, we chose to use the Ricker model for all stocks (Figure S1, Table S2) for consistency reasons, but also as a means to estimate the maximum recruitment capacity (R_{MAX}, see below), a proxy of recruitment success which is based on the Ricker model (Britten et al. 2016). As a measure of the goodness of fit of the Ricker model, we estimated the square of the Pearson correlation coefficient (squared correlation) between observed and fitted values (Ogle 2016).

The ordinary fit of the Ricker model assumes that the coefficients *a* and *b* do not vary with time. A fast and efficient way to assess stationarity of the SR relationship is to examine the plot of model residuals against time (years), as exemplified in Britten et al. (2016). Obvious structure in residual variation (i.e. directed declines, threshold-like dynamics, or regime shifts) suggests that productivity might have changed over time (Figure S2). We examined carefully the behavior of the Ricker residuals for each stock (Table S2) and we subsequently excluded from any further analyses those stocks with obvious structure in residual variation. Stocks for which at least one of the Ricker parameters (a, b) were not significant ($p>0.05$) were also excluded. In total, the Ricker fit was considered acceptable for 26 stocks (Tables S2, S3).

Recently, Britten et al. (2016) introduced the use of maximum recruitment capacity (R_{MAX}), as a measure of stock productivity at the recruitment stage:

$$R_{MAX} = \frac{a}{b} e^{-1}$$

R_{MAX} is calculated from the coefficients of the Ricker curve and is an attractive, biomass-independent measure of maximum recruitment. It does not depend on current stock size, allowing comparison of both abundant and heavily depleted stocks. Furthermore, R_{MAX} was shown to be highly correlated with alternative biomass-dependent measures of recruitment success (Britten et al. 2016).

We calculated the R_{MAX} for each stock with acceptable Ricker fit (Table S4) and then we examined its relationship with parameters such as the coefficient of variation and first order autocorrelation in R, SSB, R/SSB, using general linear models. We tested various transformation options and we applied a backward stepwise selection procedure, testing also the effects of 'Group' (NE Atlantic, NW Atlantic, NE Pacific, Non-upwelling, Upwelling) as well as all two and three-way interactions of 'Group' with covariates. In the final model, the R_{MAX} was significantly and linearly related with ln(CV(R)) and first order autocorrelation in R (autoR) (Table S5).

The CV(R) can be considered as an indicator of inter-annual (high frequency) variability in R. However, from the 26 stocks used in the analysis, the four sardine stocks (Japanese stocks, Californian sardine, South African sardine) had the highest CV(R) values which could, in part, be attributed to the fact that the time series of the sardine stocks included periods of stock collapses (with prolonged, low values of R) which could have inflated their CV(R). To confirm that the negative relationship between R_{MAX} and CV(R) (Table S5) is mainly expressing the effect of inter-annual (high frequency) variability on recruitment capacity, we repeated the analysis after excluding the four sardine stocks. The final relationship was:

$$R_{MAX} = 8.65 - 1.68 \times \ln(CV(R)) + 0.73 \times autoR, \text{ adj.} r^2 = 0.92, p < 0.001$$

This relationship was very similar to that of Table S5 that included the sardine stocks.

LITERATURE CITED

Anonymous (2015) Report of the Working Group on Stock Assessment of Small Pelagic species (WGSASP). Rome, Italy, 23 November – 28 November 2015. GFCM-SAC.

http://www.fao.org/gfcm/reports/technical-meetings/en/?page=3&ipp=10&no_cache=1&tx_dynalist_pi1[par]=YToxOntzOjE6IkwiO3M6MToiMCI7fQ==

Bolker B, R Development Core Team (2016) bbmle: Tools for General Maximum Likelihood Estimation.

Britten GL, Dowd M, Worm B (2016) Changing recruitment capacity in global fish stocks. Proc Natl Acad Sci USA 113:134–9

Burnham KP, Anderson DR (2002) Model selection and multimodel inference: a practical information-theoretic approach, Second. Springer

Ogle DH (2016) Introductory Fisheries Analyses with R. CRC Press, Taylor & Francis Group

R Core Team (2015) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/

Ricard D, Minto C, Jensen OP, Baum JK (2012) Examining the knowledge base and status of commercially exploited marine species with the RAM Legacy Stock Assessment Database. Fish Fish 13:380–398

Table S1. Clupeoid stocks used in the SR analysis. Each stock was assigned to a group: The groups 'NE Atlantic', 'NW Atlantic' and 'NE Pacific' refer to herring (*Clupea*) stocks whereas the groups 'Non-upwelling' and 'Upwelling' refer to anchovy, sardine, sprat and menhaden stocks. The length of the time series (number of years) is also shown.

Common name – Region	Scientific name	Group	Time Series	Number of years
Anchovy Adriatic Sea GSA 17-18 * stock ID: anchGSA17_18	*Engraulis encrasicolus*	Non-Upwelling	1975-2014	40
Anchovy ICES VIII stock ID: ANCHOBAYB	*Engraulis encrasicolus*	Non-Upwelling	1986-2007	22
Anchovy South Africa stock ID: ANCHOSA	*Engraulis encrasicolus*	Upwelling	1984-2011	28
Argentine anchoita Northern Argentina stock ID: ARGANCHONARG	*Engraulis anchoita*	Non-Upwelling	1989-2007	19
Peruvian anchoveta North-Central Peru stock ID: PANCHPERUNC	*Engraulis ringens*	Upwelling	1959-2008	50
Peruvian anchoveta Chile Region V-X stock ID: PANCHCHVX	*Engraulis ringens*	Upwelling	1960-2012	53
Peruvian anchoveta North Chile stock ID: PANCHNCH	*Engraulis ringens*	Upwelling	1984-2012	29
Peruvian anchoveta South Chile stock ID: PANCHSCH	*Engraulis ringens*	Upwelling	1984-2012	29
Japanese anchovy Pacific Coast of Japan stock ID: JANCHOPJPN	*Engraulis japonicus*	Non-Upwelling	1978-2009	32
Herring Baltic Sea ICES SD 22-24-IIIa stock ID: HERR2224IIIa	*Clupea harengus*	NE Atlantic	1991-2011	21
Herring Baltic Sea ICES SD 25-32 stock ID: HERR2532	*Clupea harengus*	NE Atlantic	1973-2011	39
Herring Baltic Sea ICES SD 30 stock ID: HERR30	*Clupea harengus*	NE Atlantic	1972-2011	40
Herring Baltic Sea ICES SD 31 stock ID: HERR31	*Clupea harengus*	NE Atlantic	1979-2010	32
Herring Baltic Sea ICES 28 stock ID: HERRRIGA	*Clupea harengus*	NE Atlantic	1976-2011	36
Herring Northern Irish Sea stock ID: HERRNIRS	*Clupea harengus*	NE Atlantic	1960-2010	51
Herring Norwegian Spring Spawning Herring stock ID: HERRNORSS	*Clupea harengus*	NE Atlantic	1988-2014	27
Herring North Sea stock ID: HERRNS	*Clupea harengus*	NE Atlantic	1960-2011	52
Herring ICES VIIa-g-h-j stock ID: HERRSIRS	*Clupea harengus*	NE Atlantic	1957-2010	54
Herring ICES Via stock ID: HERRVIa	*Clupea harengus*	NE Atlantic	1956-2010	55
Herring ICES VIa-VIIb-VIIc stock ID: HERRVIaVIIbc	*Clupea harengus*	NE Atlantic	1956-2010	55
Herring Iceland (Summer spawners) stock ID: HERRIsum	*Clupea harengus*	NE Atlantic	1984-2011	28
Herring NAFO 4R fall spawners stock ID: HERR4RFA	*Clupea harengus*	NW Atlantic	1971-2003	33
Herring NAFO 4R spring spawners stock ID: HERR4RSP	*Clupea harengus*	NW Atlantic	1963-2004	42
Herring NAFO 4T fall spawners stock ID: HERR4TFA	*Clupea harengus*	NW Atlantic	1974-2007	34
Herring NAFO 4T spring spawners stock ID: HERR4TSP	*Clupea harengus*	NW Atlantic	1974-2007	34
Herring Scotian Shelf and Bay of Fundy stock ID: HERR4VWX	*Clupea harengus*	NW Atlantic	1964-2006	43
Herring Northwestern Atlantic Coast stock ID: HERRNWATLC	*Clupea harengus*	NW Atlantic	1960-2005	46
Pacific herring Central Coast stock ID: HERRCC	*Clupea pallasii*	NE Pacific	1951-2007	57

Common name – Region	Scientific name	Group	Time Series	Number of years
Pacific herring Prince Rupert District stock ID: HERRPRD	*Clupea pallasii*	NE Pacific	1951-2007	57
Pacific herring Prince William Sound stock ID: HERRPWS	*Clupea pallasii*	NE Pacific	1980-2006	27
Pacific herring Queen Charlotte Islands stock ID: HERRQCI	*Clupea pallasii*	NE Pacific	1951-2007	57
Pacific herring Sitka stock ID: HERRSITKA	*Clupea pallasii*	NE Pacific	1978-2007	30
Pacific herring Strait of Georgia stock ID: HERRSOG	*Clupea pallasii*	NE Pacific	1951-2007	57
Pacific herring West Coast of Vancouver Island stock ID: HERRWCVANI	*Clupea pallasii*	NE Pacific	1951-2007	57
Gulf menhaden Gulf of Mexico stock ID: MENATGM	*Brevoortia patronus*	Non-Upwelling	1948-2011	64
European pilchard Adriatic Sea GSA 17-18 * stock ID: sardGSA17_18	*Sardina pilchardus*	Non-Upwelling	1975-2014	40
European pilchard ICES VIIIc-IXa stock ID: SARDPVIIIc_IXa	*Sardina pilchardus*	Upwelling	1978-2011	34
Sardine South Africa stock ID: SARDSA	*Sardinops sagax*	Upwelling	1984-2011	28
Chilean herring Chile Region V-X stock ID: CHERRCHVX	*Strangomera bentincki*	Upwelling	1960-2012	53
Pacific sardine US West Coast stock ID: SARDPCOAST	*Sardinops sagax*	Upwelling	1981-2007	27
Japanese sardine Pacific Coast of Japan stock ID: PILCHPJPN	*Sardinops melanostictus*	Non-Upwelling	1976-2009	34
Japanese sardine Tsushima Strait stock ID: PILCHTSST	*Sardinops melanostictus*	Non-Upwelling	1960-2010	51
Sprat Baltic Sea ICES SD 22-32 stock ID: SPRAT22_32	*Sprattus sprattus*	Non-Upwelling	1973-2011	39

Table S2. Summarised information on the Ricker model fits on the normalized data of recruitment (R) and spawning stock biomass (SSB). The density-independent (ɑ) and density-dependent (b) coefficients, as well as the standard errors (in brackets), the AIC value and the squared correlation between the observed and predicted values are shown. Finally, we indicate (last column) the cases in which one or both model coefficients were not significant as well as the stocks which exhibited systematic errors in the residuals of the Ricker model (see Figure S2 for examples of residual plots implying directed declines, threshold-like shifts and reversing regime shifts).

