ISC/15/PBFWG-1/05

Estimation of annual stock indices for Pacific bluefin tuna using landing data at Sakai-minato Port

Minoru Kanaiwa[1],Atsuya Yamamoto [1], Yukio Ishihara[2], Isana Tsuruoka[3], Kazuhiro Oshima[3], Hiromu Fukuda[3] and Yukio Takeuchi[3]

1) Tokyo University of Agriculture
196 Yasaka, Abashiri, Hokkaido 099-2493, JAPAN
2)Tottori Prefectural Fisheries Experiment Station
107 Takenouchi-Danchi, Sakaiminato, Tottori 684-0046, JAPAN
3) National Research Institute of Far Seas Fisheries
5-7-1, Orido, Shimizu-ku, Shizuoka 424-8633, JAPAN

April. 2015

Working document submitted to the Meeting of the Pacific Bluefin Tuna Working Group, International Scientific Committee for Tuna and Tuna-Like Species in the North Pacific Ocean (ISC), 20-24 April 2015, Shizuoka, Shizuoka, Japan. **Document not to be cited without author's permission.**

Abstract

For highly migratory pelagic fishes like Pacific bluefin tuna (PBF: *Thunnus orientalis*), commercial fishery data is important and Sakai-minato port is one of biggest fishery ports for PBF. Purse seine is one of the major fisheries for PBF in Japan but no abundance indices of this fishery were provided to use in the past stock assessment (Anon. 2012).

Kanaiwa et al. (2012) provided the nominal CPUE by this fishery and mentioned the annual differences in length distribution were problem to standardize it. In this document we tried to explain catch at age per each set of purse sine by latitude, longitude, sea surface temperature, salinity, water current, year, day from July. 1st and ages estimated from growth curve used for current stock assessment with length using Random forest. We provided the annual trend by using marginal mean of year from this model for each age.

Because statistically there was no problem on this standardization, this standardized CPUE could become one of candidate as abundance indices to use stock assessment. Standardized CPUE for all ages became smoother than nominal CPUE. For all age, decreasing trend occurred between 2003 and 2006. For age 3- and 4, increasing trend occurred during most recent few years. In same time, this trend has conflict among other information e.g. standardized CPUE of trolling fishery in the East China Sea. So careful consideration was required when these indices would be included.

Introduction

Japanese purse sine in Sea of Japan landing in Sakai-minato port in Tottori prefecture is one of the biggest fisheries for Pacific bluefin tuna (PBF), however in the past stock assessment the annual trend of this fishery was not used as stock indices. Usually purse seine has the problem to estimate stock indices using this fishery data because of the difficulty to define effort which has liner relationship with catch (Gaertner & Dreyfus-Leon 2004).

However there are some reasons why it is simpler and easier to define effort for this fishery, i.e. they have only targeted PBF and have not used FAD to gather fishes and also have not use helicopter to find schools. Kanaiwa et al. (2008) compared several candidates of abundance indices and showed that there was no evidence that nominal CPUE (i.e. average catch per each landing) does not represent the stock abundance due to some bias. In that paper, nominal CPUE of this fishery as one of the candidates of stock abundance indices was concerned and a correlation between nominal catch per set number and age 4 estimated stock trend between 1987 and 2007 was shown.

In former stock assessment there are two concerns about this index. 1st issue was that flat trend of CPUE and 2nd issue was reasonableness of the definition of effort

(Annon. 2014). To address this issue standardization of effort was required.

Kanaiwa et al. (2012) also showed spatiotemporal change of operations for this fishery. These facts showed the requirement to standardize this CPUE considering spatiotemporal dynamics of length composition of PBF catch (Annon. 2008; Fig. 6). The components of generalized linear model (GLM) is one of the most popular methods to estimate annual trends from fishery catch and effort data (Shono, 2004) however GLM has the limitation of not using for the data which has high order interaction among explanatory variables and in which there is many lack of data for some interactions. To address this issue, in this paper we used random forest (RF: Breiman, 2001) to standardize CPUE of this fishery. RF is a combination of tree predictors which allow the uncertainty of data and explanatory variables (ibid.). This model also allows higher degree of interactions among explaining variables.

Materials and methods

Data

The landing data in Sakai-minato port collected by the Tottori Prefectural Fisheries Experimental Station between 2003 and 2014 were analyzed. The data include fish length, frequencies of fish sampled, number of fish caught, vessel name and landing date for each landing. The logbook data was used to get the information of operation location i.e., latitude and longitude of operation.

Sea surface temperature, salinity, current velocity (N-S and E-W) were estimated by using Japan sea data assimilation experiment (JADE: http://jade.dc.affrc.go.jp/jade/) and water depth was referred from the chart by Japan hydrographic association.

Age separation

The growth model used for recent stock assessment was used to split ages from length. The equation was follows:

$$L_t = 254.413\left\{1 - e^{-0.157474\,(t+0.560689)}\right\} \qquad \text{Annon. (2014).}$$

Age considering the relative landing date from July 1st to calculate length and for each individual, the age whose length was proximal with observed length was adapted as estimated age, respectively. The ages were limited between 3 and 6 and younger and older ages than this range of ages were included in 3 and 6 ages, respectively because of small number of data for each age (Table 1 and 2). The split process and characteristics for each age are shown in Figs. 1-6.

Model

Random Forest

Random forest (Breiman, 2001: RF) for regression was used to standardize CPUE to address annual stock abundance trend for each ages. The catch in number for each ages were estimated using total catch for each landing and the age ratio for each landing. If there was 0 ratio of some ages, the catch for that ages were set as 0. These catch at ages were used as response variable. Latitude, longitude, sea surface temperature, salinity, water current (horizontal and vertical), vessel's name, year, elapsed days from July 1st, ages were used as explanatory variables.

Each trial two-thirds of data sampled without replacement was used to construct model and remaining data was used to validate model. 1,000 trial of this resampling ran to get median and standard deviation of marginal mean of year for each age. Number of variables randomly sampled as candidates at each split was set as 5 because of out of bag (OOB) error's dynamics (Fig. 7). Number of trees to grow was set as 2,500 and would check the convergences later by OOB error.

Generalized Linear Model

The generalized linear model (GLM) was conducted to compare the result with random forest. The standardized equation is below:

Catch at agte + minimu positive catch / 10 = $\Sigma \alpha_i x_i$ + intercept + log normal error.

Here, α_i meant coefficient for each explanatory variable and x_i meant explanatory variable which is same with random forest except vessel's name. The reason why vessel's name is removed from explanatory variable is that from random forest analysis this variable has less informative and to save on machine power. Interactions among all explanatory variables except year and interactions between year and ages and between year and date were introduced for initial model and both direction of step wised method with AIC as indicator was used to get optimal model. Latitude and longitude were treated as orthogonal polynomials of 3 degrees and sea surface temperature, salinity, water current (horizontal and vertical) were treated as orthogonal polynomials of 2 degrees.

Results

Random Forest

The OOB error was asymptotically stable value larger than 500 trees to grow (Fig. 8) so we assess model was converged. We checked the residuals pattern for each year and age (Fig. 9 and 10) using test data i.e. one-third data not used to construct model and could not find any particular patterns. Finally we conclude model could follow and standardize without any statistical problem.

Explanatory variable of Age was much more important than other factors (Fig. 11) and explanatory variables of area (i.e. latitude and longitude) had higher information than other factors by reduction of mean squared error of OOB (%IncMSE) and residual sum of squares (IncNodePurity).

Partial dependences (PD) of all explanatory variables were shown in Fig. 12. Ages 3- and 4 were higher PD than other ages. East area was higher PD than west area. Around 36.5 degrees north was lowest PD. Earlier date was higher PD than later. Shallower than 500m was higher PD than deeper. Lower sea surface temperature (SST) was higher PD than higher SST. Around 34‰ salinity was higher than 33.5‰. Both velocity of water current, around 0m/s was lowest. Earlier year and late was higher than middle year. Each vessel had some variation in PD but this factor had less information than others.

Annual trends of standardized CPUE for each age were shown in Fig. 13 and Table 3. For all age, decreasing trend occurred between 2003 and 2006. For age 3- and 4, increasing trend occurred during most recent few years. For age 5 and 6+ there was almost flat trend after 2007 (Fig. 14).

Generalized linear model

As optimal model, all independent explanatory variables are adopted and interaction between year:age, year:date, date:lat, date: depth, date:EW velocity, date:NS velocity, age:lat, age:depth, age:SST, lat:lon, lat:depth, lat: EW velocity, lon:SST, lon:EW velocity, lon:NS velocity, depth:salinity, depth:NS velocity, SST:salinity, SST:EW velocity, salinity:NS velocity were adopted (Appendix 1). The diagnostics of GLM were shown in Fig. 15 and residuals distribution were shown in Fig 16 and 17. There were several pattern was observed and leverage was high. Calculates type-III analysis of variance table were provided and most variables were significant on 5% level (Appendix 2). Standardized CPUE was fluctuated year by year (Fig. 18 and Table. 4).

Discussions

The standardization of random forest did not show any statistical problem on convergences and the pattern of residuals. The estimated partial dependences were reasonable to explain catch by each explanatory variable. Because there is no information that the effort of this fishery would change by factors except from ones considered in this paper, there is no reason to conclude this standardization was failed statistically and on fishery science.

All standardized CPUE of RF became smoother than nominal CPUE (Fig. 19). The standardized CPUE from age 3- to 5 had similar trend and they were different trend with the standardized CPUE of trolling fishery in the East China Sea (Fig. 20).

In contrast, the standardization of GLM showed several problems, i.e. bias of residuals and high leverage data (Fig. 15-17). The standardized indices were almost same with nominal CPUE (Fig. 21). From here onwards, the standardization might not be done successfully. This fact showed the standardized CPUE of RF is better than standardized CPUE of GLM to use as stock abundance indices by this fishery.

In former stock assessment, there were some indices representing age 0 and older than 6 but not between 3 and 6. The standardized CPUE presented in this paper would fill in that blank so it might be variable if it would be used as the candidate of stock indices. In this point, this standardized CPUE of RF shown in this paper would be valuable.

There are several issues on this standardization of RF, 1st issue is age splitting. Fig. 3 shows the length distribution for each age sometimes have two peaks because the peak of length is shifted from the estimated length of growth curve which is used for stock assessment. 2nd issue is conflict trend with other information especially with CPUE of troll fishery. This may mean the standardization is still not enough even if all diagnostics don't show any problem.

References

Anonymous (2008) Report of the ISC Pacific bluefin tuna working group meeting held in May 2008, Shimizu, Japan.Breiman, L. (2001) Random Forests. Machine Learning 45:5-32

Anonymous (2014) Stock assessment of bluefin tuna in the Pacific Ocean in 2014. ISC PBF WG.

Gaertner, D. and M. Dreyfus-Leon (2004) Analysis of non-linear relationship between catch per unit and abundance in a tuna purse-seine fishery simulated with artificial neural networks.

ICES Journal of Marine Science, 61: 812-820.Kanaiwa, M., A. Shibano, T. Shimura, Y. Uji and Y. Takeuchi. (2008) Preliminary analysis of the stock abundance indices for Pacific Bulefin Tuna (*Thunnus orientalis*) landed by Japanese Purse Seiners in Sakai-Minato. ISC/08/PBFWG-2/05. 21pp.

Kanaiwa, M., T. Shimura, R. Uji, Y. Ishihara and Y. Takeuchi (2012) CPUE analysis for Japanese purse seine in Sea of Japan. ISC/12/PBFWG-1/09. 5pp.

Shono, H. (2004) A review of some statistical approached used for CPUE standardization. Bull. Jpn. Soc. Fish. Oceanogr. 68: 106-120 (in Japanese).

