Space-time modelling of fishery-independent setline survey data

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PURPOSE

To provide the Commission with a summary of the methods and output of the space-time modelling in 2017, the results of this year's IPHC fishery-independent setline survey (FISS) expansions in IPHC Regulatory Areas 4B and 2A, and the results of an evaluation of previous setline survey expansions in Regulatory Areas 2A and 4A including the implications for future expansions in these areas.

BACKGROUND

In 2016, a space-time modelling approach was introduced to estimate time series of weight and numbers-per-unit-effort (WPUE and NPUE), and to estimate the stock distribution of Pacific halibut among IPHC Regulatory Areas. This represented an improvement over the largely empirical (data-based) approach used previously, as it made use of additional information within the setline survey data regarding the degree of spatial and temporal of Pacific halibut density, along with information from covariates such as depth (see Webster 2016b and 2017). The modelling also incorporated data from recent setline survey expansions in Regulatory Area 2A (2011 and 2014), Area 4A (2014) and Area 4CDE (2015 and 2016), without the need for applying ad hoc adjustment factors to account for changes in the spatial coverage of the setline survey.

At the 92nd Session of the IPHC Interim Meeting (IM092), the Commission made the following recommendation to the IPHC Secretariat:

> "*The Commission **RECOMMENDED** that the IPHC Staff develop an information paper associated with the survey expansion, which details the likely implications of periodic survey expansion on the stock assessment and apportionment, taking into consideration potential population variability of Pacific halibut in expansion areas which are infrequently surveyed. The paper shall be submitted for initial consideration at the Commission's Work Meeting in September 2017*." (IM092, para. 38)

The requested evaluation was carried in out in 2017 for Regulatory Areas 2A and 4A.

INTRODUCTION

The IPHC fishery-independent setline survey (FISS or setline survey) provides data used to compute indices of Pacific halibut density for use in monitoring stock trends, estimating stock distribution, and as an important input in the stock assessment. Stock distribution estimates are based on the annual mean weight-per-unit effort (WPUE) for each Regulatory Area, computed as the average of WPUE of O32 (greater than or equal to 32" or 81.3cm in length) Pacific halibut estimated at each station in an area. Mean numbers-per-unit-effort (NPUE) is used to index the trend in Pacific halibut density in the stock assessment models. In 2016, the IPHC Secretariat moved to a space-time modelling approach for estimating these indices and calculating estimates of stock distribution (Webster 2017), an approach that was continued in 2017.

In most IPHC Regulatory Areas, the standard, annual setline survey's 18.5 km (10 nmi) grid is fished in waters within the 37-503 m (20-275 fm) depth range. Information from commercial fishery data and other fishery-independent sources showed the presence of Pacific halibut down to depths of 732 m (400 fm) and in waters shallower than 37m in some Regulatory Areas. Further, most Regulatory Areas had significant gaps in coverage within the standard 37-503 m depth range. The incomplete coverage of Pacific halibut habitat by the setline survey likely led to biased estimates of WPUE and NPUE density indices in some Regulatory Areas that were then used in the stock assessment modelling and for stock distribution estimation. For this reason, the IPHC has been undertaking a sequence of setline survey expansions since 2014 (following a 2011 pilot), with stations added to the standard grid to cover habitat not previously sampled in our setline survey. The expansions involve adding stations to one or two Regulatory Areas each year, and reverting to the annual grid for those areas in subsequent years. In 2017, setline survey expansions took place in Areas 4B and 2A. Regulatory Area 4B's expansion resulted in a total of 202 setline survey stations, more than double the 89 annually fished stations (Figure 1).

Regulatory Area 2A's 2017 expansion had three components: a repeat of the 2014 expansion, including deep (503-732 m) and shallow (18-37 m) stations, stations within the Salish Sea, and stations in California from 39°N to 42°N (Figures 2 to 4); new stations in California from 37.75°N to 39°N (Figure 4); and additional stations off the north Washington coast (north of 46°53.3' N, within 37-503 m; Figure 2) resulting in a doubling of station density in that region. The new stations in California allowed the IPHC to get direct information on density in a region that Pacific halibut are known to inhabit (albeit at low densities), as shown by catches of Pacific halibut on the National Marine Fisheries Service (NMFS) West Coast trawl survey (Webster 2016a). The increased station density off the north Washington Coast was motivated by stakeholder concerns that the standard 18.5 km station spacing may be missing localised patches of relatively high Pacific halibut density in that region, and that a denser grid would be more likely to detect such patches if they exist.

One advantage of the space-time modelling approach is that the effect of the setline survey expansions on estimates of density indices and their uncertainty can be investigated in a straightforward manner, by comparing the estimates we obtained with those we would have obtained in the absence of the data from the expansions. In order to undertake such an evaluation, we need an expansion to have already been carried out. Further, to help assess the need for future repeats of the expansion, it helps for some time to have elapsed since the expansion took place. For this reason, this report focuses on Regulatory Area 2A, which had setline survey expansions in 2011 and 2014, and Regulatory Area 4A (expansion in 2014). Work was undertaken prior to the 2017 setline survey, so data from this year's setline survey were not included in the Regulatory Area 2A evaluation.