Stock	ɑ	b	ɑ p-value	b p-value	AIC	squared correlation	
Anchovy Adriatic Sea GSA 17-18 stock ID: anchGSA17_18	0.74 (0.06)	-0.06 (0.03)	0.00	0.07	-14.3	0.88	-Non-significant b -Residuals displayed a changing regime
Anchovy ICES VIII stock ID: ANCHOBAYB	1.55 (0.59)	0.38 (0.18)	0.01	0.04	54.1	0.04	
Anchovy South Africa stock ID: ANCHOSA	1.00 (0.25)	0.21 (0.13)	0.00	0.12	62.4	0.24	Non-significant b
Argentine anchoita Northern Argentina stock ID: ARGANCHONARG	1.24 (0.46)	0.23 (0.13)	0.01	0.07	31.3	0.05	Non-significant b
Peruvian anchoveta North-Central Peru stock ID: PANCHPERUNC	0.97 (0.18)	0.14 (0.11)	0.00	0.20	107.5	0.50	Non-significant b
Peruvian anchoveta Chile Region V-X stock ID: PANCHCHVX	1.88 (0.30)	0.28 (0.08)	0.00	0.00	25.1	0.36	
Peruvian anchoveta North Chile stock ID: PANCHNCH	0.34 (0.20)	0.26 (0.23)	0.10	0.26	100.3	0.06	-Non-significant a and b -Residuals displayed an abrupt shift
Peruvian anchoveta South Chile stock ID: PANCHSCH	1.20 (0.29)	0.26 (0.10)	0.00	0.01	49.6	0.04	
Japanese anchovy Pacific Coast of Japan stock ID: JANCHOPJPN	3.79 (0.39)	0.50 (0.06)	0.00	0.00	31.1	0.53	
Herring Baltic Sea ICES SD 22-24-IIIa stock ID: HERR2224IIIa	1.79 (0.51)	0.26 (0.51)	0.00	0.01	29.6	0.00	
Herring Baltic Sea ICES SD 25-32 stock ID: HERR2532	1.71 (0.19)	0.20 (0.05)	0.00	0.00	22.2	0.48	
Herring Baltic Sea ICES SD 30 stock ID: HERR30	0.71 (0.15)	0.05 (0.09)	0.00	0.57	68.5	0.31	Non-significant b
Herring Baltic Sea ICES SD 31 stock ID: HERR31	1.29 (0.34)	0.33 (0.12)	0.00	0.01	64.3	0.07	
Herring Baltic Sea ICES 28 stock ID: HERRRIGA	0.36 (0.11)	-0.05 (0.09)	0.00	0.60	55.1	0.22	Non-significant b
Herring Northern Irish Sea stock ID: HERRNIRS	1.69 (0.08)	0.27 (0.08)	0.00	0.00	92.3	0.28	Residuals displayed a changing regime
Herring Norwegian Spring Spawning Herring stock ID: HERRNORSS	1.52 (0.19)	0.60 (0.19)	0.15	0.00	76.7	0.09	Non-significant a
Herring North Sea stock ID: HERRNS	3.08 (0.07)	0.63 (0.07)	0.00	0.00	85.6	0.29	
Herring ICES VIIa-g-h-j stock ID: HERRSIRS	1.18 (0.24)	0.25 (0.08)	0.00	0.00	97.7	0.08	
Herring ICES VIa stock ID: HERRVIa	0.59 (0.09)	0.08 (0.09)	0.00	0.39	111.5	0.36	Non-significant b

Stock	α	b	α p-value	b p-value	AIC	squared correlation	
Herring ICES VIa-VIIb-VIIc stock ID: HERRVIaVIIbc	1.41 (0.21)	0.38 (0.08)	0.00	0.00	97.4	0.07	
Herring Iceland (Summer spawners) stock ID: HERRIsum	1.67 (0.62)	0.35 (0.12)	0.01	0.00	41.3	0.00	Residuals displayed an abrupt shift
Herring NAFO 4R fall spawners stock ID: HERR4RFA	1.29 (0.89)	0.46 (0.16)	0.15	0.00	77.3	0.09	Non-significant a
Herring NAFO 4R spring spawners stock ID: HERR4RSP	1.00 (0.39)	0.72 (0.17)	0.01	0.00	116.9	0.06	
Herring NAFO 4T fall spawners stock ID: HERR4TFA	4.25 (1.01)	0.69 (0.09)	0.00	0.00	40.9	0.12	
Herring NAFO 4T spring spawners stock ID: HERR4TSP	2.87 (1.03)	0.77 (0.16)	0.01	0.00	68.1	0.01	
Herring Scotian Shelf and Bay of Fundy stock ID: HERR4VWX	1.63 (0.34)	0.53 (0.10)	0.00	0.00	87.8	0.12	
Herring Northwestern Atlantic Coast stock ID: HERRNWATLC	1.91 (0.39)	0.53 (0.11)	0.00	0.00	83.0	0.13	
Pacific herring Central Coast stock ID: HERRCC	1.21 (0.23)	0.49 (0.10)	0.00	0.00	119.8	0.08	
Pacific herring Prince Rupert District stock ID: HERRPRD	2.47 (0.43)	0.62 (0.08)	0.00	0.00	104.0	0.08	
Pacific herring Prince William Sound stock ID: HERRPWS	0.53 (0.19)	0.28 (0.19)	0.01	0.15	70.7	0.12	Non-significant b
Pacific herring Queen Charlotte Islands stock ID: HERRQCI	1.04 (0.20)	0.66 (0.13)	0.00	0.00	149.1	0.01	
Pacific herring Sitka stock ID: HERRSITKA	0.44 (0.18)	0.17 (0.15)	0.02	0.27	69.8	0.09	Non-significant b
Pacific herring Strait of Georgia stock ID: HERRSOG	3.00 (0.37)	0.44 (0.06)	0.00	0.00	61.5	0.20	
Pacific herring West Coast of Vancouver Island stock ID: HERRWCVANI	3.44 (0.40)	0.63 (0.07)	0.00	0.00	81.1	0.05	
Gulf menhaden Gulf of Mexico stock ID: MENATGM	3.42 (0.59)	0.41 (0.05)	0.00	0.00	20.0	0.06	
European pilchard Adriatic Sea GSA 17-18 stock ID: sardGSA17_18	1.42 (0.10)	0.12 (0.04)	0.00	0.00	3.2	0.87	Residuals displayed a changing regime
European pilchard ICES VIIIc-IXa stock ID: SARDPVIIIc_IXa	0.81 (0.29)	0.20 (0.11)	0.00	0.06	69.4	0.05	-Non-significant b -Residuals displayed a progressive decline
Sardine South Africa stock ID: SARDSA	2.05 (0.26)	0.48 (0.09)	0.00	0.00	38.7	0.52	
Chilean herring Chile Region V-X stock ID: CHERRCHVX	1.53 (0.48)	0.43 (0.19)	0.00	0.02	61.7	0.19	Residuals displayed a changing regime
Pacific sardine US West Coast stock ID: SARDPCOAST	2.47 (0.46)	0.81 (0.13)	0.00	0.00	59.8	0.37	
Japanese sardine Pacific Coast of Japan stock ID: PILCHPJPN	1.26 (0.28)	0.51 (0.18)	0.00	0.00	103.0	0.53	
Japanese sardine Tsushima Strait stock ID: PILCHTSST	1.35 (0.18)	0.34 (0.11)	0.00	0.00	128.4	0.53	
Sprat Baltic Sea ICES SD 22-32 stock ID: SPRAT22_32	0.94 (0.25)	0.24 (0.11)	0.00	0.03	82.7	0.09	

Table S3. Numbers of stocks analyzed and percentages of stocks with non-significant Ricker parameter(s) (ɑ and/or b) and with obvious structure in residuals. The Ricker model fit was considered ‘acceptable’ when both Ricker parameters were significant ($p<0.05$) and the plots of model residuals against time (year) did not displayed obvious structure (e.g. Figure S2). The groups NE, NW Atlantic and NE Pacific include herring stocks, the Upwelling and Non-Upwelling groups include anchovy, sardine, sprat and menhaden stocks.

Group	Number of stocks analyzed	Percent with non-significant Ricker parameter(s)	Percent with structure in Ricker residuals	Number of stocks with acceptable model fit	Percent with acceptable model fit
NE Atlantic	12	33	17	6	50
NE Pacific	7	29	0	5	71
NW Atlantic	6	17	0	5	83
Upwelling	9	44	22	4	44
Non-Upwelling	9	22	33	6	67
TOTAL	43	30	16	26	60

Table S4. Estimates of selected parameters from stock assessment data and Ricker model fits for the clupeoid stocks examined in this study. autoR: first order autocorrelation in recruitment. CV(R): coefficient of variation of recruitment. CV(R/SSB): coefficient of variation of recruitment rate. R_{MAX}: maximum recruitment capacity. F: average fishing mortality. NA: non-available in the database.