Tables and Figures

Table 1 Observed numbers of individuals for ages split between 2- and 10+

	2−	3	4	5	6	7	8	9	10+
2003	0	234	954	559	146	108	123	200	571
2004	1	3337	681	1503	830	369	140	141	716
2005	0	494	4667	4570	927	1757	775	224	844
2006	0	70	949	2719	2242	400	798	573	475
2007	84	4354	6043	1938	518	287	85	185	494
2008	135	4095	6262	7082	479	330	104	72	546
2009	0	170	746	606	176	48	56	57	440
2010	5	754	174	1359	276	192	49	16	47
2011	1023	6936	3800	7714	366	381	144	59	165
2012	0	46	1163	3794	1360	258	109	51	157
2013	63	16989	1882	1812	1089	275	76	17	90
2014	10	3251	13034	996	30	164	127	42	69

Table 2 Observed numbers of individuals for ages split between 3- and 6+

	3−	4	5	6+
2003	234	954	559	1148
2004	3338	681	1503	2196
2005	494	4667	4570	4527
2006	70	949	2719	4488
2007	4438	6043	1938	1569
2008	4230	6262	7082	1531
2009	170	746	606	777
2010	759	174	1359	580
2011	7959	3800	7714	1115
2012	46	1163	3794	1935
2013	17052	1882	1812	1547
2014	3261	13034	996	432

Table 3 Nominal CPUE and median and standard deviation of marginal means for standardized CPUE for each age by Random forest

year	nCPUE3−	sCPUE3−	SD3−	nCPUE4	sCPUE4	SD4	nCPUE5	sCPUE5	SD5	nCPUE6+	sCPUE6+	SD6+
2003	52.42	133.60	33.43	198.74	178.36	31.91	108.29	175.83	20.60	115.48	157.21	17.30
2004	488.05	109.90	30.96	58.45	141.50	22.74	117.97	150.27	15.11	161.53	138.05	14.81
2005	37.66	82.53	19.28	352.07	131.96	20.34	307.96	149.53	15.30	189.57	135.03	15.13
2006	4.69	64.45	13.84	57.75	113.09	19.20	117.64	134.25	13.25	200.51	114.14	11.43
2007	333.24	66.96	14.00	354.12	118.06	20.14	81.77	131.70	13.89	71.09	95.74	10.47
2008	197.35	65.87	14.40	262.02	118.03	21.21	242.28	132.95	14.30	53.31	88.27	9.34
2009	84.83	65.74	14.95	339.27	117.53	23.11	84.19	132.49	15.11	89.08	83.54	9.20
2010	324.91	65.25	14.85	39.08	115.11	22.54	81.20	133.91	15.04	29.85	82.72	9.13
2011	446.16	66.35	14.89	167.31	117.33	22.16	258.16	146.69	17.47	27.69	86.58	9.82
2012	2.07	66.36	14.96	53.24	117.52	22.13	178.82	148.01	17.17	89.47	88.81	9.66
2013	852.42	72.73	16.45	91.54	122.61	22.95	81.21	147.99	16.82	68.08	91.26	9.56
2014	264.51	76.62	17.14	1042.65	145.24	29.25	49.48	148.76	16.76	15.33	92.11	9.63

Table 4. Least squared means and 95% upper and lower limits for standardized CPUE for each age by GLM

Year	3sCPUE	lower	upper	4sCPUE	lower	upper	5sCPUE	lower	upper	6sCPUE	lower	upper
2003	9.162	1.353	58.941	24.948	3.829	159.562	15.575	2.359	99.819	16.264	2.467	104.209
2004	13.932	4.872	39.501	28.422	10.007	80.394	54.101	19.106	152.861	40.545	14.302	114.606
2005	3.686	1.557	8.548	112.253	49.084	256.552	164.181	71.816	375.171	91.385	39.949	208.882
2006	0.546	0.150	1.574	14.485	5.532	37.672	76.268	29.388	197.680	128.251	49.460	332.307
2007	33.126	13.612	80.408	119.405	49.220	289.468	34.449	14.158	83.614	25.769	10.576	62.582
2008	10.478	4.357	25.004	74.051	31.144	175.882	128.797	54.212	305.807	26.856	11.258	63.874
2009	4.154	1.449	11.588	44.490	16.130	122.405	34.374	12.448	94.613	20.439	7.376	56.327
2010	15.646	4.863	49.852	20.124	6.275	64.058	70.653	22.203	224.355	18.517	5.769	58.960
2011	13.371	5.277	33.645	76.957	30.661	192.935	339.297	135.384	850.115	14.683	5.801	36.933
2012	1.049	0.274	3.430	86.513	28.084	266.076	204.463	66.465	628.552	41.381	13.398	127.377
2013	19.873	5.657	69.194	9.536	2.678	33.331	11.056	3.116	38.604	11.565	3.262	40.369
2014	16.280	5.308	49.508	254.166	83.853	769.987	31.184	10.229	94.648	6.040	1.927	18.495

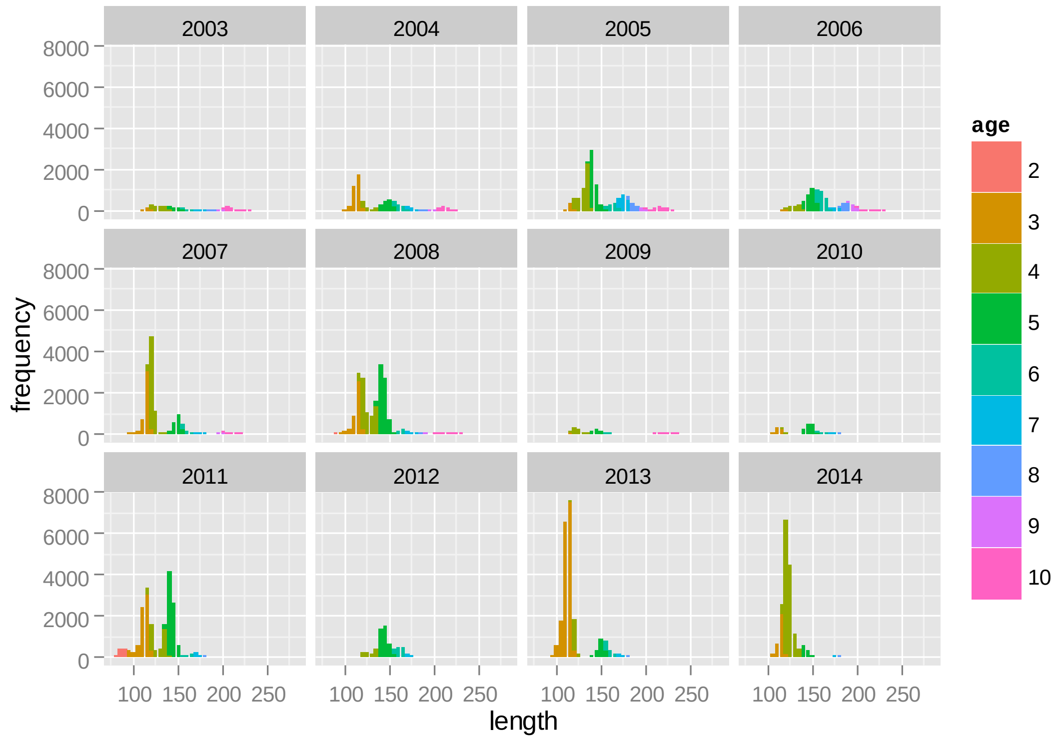

Fig. 1. Observed length distribution colored by ages between 2- and 10+ for each year.

Histograms show length distributions for each year colored by ages. Each color shows each age. Bin size is 5cm.

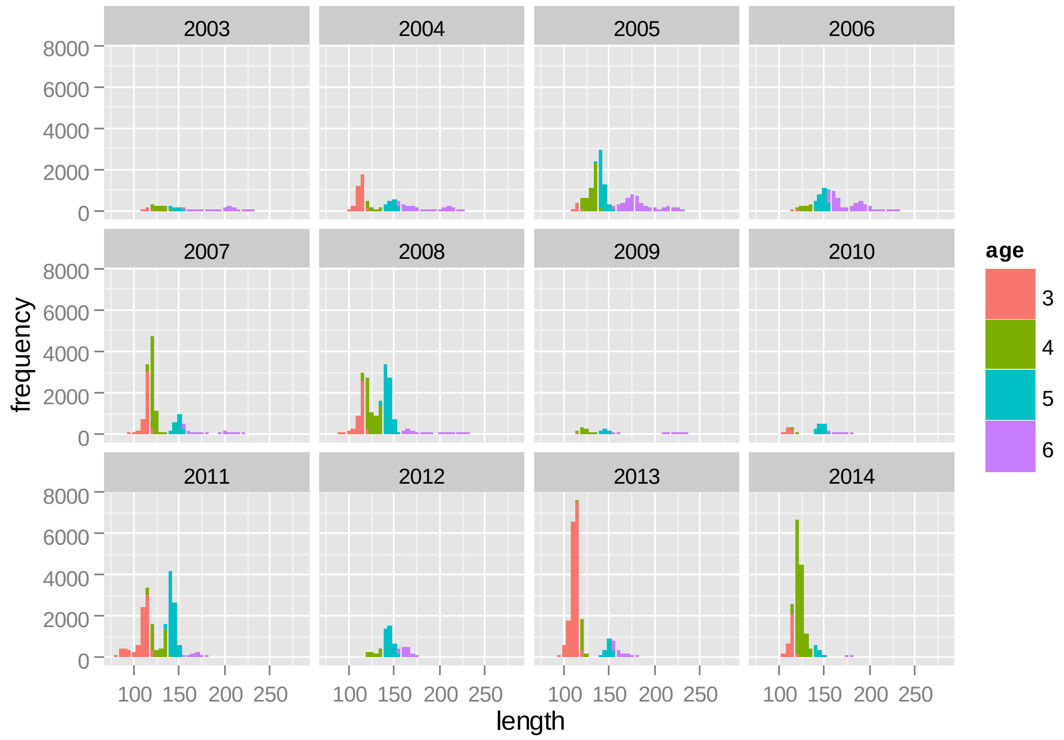

Fig. 2. Observed length distribution colored by ages between 3- and 6+ for each year.
Histograms show length distributions for each year colored by ages. Each color shows each age. Bin size is 5cm.

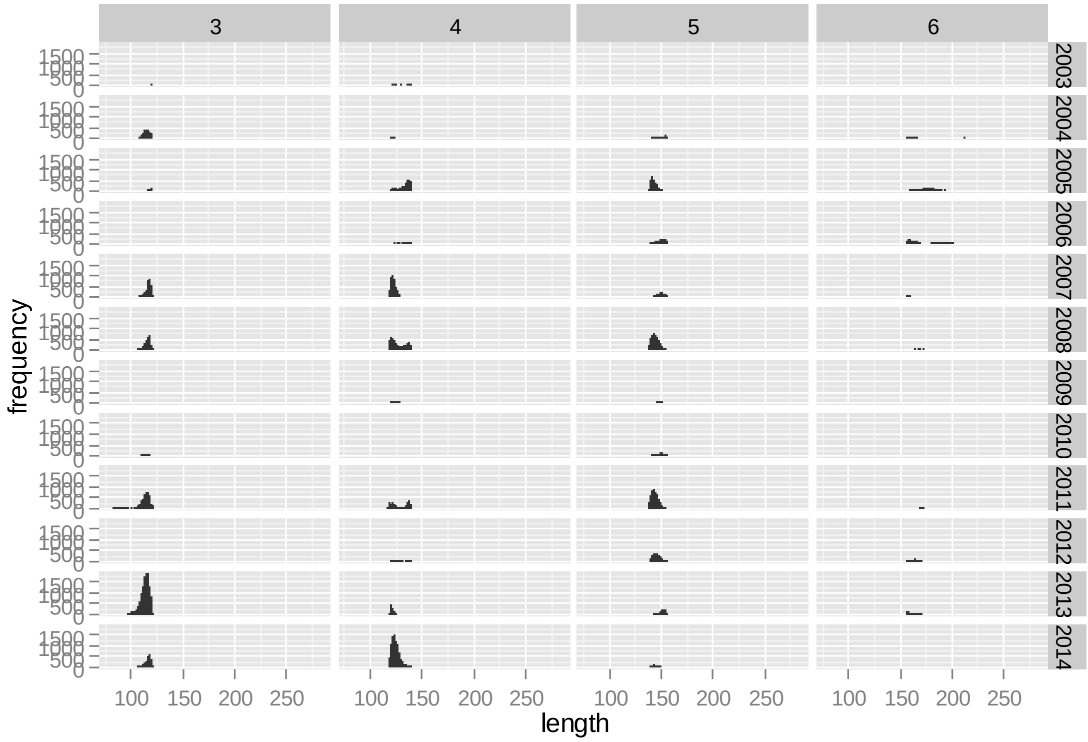

Fig. 3. Length distribution for each age and year.