In this report we outline updates to the space-time modelling of WPUE and NPUE indices of density and present summaries of modelling results for 2017, and present results of the setline survey expansions in Regulatory Areas 4B and 2A. For the evaluation of the need for future repeats of setline survey expansions, we compare estimated mean WPUE and its uncertainty between models fitted using all available setline survey data and those using subsets of the data that exclude groups of expansion stations.

Space-time modelling of WPUE and NPUE

Space-time modelling of setline survey data followed the methods outlined in Webster (2017). In addition to the inclusion of new 2017 setline survey data, data from 1993 to 1997 were also used in the modelling this year. The IPHC setline survey coverage in those years was less consistent than the current annual setline survey, with not all Regulatory Areas being fished each year, or only parts of some Regulatory Areas surveyed in some years (Soderlund et al. 2012). Nevertheless, with the model able to predict in unsurveyed locations, the addition of these data allows us to extend our understanding of changes in Pacific halibut density and distribution back to 1993. Space-time models were fitted to O32 WPUE, total NPUE, and total WPUE. Of these three variables, only O32 WPUE and total NPUE were modelled in 2016.

The standard NMFS Bering Sea trawl survey grid has been fished annually (sometimes with expansions) since 1982 (Lauth and Nichol 2013), and data from this trawl survey from 1993-1997 were also included in the modelling for Regulatory Areas 4A and 4CDE. In 2017, a northern expansion of the Bering Sea trawl survey was fished for the second time (it was first fished in 2010), giving the Bering Sea complete coverage and providing valuable data for improving space-time model estimates of WPUE and NPUE in the northern Bering Sea. Data from the Alaska Department of Fish and Game's (ADFG) triennial Norton Sound trawl survey (Soong and Hamizaki 2012) are also used in the modelling, and along with new data from the 2017 ADFG trawl survey, data from 1996 were added to the data previously used.

The expanded setline survey in California allowed us to produce a direct density estimate as far south as to 37.75°N in the space-time models, where previously an adjustment scalar based on the West Coast trawl survey data had to be applied to account for Pacific halibut within 37.75°N and 39°N. In the modelling, a new covariate was included identifying stations north and south of 40°N. This was needed to improve prediction south of 40°N, where catch rates were extremely low: without this covariate, model predictions of WPUE and NPUE in this region in unsurveyed years would approach the overall Regulatory Area 2A mean, and would therefore likely be positively biased, with bias getting worse with increasing years before or after the setline surveys.

Estimated mean O32 WPUE by Regulatory Area and year is presented in Figure 1. The shaded regions represent 95% posterior credible intervals, i.e., there is a 95% chance that the true mean for each area and year is within these intervals. In general, the 95% intervals for years from 1993-97 are much wider, due to the less consistent setline survey coverage prior to the implementation of the modern annual setline survey design in 1998. In the case of Regulatory Areas 4A and 4CDE, there were no longline data prior to 1997, and the estimates are therefore highly influenced by the NMFS trawl survey data in those years. The trawl survey fishes waters shallower than the setline survey, and its stations have lower WPUE on average than setline survey stations set along the Bering Sea shelf edge. In years with no setline survey, the trawl data influences estimates at unsurveyed locations along the edge through spatial dependence, leading to lower estimates as time prior to the setline surveys increases. This is likely a factor in the low estimates of WPUE in Areas 4A and 4CDE from 1993-96.

Figure 2 compares the estimated mean O32 WPUE time series from the 2016 space-time modelling with this year's estimates. Some differences between the two sets of estimates can be expected, due to changes to the data inputs leading influencing predictions at unsurveyed locations in particular through revision of model parameter estimates. The two sets of estimated time series, however, are extremely consistent, with any differences well within the levels of uncertainty shown by the 95% intervals. Notable differences are at the terminal years of the 2016 time series (1998 and 2016), where new data (from 1997 and prior years, and 2017) influence the new estimates from those terminal years. This is due to temporal dependence in the data, and accounting for such dependence has the effect of smoothing out the time series. Another important change from 2016 is the much narrower 95% intervals for Regulatory Area 4B's O32 WPUE estimates. The 2017 expansion more than doubled setline survey coverage in that area, leading to more precise estimates not only in 2017, but in all other years because of improved predictions at unsurveyed locations.

