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Relationships between fleet-specific spawning potential ratios and measures of catch and effort for North Pacific albacore tuna [1]

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ABSTRACT

The WCPFC and IATTC adopted harvest strategies for NPALB in 2023. These harvest strategies include harvest control rules that mandated reductions in fishing intensity if the female spawning stock biomass fell below reference points. Fishing intensity in the NPALB stock assessment and harvest strategy was defined as $F_{\%SPR}$, which is the fishing intensity associated with a specific spawning potential ratio (SPR). The WCPFC NC and IATTC requested that further work be performed to relate reductions in fishing intensity to more traditional measures of catch and/or effort. The aim of this working paper is to: 1) estimate the fleet-specific fishing intensities from the 2023 stock assessment results; and 2) relate changes in the estimated fleet-specific fishing intensities to multiple fleet-specific measures of effort and catch. The base case model for the 2023 stock assessment was used to estimate the fleet-specific $F_{\%SPR}$. In order to simplify this analysis, fleets from the same country, gear, and areas were combined into fleet groups for this analysis. Quarterly effort data for each fleet group were collated from national databases or RFMOs. Estimated catches in metric tons and numbers for each fleet were extracted from the 2023 stock assessment model and combined into the fleet groups. A cross-correlation was first performed on the catch and effort data for each fleet group, together with the estimated fleet-specific SPR. Depending on the fleet group and the results from the cross-correlation, one or more effort and/or catch variables were used as explanatory variables in a series of generalized linear models to explain the changes in SPR. All fleet groups exhibited strong relationships between catch and SPRs. However, these relationships are expected to change if recruitment and/or fleet selectivity change substantially in the future. This analysis is based on historical (1994 – 2021) conditions in the 2023 assessment and if the stock conditions are very different, the analysis may not be useful. It is therefore recommended that the fleet-specific catch and effort reduction per unit of SPR presented in this analysis be thought of as approximate and illustrative, and will likely need to be reevaluated if SSB falls below the threshold or limit reference points, as this may be an indication of exceptional circumstances. The relationships between effort and SPRs are fleet-specific and more variable than between catch and SPR. Some of the fleet groups (e.g., JPPL and EPPOSF) exhibited moderately strong relationships between effort and SPRs, and may be able to be managed using effort. However, the increased variability in the relationships between effort and SPRs should be taken into account. It is recommended that the ALBWG consider the information from this paper to develop advice on how fishing intensity should be interpreted into actual management under this harvest strategy.

INTRODUCTION

The Albacore Working Group (ALBWG) of the International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean (ISC) conducted the latest stock assessment for North Pacific albacore tuna (NPALB) in 2023 (ALBWG 2023). The NPALB stock is managed by two regional fisheries management organizations (RFMOs): the Western and Central Pacific Fisheries Commission’s Northern Committee (WCPFC NC) and the Inter-American Tropical Tuna Commission (IATTC) in the Western and Central Pacific Ocean (WCPO) and the Eastern Pacific Ocean (EPO), respectively. At the request of the RFMOs, the ALBWG conducted a management strategy evaluation (MSE) for NPALB during 2015 – 2021. The RFMOs subsequently used the MSE results to develop harvest strategies for the stock, which were adopted in 2023 (WCPFC NC Harvest Strategy 2023-01; IATTC Resolution C-23-02).

These harvest strategies include harvest control rules (HCRs) that mandated reductions in fishing intensity, which is calculated in terms of spawning potential ratio, if the female spawning stock biomass (SSB) falls below the adopted reference points. However, given that WCPFC and IATTC members have traditionally used catch and/or effort controls to manage their fisheries, both RFMOs requested that further work be performed to relate reductions in fishing intensity to more traditional measures of catch and/or effort. For example, IATTC Resolution C-23-02 stated that "The IATTC scientific staff in 2024 shall collaborate with the ISC to advise how fishing intensity should be interpreted to actual management under this harvest strategy". In order to provide this advice, the WG would have to evaluate the potential relationships between fishing intensity and traditional measures of catch and effort.

The aim of this working paper is to: 1) estimate the fleet-specific fishing intensities from the 2023 stock assessment results; and 2) relate changes in the estimated fleet-specific fishing intensities to multiple fleet-specific measures of effort and catch. The information from this paper could then be used by the WG to develop advice on how fishing intensity should be interpreted into actual management under this harvest strategy.

MATERIALS AND METHODS

Fishing Intensity and Spawning Potential Ratios (SPRs)

Fishing intensity in the NPALB stock assessment and harvest strategy is defined as $F_{\%SPR}$, which is the fishing intensity associated with a specific spawning potential ratio (SPR). The SPR is the ratio of the equilibrium female spawning stock biomass (SSB) per recruit that would result from the estimated F-at-age relative to that of an unfished population. Therefore, a lower $F_{\%SPR}$ indicates a lower proportion of SSB relative to an unfished population, and hence a higher fishing intensity (Goodyear 1993). For example, the 2023 assessment estimated that the $F_{\%SPR,\ 2018\text{-}2020}$ was approximately 59.0%, which means that the SSB would be 59% of an unfished population with the same recruitment, if the fishing intensity is maintained over the long term.

Fishing intensity and SPRs are particularly useful in stocks like NPALB, where: 1) there are multiple fisheries exploiting different age classes on the same stock due to different selectivities and/or availability; and 2) important reference points are based on dynamic SSB_0 ($SSB_{current,F=0}$). Using fishing intensity and SPRs allow fishing mortality at different age classes to be related to impacts on SSB equivalence and compared using the same units. Fishing mortality on different age-classes have differing impacts on SSB. In this study, following the 2023 assessment, female albacore are assumed to have different age-specific natural mortality and average weights (Table 1). These age-specific differences in biology causes fishing on different age classes to have different impacts on the resulting SSB (Table 2). Fisheries with different age selectivities and/or availabilities will therefore have different levels of catch-per-recruit and $F_{\%SPR}$, even with the same level of maximum F-at-age (Fig. 1). It should be noted that the 2023 NPALB assessment only calculates female SSB and that male albacore do not contribute directly to female SSB, and hence male albacore are not included in SPR calculations.

The 2023 stock assessment used the Stock Synthesis (SS) modelling platform (Methot and Wetzel 2013). However, SS currently only reports the overall $F_{\%SPR}$ but does not report fleet-specific $F_{\%SPR}$. The fleet-specific $F_{\%SPR}$ for this study was calculated from the fleet-specific F-at-age and biological parameters, using the methods described in Lee & Taylor (2023). In short, the seasonal, fleet-specific F-at-age and biological parameters (e.g., M-at-age, weight-at-age, maturity-at-age) reported by SS were used to simulate a fished population until a stable age distribution is approximated. The SSB per recruit of the fished population during the spawning season was then divided by the SSB per recruit of an unfished population with the same biological parameters to calculate the $F_{\%SPR}$ for the fleet. Lee & Taylor (2023) showed that this method closely approximated the total $F_{\%SPR}$ reported by SS if the total F-at-age was used in the calculations, however, using fleet-specific $F_{\%SPR}$ results in small errors. The cause for these errors are currently unclear but likely resulted from very small fleet-specific F-at-age estimates and rounding in the SS reports. A preliminary analysis using the 2023 NPALB assessment indicated that the $F_{\%SPR}$ calculations for this analysis had errors approximating 2% of the total SPR.

The base case model for the 2023 stock assessment was used to estimate the fleet-specific $F_{\%SPR}$. The fleet structure of the 2023 assessment was relatively complex, with 35 fleets due to various combinations of country, gear, catch unit, area, and season. In order to simplify this analysis, fleets were combined into fleet groups for this analysis (Table 3).

Data

Quarterly effort data for each fleet group were collated from national databases or RFMOs (Table 3). Effort data of longline fleets generally consisted of number of vessels, number of hooks (1000s of hooks), and number of sets or days (longline vessels typically put out one longline set per day). However, some longline fleets only had number of hooks as available effort data (CNLL, KRLL, and VUOTHLL). Effort data of surface fleets (i.e., pole-and-line, troll) generally included number of vessels, and number of fishing days. However, the Japan pole-and-line fleet group (JPPL; fleet group 2) included effort measures like average number of poles and number of pole-days (number of fishing days * average number of poles). In addition, the WG had previously noted that some JPPL vessels switch between targeting albacore and skipjack, and the amount of skipjack catch may help resolve target switching. It should be noted that fleet group 9 was a group consisting of miscellaneous fisheries, and no effort data was available for that fleet group. Annual effort data were assembled from the quarterly effort by simple summing of quarterly effort. However, this could not be applied to the number of vessels because many vessels operated over several quarters. The exception would be for the US longline fleets because set-by-set effort data were available for analysis.

Estimated catches in metric tons and 1000s of fish for each fleet were extracted from the 2023 stock assessment model and combined into the fleet groups (Table 4). Estimated annual SPRs for specific fleet groups are shown in Table 5. Estimated annual effort in vessel-days for the JPPL and EPOSF are shown in Table 6.

Analysis

The analyses in this study proceeded in two steps. First, a cross-correlation using Pearson's correlation coefficient was performed on the measures of catch and effort for each fleet group, together with the estimated fleet-specific SPR (Table 5). Then depending on the fleet and the results from the cross-correlation, one or more effort and/or catch variables were used as explanatory variables in a series of generalized linear models (GLMs) to explain the changes in SPR. The GLMs assumed that the intercept was at 0 (i.e., no intercept was estimated) because a catch or effort of 0 is expected to result in no change in SPR. Given the large number of correlations and GLMs performed, as well as the lack of observation error, the statistical significance of the results should be interpreted with caution.

RESULTS AND DISCUSSION

Age-specific Fishing Impacts on Female SSB

The biological parameters for this study were the same as that for the 2023 stock assessment (ALBWG 2023). The natural mortality of female NPALB decreases by age from age-0 to age-2, before rising to 0.48 y^{-1} t age-3+ (Table 1). The weight of an individual female NPALB at the beginning of season 3 increases rapidly as a juvenile before slowing as an adult (Table 1). Based on biological studies (Chen et al. 2010), NPALB was assumed to be 50% mature at age-5 before becoming fully mature at age-6, and fecundity of an adult female was assumed to be proportional to body weight (ALBWG 2023).

Combining the above biological parameters results in the age-specific fishing impact of catching female fish on age-specific yields and SSB (Table 2). The impact of fishing 1 mt of female fish are highest for age-0 and age-1 fish (Table 2). However, fishing impacts of age-2 and age-3 female fish on SSB are lower than on age-1 and age-4 fish (Table 2). Similar patterns also occur with respect to expected yields at different ages. For example, instead of catching 1 mt of fish at age-2, waiting one year for the fish to grow into age-3 is expected to result in a marginally higher yield of 1.02 mt, even though only 62.8% of the age-2 fish are expected to survive till age-3 due to natural mortality. It should be noted that if fishing mortality is considered, the expected yield would be lower.

Given the age-specific impacts of fishing, fleets with different age-selectivies and/or availabilities are expected to have different impacts on SSB and SPR. A fleet with higher selectivities for juvenile albacore (e.g., JPPL, EPOSF) is expected to have a larger impact on female SSB (i.e., a larger decline in SPR) than a fleet with higher selectivity for older fish (e.g., USLL) for the same maximum F-at-age (Fig. 1). However, the fleet fishing on juvenile albacore is expected to have a higher yield per recruit than for the fleet fishing on large adults, for the same maximum F-at-age (Fig. 1). Therefore, the relationships between catch and changes in SPR for fleets with different age-selectivities and/or availabilities are expected to have different slopes. It is important to note that the relationships between yield-per-recruit, F-at-age, and SPRs are non-linear and it is important to re-evaluate the relationships if the SSB and SPR levels are substantially different from historical levels.

Catch and Effort

The results of the cross-correlation are shown as pairs plots. The pairs plots indicated that there were very strong correlations between some catch and effort variables (Figs. 2 – 19). Catch in weight was highly correlated with catch in numbers for all fleet groups. For fleet groups with variable selectivity (e.g., two or more fleets with different selectivity, or highly time varying selectivity), the correlation was degraded due to variable weight per fish. Given the strong correlation between catch in weight and catch in numbers, further analysis would be focused primarily on catch in weight data but the results would apply reasonably well to catch in numbers, albeit with different numbers and units.