Histograms show length distribution of each age by each year.　Bin size is 1cm.

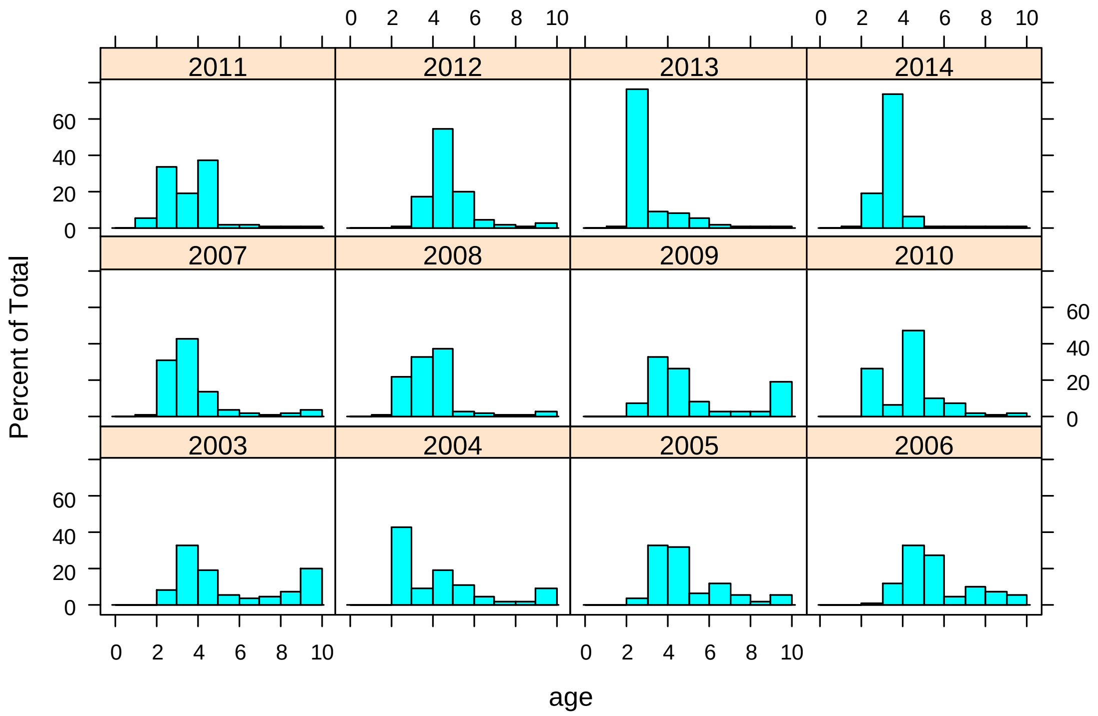

Fig. 4. Age distribution split between 2- and 10+ for each year

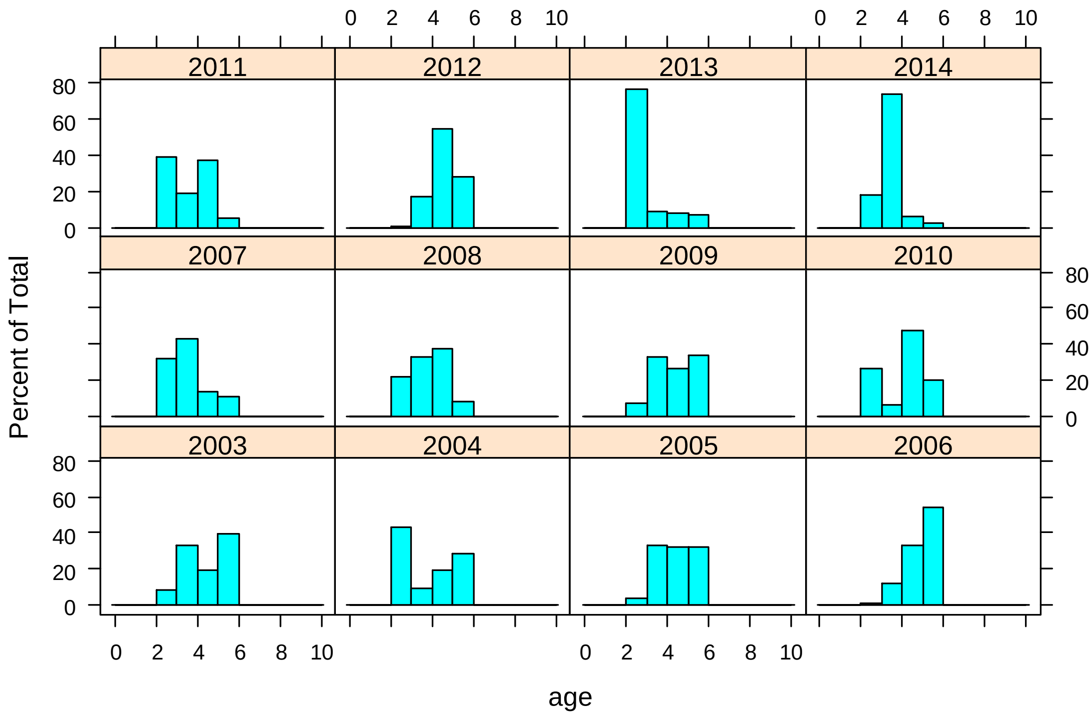

Fig. 5. Age distribution split between 3- and 6+ for each year

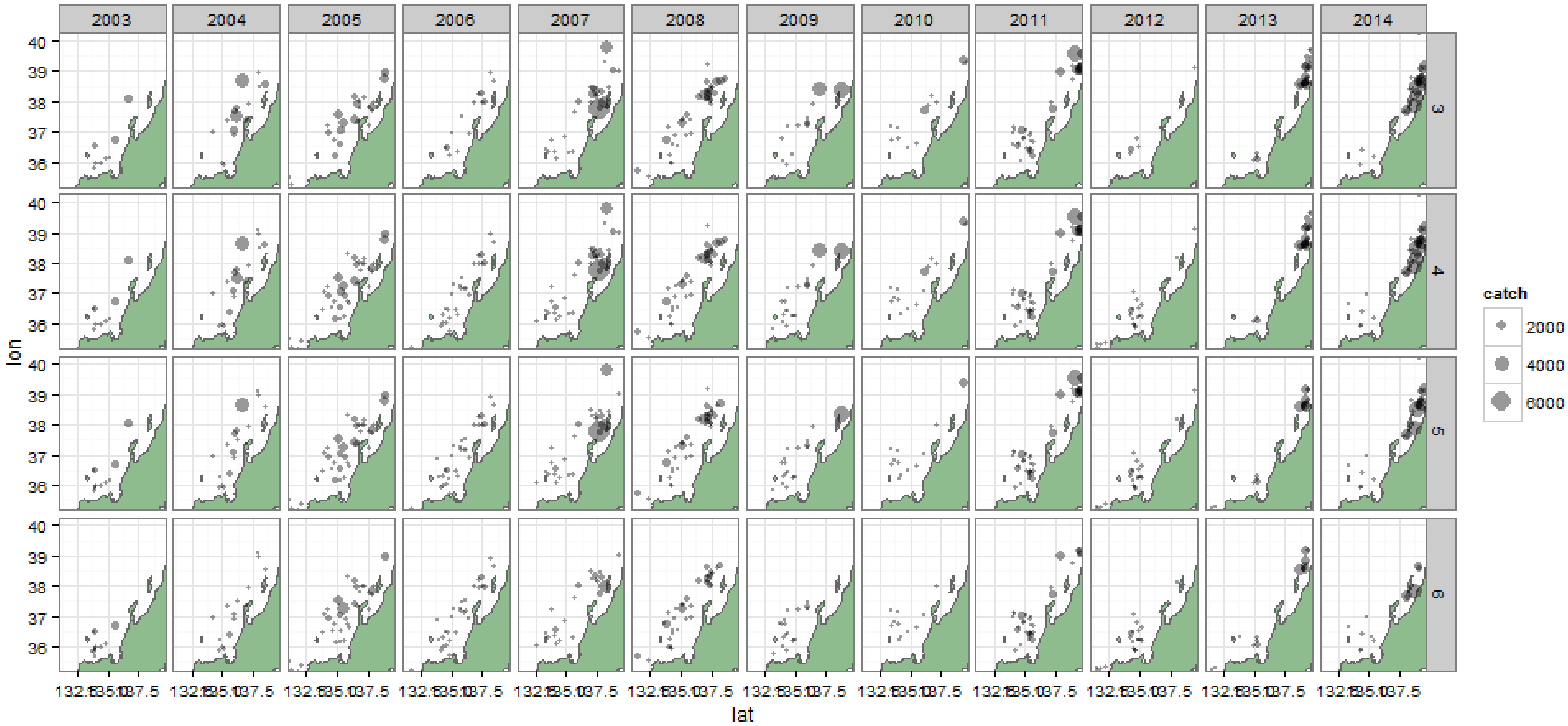

Fig. 6. Spatiotemporal distribution of catch by each age

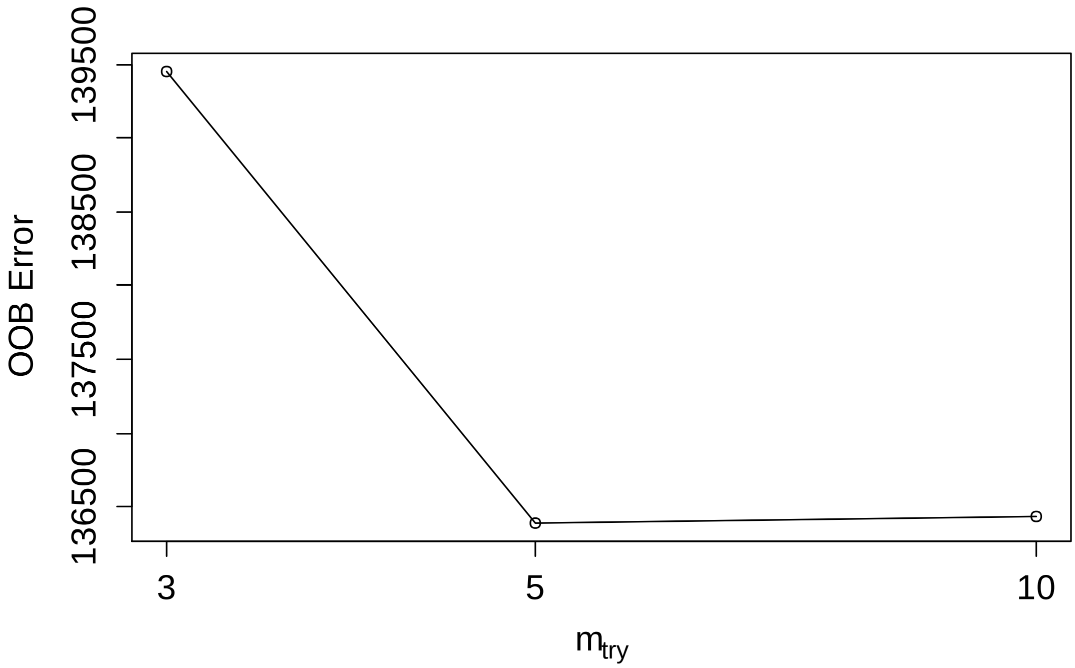

Fig. 7. OOB error by Number of variables randomly sampled as candidates at each split (m_{try})