Results from space-time modelling of total NPUE are presented in Figure 3, and a comparison with the 2016 estimates is shown in Figure 4. As with the O32 WPUE results, the 2017 estimates are generally very similar to those obtained in 2016. We have already noted the change in Regulatory Area 4B estimates above, with the data from the expanded setline survey leading to higher mean NPUE model estimates than those obtained in 2016 prior to the expansion. The other noteworthy difference from 2016 is the much greater estimates of uncertainty in the 2017 NPUE estimates in Regulatory Area 3A. This is due to high estimates of variance at unsurveyed locations, particularly within Cook Inlet which contains a large number of potential future expansion stations. This increased uncertainty appears due to the addition of 1993-1997 data affecting the estimates of the degree of spatial dependence, which was estimated to be stronger in the 2016 modelling than the 2017 modelling that included the earlier data. The greater uncertainty in the 2017 estimates in Regulatory Area 3A also leads to wider 95% intervals for the coastwide time series.

The times series of mean Total (all sizes) WPUE and O32 WPUE are compared in Figure 5. Although direct observations of Total WPUE will always exceed those of O32 WPUE, this is not necessarily true of model estimates. In Regulatory Areas 4A and 4CDE there are regions with large gaps in survey coverage, particularly in the early part of the 1993-2017 time series, and therefore the estimates depend to a large degree on the model predictions in unsurveyed regions. In years without IPHC setline survey coverage, data from the annual NMFS trawl survey strongly influence these predictions. Both spatial and temporal dependence were estimated to be stronger for the Total WPUE data than the O32 data, which means that the influence of trawl survey data on predictions at unsurveyed locations for Total WPUE is greater than it is for O32 WPUE data.

Results of setline survey expansions in Regulatory Areas 4B and 2A

Figure 6 shows a map of O32 WPUE at each fished station in Area 4B. The station catch rates varied greatly among the regions covered by expansion stations. Eastern stations had the highest WPUE, with several stations having values close to or above 180 kg/skate (400 lb/skate). Elsewhere, new stations had relatively low catch rates on average, with the majority catching no Pacific halibut. Average WPUE at the new expansion stations was 26.4 kg/skate (58.2 lb/skate), while at annually fished stations, it was 20.5 kg/skate (45.2 lb/skate). These results imply that at current Pacific halibut densities, the annual Area 4B setline survey was undersampling high-density habitat relative to low-density habitat. Prior to the use of the space-time model, this would have led to a negative bias in estimates of mean WPUE in Area 4B. Instead, the time series of estimated mean O32 WPUE from the 2017 modelling was very similar to the one estimated in 2016 prior to the expansion (Figure 7). This implies that, at least on average, the model predictions of WPUE in previously unsurveyed parts of Area 4B had little bias. This was not the case for total NPUE, which was underestimated in last year's modelling (Figure 8), and therefore the setline survey expansion has led to a correction in the bias of previous estimates of NPUE in Regulatory Area 4B.

The O32 WPUE at each station in Area 2A in 2017 is shown in Figures 9-11. The California expansion south of 39°N captured a single Pacific halibut on a station outside of San Francisco Bay (Figure 9). This confirms that while Pacific halibut are present in this region, densities are very low.

Central Oregon stations had the highest O32 WPUE in Area 2A during 2017 (Figure 10), but catch rates north of there, particularly off Washington (Figure 11), appear to have been greatly affected by an extensive area of low dissolved oxygen centred off the Washington coast (Figure 12). WPUE was zero at almost all stations within the area that had dissolved oxygen less than 0.9 ml/l, and lower than in recent years on average elsewhere off the Washington coast. The area of low dissolved oxygen encompassed the region covered by the dense grid expansion, and so likely affected catches on the new expansion stations, along with neighbouring stations on the annual grid. In 2016, mean O32 WPUE at stations off the north Washington coast was 15.0 kg/skate (33.0 lb/skate). The same annually fished stations in 2017 had mean WPUE of 4.5 kg/skate (9.9 lb/skate), and the new dense grid expansion stations had mean of 7.4 kg/skate (16.3 lb/skate). We made no adjustment for the effect of the hypoxic zone on catches in the modelling, which assumes that Pacific halibut were able to avoid areas of extremely low oxygen and therefore became available to the setline survey elsewhere.

The effect the inclusion of data from the dense grid expansion stations on average O32 WPUE was small (Figure 13). Estimated mean WPUE for Regulatory 2A in 2017 was 2.8% higher with the dense grid data included in the modelling than it was without, a difference that is well within the uncertainly in the estimates shown by the 95% intervals in Figure 13. Note that the model output used for stock assessment and stock distribution estimation comes from fitting models that include the dense grid data, along with all other setline survey expansion data.

Evaluation of the need for future setline survey expansions

Methods: Regulatory Area 2A

This Regulatory Area is unique in having already had a full expansion of the setline survey grid down to 42°N in two years, 2011 and 2014 (prior to this year’s setline survey). A comparison of model output including and excluding the 2014 expansion data allows us to assess what is gained by having the expansion repeated after a three-year interval. The 2014 expansion also included additional stations between the latitudes of 39°N and 42°N (northern California), which are considered separately as described below.