For longline fleet groups, the number of days or sets were highly correlated with the number of hooks set on both seasonal and annual basis. Similarly, longline fleets with data on number of vessels (JPLL – Fig. 2, USLL – Fig. 6 & 7, and TWLL – Fig. 8) showed strong correlations between number of vessels and number of hooks. There was a consistently strong correlation between number of sets or days, and the number of hooks set for all longline fleets with available effort data (JPLL – Fig. 2 & 3, USLL – Fig. 6 & 7, and TWLL – Fig. 8 & 9). The other longline fleets (KRLL, CNLL, and VUOTHLL) only had hooks for effort data. For longline effort, this study would be focused on number of hooks, which is the traditional unit of effort for longline gear, but the results would apply reasonably well to number of sets, and to a lesser extent number of vessels. The number of hooks of longline fleet groups were generally weakly correlated with the catch in weight, and the relationship varied by fleet.

For the two fleet groups using surface gears (JPPL and EPOSF), this study focused on the number of vessel days, which is the traditional unit of effort for these fleets. For both surface fleet groups, the number of vessel days were strongly correlated with the number of vessels. Therefore, the results of the analysis could be applied to the number of vessels as well, albeit with more uncertainty and variability. In addition, the JPPL fleet group effort data included the number of pole-days, which was highly correlated with number of vessel days.

SPR vs Catch and Effort

The pairs plots of all longline fleet groups show that catch was very highly negatively correlated with fleet-specific SPR (Figs. 2 – 19). Results from single variable GLMs between seasonal, fleet-specific SPRs and seasonal fleet-specific catch in weight as explanatory variables, indicate that catches would have to be reduced by 901 – 1,473 mt, depending on fleet group, in order to increase SPR by 1%pt (i.e., lower fishing impact and fishing mortality) (Fig. 20). Another way to look at this is that fleet groups with higher catch (mt) per unit of SPR has lower impact on the female SSB per unit of catch in weight. The fishing impact on SSB per unit of catch depends on the ages and sex ratios of fish (i.e., removing male fish do not impact SPR) caught by the fleet group (Table 2). For example, the GLM results of USLL (fleet group 3), which catches both the largest fish and the highest proportions of male fish, show the highest catch (mt) per unit of change in SPR among all fleet groups (Fig. 20).

The correlations between the number of hooks and SPRs were highly variable and fleet-specific (Figs. 2 – 3; 6 – 15). Some longline fleet groups (JPLL, and CNLL) had moderate correlations between number of hooks and SPRs but other longline fleet groups (USLL, TWLL, KRLL, and VUOTHLL) had much weaker relationships. Even among the longline fleet groups with stronger relationships, the correlations between number of hooks and SPRs were more variable than between catch and SPRs.

Similar to the longline fleet groups, the surface fleet groups also showed that their fleet-specific catch was highly correlated with the fleet-specific SPRs (JPPL, Figs. 4 – 5; EPOSF, Figs. 16 – 17). However, the relationships between catch and SPRs for the surface fleet groups were slightly more variable and uncertain than for the longline fleet groups. This was because the surface fleet groups caught predominantly juvenile fish (Ages 2 – 4) and exhibited variable selectivity due to changes in availability. Therefore, these fleet groups were more sensitive to changes in recruitment and availability. Interestingly, results of the GLMs between catch and SPR indicate that catches of both fleet groups would have to be reduced by similar amounts in order to increase SPR by 1 %pt (Fig. 20). In addition, it was noted that the JPPL fleet group exhibited a stronger relationship between effort and skipjack catch, as compared to albacore catch (Fig. 4). This was likely due to skipjack being the primary target species for this fishery.

Both surface fleet groups also showed moderately strong correlations between the effort (number of vessel days) and SPRs (JPPL, Figs. 4 – 5; EPOSF, Figs. 16 – 17). These relationships between effort and SPRs were weaker than for the corresponding relationships between catch and SPRs. In contrast to the similar impact on SSB per unit of catch in weight, the GLMs for effort (number of vessel days) show an order of magnitude difference between the two fleet groups (Fig. 21). This is likely due to the order of magnitude difference between the recorded effort for these fleets.

Overall

It should be noted that both RFMOs currently maintain fishing effort for NPALB at or below the average of 2002 – 2004 levels (e.g., IATTC Resolution C-05-02) and that has maintained the fishing impact on NPALB around or below the target reference point of 45% $F_{\%SPR}$.

All fleet groups exhibited strong relationships between catch and SPRs. However, these relationships are expected to change if recruitment and/or selectivity or availability patterns change substantially. It should be noted that this analysis is based on historical (1994 – 2021) conditions in the 2023 assessment and if the stock conditions are very different, the results from this analysis should be treated with caution. For example, if the SSB falls below the threshold or limit reference points for NPALB (30%$SSB_{current,F=0}$ and 14%$SSB_{current,F=0}$), the recruitment, selectivities, and availability may be very different from the historical average, which in turn will change the amount of fleet-specific catch reduction needed for each unit of desired SPR change. It is therefore recommended that the fleet-specific catch and effort reduction per unit of SPR (Figs. 20 & 21) be thought of as approximate and illustrative, and may need to be reevaluated if SSB falls below the threshold or limit reference points.

The relationships between effort and SPRs are fleet-specific and more variable than for catch. Some of the fleet groups, especially the fleets using surface gears (i.e., JPPL and EPPOSF) exhibit moderately strong relationships between effort and SPRs, and may be able to be managed using effort. The increased variability in the relationships between effort and SPRs should be taken into account. In addition, it should be noted that the WCPFC has adopted a harvest strategy for skipjack tuna in the WCPO (WCPFC CCM 2020-01) and the JPPL fishery, which targets primarily skipjack tuna, is managed using effort controls under that harvest strategy.

An approach to translating fishing intensity ($F_{\%SPR}$) into operational control measures may be for the RFMOs to specify the exact amounts of catch and effort for each fleet, and potentially change those amounts after every assessment. Another alternative approach would be for the RFMO to specify changes in $F_{\%SPR}$ for members but allow individual members to determine how to achieve those changes in $F_{\%SPR}$.

It is recommended that the WG consider the information from this paper to develop advice on how fishing intensity should be interpreted into actual management under this harvest strategy.

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Table 1. Female weight-at-age at the beginning of Season 3 and annual instantaneous mortality rates in the 2023 NPALB stock assessment.

Age-class	Average female weight-at-age at the start of season 3 (kg)	Female natural mortality (y^{-1})
0	0.13	0.790
1	2.26	0.505
2	5.10	0.465
3	8.31	0.480
4	11.40	0.480
5	14.13	0.480
6	16.42	0.480
7	18.27	0.480
8	19.73	0.480
9	20.86	0.480
10	21.73	0.480
11	22.39	0.480
12	22.89	0.480
13	23.27	0.480
14	23.55	0.480
15+	23.91	0.480

Table 2. Female age-specific yield (mt) and SSB equivalent (mt), if 1 metric ton (upper triangle; horizontal bands) or 1000 fish (lower triangle; vertical bands) of female albacore at specific ages are removed from the population. For example, if 1 mt of age-12 fish are removed, (reading along the horizontal bands) this will be equivalent to 1.67 mt of female SSB; or 0.63 mt of age-13 fish after you wait one year, and 0.39 mt of age-14 fish if you wait two years. If 1000 fish of age-12 are removed, (reading down the vertical bands) this will yield 22.89 mt of age-12 fish and be equivalent to 38.28 mt of female SSB; or 14.40 mt of age-13 fish after you wait one year, and 9.02 mt of age-14 fish if you wait two years.

	Age-0	**Age-1**	**Age-2**	**Age-3**	**Age-4**	**Age-5**	**Age-6**	**Age-7**	**Age-8**	**Age-9**	**Age-10**	**Age-11**	**Age-12**	**Age-13**	**Age-14**	**Age-15+**	**SSB equiv. (mt)**	**Yield (mt)**
Age-0		8.02	10.92	11.17	9.48	7.27	5.23	3.60	2.41	1.57	1.01	0.65	0.41	0.26	0.16	0.27	19.20	1.00
Age-1	1.03		1.36	1.39	1.18	0.91	0.65	0.45	0.30	0.20	0.13	0.08	0.05	0.03	0.02	0.03	2.40	1.00
Age-2	1.40	3.08		1.02	0.87	0.67	0.48	0.33	0.22	0.14	0.09	0.06	0.04	0.02	0.01	0.02	1.76	1.00
Age-3	1.43	3.15	5.22		0.85	0.65	0.47	0.32	0.22	0.14	0.09	0.06	0.04	0.02	0.01	0.02	1.72	1.00
Age-4	1.21	2.67	4.43	7.05		0.77	0.55	0.38	0.25	0.17	0.11	0.07	0.04	0.03	0.02	0.03	2.03	1.00
Age-5	0.93	2.05	3.40	5.41	8.74		0.72	0.50	0.33	0.22	0.14	0.09	0.06	0.04	0.02	0.04	2.14	1.00
Age-6	0.67	1.47	2.44	3.89	6.29	10.16		0.69	0.46	0.30	0.19	0.12	0.08	0.05	0.03	0.05	1.98	1.00
Age-7	0.46	1.02	1.68	2.68	4.33	7.00	11.31		0.67	0.44	0.28	0.18	0.11	0.07	0.04	0.07	1.87	1.00
Age-8	0.31	0.68	1.12	1.79	2.89	4.68	7.56	12.21		0.65	0.42	0.27	0.17	0.11	0.07	0.11	1.80	1.00
Age-9	0.20	0.44	0.74	1.17	1.89	3.06	4.94	7.99	12.91		0.64	0.41	0.26	0.16	0.10	0.17	1.75	1.00
Age-10	0.13	0.29	0.47	0.75	1.22	1.97	3.19	5.15	8.32	13.45		0.64	0.40	0.25	0.16	0.26	1.72	1.00
Age-11	0.08	0.18	0.30	0.48	0.78	1.26	2.03	3.28	5.31	8.57	13.86		0.63	0.40	0.25	0.41	1.69	1.00
Age-12	0.05	0.12	0.19	0.30	0.49	0.80	1.29	2.08	3.36	5.42	8.77	14.17		0.63	0.39	0.65	1.67	1.00
Age-13	0.03	0.07	0.12	0.19	0.31	0.50	0.81	1.31	2.11	3.41	5.51	8.91	14.40		0.63	1.03	1.66	1.00
Age-14	0.02	0.05	0.08	0.12	0.19	0.31	0.51	0.82	1.32	2.14	3.45	5.58	9.02	14.57		1.65	1.65	1.00
Age-15+	0.03	0.07	0.12	0.20	0.32	0.52	0.83	1.35	2.18	3.52	5.69	9.20	14.86	24.02	38.82			
SSB equiv. (mt)	2.46	5.42	8.97	14.29	23.09	30.24	32.46	34.18	35.51	36.52	37.28	37.85	38.28	38.59	38.82			
Yield (mt)	0.13	2.26	5.10	8.31	11.40	14.13	16.42	18.27	19.73	20.86	21.73	22.39	22.89	23.27	23.55			

Table 3. Fleet groups used in this study with reference to the fleets in the 2023 stock assessment.

Fleet Group	Fleet Group Name	Fleet ID in 2023 assessment	Units of Effort	Fleet Group Description
1	JPLL	F1 to F20	Hooks, Vessels, Days	Japan longline; all areas; all seasons
2	JPPL	F21 to F24	Vessels, Days, Poledays, Avg poles, SKJ catch	Japan pole-and-line; all areas; all seasons
3	USLL	F26 & F27	Hooks, Vessels, Sets	US longline; all areas; all seasons
4	TWLL	F28 & F29	Hooks, Vessels, Days	Taiwan longline; all areas; all seasons
5	KRLL	F30	Hooks	Korea longline; all areas; all seasons
6	CNLL	F31 & F32	Hooks	China longline; all areas; all seasons
7	VUOTHLL	F33	Hooks	Vanuatu & Others longline; all areas & seasons
8	EPOSF	F34	Vessels, Days	EPO Surface fleet (primarily US and Canada); all seasons
9	MISC	F35	NA	Miscellaneous fleets from Japan, Taiwan, & Korea

Table 4. Annual catch in weight (t) by fleet estimated by the 2023 base case assessment model. Catch in weight include estimates based on catch in numbers for some fleets. See Table 3 for fleet abbreviations.