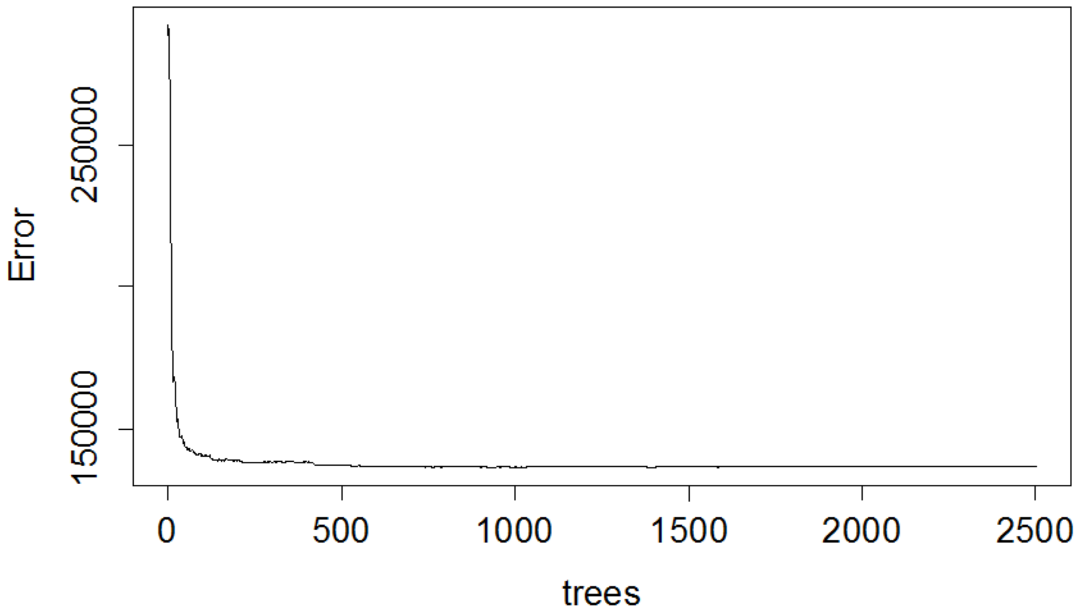

Fig. 8. OOB error by number of trees to grow (trees)

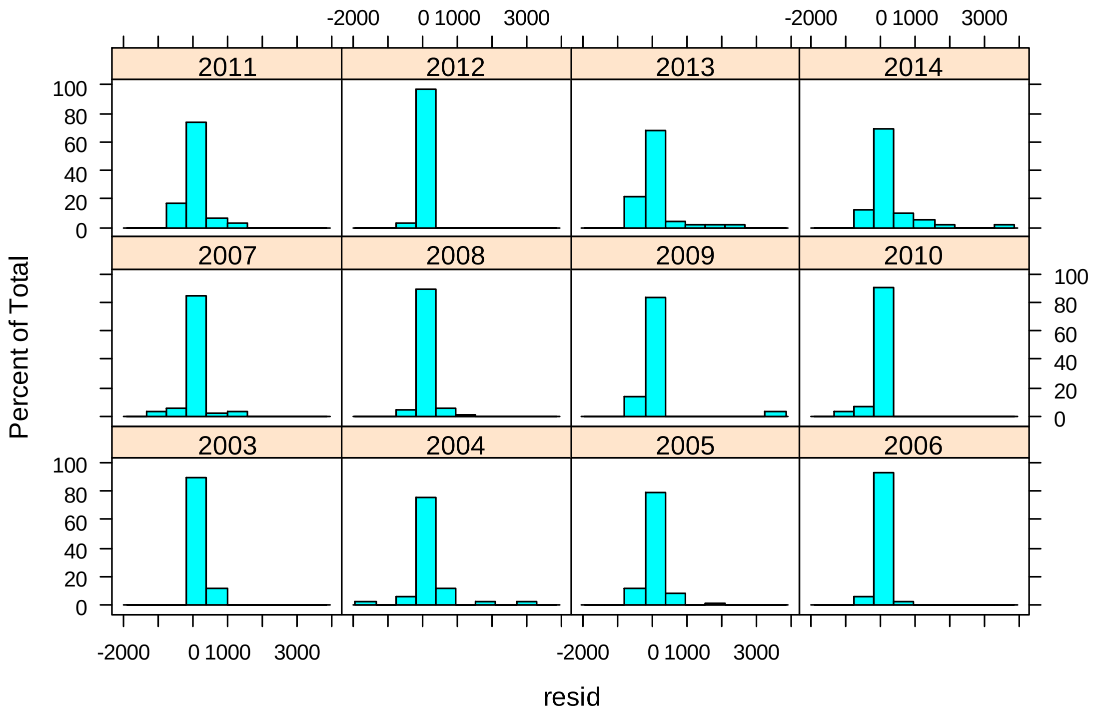

Fig. 9. Residual patter of each year.

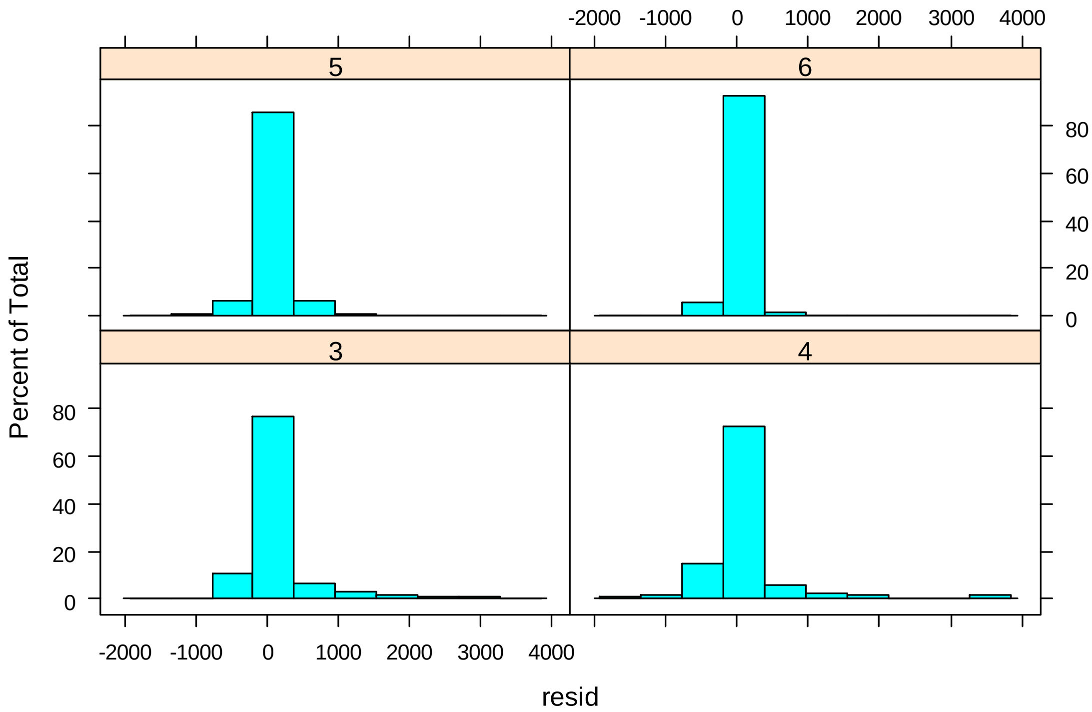

Fig. 10. Residual patter of each age.

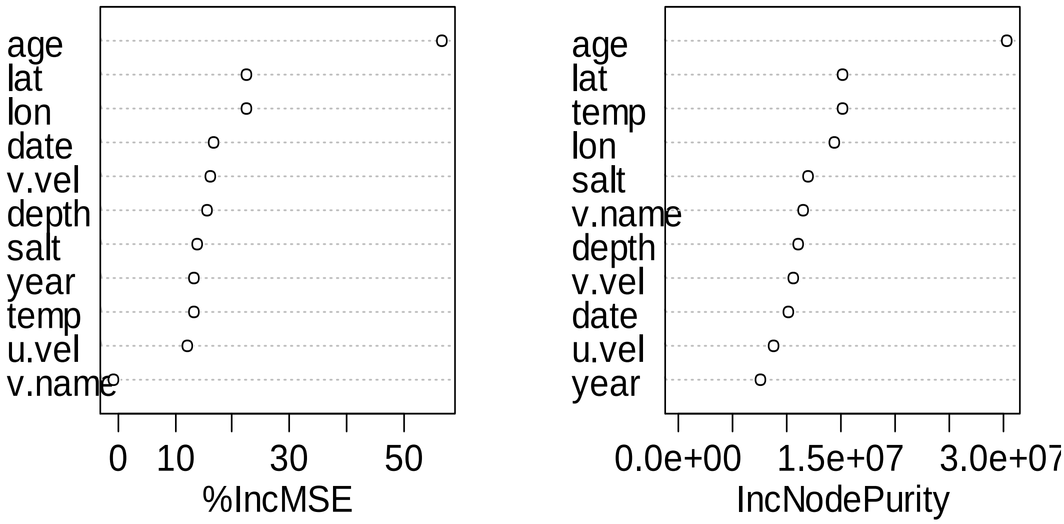

Fig. 11. Importance for each explanatory variable

Left figure shows for each tree, the prediction error on the out-of-bag portion of the data is recorded by mean squared error. Right figure shows the total decrease in node impurities from splitting on the variable, averaged over all trees by residual sum of squares.

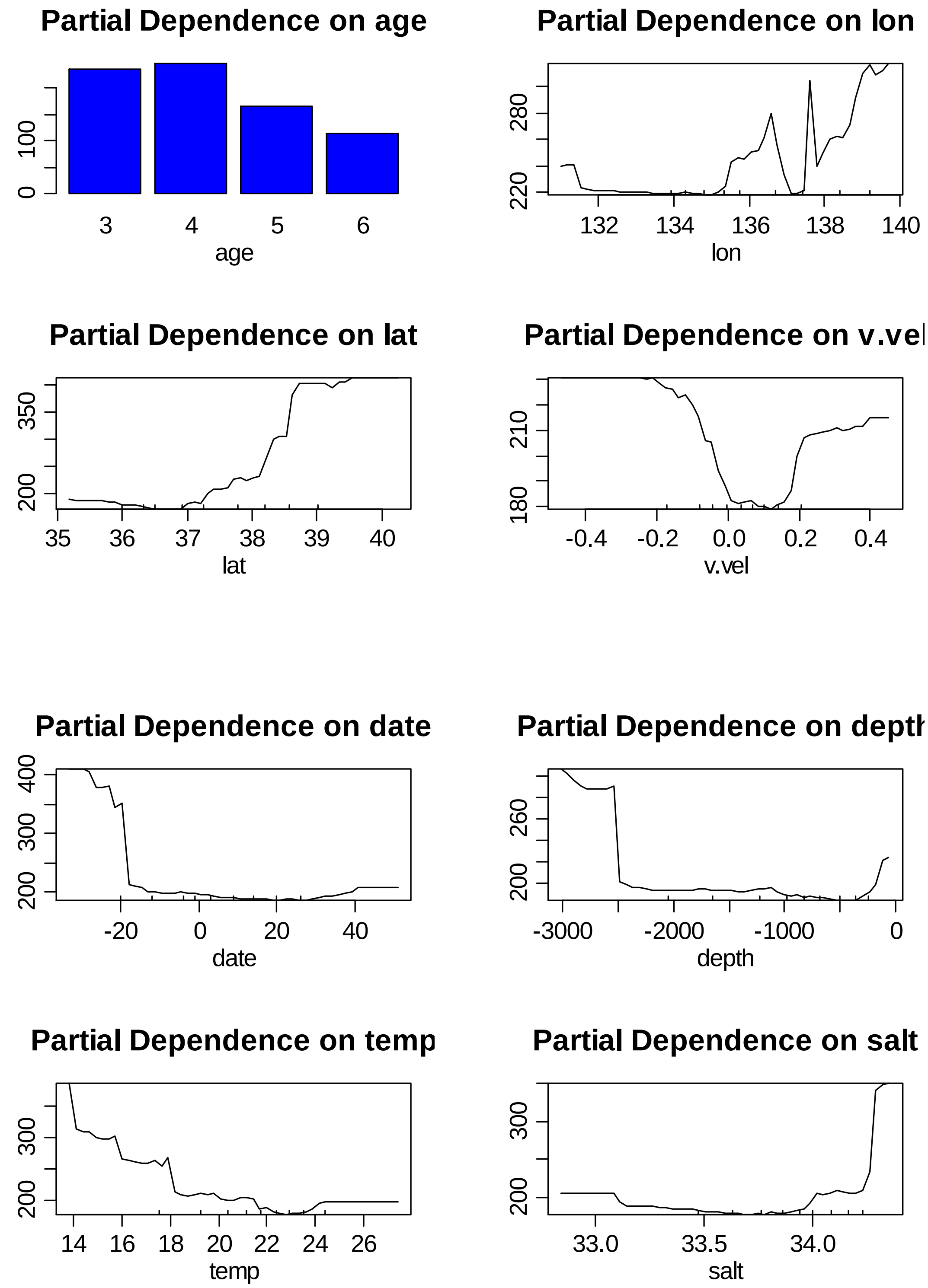

Fig. 12. Partial dependence for each explanatory variable.