For our comparisons, the setline survey expansion stations were split into three geographic regions: coastal deep expansion (DE) and shallow expansion (SE) stations in Oregon and Washington (fished in 2011 and 2014); Salish Sea stations (2011 and 2014); and northern California stations (2014). In this way, we are able to examine the relative contribution of each component of the full expansion to improving estimates of density. Note that a subset of the full 2014 California expansion stations was fished in 2013. As this excluded deep and shallow FISS stations, and stations between 39° and 40°, this is perhaps best considered as a pilot expansion into California and is not an expansion design that is likely to be repeated.

We fitted models to the full data set, along with seven subsets in the following order:

- Annually fished stations only (96 since 2011)
- Annually fished stations, plus 2011 DE/SE stations in OR and WA coastal waters

- Annually fished stations, plus 2011 and 2014 DE/SE stations in OR and WA coastal waters
- Annually fished stations, plus 2011 and 2014 DE/SE stations in OR and WA coastal waters, and 2011 Salish Sea stations
- Annually fished stations, plus 2011 and 2014 DE/SE stations in OR and WA coastal waters, and 2011 and 2014 Salish Sea stations
- Annually fished stations, plus 2011 and 2014 DE/SE stations in OR and WA coastal waters, 2011 and 2014 Salish Sea stations, and 2014 California stations
- All available data (also includes 2013 California expansion stations)

All model runs included data from 1998 to 2016, using the methods discussed in Webster (2017).

Methods: Regulatory Area 4A

The FISS expansion in 2014 in Regulatory Area 4A included additional stations along the Area 4A shelf edge, and the Aleutian Islands. The bulk of the shelf edge setline survey expansion stations are in relatively flat habitat that is likely more homogenous than the areas of incomplete annual setline survey coverage in the Aleutian component of Regulatory Area 4A. It is also surrounded by annually fished setline survey stations and NMFS trawl stations, with some of the latter actually located within the region that does not have annual setline survey coverage. Thus, we may expect that omitting shelf edge expansion stations to have a less significant effect on WPUE estimates than omitting stations along the Aleutian Islands. For this reason, we considered these regions separately in evaluating the effect of the 2014 setline survey expansion of estimates of WPUE. Thus, we fitted models to the following subsets of data and compared the output to that from the model with all setline survey stations:

- Annually fished stations
- Annually fished stations + 2014 shelf edge expansion stations
- Annually fished stations + 2014 Aleutian Islands expansion stations
- All available data

As with Regulatory Area 2A above, model runs included data from 1998 to 2016, using the methods described in Webster (2017).

Results: Regulatory Area 2A

Figure 14 shows the absolute relative difference in estimated mean WPUE (hence called the “relative error”) for Regulatory Area 2A between models using subset of the data and a model fit with all available data.

The model fitted to the smallest subset of data, the 96 annually fished stations off the WA and OR coasts, has very high relative error, being greater than 40% in all years. Areas like the Salish Sea, and particularly California, are distant from the annually fished stations, and estimated WPUE in these regions approaches the Regulatory Area 2A mean, which is likely unrealistically high in most years in these regions. Also, the lack of data from deep and shallow waters means that WPUE estimates at these depths is informed by spatial proximity to setline survey stations in 37-503 m (20-275 fm) waters through the spatial dependence model, leading again to over-estimates of WPUE (since the data generally show below-average WPUE outside of 37-503 m, 20-275 fm).

Adding the 2011 deep and shallow setline survey stations to the annually fished stations provided a substantial improvement, with relative error reducing to below 30% in most years. There is only a small further improvement in relative error from inclusion of the 2014 deep and shallow data. A similar improvement is observed when the 2011 Salish Sea data are included, with inclusion of the 2014 data having a minimal further effect on relative error. The remaining improvement comes from including the 2014 California data, which brings the relative error close to zero (showing that the 2013 California data have little effect on relative error).

Also of interest is the effect of the setline survey expansions on the precision of the mean WPUE estimate for Area 2A. Figure 15 shows the estimated sample coefficients of variation for the subset models listed above, along with the model that uses all available data. Inclusion of the data from deep and shallow stations has, at best, modest effects on relative precision. A greater improvement is found when Salish Sea stations are added, but the greatest decrease comes with the addition of the California stations in 2014. Without the direct observations in California, estimates of WPUE in this region were very imprecise, and this imprecision contributed significantly to the variability in the overall estimates for Regulatory Area 2A. We note that even with the full data set, CVs have been increasing since 2014, as time since the most recent FISS expansion increases. Nevertheless, CVs remain at low levels, and it is not clear from the data in this figure what setline survey expansion frequency would be required to maintain precise estimates of mean WPUE. CVs came down after 2010, but this was only in part due to the expansions, as the distribution of Pacific halibut also became less patchy during this time.