	Estimated fleet-specific catch (mt)								
Year	**JPLL**	**JPPL**	**USLL**	**TWLL**	**KRLL**	**CNLL**	**VUOLL**	**EPOSF**	**MISC**
1994	29,045	26,389	565	83	2	11	0	13,282	3,386
1995	28,647	20,981	885	4,279	13	16	0	10,226	2,703
1996	31,835	20,272	1,187	7,596	157	15	1	20,684	1,798
1997	38,352	32,238	1,660	9,456	404	14	2	17,769	3,546
1998	35,755	22,926	1,130	8,810	225	11	4	20,097	3,301
1999	33,249	50,369	1,553	8,392	98	142	2	17,121	8,493
2000	29,318	21,550	956	8,842	15	27	8	16,349	3,409
2001	28,053	29,430	1,305	8,685	63	438	69	18,628	1,738
2002	24,546	48,271	525	7,965	111	380	2,068	18,816	4,949
2003	21,216	36,143	526	7,164	146	822	1,996	23,406	1,955
2004	17,046	32,255	361	4,987	77	845	4,481	23,159	8,178
2005	20,297	16,133	296	4,472	419	462	3,272	15,223	2,154
2006	21,281	15,400	270	4,316	134	1,028	3,292	18,972	1,363
2007	23,073	37,768	344	2,916	136	104	3,240	18,533	6,727
2008	19,046	19,060	384	3,069	400	188	2,851	17,655	4,571
2009	21,858	31,172	301	2,379	95	104	1,676	19,032	2,860
2010	21,414	19,561	476	2,818	107	910	2,546	19,110	1,045
2011	21,851	25,704	809	3,434	78	2,839	3,716	15,988	1,078
2012	23,702	33,742	933	2,641	156	5,256	2,693	17,871	5,036
2013	21,003	33,568	365	4,428	173	3,255	3,532	18,244	2,566
2014	21,328	29,433	262	2,616	116	1,760	3,175	19,256	2,451
2015	22,647	21,294	308	3,020	38	1,723	3,452	16,923	1,778
2016	17,238	14,435	272	3,406	56	684	1,413	14,277	4,021
2017	17,735	20,891	130	4,332	202	969	2,171	9,649	1,610
2018	13,520	17,875	107	4,514	101	846	2,049	10,827	3,270
2019	12,579	8,508	114	5,453	65	1,372	2,274	11,537	1,734
2020	13,911	36,534	166	3,810	56	1,320	1,774	10,161	6,945
2021	19,882	10,593	241	5,953	275	791	2,852	6,945	2,639

Table 5. Annual fleet-specific fishing intensity ($F_{\%SPR}$) estimated by the 2023 base case assessment model. Note that values are the estimated spawning potential ratios (SPRs) if only the specified fleet was fishing. Hence, lower $F_{\%SPR}$ values indicate higher fishing intensity. See Table 3 for fleet abbreviations.

	Estimated fleet-specific fishing intensity ($F_{\%SPR}$)								
Year	**JPLL**	**JPPL**	**USLL**	**TWLL**	**KRLL**	**CNLL**	**VUOLL**	**EPOSF**	**MISC**
1994	76.0	84.3	99.4	99.9	100.0	100.0	100.0	90.8	97.5
1995	77.7	87.4	99.3	96.3	100.0	100.0	100.0	93.5	97.7
1996	77.4	84.5	99.2	93.8	99.9	100.0	100.0	87.3	98.8
1997	74.6	81.8	98.9	92.6	99.7	100.0	100.0	87.7	97.6
1998	75.1	85.0	99.3	92.7	99.8	100.0	100.0	86.6	97.2
1999	75.9	61.4	99.1	92.3	99.9	99.9	100.0	86.2	93.1
2000	77.9	85.4	99.4	91.5	100.0	100.0	100.0	85.1	97.0
2001	77.6	78.5	99.3	91.8	99.9	99.5	99.9	85.7	98.1
2002	80.0	63.0	99.7	92.2	99.9	99.6	97.8	84.8	96.6
2003	81.8	75.0	99.7	92.8	99.9	99.2	97.8	80.8	97.7
2004	83.9	67.1	99.8	94.6	99.9	99.2	94.9	78.9	92.9
2005	80.3	87.6	99.8	94.8	99.6	99.6	96.0	84.8	97.2
2006	79.6	83.6	99.8	95.0	99.9	98.9	96.1	85.1	98.8
2007	79.1	72.2	99.7	96.8	99.9	99.9	96.4	85.1	94.8
2008	82.4	86.6	99.7	96.7	99.6	99.8	96.9	86.4	96.3
2009	80.7	74.5	99.7	97.5	99.9	99.9	98.2	84.4	97.6
2010	81.0	84.2	99.6	97.1	99.9	99.2	97.3	84.3	99.0
2011	81.0	78.6	99.3	96.4	99.9	97.6	96.0	87.4	99.1
2012	80.4	76.4	99.2	97.3	99.9	95.5	97.2	86.4	95.9
2013	82.2	74.2	99.7	95.5	99.8	97.1	96.4	85.6	98.0
2014	82.0	78.2	99.8	97.3	99.9	98.4	96.7	83.1	97.7
2015	80.1	80.3	99.7	96.9	100.0	98.4	96.2	85.4	98.2
2016	84.3	83.2	99.8	96.5	100.0	99.3	98.4	86.8	96.5
2017	83.9	81.3	99.9	95.8	99.8	99.1	97.6	90.0	98.4
2018	86.7	79.3	99.9	95.6	99.9	99.2	97.6	89.9	96.1
2019	87.5	87.9	99.9	95.0	99.9	98.7	97.4	92.5	98.5
2020	88.4	73.3	99.9	96.7	100.0	98.8	98.4	94.3	96.5
2021	85.0	95.2	99.8	95.3	99.8	99.3	97.9	96.3	98.6

Table 6. Annual fleet-specific fishing effort (vessel days) for the JPPL and EPOSF surface fleets. See Table 3 for fleet abbreviations.

	Fishing effort (vessel days)	
Year	**JPPL**	**EPOSF**
1994	2,266	NA
1995	1,893	19,884
1996	2,421	25,743
1997	4,205	23,484
1998	3,226	19,001
1999	4,817	30,656
2000	2,942	25,215
2001	3,962	27,681
2002	4,242	21,329
2003	3,727	24,378
2004	2,641	26,250
2005	2,833	20,889
2006	2,282	18,258
2007	3,658	18,518
2008	2,124	15,656
2009	2,507	19,889
2010	2,338	20,020
2011	1,866	22,531
2012	3,675	21,363
2013	2,447	19,471
2014	2,697	16,863
2015	2,502	16,977
2016	1,833	18,051
2017	2,171	17,631
2018	1,989	15,190
2019	713	14,866
2020	1,836	11,933
2021	1,442	10,385

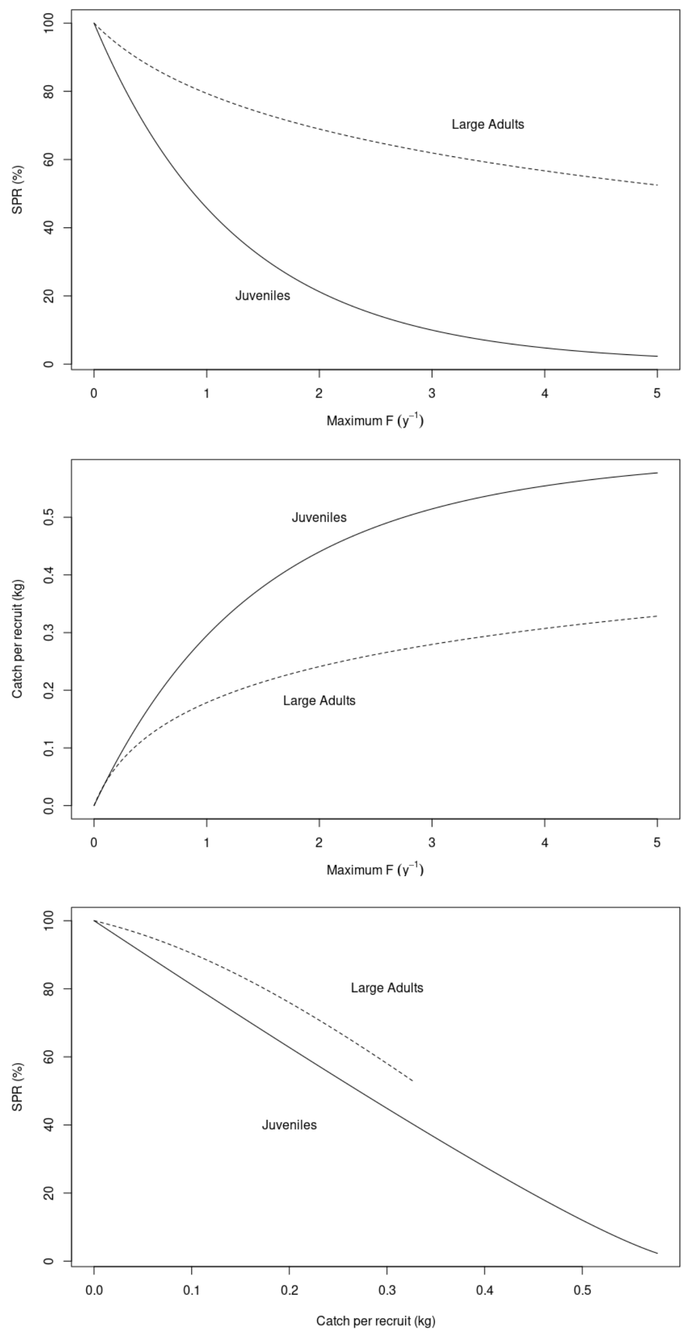

Figure 1. Simulated relationships between a range of maximum Fs (y^{-1}), catch per recruit (kg), and spawning potential ratio (SPR; %) for two hypothetical fleets with one fleet fishing primarily on juveniles (solid lines), and another primarily on large adults (dashed lines).

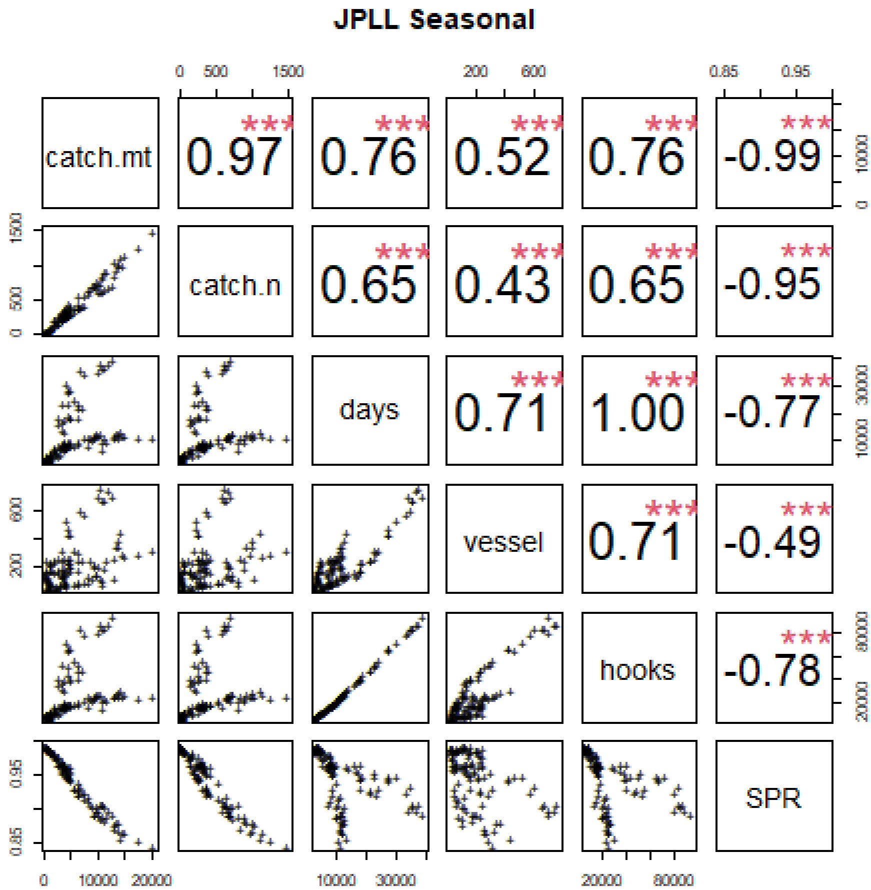

Figure 2. Pairs plot and correlations of quarterly catch (metric tons and 1000s of fish), and effort (number of fishing days, number of vessels, and 1000s of hooks) versus estimated quarterly spawning potential ratios for Japan longline in all areas (Fleets 1 to 20 in the 2023 assessment). Lower triangle shows plots of variable pairs. Upper triangle shows Pearson correlation coefficients, with asterisks indicating statistical significance (* p<0.05; ** p<0.01; *** p<0.001).