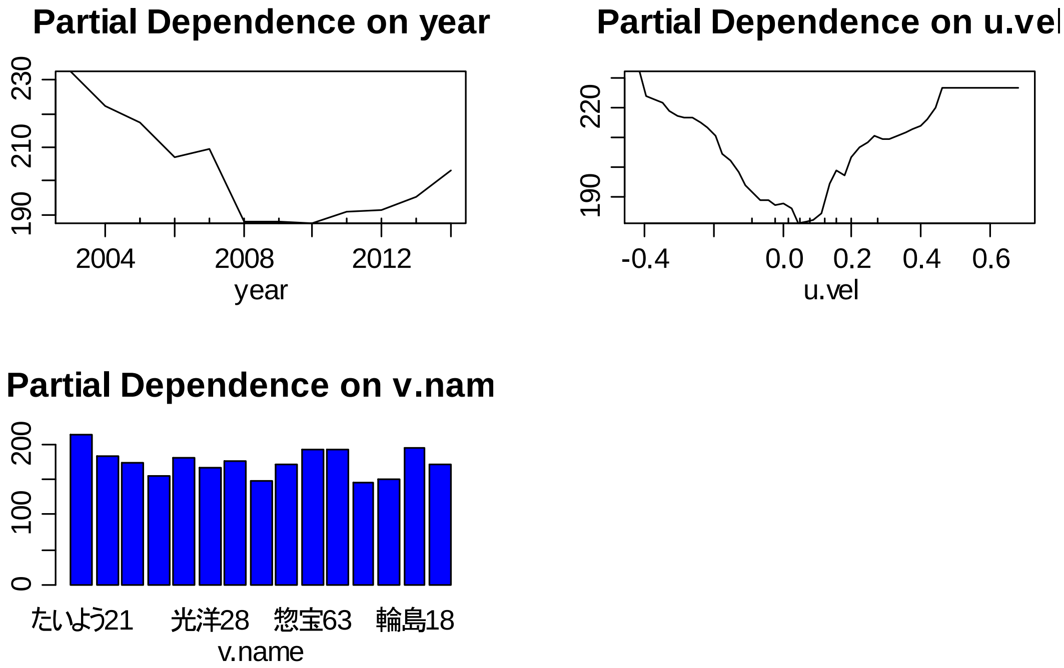

Fig. 12. continue

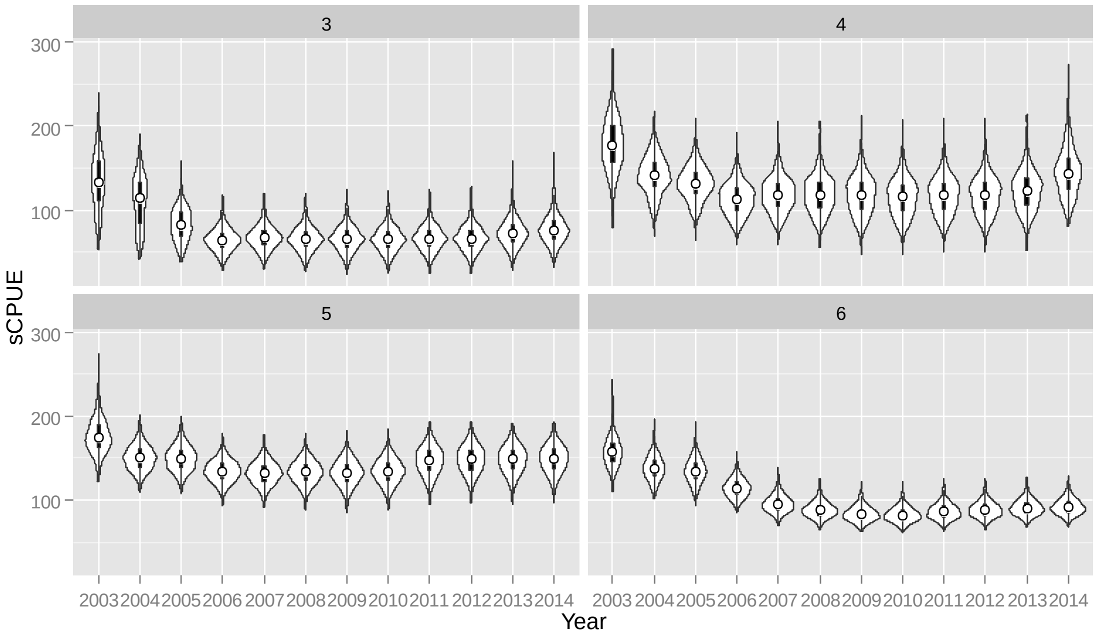

Fig. 13. Estimated standardized CPUE as marginal mean by 1,000 times resampling. White points show mean value and boxplot overlapped on violin plot.

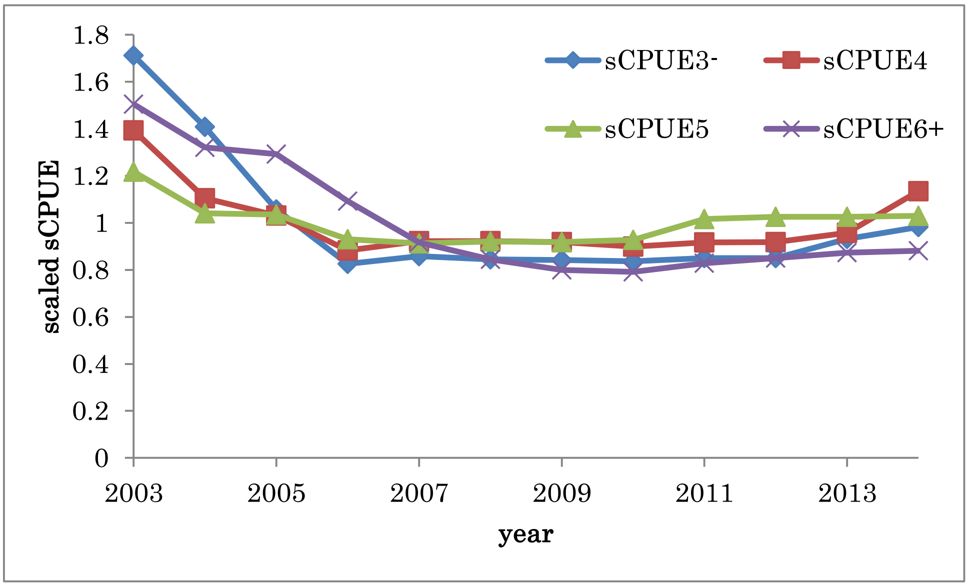

Fig. 14. Scaled standardized CPUE (sCPUE/average of sCPUE for each age).