These results show that the 2011 setline survey expansion was on its own sufficient in reducing relative error due to lack of coverage in deep and shallow waters and the Salish Sea up to and including 2016, while the 2014 California expansion was also important for minimising relative error. Thus, the reduction in relative error from an expansion is maintained for several years after the expansion. Based on these results, the expansions in Regulatory Area 2A may not need to be repeated more frequently than every six years. With increasing time, and in the absence of new model covariates (say, for region or latitude), we would still expect estimates in unsurveyed regions to approach the Regulatory Area 2A mean, but it is clear from these results that this is something that occurs relatively slowly.

Results: Regulatory Area 4A

The relative error in models fitted to subsets of the Regulatory Area 4A data is shown in Figure 16. Compared to a model fitted to the annually fished setline survey stations only, addition of expansion stations along the Regulatory Area 4A shelf edge in 2014 leads to small to modest reductions in relative error. A much larger gain comes from the setline survey expansion along the Aleutian Islands, which reduces relative error to below 10% in all years. There is some further benefit from including both components of the 2014 expansion (difference between green line and zero), but the Aleutian setline survey expansion was clearly the more important. Note also that the benefit from including setline survey expansion stations diminishes going back in time, due to the decreasing influence of the 2014 setline survey expansion data on estimates in coverages gaps as time from 2014 increases.

As with relative error, the expansion into the Aleutian Islands had a much greater impact on the CV of mean WPUE than the shelf edge setline survey expansion (Figure 17). Since 2014, the CV has increased quickly, although based on years prior to 2014, we may expect the CV to again stabilise at around 12-13% in the absence of repeats of the setline survey expansion stations in Regulatory Area 4.

In conclusion, due to the presence of NMFS trawl stations near to and within the region of the Regulatory Area 4A shelf edge without annual coverage, this region need only be surveyed infrequently by the setline survey. Regarding the Aleutian Islands, the largest coverage gap is in the western part of this region, where many stations have high WPUE, and includes stations in deep water and standard depths somewhat distant from annually fished stations. An argument could be made for fishing these stations frequently, while (to maintain costs if necessary) reducing coverage in the low-density part of Regulatory Area 4A south-east of the Aleutian Islands.

Implications for stock distribution estimates and the stock assessment

Currently, a Regulatory Area's portion of the coastwide stock distribution is estimated as its biomass index divided by the coastwide biomass index, where an area's biomass index is its mean estimated O32 WPUE (at all stations in the IPHC's setline survey design) multiplied by bottom area. As the examples in Regulatory Areas 2A and 4A show, the first time a setline survey expansion occurs in an area leads to improvements in the relative accuracy of the indices, and more accurate estimates of biomass shares result. The results presented in this report show those gains in accuracy persist with time, with the 2014 setline survey in Regulatory Area 2A having a small effect on the WPUE index relative to the 2011 setline survey. Based on those results, we can expect improvements in stock distribution estimates to also persist for several years after the initial setline survey expansion. With the setline survey expansion being fished only once in Regulatory Area 4A, it is less clear how soon this area, in particular its western portion, should be revisited. The setline survey expansion there had a clear effect on the estimates of biomass distribution, but as time passes since 2014, we can expect model estimates to become driven by a combination of area-wide changes in density, and observed WPUE at the small number of stations that are fished annually there. This increases the chance of bias in the overall estimates of WPUE and biomass distribution for Regulatory Area 4A. It would be prudent, therefore, to re-survey western Regulatory Area 4A in the near future to get a direct measure of its temporal variability and the effect the lack of full annual setline survey coverage in has on the quality of estimates for Regulatory Area 4A as a whole.

Regarding the effect of expansions on the stock assessment, their primary contribution is in improving the coastwise index of total NPUE, a key input into the assessment modelling. This index, like coastwide WPUE, is constructed as a weighted average of Regulatory Area NPUE indices, where bottom areas are used as weights. Thus, data from the largest areas, specifically Regulatory Areas 2B, 3A, 3B and 4CDE, along with Regulatory Area 2C (currently the area with highest density) have the most influence on the coastwide NPUE index. The setline survey expansions in Regulatory Areas 2A and 4A may have led to an index that is slightly higher or lower than it would have been in the absence of data from the expansions, but the effect on trend in the index can only be minor. Nevertheless, the expansion stations over all Regulatory Areas combined represent around 35% of all setline survey stations (Webster et al. 2015), and if the trend for expansion stations differs on average from the trend in annually surveyed stations, there will be bias in the estimates of coastwide NPUE trends in the absence of regular surveys of those stations. The potential scale of this bias can only be assessed once the full series of setline survey expansions have been completed in 2019.