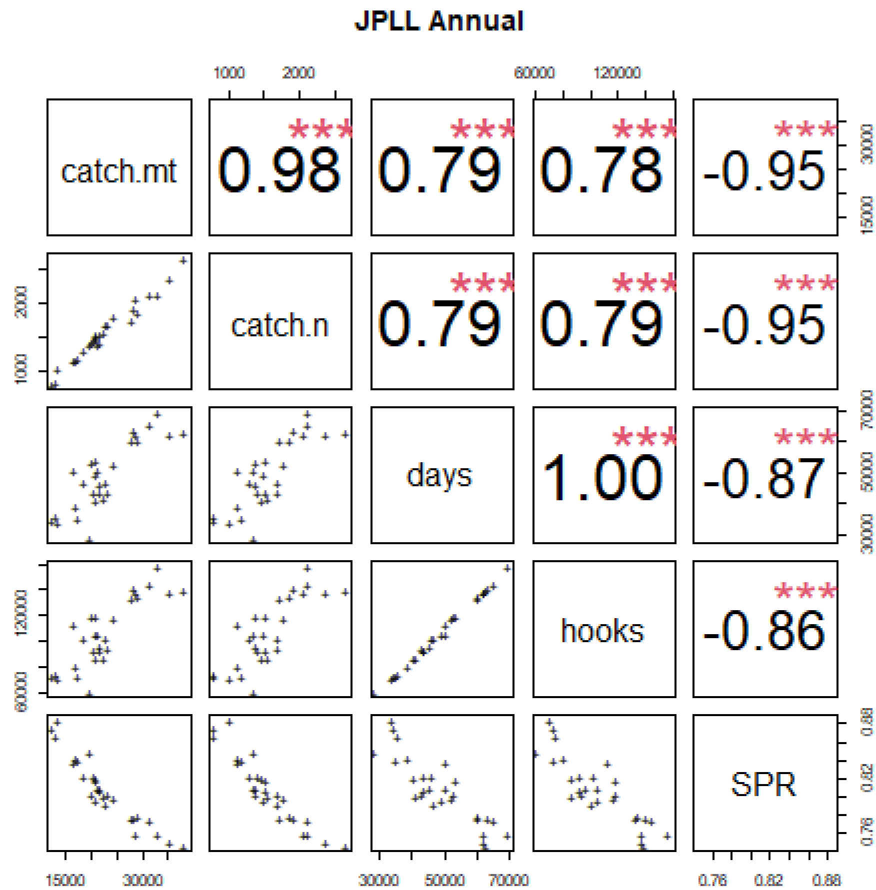

Figure 3. Pairs plot and correlations of annual catch (metric tons and 1000s of fish), and effort (number of fishing days, and 1000s of hooks) versus estimated annual spawning potential ratios for Japan longline in all areas (Fleets 1 to 20 in the 2023 assessment). Lower triangle shows plots of variable pairs. Upper triangle shows Pearson correlation coefficients, with asterisks indicating statistical significance (* p<0.05; ** p<0.01; *** p<0.001).

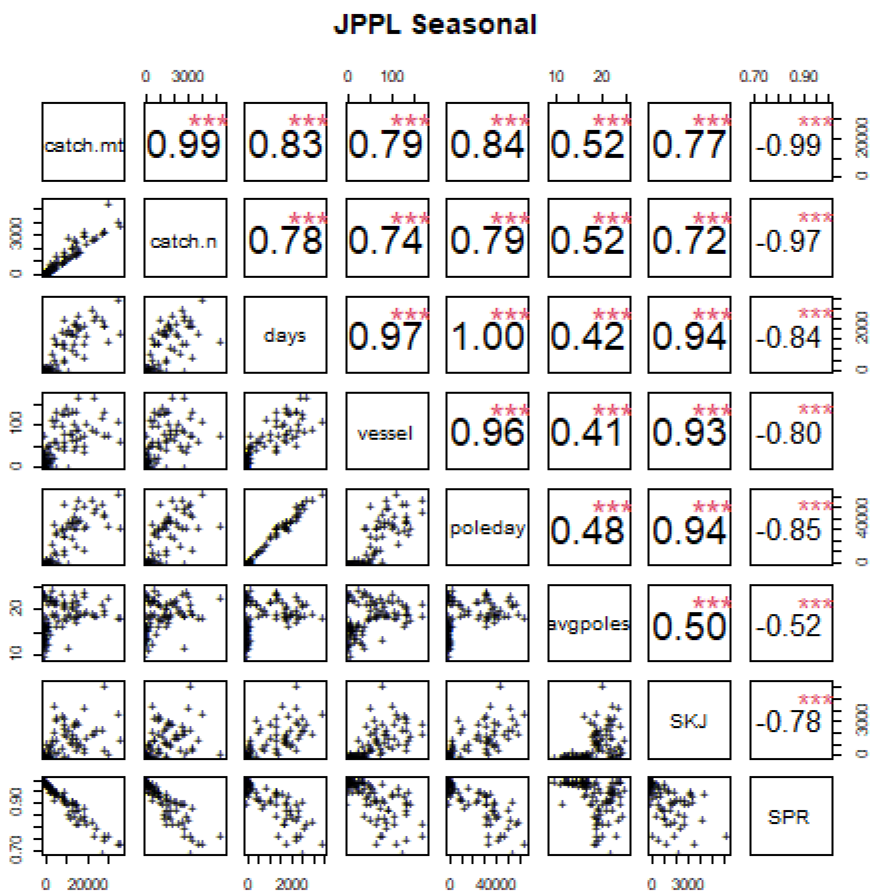

Figure 4. Pairs plot and correlations of quarterly catch (metric tons and 1000s of fish), and effort (number of fishing days, number of vessels, number of pole-days, average number of poles, and skipjack catch (mt)) versus estimated quarterly spawning potential ratios for Japan pole-and-line in all areas (Fleet 21 to 25 in the 2023 assessment). Lower triangle shows plots of variable pairs. Upper triangle shows Pearson correlation coefficients, with asterisks indicating statistical significance (* $p<0.05$; ** $p<0.01$; *** $p<0.001$).

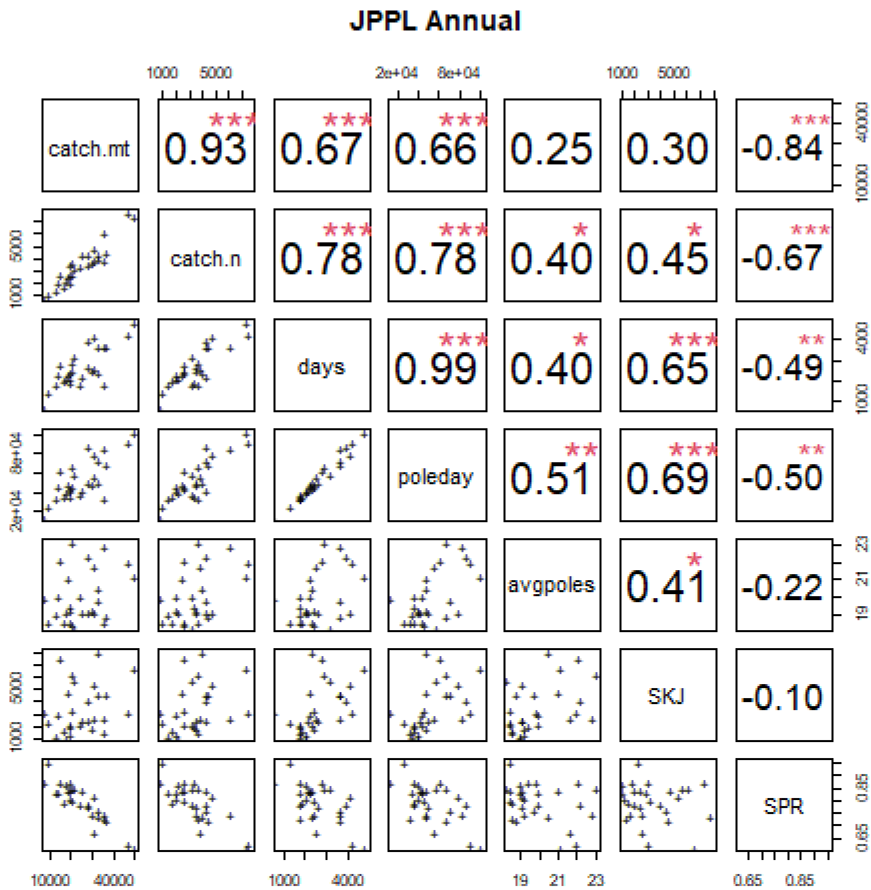

Figure 5. Pairs plot and correlations of annual catch (metric tons and 1000s of fish), and effort (number of fishing days, number of pole-days, average number of poles, and skipjack catch (mt)) versus estimated annual spawning potential ratios for Japan pole-and-line in all areas (Fleet 21 to 25 in the 2023 assessment). Lower triangle shows plots of variable pairs. Upper triangle shows Pearson correlation coefficients, with asterisks indicating statistical significance (* p<0.05; ** p<0.01; *** p<0.001).

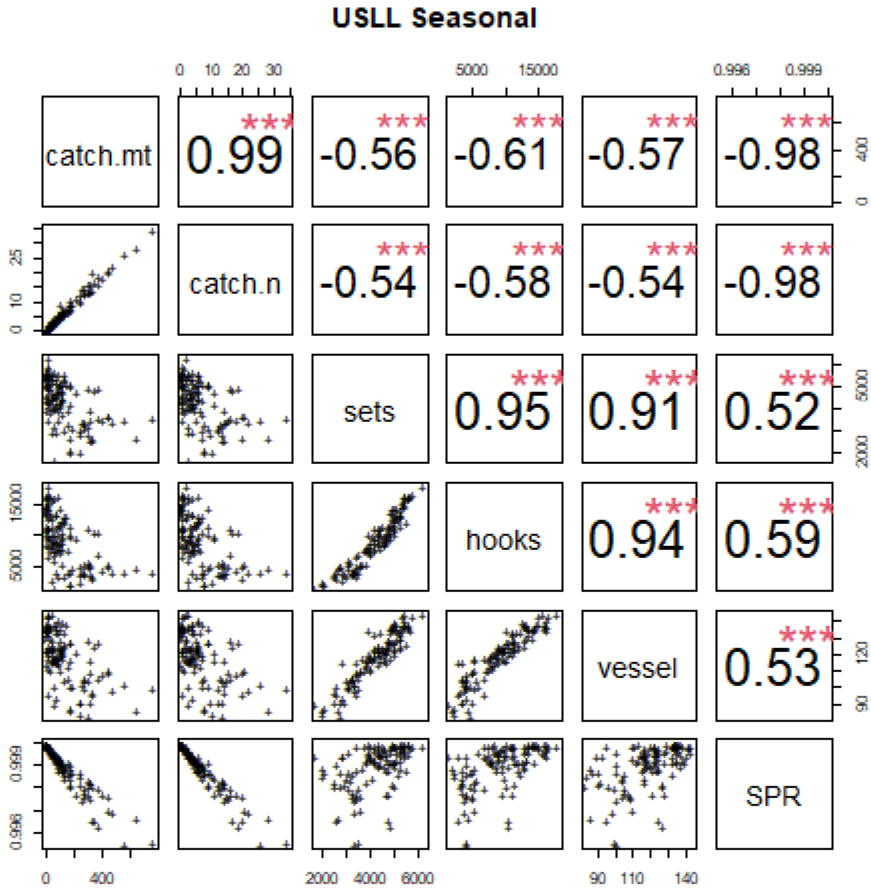

Figure 6. Pairs plot and correlations of quarterly catch (metric tons and 1000s of fish), and effort (number of sets, number of vessels, and 1000s of hooks) versus estimated quarterly spawning potential ratios for US longline in all areas (Fleets 26 and 27 in the 2023 assessment). Lower triangle shows plots of variable pairs. Upper triangle shows Pearson correlation coefficients, with asterisks indicating statistical significance (* p<0.05; ** p<0.01; *** p<0.001).