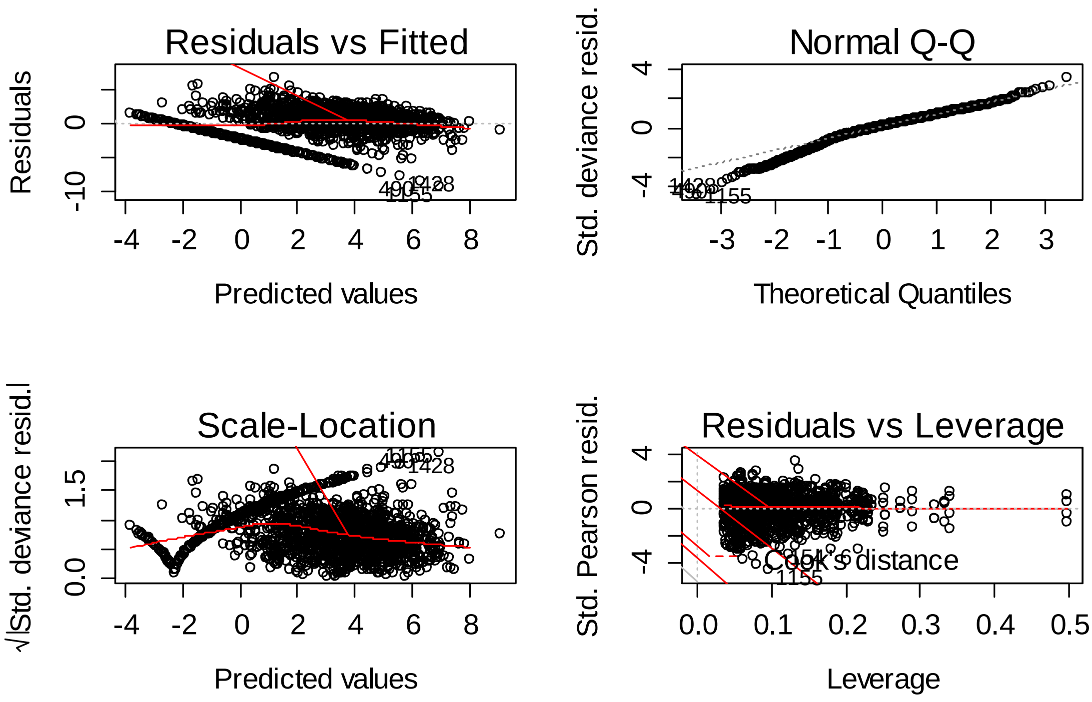

Fig. 15 Diagnostics of GLM

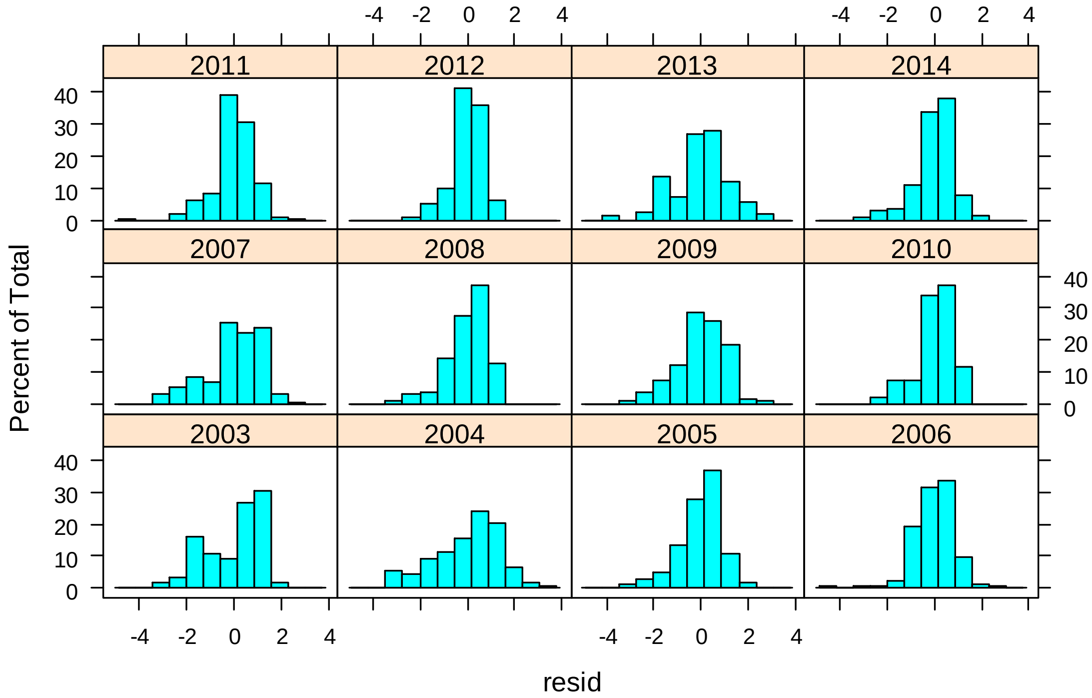

Fig. 16 Studentized residual distribution of GLM for each year

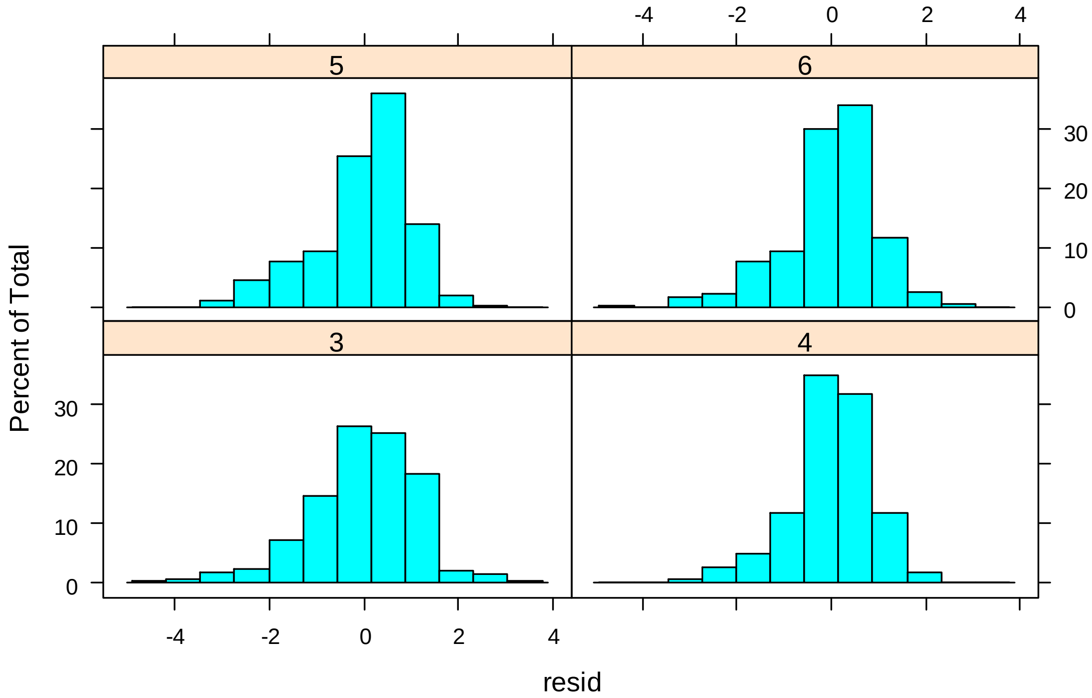

Fig. 17 Studentized residual distribution of GLM for each age

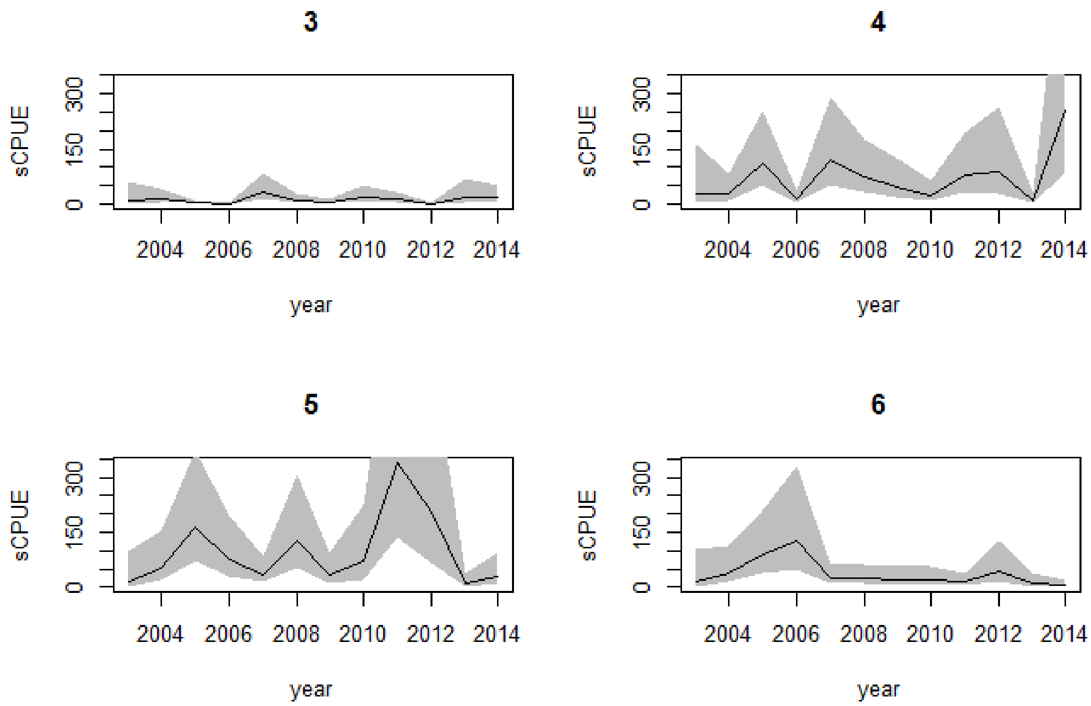

Fig. 18 Standardized CPUE by GLM

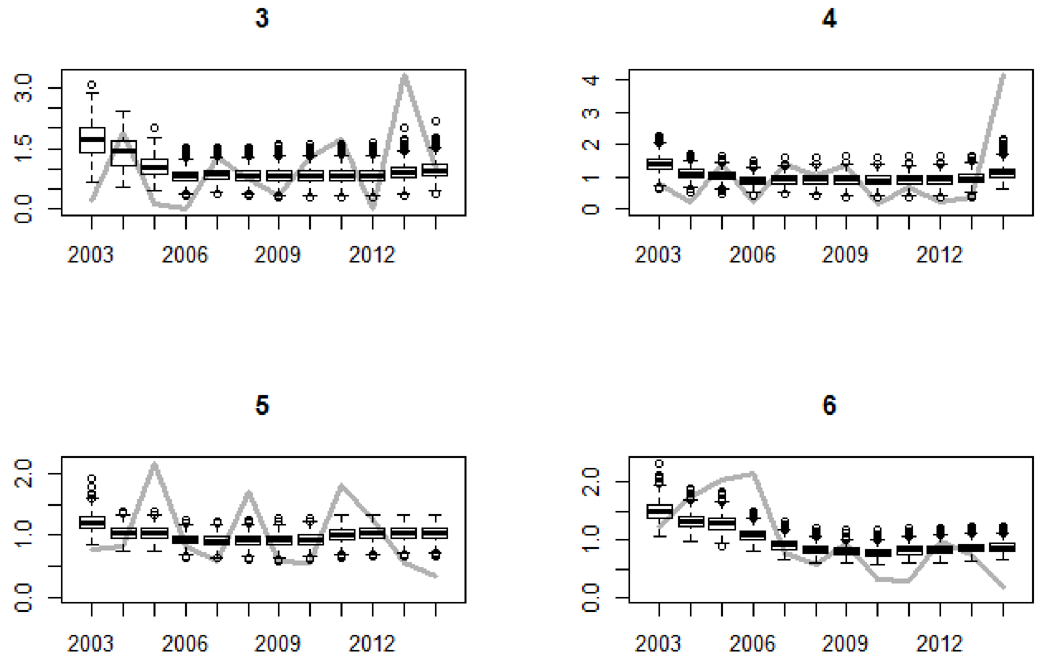

Fig. 19. Scaled standardized CPUE vs nominal CPUE

Box plot shows scaled standardized CPUE (sCPUE/average) and gray line shows scaled nominal CPUE (nCPUE/average).

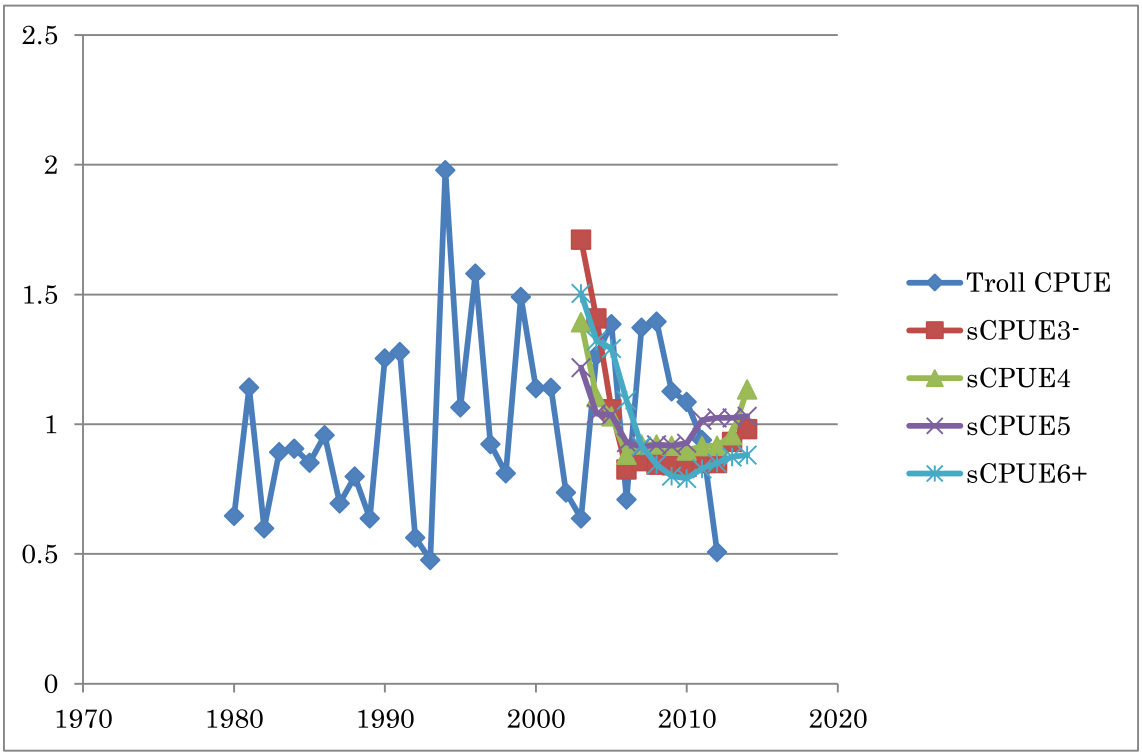

Fig. 20. Comparison between scaled sCPUE of purse seine and scaled nominal CPUE of troll fishery in Sea of Japan.