Recommendations for FISS expansion frequency

Table 1 provides a summary of the information we have gained from setline survey expansions to date in Regulatory Areas 2A and 4A. Based on the assessment of the data presented in this paper, we have given a recommendation of the future setline survey frequency in expansion regions. This recommendation is based on a region's influence on the overall density indices for its Regulatory Area, which is affected by its density, variability and size (number of stations). Northern California (north of 40°N), represents the southern limit of Pacific halibut at densities significantly above zero, and as such a case can be made for relatively frequent setline surveys here in order to monitor whether the Pacific halibut range is increasing or retracting. Data here also influence estimates in the low density regions further south, which after 2017 will only have been surveyed once or twice, something that is not the case with regions adjacent to the Salish Sea. No recommendation is currently made for the setline survey frequency from 39-40°N. This low-density region will be included in a future evaluation of all low density habitat south of 40°N, along with the setline stations surveyed within 37.75-39°N for the first time in 2017.

Table 1 also includes a qualitative measure of the relative cost of each expansion region. While the recommended frequency is based on a scientific evaluation, managers will also consider the cost of adding setline survey stations when determining if their addition is feasible in a given setline survey year. The Regulatory Area 2A expansion stations in deep and shallow coastal waters of Washington and Oregon and in the Salish Sea are relatively low cost, as they can be fished along with nearby annual stations thereby reducing fuel costs, and do not require an additional sampler. Those in California have somewhat more complicated logistics and permitting requirements, and so can be considered as medium cost relatively to annually fished parts of Regulatory Area 2A. In Regulatory Area 4A, the Aleutian Islands expansion stations are high cost due to logistics, travel, bait shipping and fishing difficulty (strong tides). The Shelf edge stations are less expensive and the tidal problems encountered when fishing the islands are not a factor there, and so we categorise these stations as medium cost.

Table 1. Summary of IPHC fishery-independent setline survey expansion data and recommendations for future survey frequency.

Reg. Area	**Expansion region**	**Density†**	**Variability (spatial/ temporal)**	**Recommend setline survey frequency**	**Cost‡**
2A	Deep and shallow waters	Low	Low	≥ 10 years	Low
2A	Salish Sea	Low-average	High	5 years	Low
2A	Northern California	Average above 40°N; low south of 40°N	Average	3-5 years north of 40°N	Medium
4A	Aleutian Islands	High	High	3-5 years	High
4A	Shelf edge	Average	Low	≥ 10 years	Medium

† Density relative to annually surveyed parts of the regulatory area

‡ Cost relative to annually surveyed parts of the Regulatory Area

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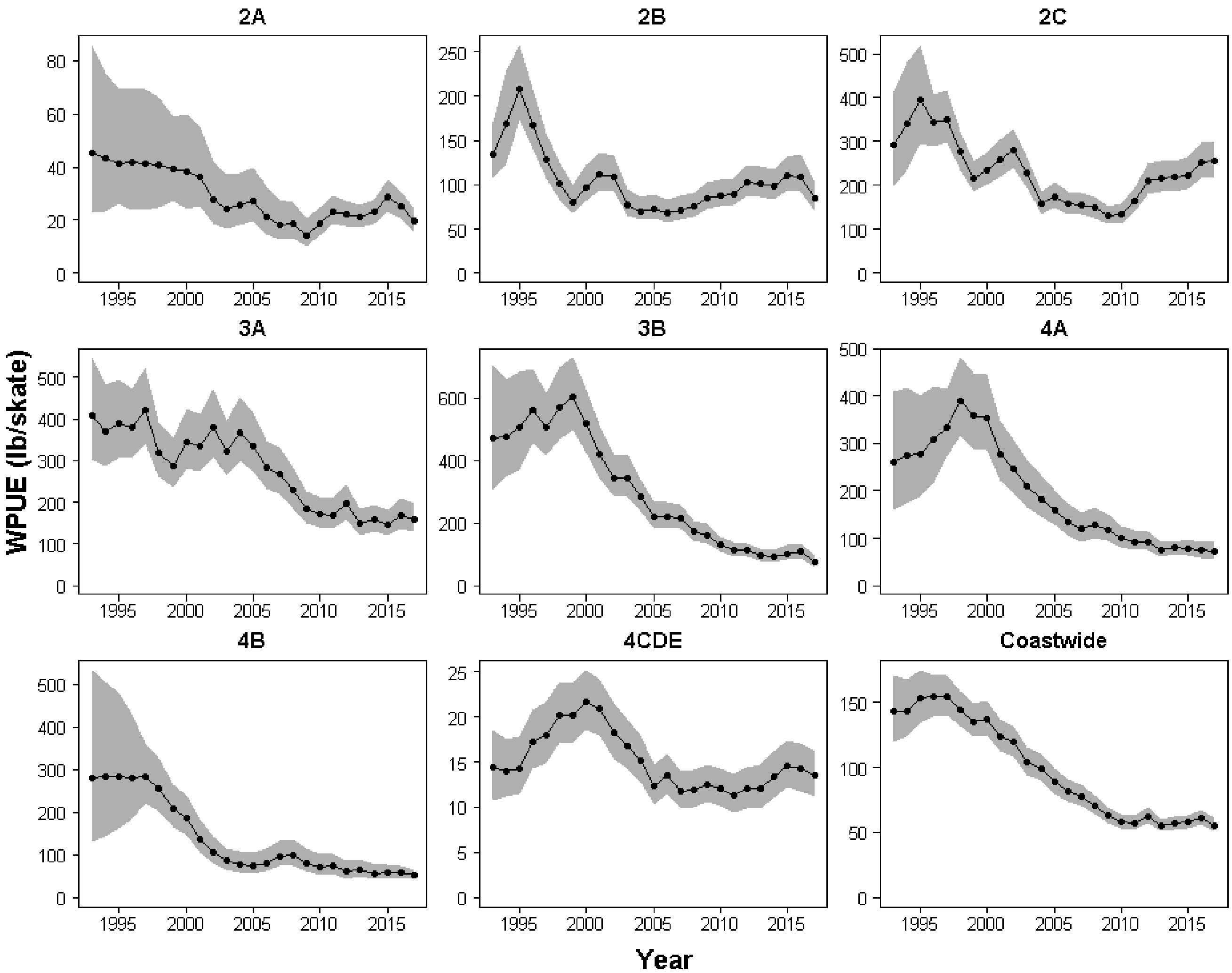