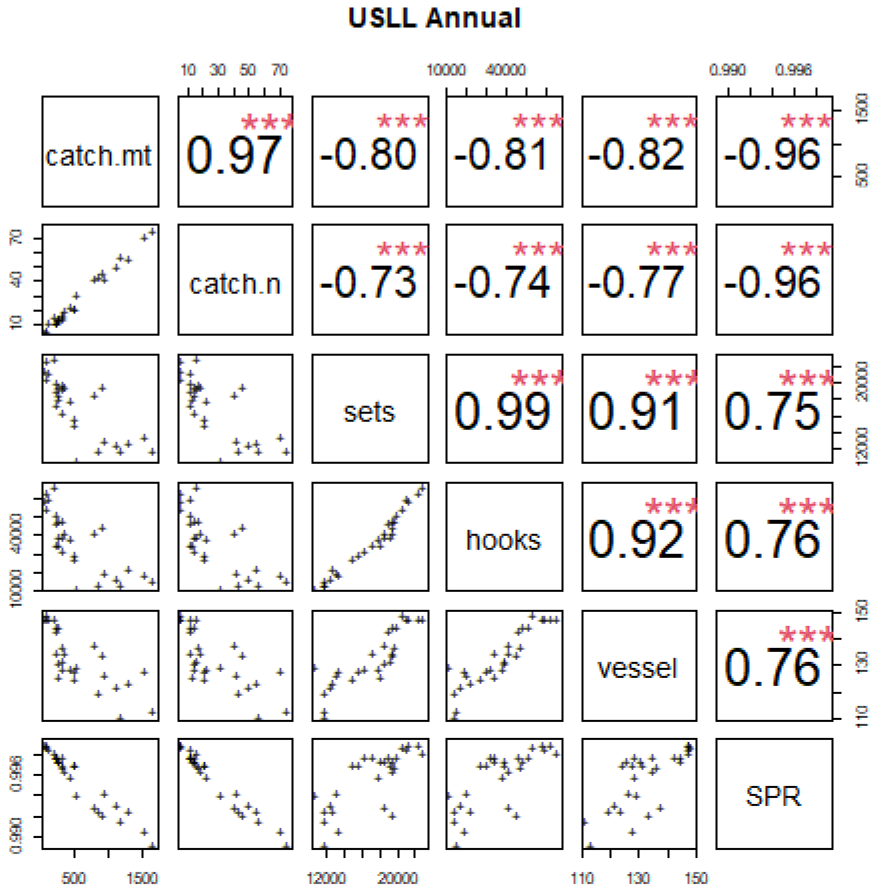

Figure 7. Pairs plot and correlations of annual catch (metric tons and 1000s of fish), and effort (number of sets, number of vessels, and 1000s of hooks) versus estimated annual spawning potential ratios for US longline in all areas (Fleets 26 and 27 in the 2023 assessment). Lower triangle shows plots of variable. Upper triangle shows Pearson correlation coefficients, with asterisks indicating statistical significance (* p<0.05; ** p<0.01; *** p<0.001).

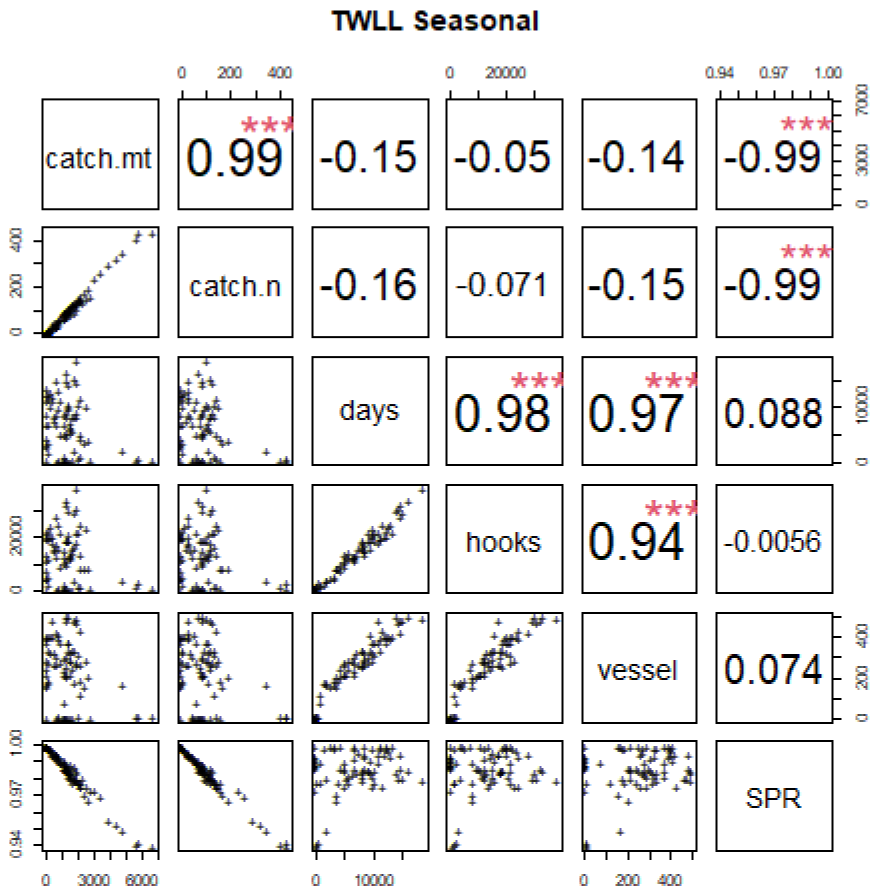

Figure 8. Pairs plot and correlations of quarterly catch (metric tons and 1000s of fish), and effort (number of fishing days, number of vessels, and 1000s of hooks) versus estimated quarterly spawning potential ratios for Taiwan longline in all areas (Fleets 28 and 29 in the 2023 assessment). Lower triangle shows plots of variable pairs. Upper triangle shows Pearson correlation coefficients, with asterisks indicating statistical significance (* p<0.05; ** p<0.01; *** p<0.001).

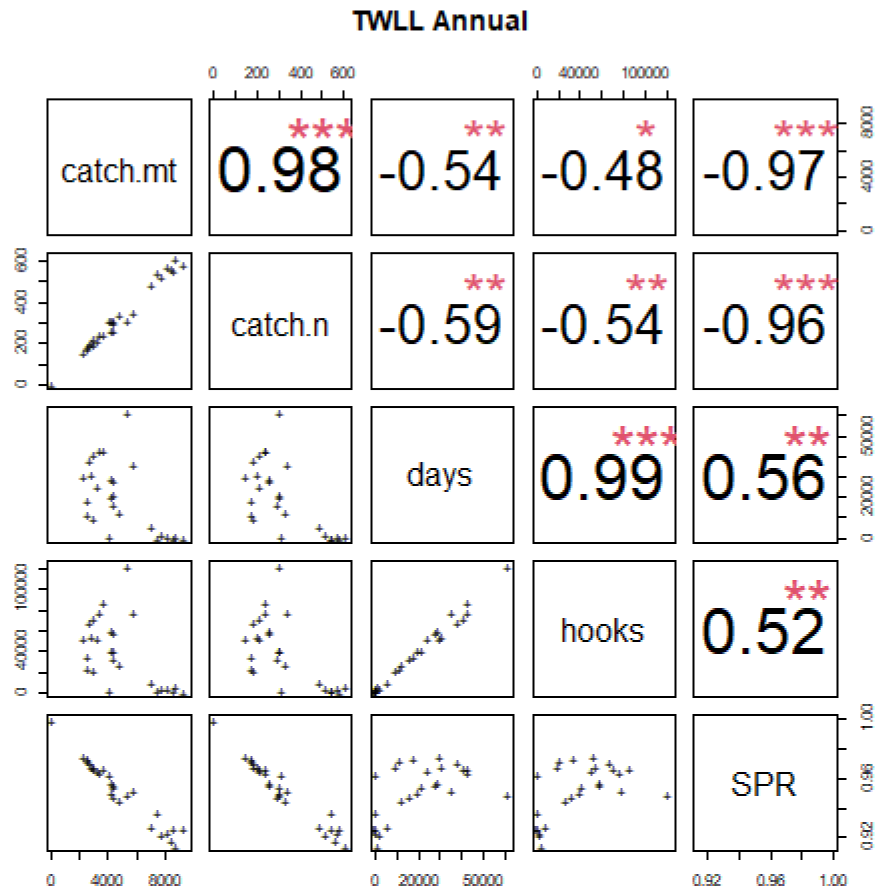

Figure 9. Pairs plot and correlations of annual catch (metric tons and 1000s of fish), and effort (number of fishing days, and 1000s of hooks) versus estimated annual spawning potential ratios for Taiwan longline in all areas (Fleets 28 and 29 in the 2023 assessment). Lower triangle shows plots of variable pairs. Upper triangle shows Pearson correlation coefficients, with asterisks indicating statistical significance (* $p<0.05$; ** $p<0.01$; *** $p<0.001$).

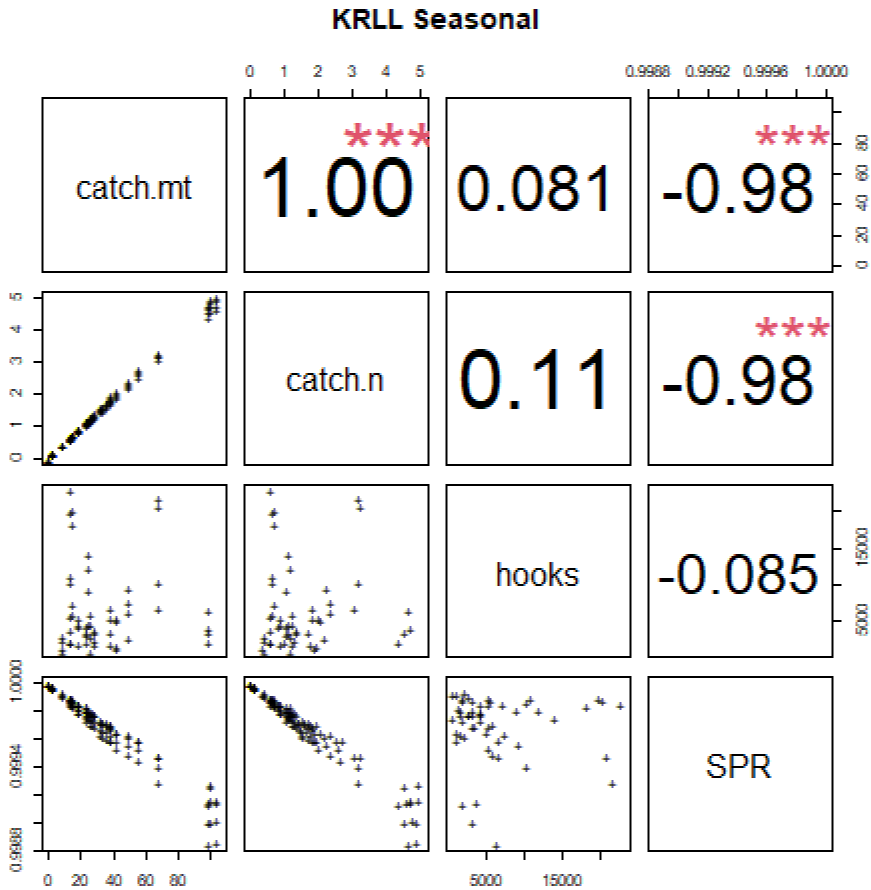

Figure 10. Pairs plot and correlations of quarterly catch (metric tons and 1000s of fish), and effort (1000s of hooks) versus estimated quarterly spawning potential ratios for Korea longline in all areas (Fleet 30 in the 2023 assessment). Lower triangle shows plots of variables. Upper triangle shows Pearson correlation coefficients, with asterisks indicating statistical significance (* p<0.05; ** p<0.01; *** p<0.001).