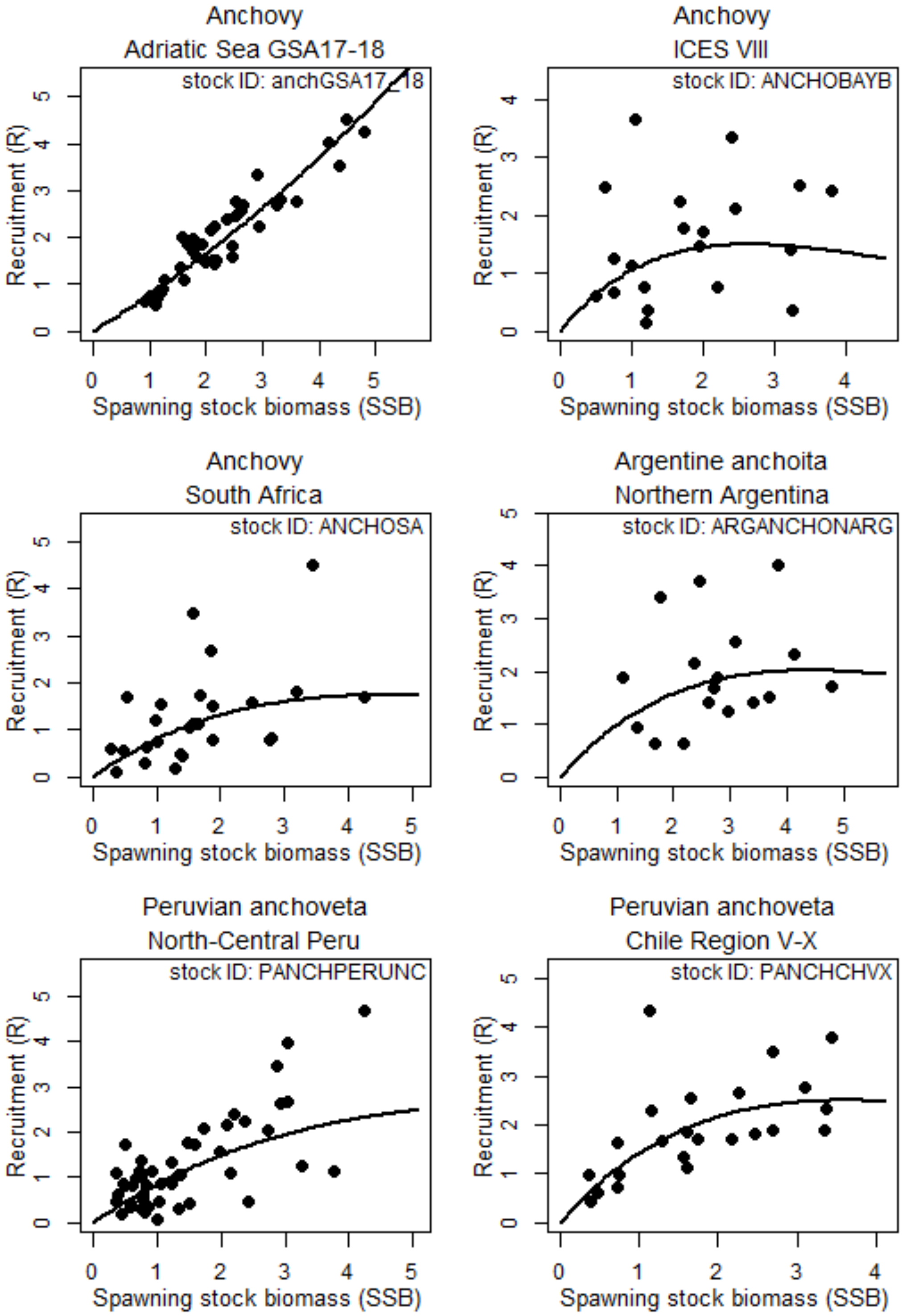
Common name - Region	autoR	CV(R)	CV(R/SSB)	R_{MAX}	F
Anchovy Adriatic Sea GSA 17-18 stock ID: anchGSA17_18	0.93	50.5	19.8	-4.94	1.98
Anchovy ICES VIII stock ID: ANCHOBAYB	0.24	64.1	91.1	1.50	2.84
Anchovy South Africa stock ID: ANCHOSA	0.51	80.0	76.0	1.74	NA
Argentine anchoita Northern Argentina stock ID: ARGANCHONARG	0.21	51.3	63.5	2.01	1.65
Peruvian anchoveta North-Central Peru stock ID: PANCHPERUNC	0.51	79.0	65.8	2.64	1.57
Peruvian anchoveta Chile Region V-X stock ID: PANCHCHVX	0.55	51.7	57.7	2.50	1.67
Peruvian anchoveta North Chile stock ID: PANCHNCH	0.58	127.0	121.6	0.48	NA
Peruvian anchoveta South Chile stock ID: PANCHSCH	0.16	62.5	69.5	1.70	1.65
Japanese anchovy Pacific Coast of Japan stock ID: JANCHOPJPN	0.75	51.2	65.4	2.81	1.57
Herring Baltic Sea ICES SD 22-24-IIIa stock ID: HERR2224IIIa	0.51	40.7	53.5	2.54	4.53
Herring Baltic Sea ICES SD 25-32 stock ID: HERR2532	0.59	45.4	37.6	3.10	3.29
Herring Baltic Sea ICES SD 30 stock ID: HERR30	0.43	66.6	56.3	5.10	3.91
Herring Baltic Sea ICES SD 31 stock ID: HERR31	0.07	69.2	75.1	1.43	2.89
Herring Baltic Sea ICES 28 stock ID: HERRRIGA	-0.01	60.3	52.1	-2.91	3.81
Herring Northern Irish Sea stock ID: HERRNIRS	0.70	64.4	77.1	2.34	2.26
Herring Norwegian Spring Spawning Herring stock ID: HERRNORSS	0.34	100.0	111.0	0.94	2.17
Herring North Sea stock ID: HERRNS	0.46	62.7	74.7	1.79	NA
Herring ICES VIIa-g-h-j stock ID: HERRSIRS	-0.03	59.9	68.2	1.74	2.40
Herring ICES VIa stock ID: HERRVIa	0.28	110.5	68.2	2.80	1.46
Herring ICES VIa-VIIb-VIIc stock ID: HERRVIaVIIbc	0.07	82.4	102.3	1.35	1.72
Herring Iceland (Summer spawners) stock ID: HERRIsum	0.22	52.1	69.6	1.76	3.82
Herring NAFO 4R fall spawners stock ID: HERR4RFA	-0.03	95.4	128.3	1.03	2.03
Herring NAFO 4R spring spawners stock ID: HERR4RSP	0.18	135.1	148.2	0.51	1.57
Herring NAFO 4T fall spawners stock ID: HERR4TFA	0.29	50.9	94.1	2.28	1.78
Herring NAFO 4T spring spawners stock ID: HERR4TSP	0.14	77.3	176.3	1.37	1.39
Herring Scotian Shelf and Bay of Fundy stock ID: HERR4VWX	0.18	84.5	72.5	1.13	1.45
Herring Northwestern Atlantic Coast stock ID: HERRNWATLC	0.09	79.5	80.9	1.34	1.61
Pacific herring Central Coast stock ID: HERRCC	-0.05	97.8	87.3	0.91	0.92

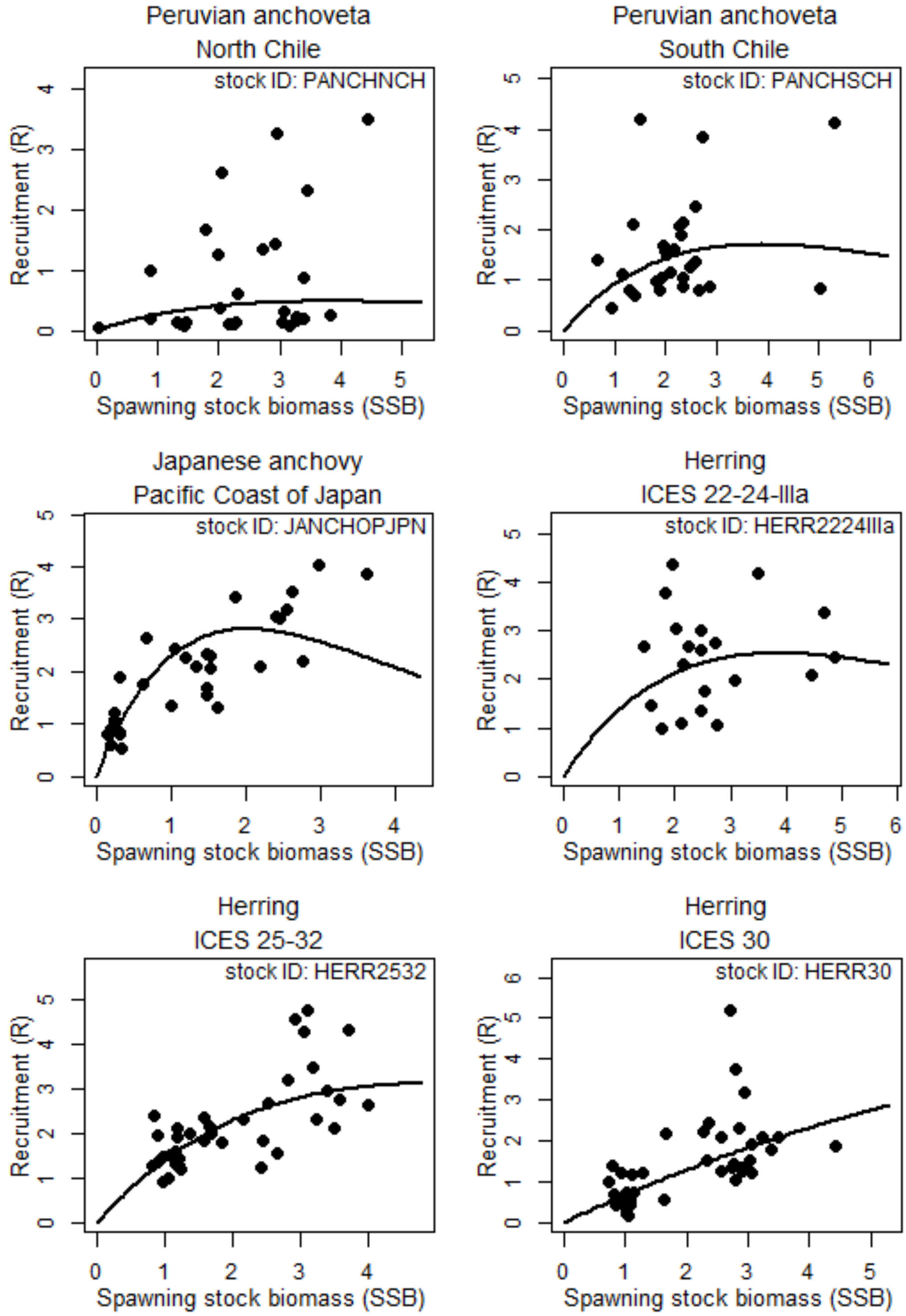
Common name - Region	autoR	CV(R)	CV(R/SSB)	R_{MAX}	F
Pacific herring Prince Rupert District stock ID: HERRPRD	-0.13	67.2	86.4	1.47	0.95
Pacific herring Prince William Sound stock ID: HERRPWS	-0.09	133.2	103.4	0.70	1.11
Pacific herring Queen Charlotte Islands stock ID: HERRQCI	-0.04	153.5	139.5	0.58	0.66
Pacific herring Sitka stock ID: HERRSITKA	-0.16	105.1	90.0	0.94	2.10
Pacific herring Strait of Georgia stock ID: HERRSOG	0.38	43.0	62.3	2.50	0.95
Pacific herring West Coast of Vancouver Island stock ID: HERRWCVANI	-0.02	55.7	70.9	2.01	0.84
Gulf menhaden Gulf of Mexico stock ID: MENATGM	0.04	34.8	59.3	3.04	1.71
European pilchard Adriatic Sea GSA 17-18 stock ID: sardGSA17_18	0.97	54.5	28.7	4.29	1.32
European pilchard ICES VIIIc-IXa stock ID: SARDPVIIIc_IXa	0.43	64.0	66.0	1.47	NA
Sardine South Africa stock ID: SARDSA	0.68	86.4	43.1	1.59	NA
Chilean herring Chile Region V-X stock ID: CHERRCHVX	0.41	85.2	117.9	1.32	0.96
Pacific sardine US West Coast stock ID: SARDPCOAST	0.30	121.1	74.5	1.13	NA
Japanese sardine Pacific Coast of Japan stock ID: PILCHPJPN	0.79	142.5	85.4	0.91	1.86
Japanese sardine Tsushima Strait stock ID: PILCHTSST	0.88	161.5	81.1	1.44	NA
Sprat Baltic Sea ICES SD 22-32 stock ID: SPRAT22_32	0.04	73.7	90.5	1.42	NA