Figure 1. Posterior means (points) and 95% posterior credible intervals (shaded regions) for mean O32 WPUE from the space-time modelling, by Regulatory Area and year from 1993-2017.

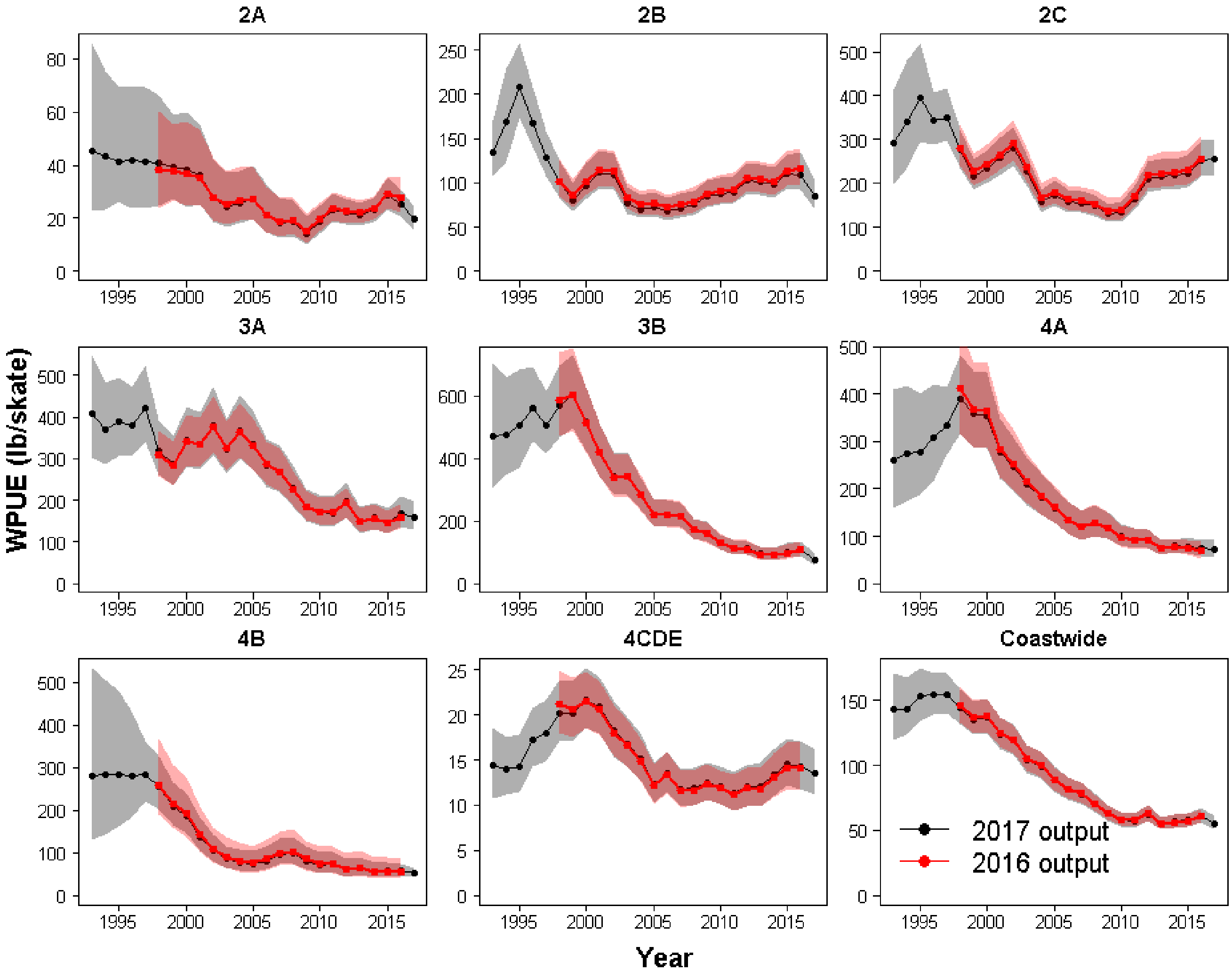

Figure 2. Posterior means (black points) and 95% posterior credible intervals (gray shaded regions) for mean O32 WPUE from the