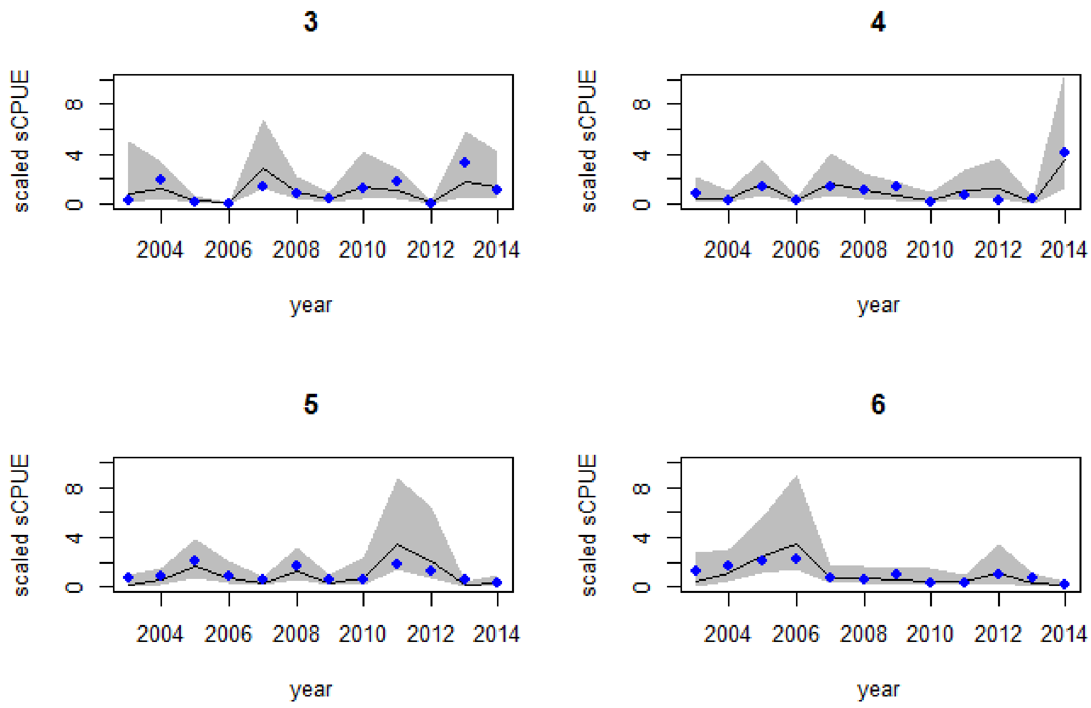

Fig. 21 Scaled sCPUE and nominal CPUE

Solid lines show scaled standardized CPUE by GLM and plots show scaled nominal CPUE for each age.

Appendix 1 summary of GLM result

```
Call:
glm(formula = log(c2 + mpc2/10) ~ as.factor(year) + date + as.factor(age) +
    poly(lat, 3) + poly(lon, 3) + poly(depth, 2) + poly(temp,
    2) + poly(salt, 2) + poly(u.vel, 2) + poly(v.vel, 2) + as.factor(year):date +
    as.factor(year):as.factor(age) + date:poly(lat, 3) + date:poly(depth,
    2) + date:poly(u.vel, 2) + date:poly(v.vel, 2) + as.factor(age):poly(lat,
    3) + as.factor(age):poly(depth, 2) + as.factor(age):poly(temp,
    2) + poly(lat, 3):poly(lon, 3) + poly(lat, 3):poly(depth,
    2) + poly(lat, 3):poly(u.vel, 2) + poly(lon, 3):poly(temp,
    2) + poly(lon, 3):poly(u.vel, 2) + poly(lon, 3):poly(v.vel,
    2) + poly(depth, 2):poly(salt, 2) + poly(depth, 2):poly(v.vel,
    2) + poly(temp, 2):poly(salt, 2) + poly(temp, 2):poly(u.vel,
    2) + poly(salt, 2):poly(v.vel, 2), family = "gaussian", data = adata)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-9.2528  -0.9614   0.2359   1.3108   6.8395

Coefficients:
                              Estimate Std. Error t value Pr(>|t|)
(Intercept)                  7.949e+00  2.870e+00   2.770 0.005684 **
as.factor(year)2004          9.535e-01  1.123e+00   0.849 0.395921
as.factor(year)2005         -3.291e-01  1.083e+00  -0.304 0.761345
as.factor(year)2006         -2.412e+00  1.071e+00  -2.252 0.024481 *
as.factor(year)2007          1.750e+00  1.094e+00   1.600 0.109814
as.factor(year)2008          6.299e-01  1.054e+00   0.597 0.550325
as.factor(year)2009         -3.838e-01  1.101e+00  -0.349 0.727408
as.factor(year)2010          7.346e-01  1.165e+00   0.631 0.528366
as.factor(year)2011          8.786e-01  1.094e+00   0.803 0.422202
as.factor(year)2012         -1.737e+00  1.100e+00  -1.579 0.114488
as.factor(year)2013          1.230e+00  1.192e+00   1.032 0.302311
as.factor(year)2014          9.266e-01  1.153e+00   0.803 0.421908
date                         4.484e-02  3.677e-02   1.220 0.222794
as.factor(age)4              6.761e-01  8.460e-01   0.799 0.424286
as.factor(age)5             -3.834e-01  8.460e-01  -0.453 0.650452
```

as.factor(age)6	-3.717e-01	8.460e-01	-0.439	0.660450	
poly(lat, 3)1	-1.411e+01	1.415e+02	-0.100	0.920582	
poly(lat, 3)2	1.811e+02	8.783e+01	2.062	0.039398	*
poly(lat, 3)3	-3.546e+01	4.497e+01	-0.788	0.430569	
poly(lon, 3)1	5.754e+01	1.394e+02	0.413	0.679766	
poly(lon, 3)2	2.466e+02	1.060e+02	2.326	0.020132	*
poly(lon, 3)3	-3.141e+01	3.855e+01	-0.815	0.415396	
poly(depth, 2)1	3.770e+00	7.902e+00	0.477	0.633331	
poly(depth, 2)2	-1.851e+00	6.915e+00	-0.268	0.789032	
poly(temp, 2)1	-5.158e+01	1.627e+01	-3.170	0.001555	**
poly(temp, 2)2	2.541e+01	9.589e+00	2.650	0.008142	**
poly(salt, 2)1	8.187e+00	7.925e+00	1.033	0.301780	
poly(salt, 2)2	7.379e+00	5.781e+00	1.277	0.201948	
poly(u.vel, 2)1	2.464e+01	5.144e+00	4.790	1.84e-06	***
poly(u.vel, 2)2	4.976e-01	5.990e+00	0.083	0.933806	
poly(v.vel, 2)1	-3.788e+00	3.760e+00	-1.008	0.313841	
poly(v.vel, 2)2	4.660e+00	4.195e+00	1.111	0.266842	
as.factor(year)2004:date	-5.790e-02	4.459e-02	-1.299	0.194268	
as.factor(year)2005:date	-5.196e-02	3.919e-02	-1.326	0.185095	
as.factor(year)2006:date	1.965e-02	3.763e-02	0.522	0.601595	
as.factor(year)2007:date	-3.193e-02	3.933e-02	-0.812	0.416959	
as.factor(year)2008:date	-3.693e-02	3.885e-02	-0.951	0.341965	
as.factor(year)2009:date	-2.016e-02	3.888e-02	-0.518	0.604264	
as.factor(year)2010:date	1.729e-02	4.119e-02	0.420	0.674705	
as.factor(year)2011:date	-4.180e-02	3.741e-02	-1.117	0.263963	
as.factor(year)2012:date	-1.693e-02	3.983e-02	-0.425	0.670814	
as.factor(year)2013:date	-5.404e-02	4.224e-02	-1.279	0.200950	
as.factor(year)2014:date	-1.744e-02	4.150e-02	-0.420	0.674359	
as.factor(year)2004:as.factor(age)4	-2.855e-01	1.057e+00	-0.270	0.787080	
as.factor(year)2005:as.factor(age)4	2.396e+00	9.566e-01	2.504	0.012380	*
as.factor(year)2006:as.factor(age)4	2.122e+00	9.763e-01	2.173	0.029922	*
as.factor(year)2007:as.factor(age)4	2.852e-01	9.772e-01	0.292	0.770428	
as.factor(year)2008:as.factor(age)4	9.525e-01	9.580e-01	0.994	0.320254	
as.factor(year)2009:as.factor(age)4	1.355e+00	1.025e+00	1.322	0.186355	
as.factor(year)2010:as.factor(age)4	-7.445e-01	1.066e+00	-0.698	0.485202	
as.factor(year)2011:as.factor(age)4	7.492e-01	9.906e-01	0.756	0.449574	

as.factor(year)2012:as.factor(age)4	3.328e+00	1.034e+00	3.218	0.001318	**
as.factor(year)2013:as.factor(age)4	-1.724e+00	1.049e+00	-1.643	0.100573	
as.factor(year)2014:as.factor(age)4	1.748e+00	1.018e+00	1.716	0.086411	.
as.factor(year)2004:as.factor(age)5	8.252e-01	1.057e+00	0.781	0.435023	
as.factor(year)2005:as.factor(age)5	3.244e+00	9.566e-01	3.391	0.000714	***
as.factor(year)2006:as.factor(age)5	4.246e+00	9.763e-01	4.349	1.46e-05	***
as.factor(year)2007:as.factor(age)5	-4.871e-01	9.772e-01	-0.498	0.618228	
as.factor(year)2008:as.factor(age)5	1.974e+00	9.580e-01	2.061	0.039510	*
as.factor(year)2009:as.factor(age)5	1.566e+00	1.025e+00	1.528	0.126637	
as.factor(year)2010:as.factor(age)5	9.765e-01	1.066e+00	0.916	0.360008	
as.factor(year)2011:as.factor(age)5	2.701e+00	9.906e-01	2.726	0.006483	**
as.factor(year)2012:as.factor(age)5	4.656e+00	1.034e+00	4.503	7.24e-06	***
as.factor(year)2013:as.factor(age)5	-1.109e+00	1.049e+00	-1.057	0.290807	
as.factor(year)2014:as.factor(age)5	1.209e-01	1.018e+00	0.119	0.905507	
as.factor(year)2004:as.factor(age)6	4.944e-01	1.057e+00	0.468	0.639993	
as.factor(year)2005:as.factor(age)6	2.616e+00	9.566e-01	2.734	0.006324	**
as.factor(year)2006:as.factor(age)6	4.722e+00	9.763e-01	4.837	1.46e-06	***
as.factor(year)2007:as.factor(age)6	-8.194e-01	9.772e-01	-0.839	0.401853	
as.factor(year)2008:as.factor(age)6	3.663e-01	9.580e-01	0.382	0.702248	
as.factor(year)2009:as.factor(age)6	1.005e+00	1.025e+00	0.981	0.326762	
as.factor(year)2010:as.factor(age)6	-4.016e-01	1.066e+00	-0.377	0.706518	
as.factor(year)2011:as.factor(age)6	-4.762e-01	9.906e-01	-0.481	0.630816	
as.factor(year)2012:as.factor(age)6	3.017e+00	1.034e+00	2.918	0.003577	**
as.factor(year)2013:as.factor(age)6	-1.107e+00	1.049e+00	-1.055	0.291508	
as.factor(year)2014:as.factor(age)6	-1.550e+00	1.018e+00	-1.522	0.128163	
date:poly(lat, 3)1	-6.539e-01	4.203e-01	-1.556	0.120024	
date:poly(lat, 3)2	-3.281e-01	3.574e-01	-0.918	0.358669	
date:poly(lat, 3)3	-1.071e+00	3.537e-01	-3.028	0.002503	**
date:poly(depth, 2)1	-8.577e-01	3.996e-01	-2.147	0.031980	*
date:poly(depth, 2)2	-1.868e-01	3.327e-01	-0.561	0.574659	
date:poly(u.vel, 2)1	-1.373e+00	3.364e-01	-4.083	4.69e-05	***
date:poly(u.vel, 2)2	2.078e-01	3.012e-01	0.690	0.490311	
date:poly(v.vel, 2)1	5.269e-01	3.262e-01	1.615	0.106502	
date:poly(v.vel, 2)2	-1.905e+00	4.000e-01	-4.763	2.10e-06	***
as.factor(age)4:poly(lat, 3)1	-1.678e+01	8.342e+00	-2.012	0.044426	*
as.factor(age)5:poly(lat, 3)1	-8.047e+01	8.342e+00	-9.647	< 2e-16	***