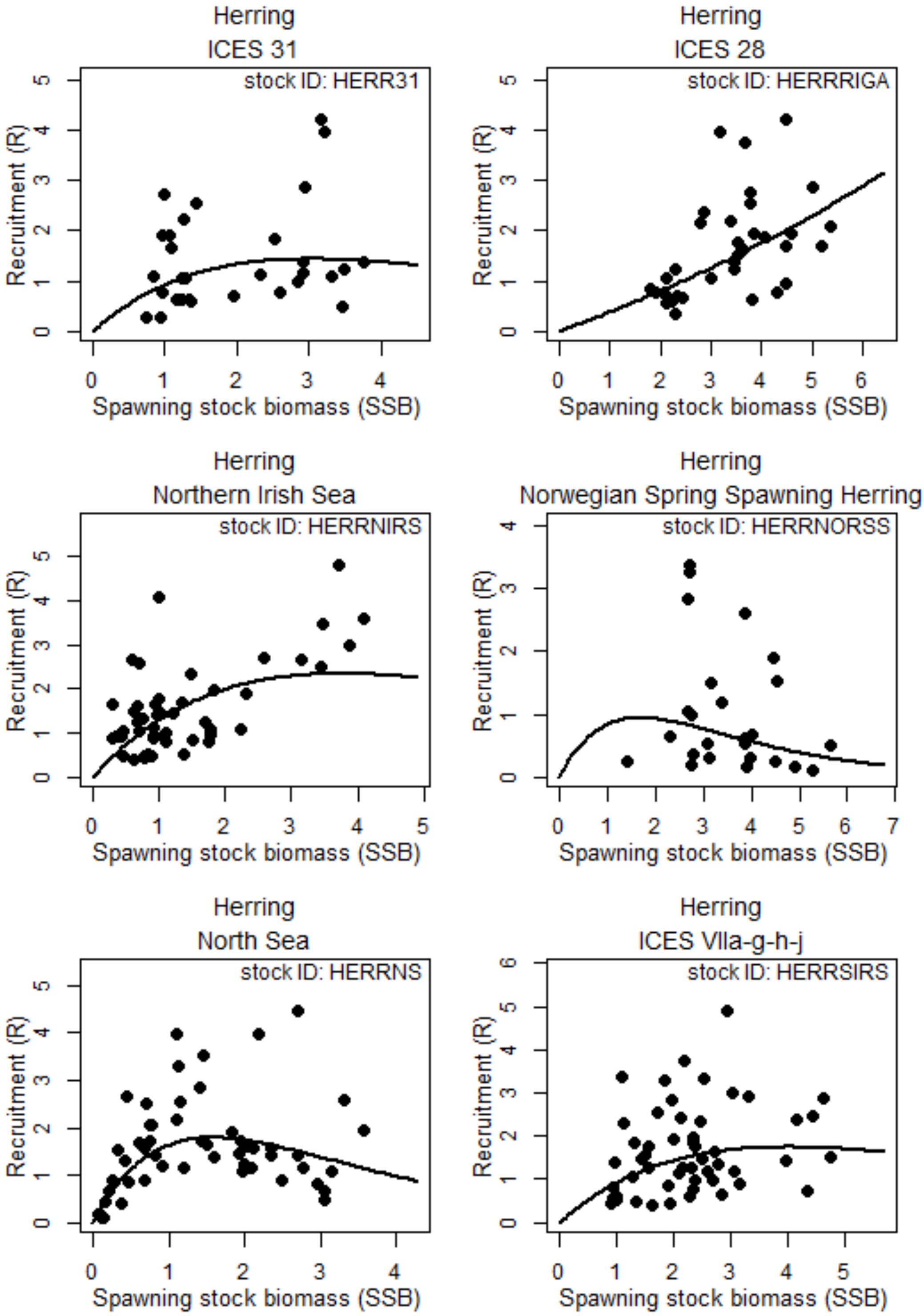
Table S5. Parameter estimates and analysis of variance table of the final linear model with maximum recruitment capacity (R_{MAX}) as the dependent variable and coefficient of variation of recruitment (CV(R)) and first order autocorrelation in recruitment (autoR) as explanatory variables.

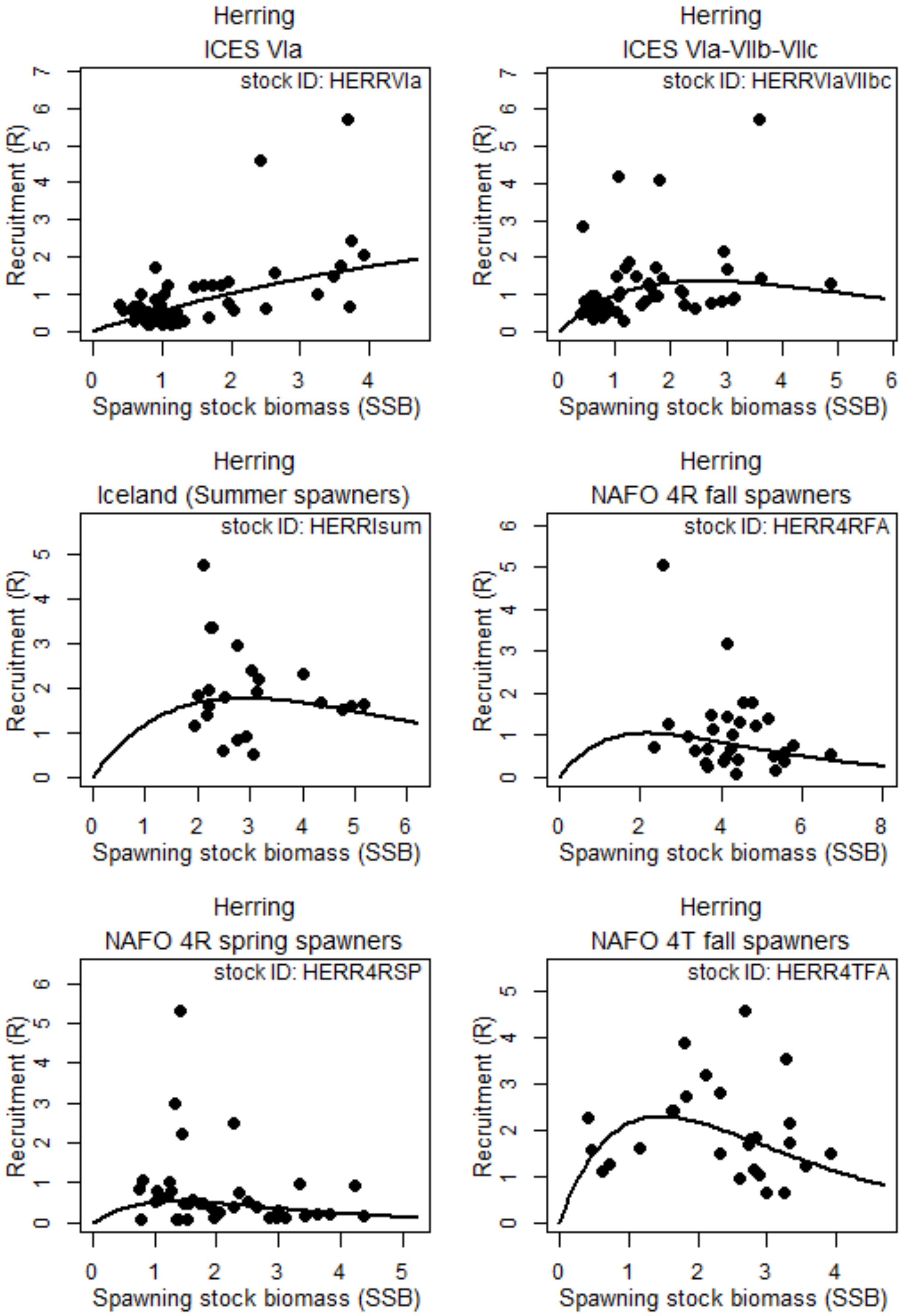
Coefficients	Estimate	SE	p	adj. r^2	
Intercept	7.98	0.48	<0.001	0.89	
ln(CV(R))	-1.53	0.11	<0.001		
autoR	0.91	0.16	<0.001		
ANOVA	**df**	**SS**	**MS**	**F**	**p**
ln(CV(R))	1	9.67	9.67	180.48	<0.001
autoR	1	1.75	1.75	32.73	<0.001
Residuals	23	1.23	0.05		

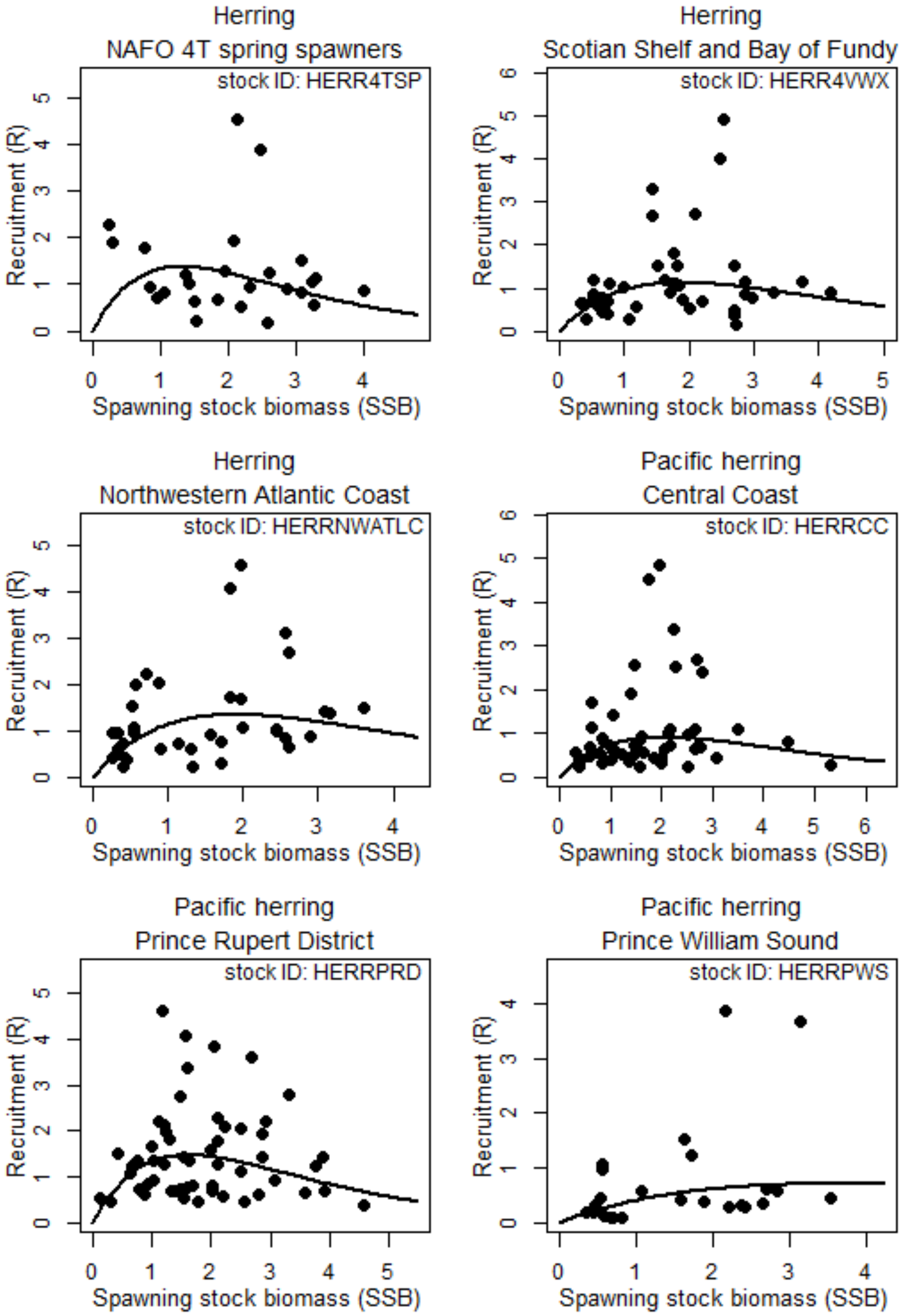
Figure S1. Relationship between spawning stock (SSB) and recruitment (R) for all 43 stocks examined in this study. The black line is the fitted Ricker model.