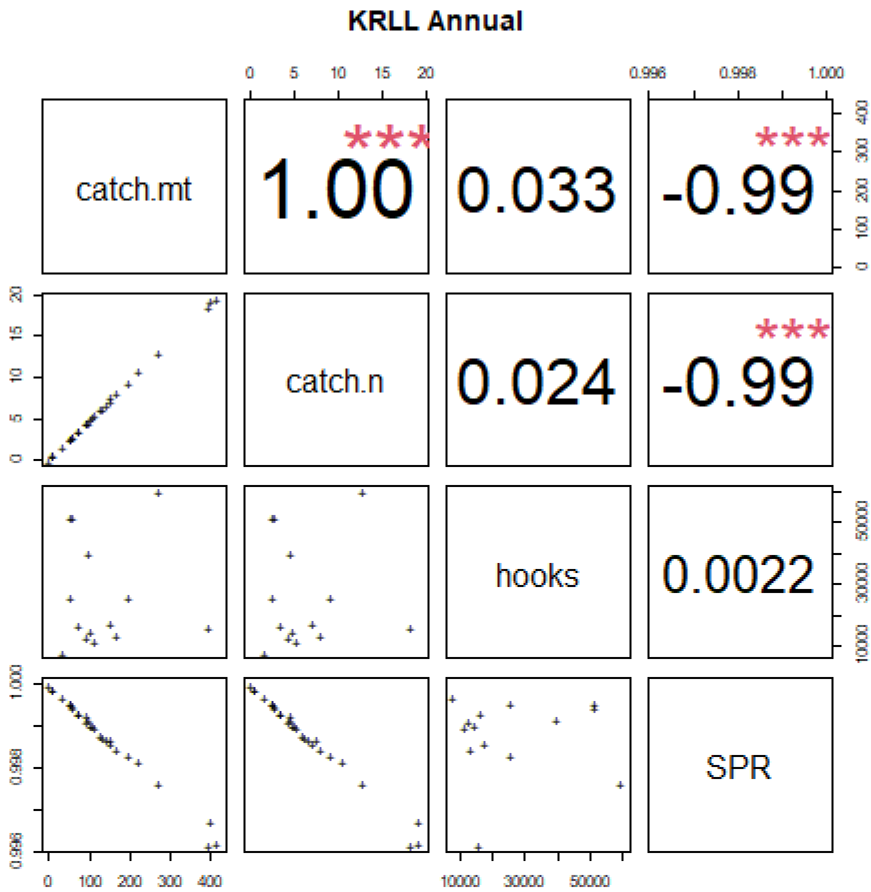

Figure 11. Pairs plot and correlations of annual catch (metric tons and 1000s of fish) and effort (1000s of hooks), versus estimated annual spawning potential ratios for Korea longline in all areas (Fleet 30 in the 2023 assessment). Lower triangle shows plots of variable. Upper triangle shows Pearson correlation coefficients, with asterisks indicating statistical significance (* p<0.05; ** p<0.01; *** p<0.001).

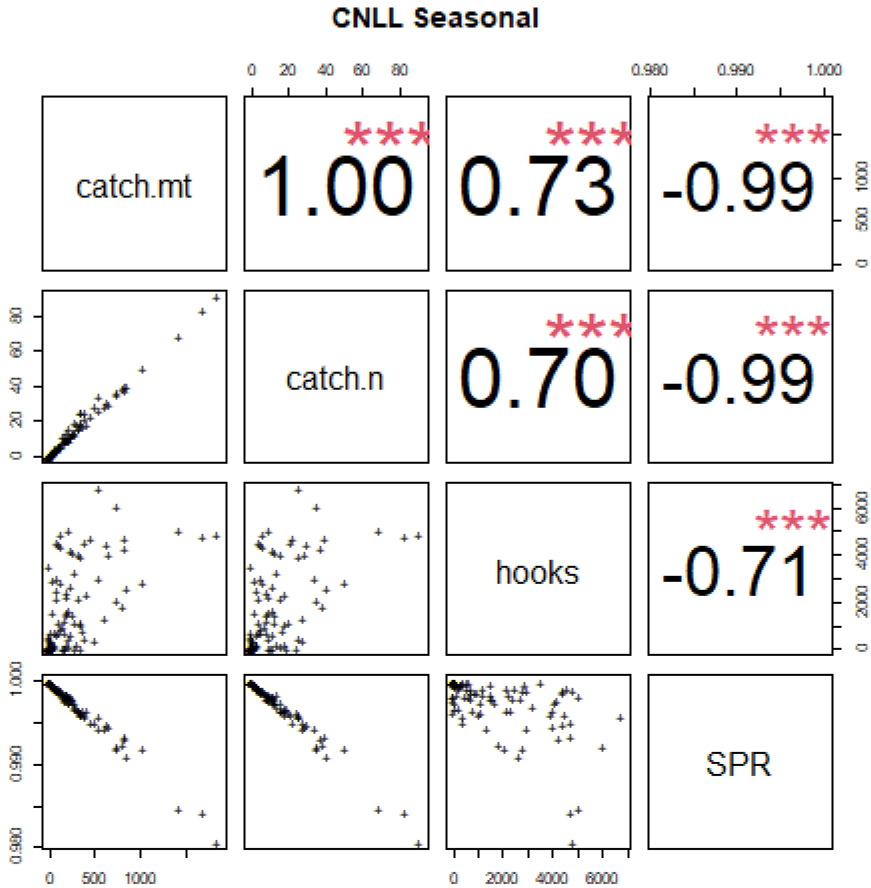

Figure 12. Pairs plot and correlations of quarterly catch (metric tons and 1000s of fish), and effort (1000s of hooks) versus estimated quarterly spawning potential ratios for China longline in all areas (Fleets 31 and 32 in the 2023 assessment). Lower triangle shows plots of variable pairs. Upper triangle shows Pearson correlation coefficients, with asterisks indicating statistical significance (* p<0.05; ** p<0.01; *** p<0.001).

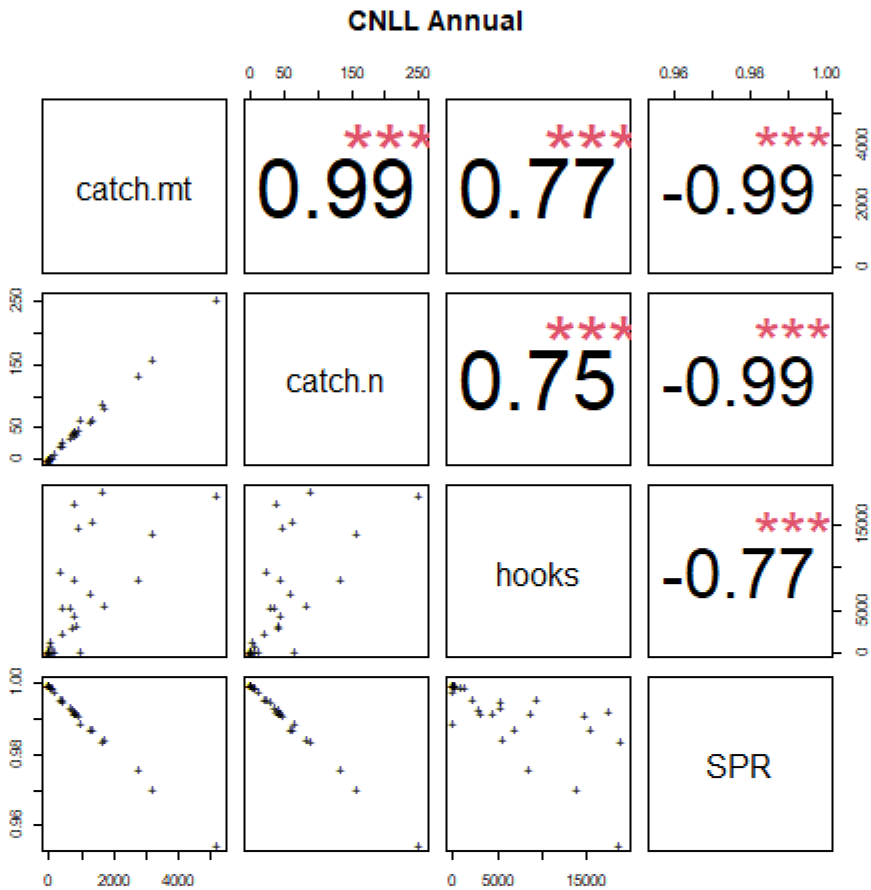

Figure 13. Pairs plot and correlations of annual catch (metric tons and 1000s of fish), and effort (1000s of hooks) versus estimated annual spawning potential ratios for China longline in all areas (Fleets 31 and 32 in the 2023 assessment). Lower triangle shows plots of variable pairs. Upper triangle shows Pearson correlation coefficients, with asterisks indicating statistical significance (* p<0.05; ** p<0.01; *** p<0.001).

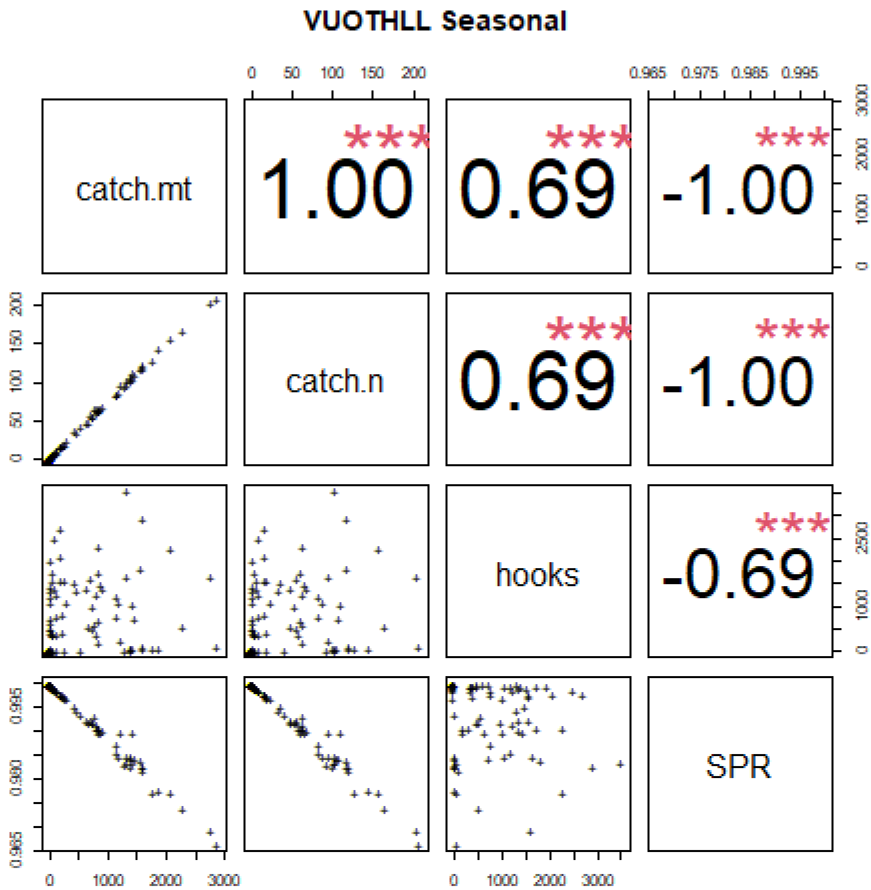

Figure 14. Pairs plot and correlations of quarterly catch (metric tons and 1000s of fish), and effort (1000s of hooks) versus estimated quarterly spawning potential ratios for Vanuatu and Others longline in all areas (Fleet 33 in the 2023 assessment). Lower triangle shows plots of variable pairs. Upper triangle shows Pearson correlation coefficients, with asterisks indicating statistical significance (* p<0.05; ** p<0.01; *** p<0.001).