as.factor(age)6:poly(lat, 3)1	-1.207e+02	8.342e+00	-14.467	< 2e-16	***
as.factor(age)4:poly(lat, 3)2	-4.031e-01	7.181e+00	-0.056	0.955239	
as.factor(age)5:poly(lat, 3)2	-4.200e+00	7.181e+00	-0.585	0.558685	
as.factor(age)6:poly(lat, 3)2	-3.507e+00	7.181e+00	-0.488	0.625317	
as.factor(age)4:poly(lat, 3)3	-3.272e+00	6.472e+00	-0.506	0.613245	
as.factor(age)5:poly(lat, 3)3	-1.199e+00	6.472e+00	-0.185	0.853008	
as.factor(age)6:poly(lat, 3)3	1.223e+01	6.472e+00	1.890	0.058986	.
as.factor(age)4:poly(depth, 2)1	-5.293e+00	7.296e+00	-0.726	0.468224	
as.factor(age)5:poly(depth, 2)1	-1.897e+01	7.296e+00	-2.600	0.009410	**
as.factor(age)6:poly(depth, 2)1	-1.550e+01	7.296e+00	-2.124	0.033810	*
as.factor(age)4:poly(depth, 2)2	-8.095e-01	6.824e+00	-0.119	0.905588	
as.factor(age)5:poly(depth, 2)2	-1.635e+01	6.824e+00	-2.396	0.016702	*
as.factor(age)6:poly(depth, 2)2	-1.120e+01	6.824e+00	-1.642	0.100866	
as.factor(age)4:poly(temp, 2)1	8.833e+00	7.599e+00	1.162	0.245235	
as.factor(age)5:poly(temp, 2)1	1.805e+01	7.599e+00	2.376	0.017646	*
as.factor(age)6:poly(temp, 2)1	5.137e+01	7.599e+00	6.760	1.98e-11	***
as.factor(age)4:poly(temp, 2)2	-1.653e+01	7.092e+00	-2.331	0.019881	*
as.factor(age)5:poly(temp, 2)2	-2.319e+01	7.092e+00	-3.270	0.001098	**
as.factor(age)6:poly(temp, 2)2	-8.184e+00	7.092e+00	-1.154	0.248724	
poly(lat, 3)1:poly(lon, 3)1	-1.661e+04	7.386e+03	-2.248	0.024697	*
poly(lat, 3)2:poly(lon, 3)1	-1.026e+02	3.942e+03	-0.026	0.979235	
poly(lat, 3)3:poly(lon, 3)1	-4.334e+03	1.890e+03	-2.293	0.021976	*
poly(lat, 3)1:poly(lon, 3)2	5.268e+03	4.714e+03	1.117	0.263964	
poly(lat, 3)2:poly(lon, 3)2	9.426e+03	3.627e+03	2.599	0.009446	**
poly(lat, 3)3:poly(lon, 3)2	2.374e+03	8.892e+02	2.670	0.007664	**
poly(lat, 3)1:poly(lon, 3)3	-4.686e+03	2.041e+03	-2.296	0.021832	*
poly(lat, 3)2:poly(lon, 3)3	-2.428e+03	8.339e+02	-2.911	0.003655	**
poly(lat, 3)3:poly(lon, 3)3	-7.131e+02	2.355e+02	-3.028	0.002507	**
poly(lat, 3)1:poly(depth, 2)1	-6.137e+02	3.064e+02	-2.003	0.045400	*
poly(lat, 3)2:poly(depth, 2)1	-7.719e+02	2.573e+02	-3.000	0.002749	**
poly(lat, 3)3:poly(depth, 2)1	-5.547e+02	2.060e+02	-2.693	0.007156	**
poly(lat, 3)1:poly(depth, 2)2	2.699e+02	2.282e+02	1.183	0.237174	
poly(lat, 3)2:poly(depth, 2)2	-1.625e+02	1.816e+02	-0.895	0.370935	
poly(lat, 3)3:poly(depth, 2)2	3.220e+02	2.125e+02	1.516	0.129848	
poly(lat, 3)1:poly(u.vel, 2)1	1.554e+03	4.256e+02	3.650	0.000271	***
poly(lat, 3)2:poly(u.vel, 2)1	1.204e+03	2.832e+02	4.254	2.24e-05	***

poly(lat, 3)3:poly(u.vel, 2)1	-3.550e+02	3.175e+02	-1.118	0.263720	
poly(lat, 3)1:poly(u.vel, 2)2	-8.448e+02	6.133e+02	-1.378	0.168527	
poly(lat, 3)2:poly(u.vel, 2)2	-4.495e+02	4.192e+02	-1.072	0.283788	
poly(lat, 3)3:poly(u.vel, 2)2	-3.702e+02	3.968e+02	-0.933	0.350921	
poly(lon, 3)1:poly(temp, 2)1	6.632e+02	5.915e+02	1.121	0.262311	
poly(lon, 3)2:poly(temp, 2)1	3.991e+02	7.054e+02	0.566	0.571593	
poly(lon, 3)3:poly(temp, 2)1	2.720e+02	4.550e+02	0.598	0.550096	
poly(lon, 3)1:poly(temp, 2)2	-6.718e+01	3.576e+02	-0.188	0.851019	
poly(lon, 3)2:poly(temp, 2)2	-4.102e+02	4.368e+02	-0.939	0.347782	
poly(lon, 3)3:poly(temp, 2)2	6.070e+01	2.952e+02	0.206	0.837081	
poly(lon, 3)1:poly(u.vel, 2)1	-1.408e+03	3.968e+02	-3.548	0.000400	***
poly(lon, 3)2:poly(u.vel, 2)1	-9.321e+02	2.907e+02	-3.207	0.001370	**
poly(lon, 3)3:poly(u.vel, 2)1	2.978e+01	2.814e+02	0.106	0.915730	
poly(lon, 3)1:poly(u.vel, 2)2	6.241e+02	5.403e+02	1.155	0.248271	
poly(lon, 3)2:poly(u.vel, 2)2	8.778e+01	3.420e+02	0.257	0.797482	
poly(lon, 3)3:poly(u.vel, 2)2	2.186e+02	2.381e+02	0.918	0.358583	
poly(lon, 3)1:poly(v.vel, 2)1	6.065e+02	1.750e+02	3.466	0.000543	***
poly(lon, 3)2:poly(v.vel, 2)1	-2.494e+02	1.901e+02	-1.312	0.189862	
poly(lon, 3)3:poly(v.vel, 2)1	2.164e+02	1.676e+02	1.291	0.196875	
poly(lon, 3)1:poly(v.vel, 2)2	-3.682e+02	1.658e+02	-2.220	0.026540	*
poly(lon, 3)2:poly(v.vel, 2)2	-2.372e+01	2.150e+02	-0.110	0.912182	
poly(lon, 3)3:poly(v.vel, 2)2	-1.462e+01	1.951e+02	-0.075	0.940290	
poly(depth, 2)1:poly(salt, 2)1	-2.156e+02	2.789e+02	-0.773	0.439728	
poly(depth, 2)2:poly(salt, 2)1	-2.060e+02	2.432e+02	-0.847	0.397118	
poly(depth, 2)1:poly(salt, 2)2	-4.450e+02	1.867e+02	-2.383	0.017291	*
poly(depth, 2)2:poly(salt, 2)2	-7.816e+01	1.680e+02	-0.465	0.641799	
poly(depth, 2)1:poly(v.vel, 2)1	6.917e+00	1.388e+02	0.050	0.960270	
poly(depth, 2)2:poly(v.vel, 2)1	1.901e+02	1.245e+02	1.527	0.126976	
poly(depth, 2)1:poly(v.vel, 2)2	-5.714e+02	1.493e+02	-3.828	0.000135	***
poly(depth, 2)2:poly(v.vel, 2)2	-3.115e+02	1.360e+02	-2.290	0.022159	*
poly(temp, 2)1:poly(salt, 2)1	1.090e+03	2.542e+02	4.286	1.93e-05	***
poly(temp, 2)2:poly(salt, 2)1	1.513e+02	2.084e+02	0.726	0.467851	
poly(temp, 2)1:poly(salt, 2)2	2.756e+02	1.674e+02	1.647	0.099794	.
poly(temp, 2)2:poly(salt, 2)2	-1.266e+02	1.477e+02	-0.857	0.391535	
poly(temp, 2)1:poly(u.vel, 2)1	8.938e+02	3.689e+02	2.423	0.015531	*
poly(temp, 2)2:poly(u.vel, 2)1	3.857e+02	2.346e+02	1.644	0.100345	

```
poly(temp, 2)1:poly(u.vel, 2)2          -9.029e+02    4.191e+02    -2.154 0.031378 *
poly(temp, 2)2:poly(u.vel, 2)2           5.805e+02    3.205e+02     1.811 0.070313 .
poly(salt, 2)1:poly(v.vel, 2)1           2.921e+02    1.958e+02     1.492 0.135852
poly(salt, 2)2:poly(v.vel, 2)1           1.511e+02    1.659e+02     0.911 0.362440
poly(salt, 2)1:poly(v.vel, 2)2          -9.302e+02    2.506e+02    -3.711 0.000214 ***
poly(salt, 2)2:poly(v.vel, 2)2          -5.369e+02    1.839e+02    -2.920 0.003556 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for gaussian family taken to be 4.549853)

    Null deviance: 15103.9  on 1643  degrees of freedom
Residual deviance:  6729.2  on 1479  degrees of freedom
AIC: 7314.4

Number of Fisher Scoring iterations: 2
```

Appendix 2 type-III analysis of variance tables for GLM

Analysis of Deviance Table (Type III tests)

Response: log(c2 + mpc2/10)

	LR Chisq	Df	Pr(>Chisq)	
as.factor(year)	81.241	11	8.489e-13	***
date	1.488	1	0.2225993	
as.factor(age)	2.070	3	0.5579831	
poly(lat, 3)	10.014	3	0.0184448	*
poly(lon, 3)	10.768	3	0.0130486	*
poly(depth, 2)	0.252	2	0.8815292	
poly(temp, 2)	11.654	2	0.0029474	**
poly(salt, 2)	3.484	2	0.1751835	
poly(u.vel, 2)	25.562	2	2.814e-06	***
poly(v.vel, 2)	2.326	2	0.3125922	
as.factor(year):date	22.443	11	0.0211548	*
as.factor(year):as.factor(age)	231.268	33	< 2.2e-16	***
date:poly(lat, 3)	15.053	3	0.0017717	**
date:poly(depth, 2)	7.269	2	0.0263952	*
date:poly(u.vel, 2)	19.349	2	6.287e-05	***
date:poly(v.vel, 2)	22.716	2	1.167e-05	***
as.factor(age):poly(lat, 3)	280.158	9	< 2.2e-16	***
as.factor(age):poly(depth, 2)	14.189	6	0.0275956	*
as.factor(age):poly(temp, 2)	65.499	6	3.411e-12	***
poly(lat, 3):poly(lon, 3)	17.993	9	0.0352604	*
poly(lat, 3):poly(depth, 2)	13.700	6	0.0331775	*
poly(lat, 3):poly(u.vel, 2)	31.211	6	2.310e-05	***
poly(lon, 3):poly(temp, 2)	11.319	6	0.0790125	.
poly(lon, 3):poly(u.vel, 2)	23.642	6	0.0006077	***
poly(lon, 3):poly(v.vel, 2)	18.664	6	0.0047706	**
poly(depth, 2):poly(salt, 2)	9.258	4	0.0549691	.
poly(depth, 2):poly(v.vel, 2)	20.958	4	0.0003228	***
poly(temp, 2):poly(salt, 2)	18.680	4	0.0009081	***
poly(temp, 2):poly(u.vel, 2)	27.403	4	1.647e-05	***
poly(salt, 2):poly(v.vel, 2)	16.664	4	0.0022460	**

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1