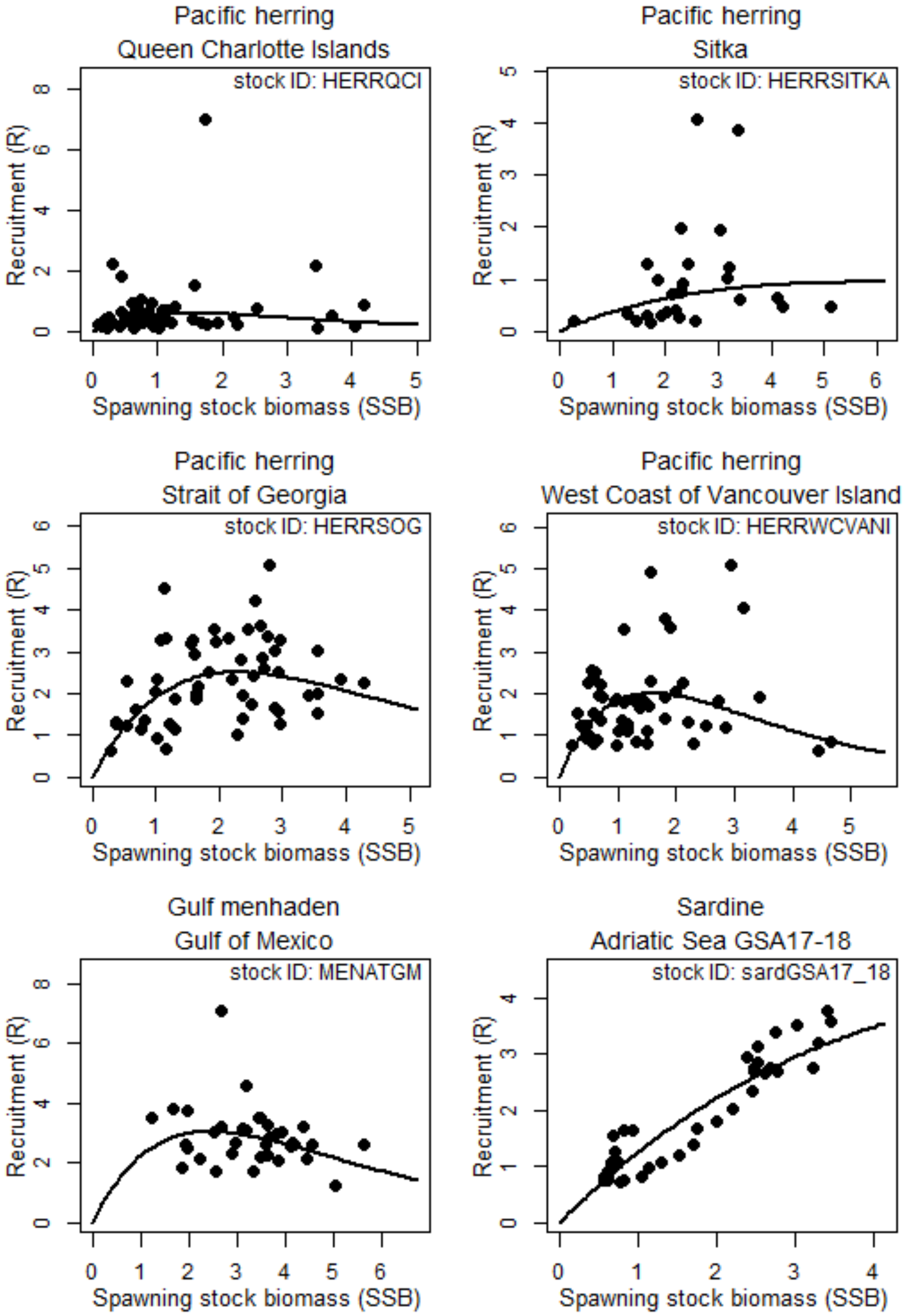


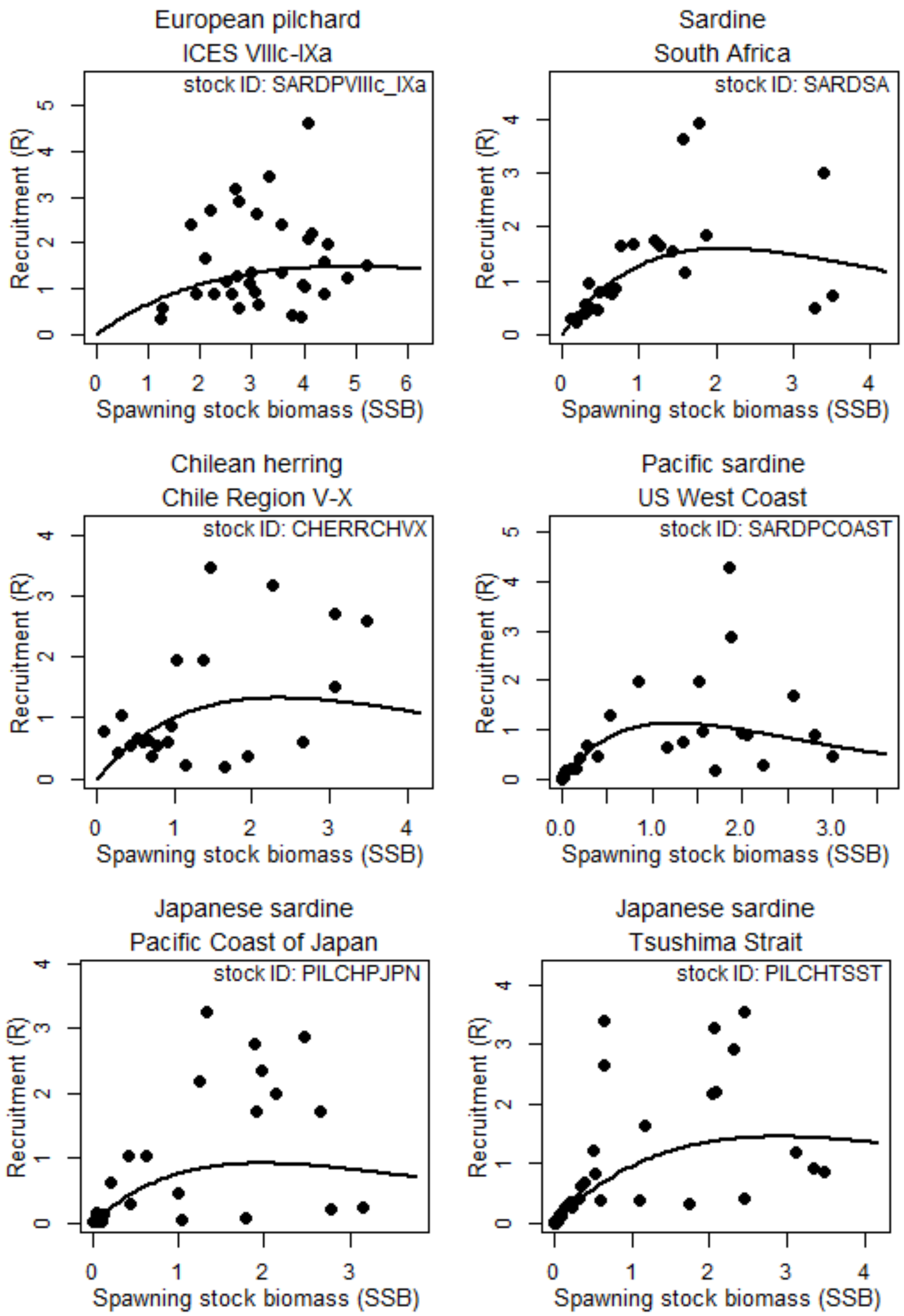

Peruvian anchoveta
North Chile
stock ID: PANCHNCH
Peruvian anchoveta
South Chile
stock ID: PANCHSCH
Japanese anchovy
Pacific Coast of Japan
stock ID: JANCHOPJPN
Herring
ICES 22-24-IIIa
stock ID: HERR2224IIIa
Herring
ICES 25-32
stock ID: HERR2532
Herring
ICES 30
stock ID: HERR30
Recruitment (R)
Spawning stock biomass (SSB)


Herring
ICES 31
stock ID: HERR31
Herring
ICES 28
stock ID: HERRRIGA
Herring
Northern Irish Sea
stock ID: HERRNIRS
Herring
Norwegian Spring Spawning Herring
stock ID: HERRNORSS
Herring
North Sea
stock ID: HERRNS
Herring
ICES VIIa-g-h-j
stock ID: HERRSIRS
Recruitment (R)
Spawning stock biomass (SSB)


Herring
ICES VIa
stock ID: HERRVIa
Recruitment (R)
Spawning stock biomass (SSB)
Herring
ICES VIa-VIIb-VIIc
stock ID: HERRVIaVIIbc
Recruitment (R)
Spawning stock biomass (SSB)
Herring
Iceland (Summer spawners)
stock ID: HERRIsum
Recruitment (R)
Spawning stock biomass (SSB)
Herring
NAFO 4R fall spawners
stock ID: HERR4RFA
Recruitment (R)
Spawning stock biomass (SSB)
Herring
NAFO 4R spring spawners
stock ID: HERR4RSP
Recruitment (R)
Spawning stock biomass (SSB)
Herring
NAFO 4T fall spawners
stock ID: HERR4TFA
Recruitment (R)
Spawning stock biomass (SSB)


Herring
NAFO 4T spring spawners
stock ID: HERR4TSP
Recruitment (R)
Spawning stock biomass (SSB)
Herring
Scotian Shelf and Bay of Fundy
stock ID: HERR4VWX
Recruitment (R)
Spawning stock biomass (SSB)
Herring
Northwestern Atlantic Coast
stock ID: HERRNWATLC
Recruitment (R)
Spawning stock biomass (SSB)
Pacific herring
Central Coast
stock ID: HERRCC
Recruitment (R)
Spawning stock biomass (SSB)
Pacific herring
Prince Rupert District
stock ID: HERRPRD
Recruitment (R)
Spawning stock biomass (SSB)
Pacific herring
Prince William Sound
stock ID: HERRPWS
Recruitment (R)
Spawning stock biomass (SSB)


Pacific herring
Queen Charlotte Islands
stock ID: HERRQCI
Pacific herring
Sitka
stock ID: HERRSITKA
Pacific herring
Strait of Georgia
stock ID: HERRSOG
Pacific herring
West Coast of Vancouver Island
stock ID: HERRWCVANI
Gulf menhaden
Gulf of Mexico
stock ID: MENATGM
Sardine
Adriatic Sea GSA17-18
stock ID: sardGSA17_18
Recruitment (R)
Spawning stock biomass (SSB)


European pilchard
ICES VIIIc-IXa
stock ID: SARDPVIIIc_IXa
Sardine
South Africa
stock ID: SARDSA
Chilean herring
Chile Region V-X
stock ID: CHERRCHVX
Pacific sardine
US West Coast
stock ID: SARDPCOAST
Japanese sardine
Pacific Coast of Japan
stock ID: PILCHPJPN
Japanese sardine
Tsushima Strait
stock ID: PILCHTSST
Recruitment (R)
Spawning stock biomass (SSB)

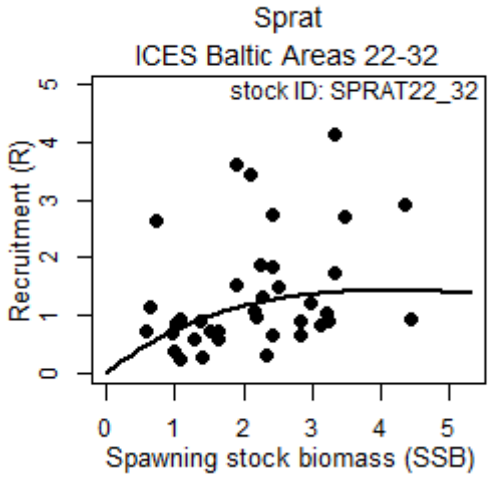


Figure S2. Examples of stocks with obvious structure (systematic errors) in the residuals of the Ricker model, indicative of a time-varying SR relationship. Plots of normalized residuals against time (year) for European pilchard (progressive decline), anchoveta (abrupt threshold) and Adriatic sardine (reversing regime shift).