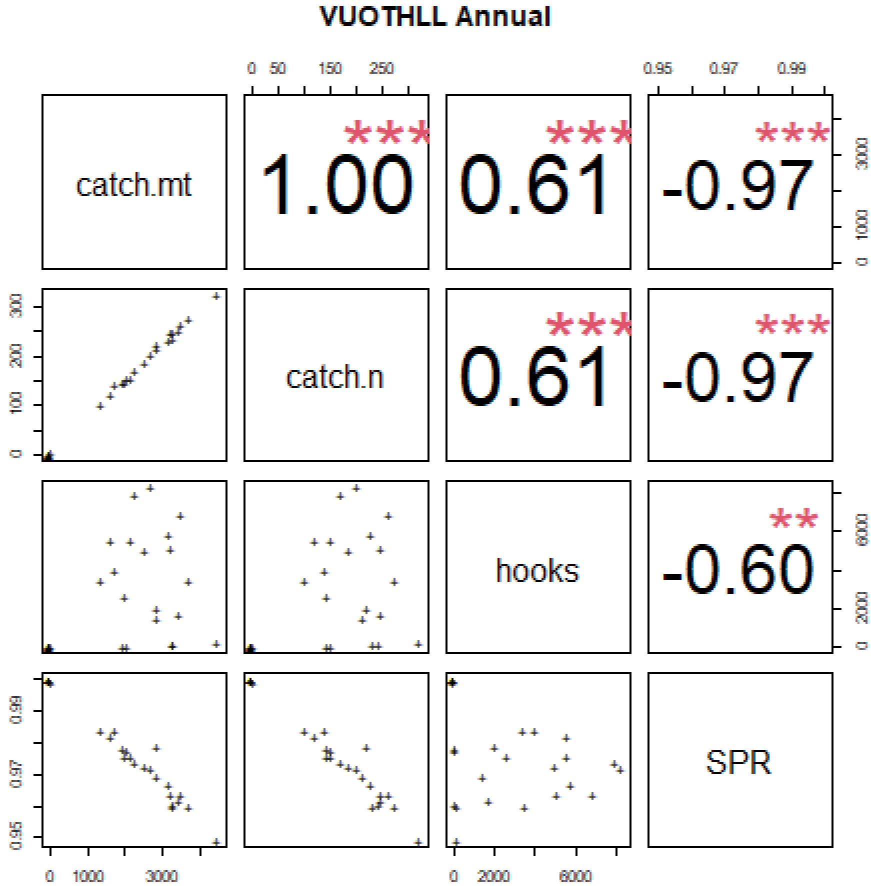

Figure 15. Pairs plot and correlations of annual catch (metric tons and 1000s of fish), and effort (1000s of hooks) versus estimated annual spawning potential ratios for Vanuatu and Others longline in all areas (Fleet 33 in the 2023 assessment). Lower triangle shows plots of variable pairs. Upper triangle shows Pearson correlation coefficients, with asterisks indicating statistical significance (* p<0.05; ** p<0.01; *** p<0.001).

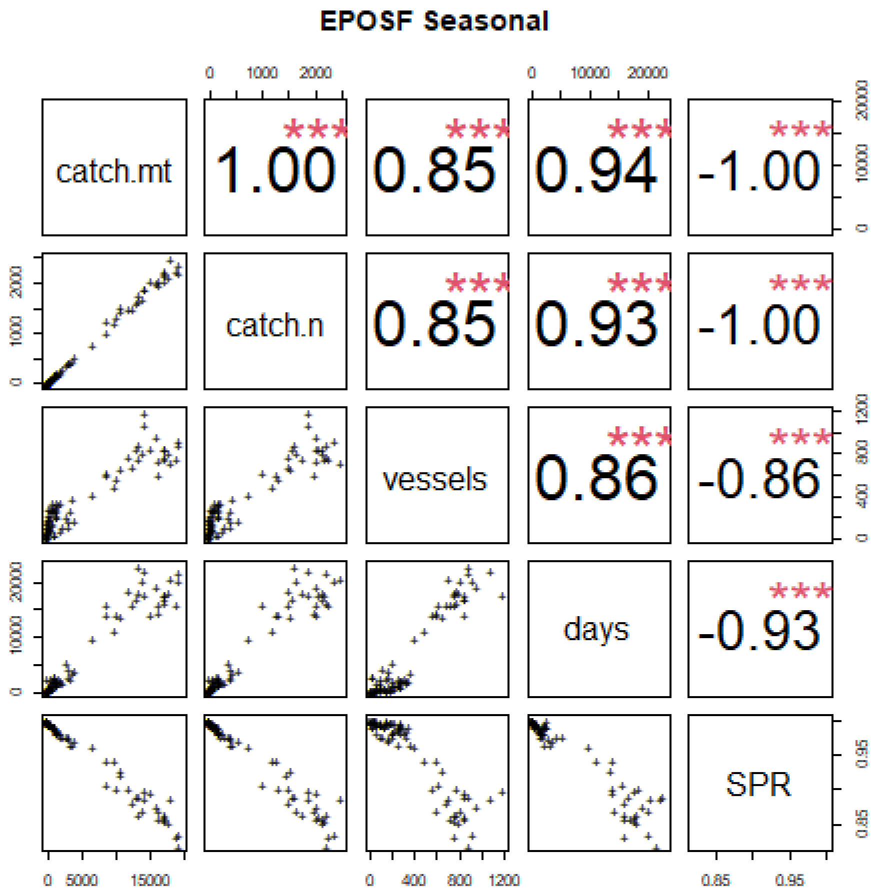

Figure 16. Pairs plot and correlations of quarterly catch (metric tons and 1000s of fish), and effort (number of fishing days, and number of vessels) versus estimated quarterly spawning potential ratios for EPO surface fleet in all areas (primarily Canada and US troll and pole-and-line; Fleet 34 in the 2023 assessment). Very low levels of effort occur in Season 1 but cannot be used due to confidentiality requirements (<3 vessels). Lower triangle shows plots of variable pairs. Upper triangle shows Pearson correlation coefficients, with asterisks indicating statistical significance (* $p<0.05$; ** $p<0.01$; *** $p<0.001$).

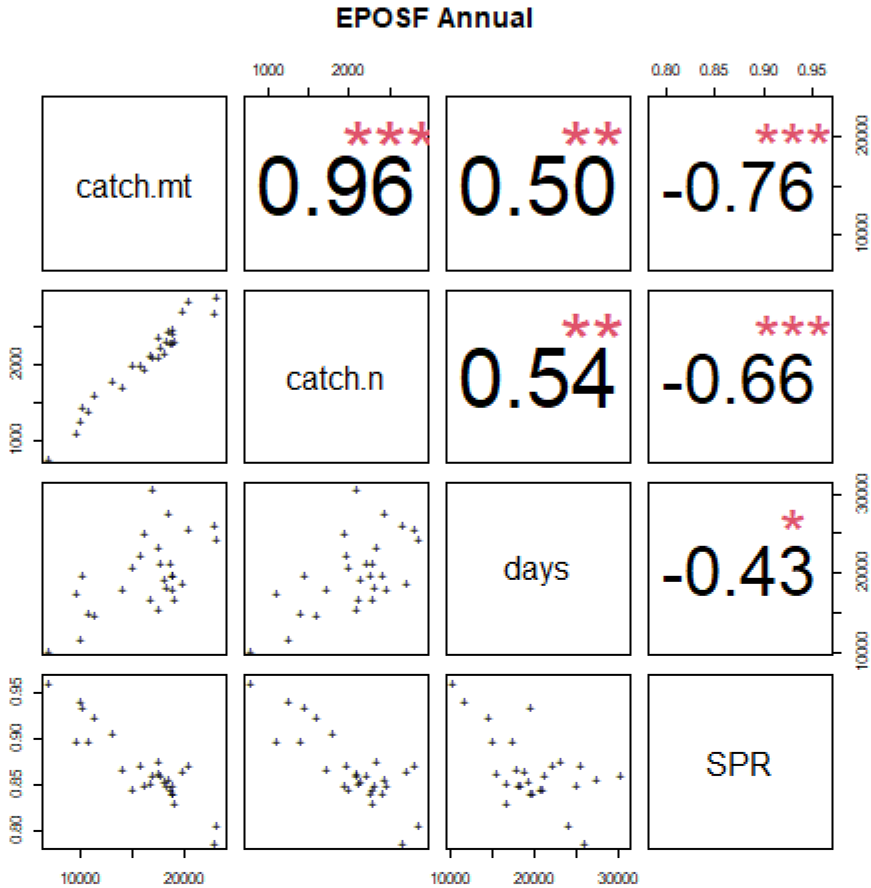

Figure 17. Pairs plot and correlations of annual catch (metric tons and 1000s of fish), and effort (number of fishing days) versus estimated annual spawning potential ratios for EPO surface fleet in all areas (primarily Canada and US troll and pole-and-line; Fleet 34 in the 2023 assessment). Lower triangle shows plots of variable pairs. Upper triangle shows Pearson correlation coefficients, with asterisks indicating statistical significance (* $p<0.05$; ** $p<0.01$; *** $p<0.001$).

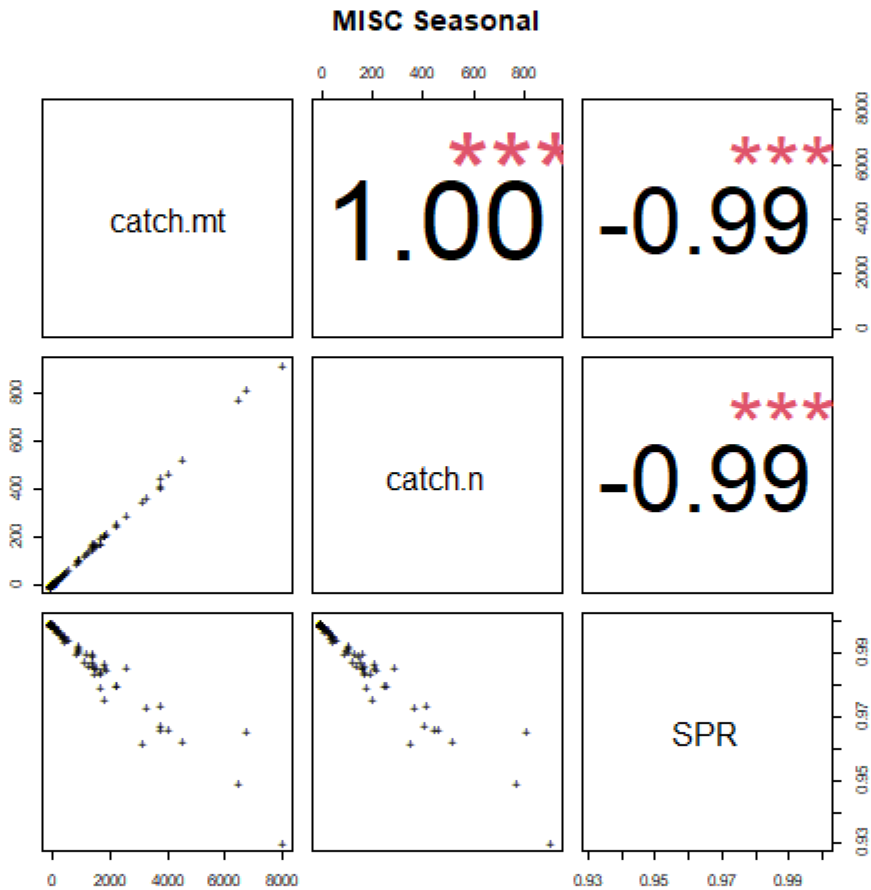

Figure 18. Pairs plot and correlations of quarterly catch (metric tons and 1000s of fish), versus estimated quarterly spawning potential ratios for the miscellaneous fleet (catch primarily from Japan purse seine; Fleet 35 in the 2023 assessment). Lower triangle shows plots of variable pairs. Upper triangle shows Pearson correlation coefficients, with asterisks indicating statistical significance (* p<0.05; ** p<0.01; *** p<0.001).