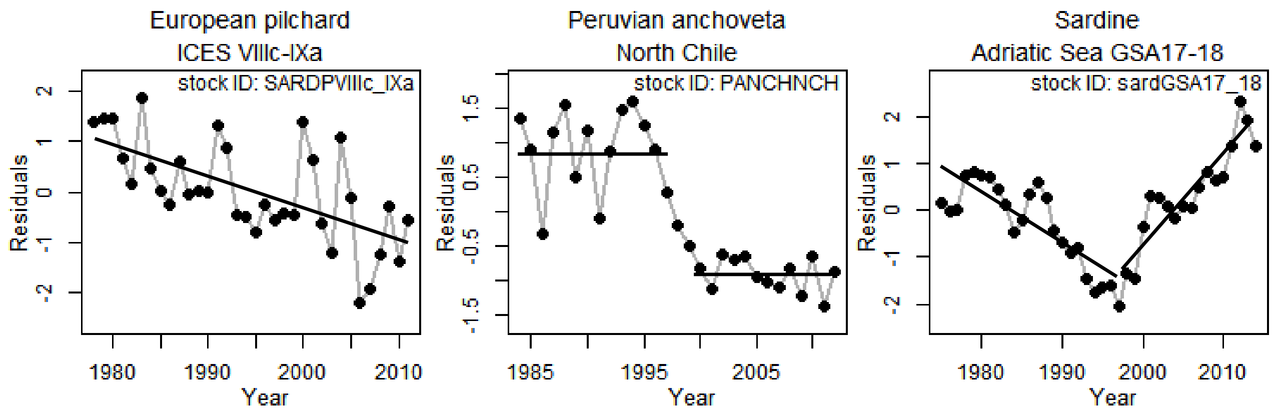
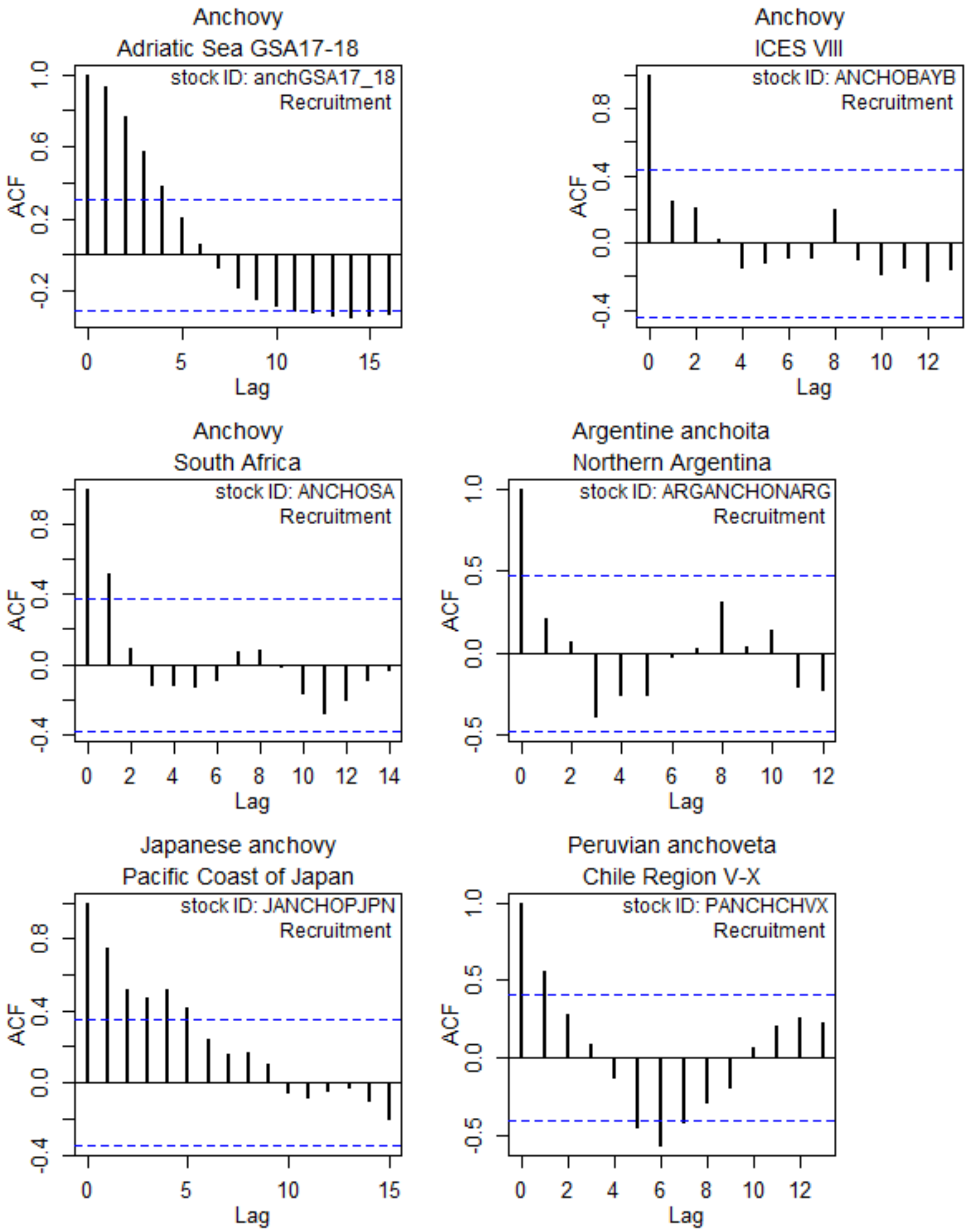
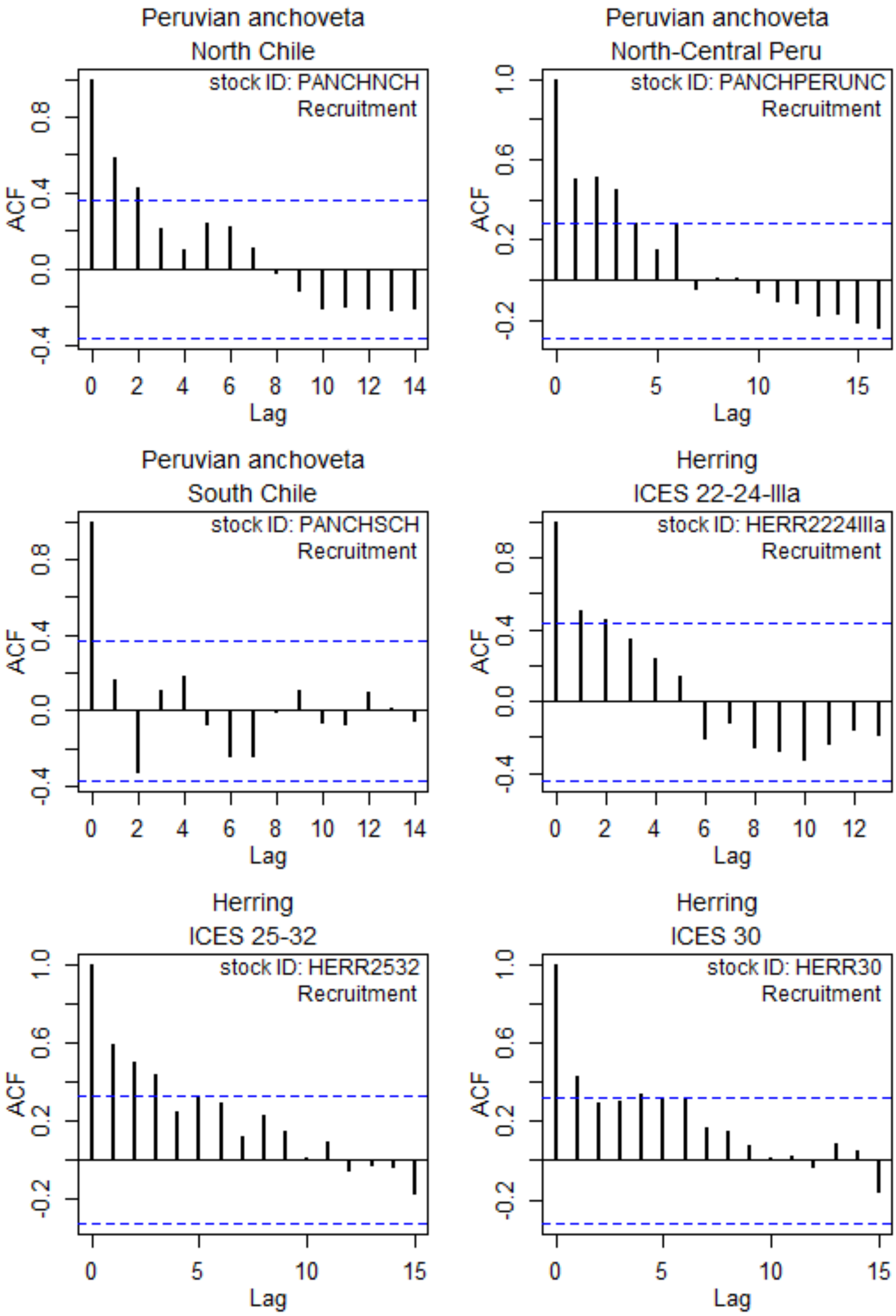
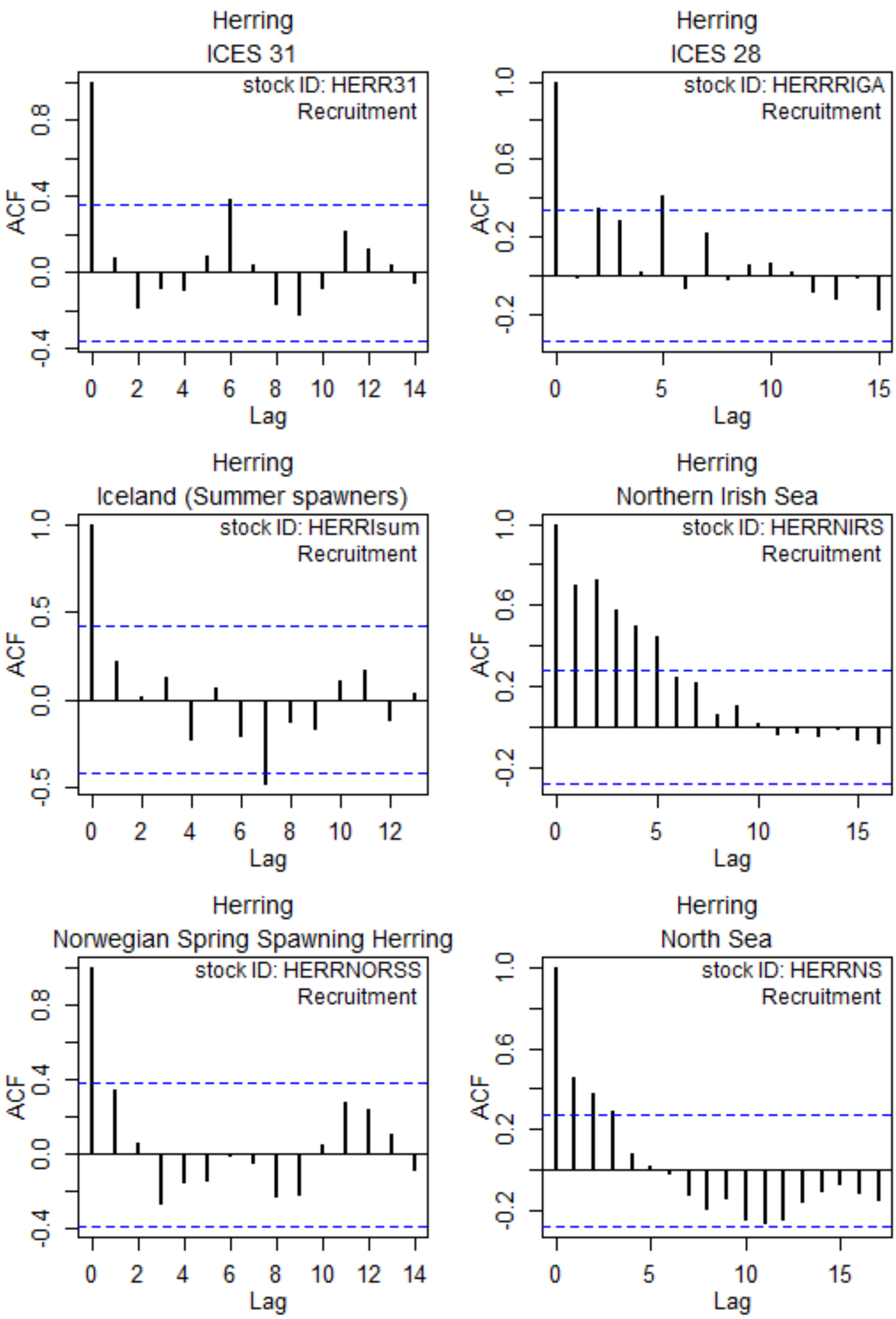
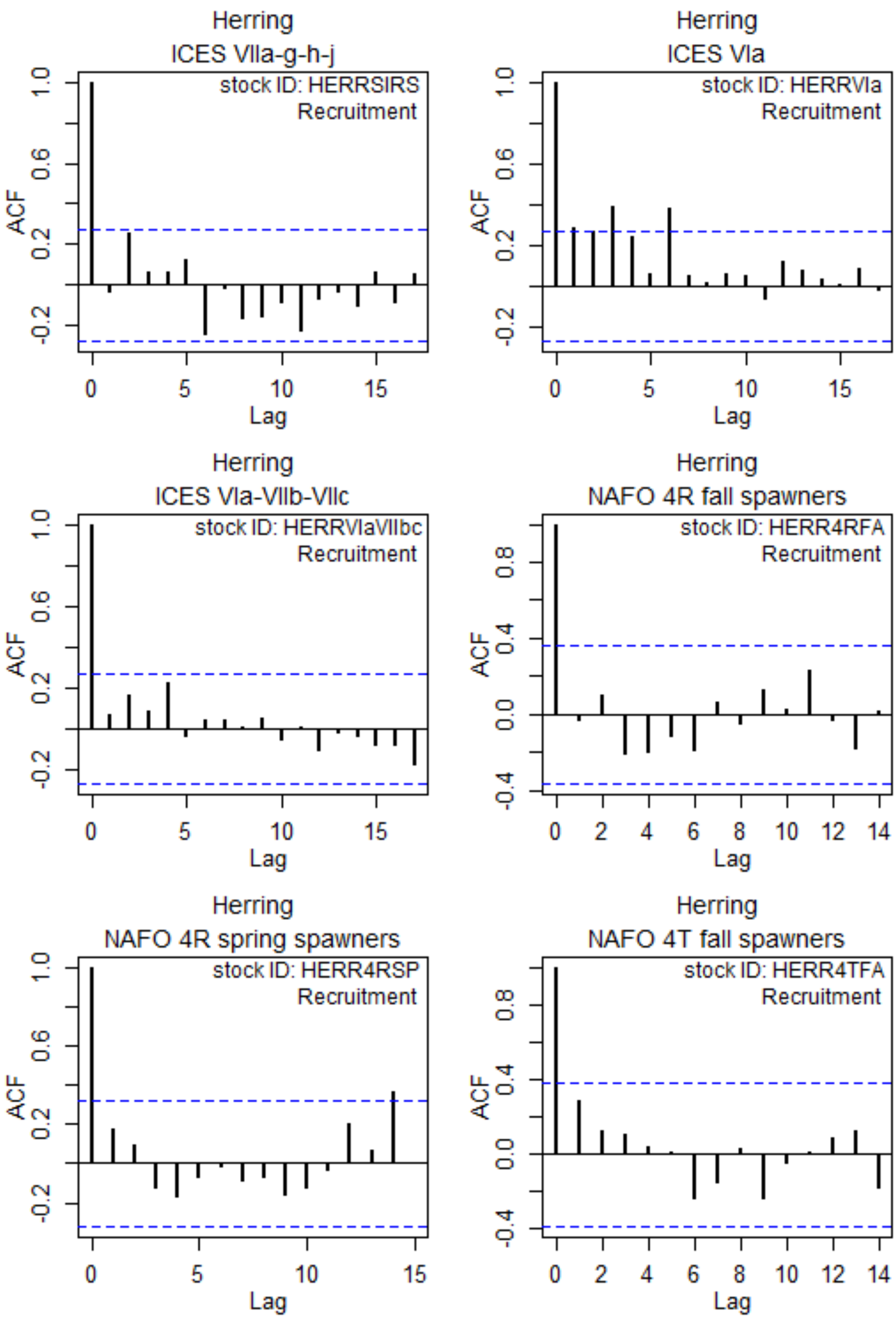


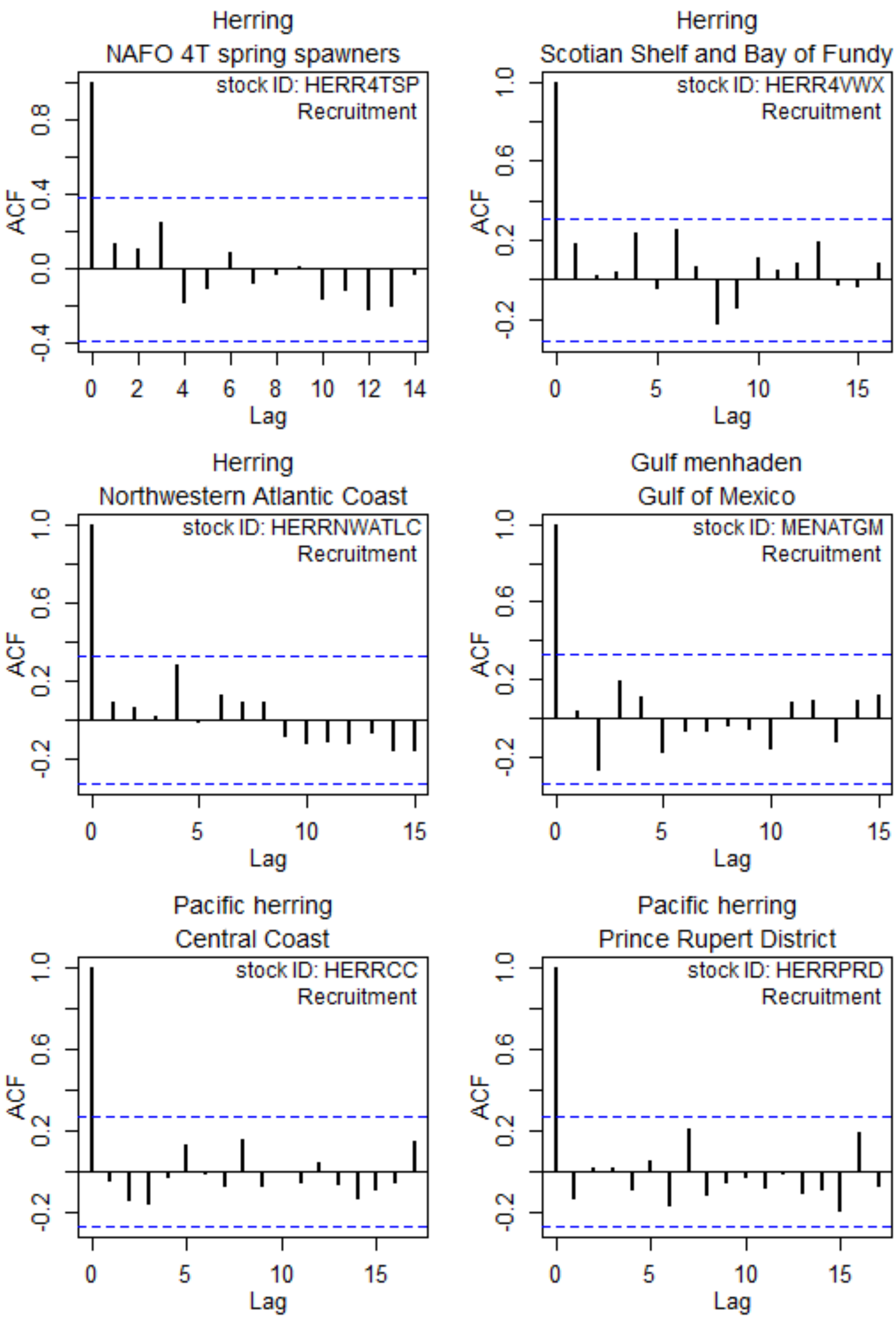
Figure S3. Autocorrelation plots for recruitment (R) for the clupeoid stocks examined in this study. The horizontal dashed lines indicate the 0.05 significance level.