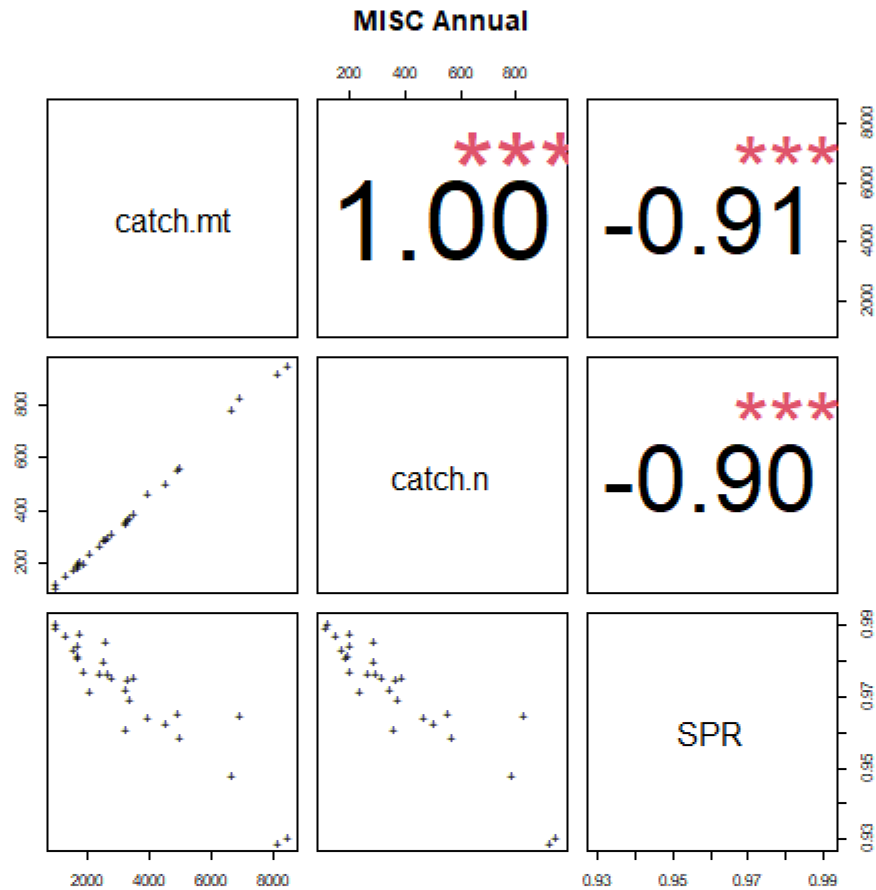

Figure 19. Pairs plot and correlations of annual catch (metric tons and 1000s of fish), versus estimated annual spawning potential ratios for the miscellaneous fleet (catch primarily from Japan purse seine; Fleet 35 in the 2023 assessment). Lower triangle shows plots of variable pairs. Upper triangle shows Pearson correlation coefficients, with asterisks indicating statistical significance (* p<0.05; ** p<0.01; *** p<0.001).

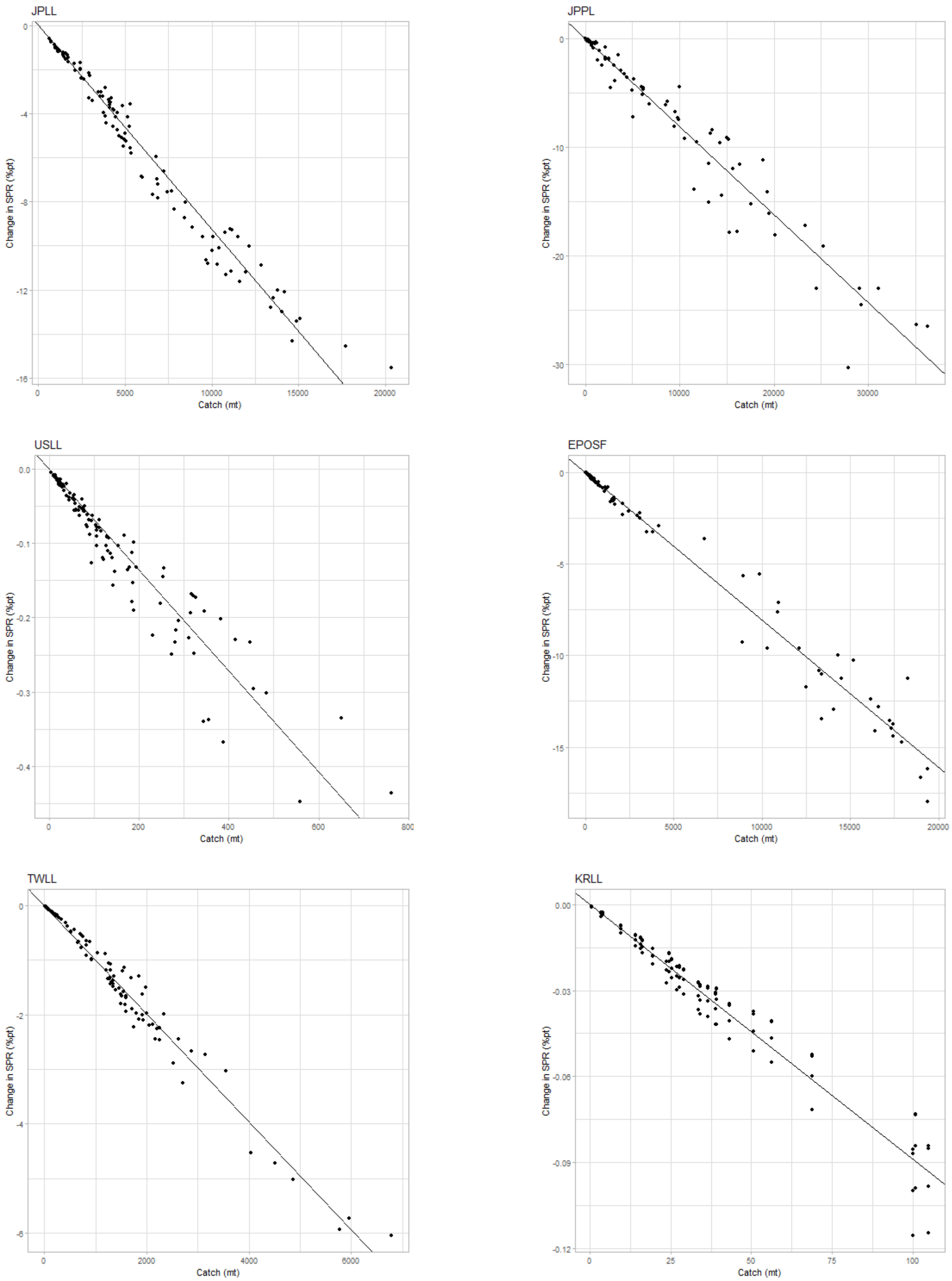

Figure 20. Estimated relationships between seasonal catch in weight (t) and expected change in spawning potential ratio (SPR; %pts) for nine fleets using single variable GLMs with a fixed intercept at 0. See Table 3 for fleet abbreviations. Note that scales of the x- and y-axes are variable.

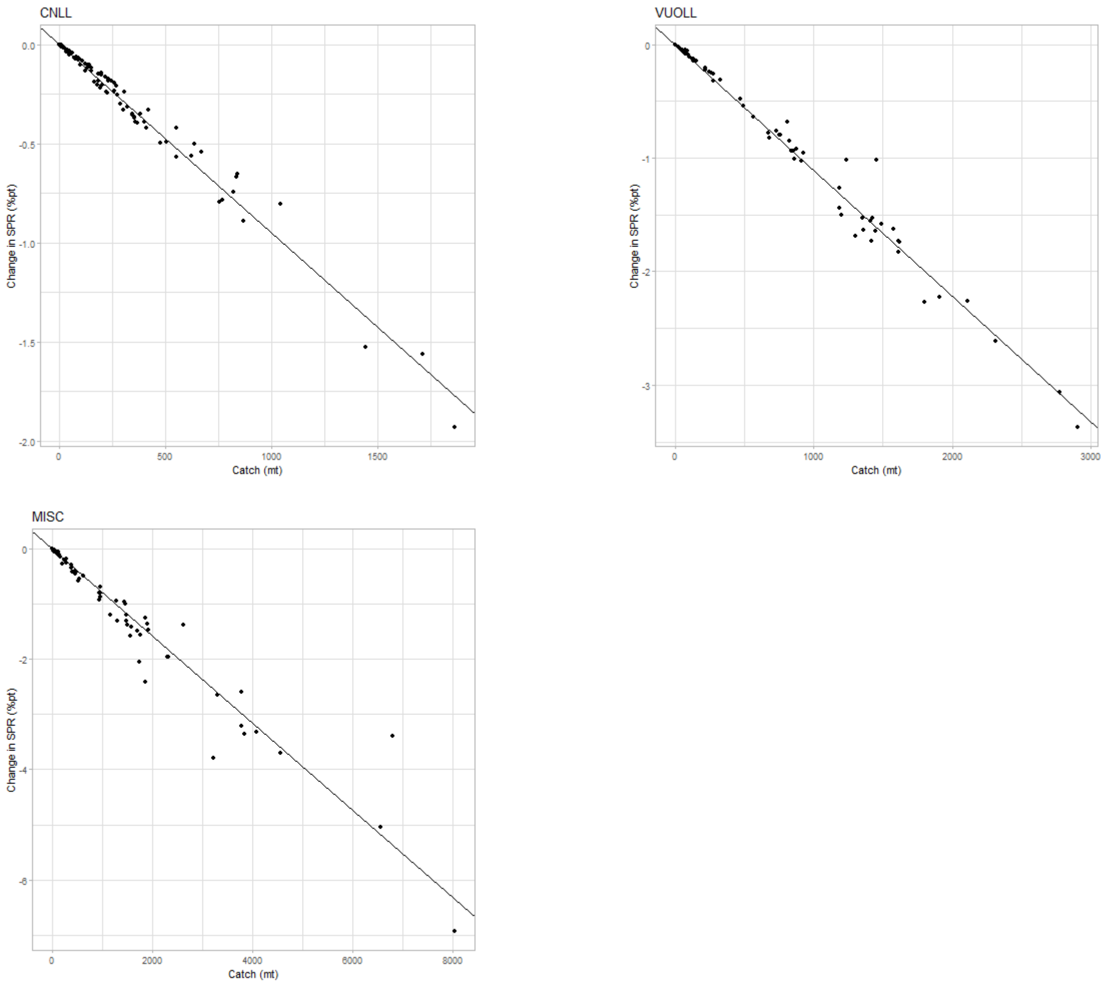

Figure 20. continued.

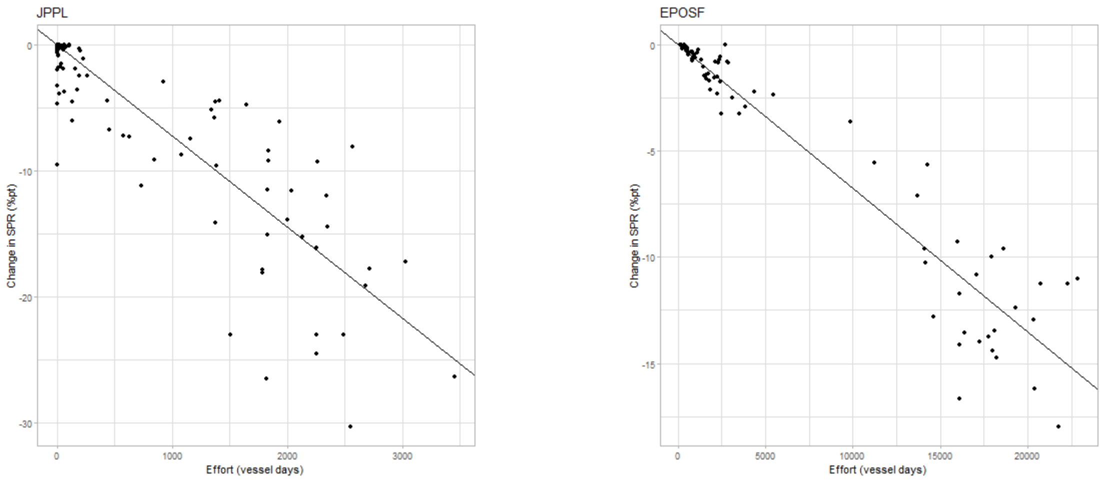

Figure 21. Estimated relationships between seasonal fishing effort (vessel days) and expected change in spawning potential ratio (SPR; %pts) for the two surface gears (troll and pole-and-line) fleets using single variable GLMs with a fixed intercept at 0. See Table 3 for fleet abbreviations. Note that scales of the x- and y-axes are variable.