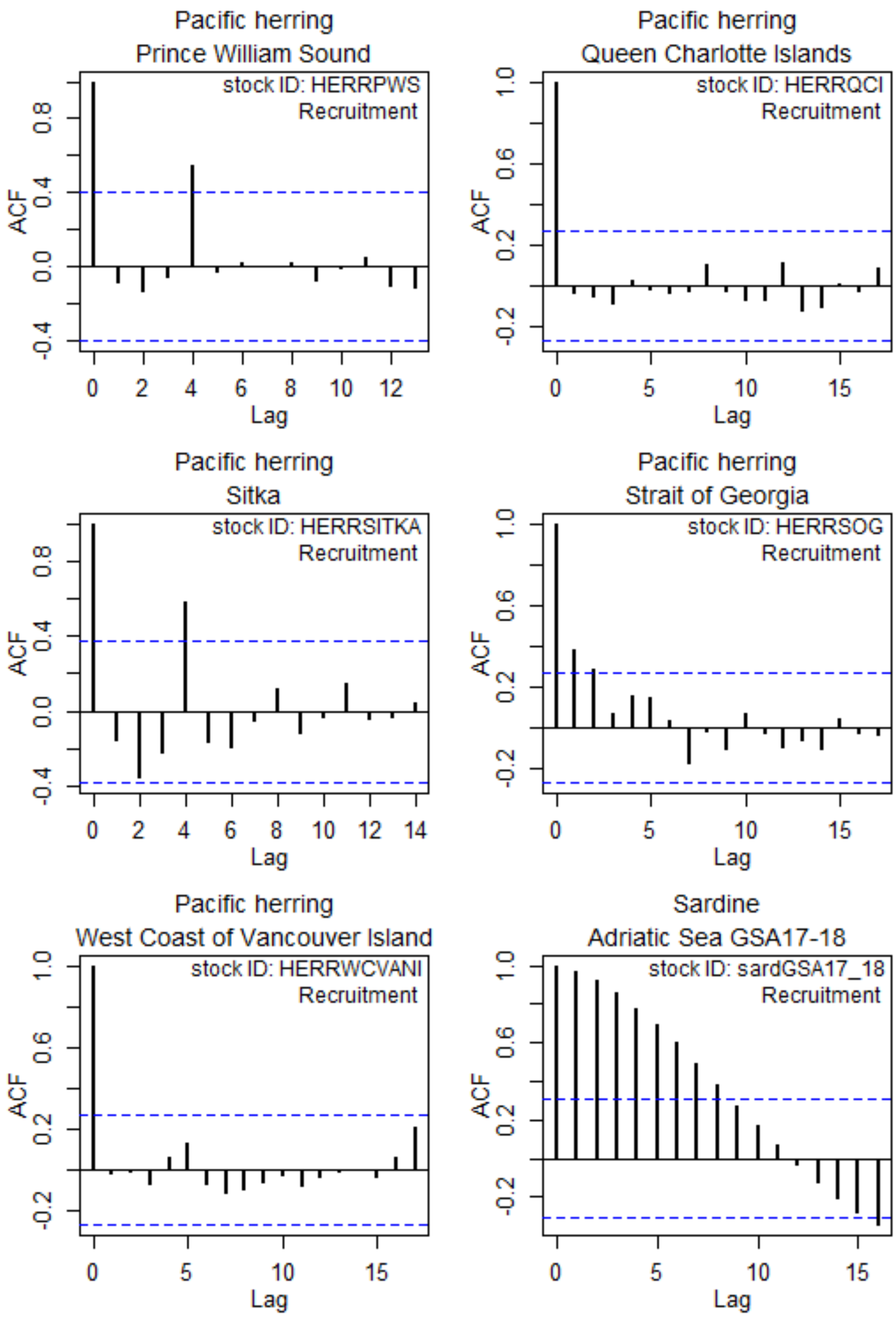


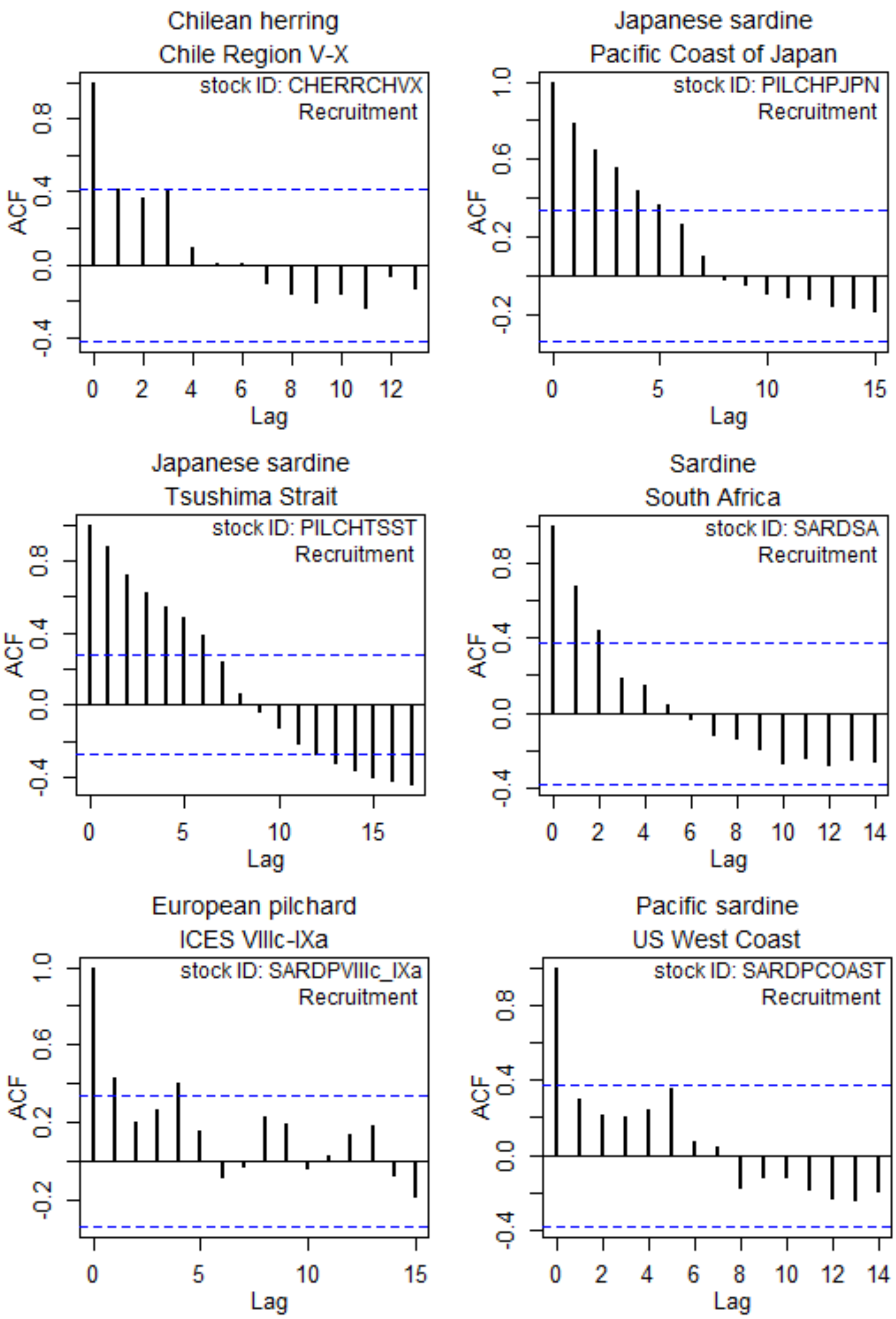

Peruvian anchoveta
North Chile
stock ID: PANCHNCH
Recruitment
ACF
Lag
Peruvian anchoveta
North-Central Peru
stock ID: PANCHPERUNC
Recruitment
ACF
Lag
Peruvian anchoveta
South Chile
stock ID: PANCHSCH
Recruitment
ACF
Lag
Herring
ICES 22-24-IIIa
stock ID: HERR2224IIIa
Recruitment
ACF
Lag
Herring
ICES 25-32
stock ID: HERR2532
Recruitment
ACF
Lag
Herring
ICES 30
stock ID: HERR30
Recruitment
ACF
Lag


Herring
ICES 31
stock ID: HERR31
Recruitment
ACF
Lag
Herring
ICES 28
stock ID: HERRRIGA
Recruitment
ACF
Lag
Herring
Iceland (Summer spawners)
stock ID: HERRIsum
Recruitment
ACF
Lag
Herring
Northern Irish Sea
stock ID: HERRNIRS
Recruitment
ACF
Lag
Herring
Norwegian Spring Spawning Herring
stock ID: HERRNORSS
Recruitment
ACF
Lag
Herring
North Sea
stock ID: HERRNS
Recruitment
ACF
Lag

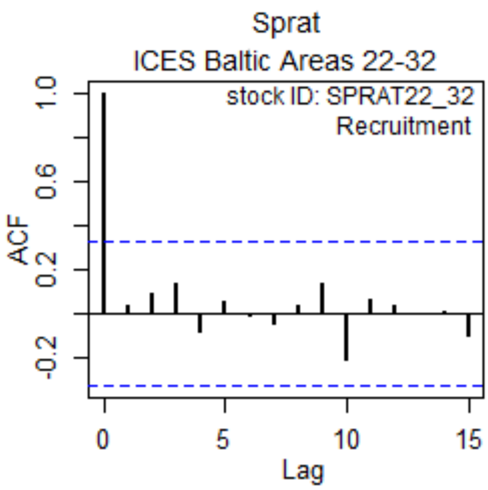

Herring
ICES VIIa-g-h-j
stock ID: HERRSIRS
Recruitment
ACF
Lag
Herring
ICES VIa
stock ID: HERRVIa
Recruitment
ACF
Lag
Herring
ICES VIa-VIIb-VIIc
stock ID: HERRVIaVIIbc
Recruitment
ACF
Lag
Herring
NAFO 4R fall spawners
stock ID: HERR4RFA
Recruitment
ACF
Lag
Herring
NAFO 4R spring spawners
stock ID: HERR4RSP
Recruitment
ACF
Lag
Herring
NAFO 4T fall spawners
stock ID: HERR4TFA
Recruitment
ACF
Lag


Herring
NAFO 4T spring spawners
stock ID: HERR4TSP
Recruitment
ACF
Lag
Herring
Scotian Shelf and Bay of Fundy
stock ID: HERR4VWX
Recruitment
ACF
Lag
Herring
Northwestern Atlantic Coast
stock ID: HERRNWATLC
Recruitment
ACF
Lag
Gulf menhaden
Gulf of Mexico
stock ID: MENATGM
Recruitment
ACF
Lag
Pacific herring
Central Coast
stock ID: HERRCC
Recruitment
ACF
Lag
Pacific herring
Prince Rupert District
stock ID: HERRPRD
Recruitment
ACF
Lag


Pacific herring
Prince William Sound
stock ID: HERRPWS
Recruitment
ACF
Lag
Pacific herring
Queen Charlotte Islands
stock ID: HERRQCI
Recruitment
Pacific herring
Sitka
stock ID: HERRSITKA
Recruitment
Pacific herring
Strait of Georgia
stock ID: HERRSOG
Recruitment
Pacific herring
West Coast of Vancouver Island
stock ID: HERRWCVANI
Recruitment
Sardine
Adriatic Sea GSA17-18
stock ID: sardGSA17_18
Recruitment



Chilean herring
Chile Region V-X
stock ID: CHERRCHVX
Recruitment
ACF
Lag
Japanese sardine
Pacific Coast of Japan
stock ID: PILCHPJPN
Recruitment
ACF
Lag
Japanese sardine
Tsushima Strait
stock ID: PILCHTSST
Recruitment
ACF
Lag
Sardine
South Africa
stock ID: SARDSA
Recruitment
ACF
Lag
European pilchard
ICES VIIIc-IXa
stock ID: SARDPVIIIc_IXa
Recruitment
ACF
Lag
Pacific sardine
US West Coast
stock ID: SARDPCOAST
Recruitment
ACF
Lag


Sprat
ICES Baltic Areas 22-32
stock ID: SPRAT22_32
Recruitment
ACF
1.0
0.6
0.2
-0.2
0
5
10
15
Lag