space-time modelling in 2017, compared with modelling output from the 2016 space-time modelling (red points and shaded regions).

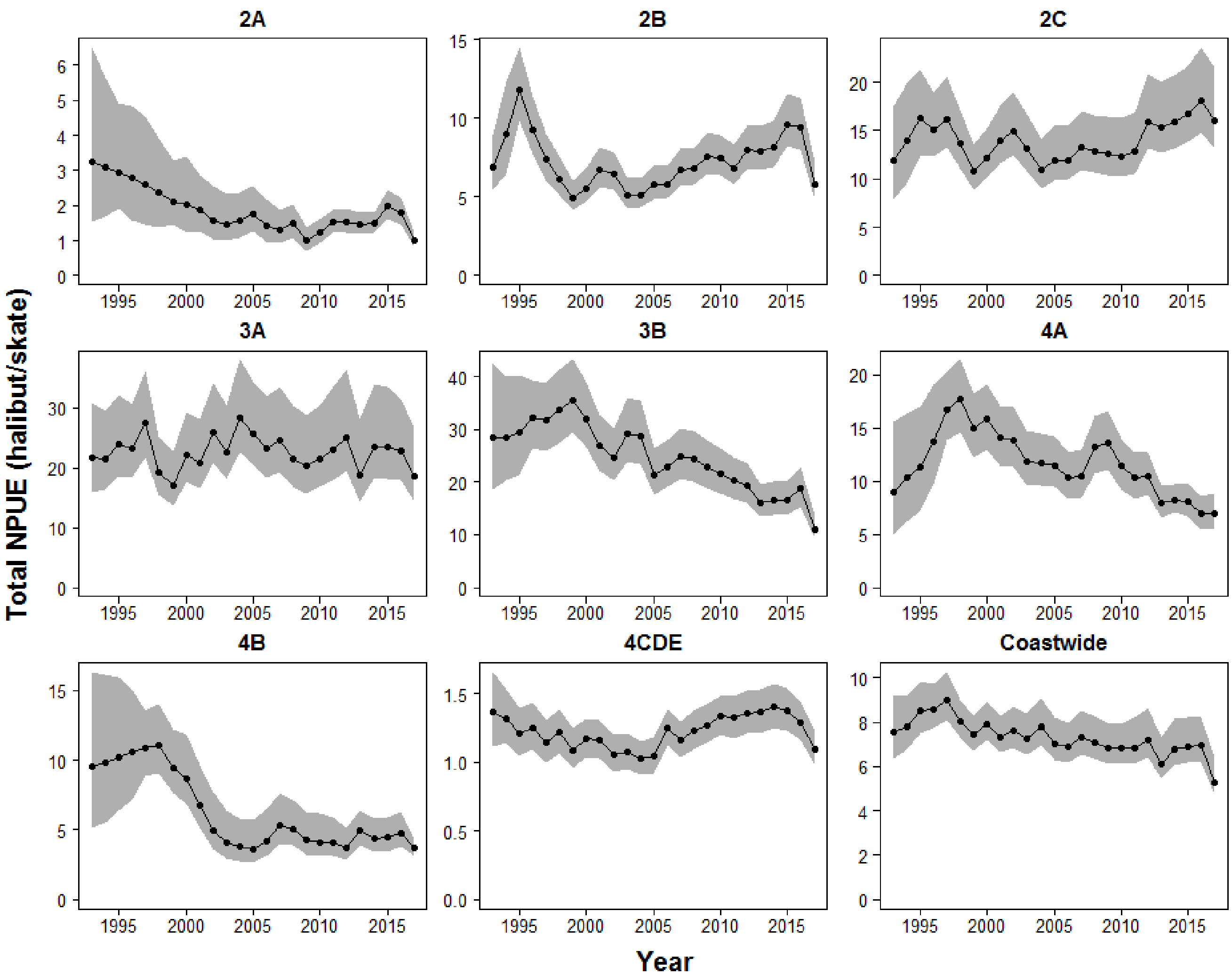

Figure 3. Posterior means (points) and 95% posterior credible intervals (shaded regions) for mean total NPUE from the space-time modelling, by Regulatory Area and year from 1993-2017.

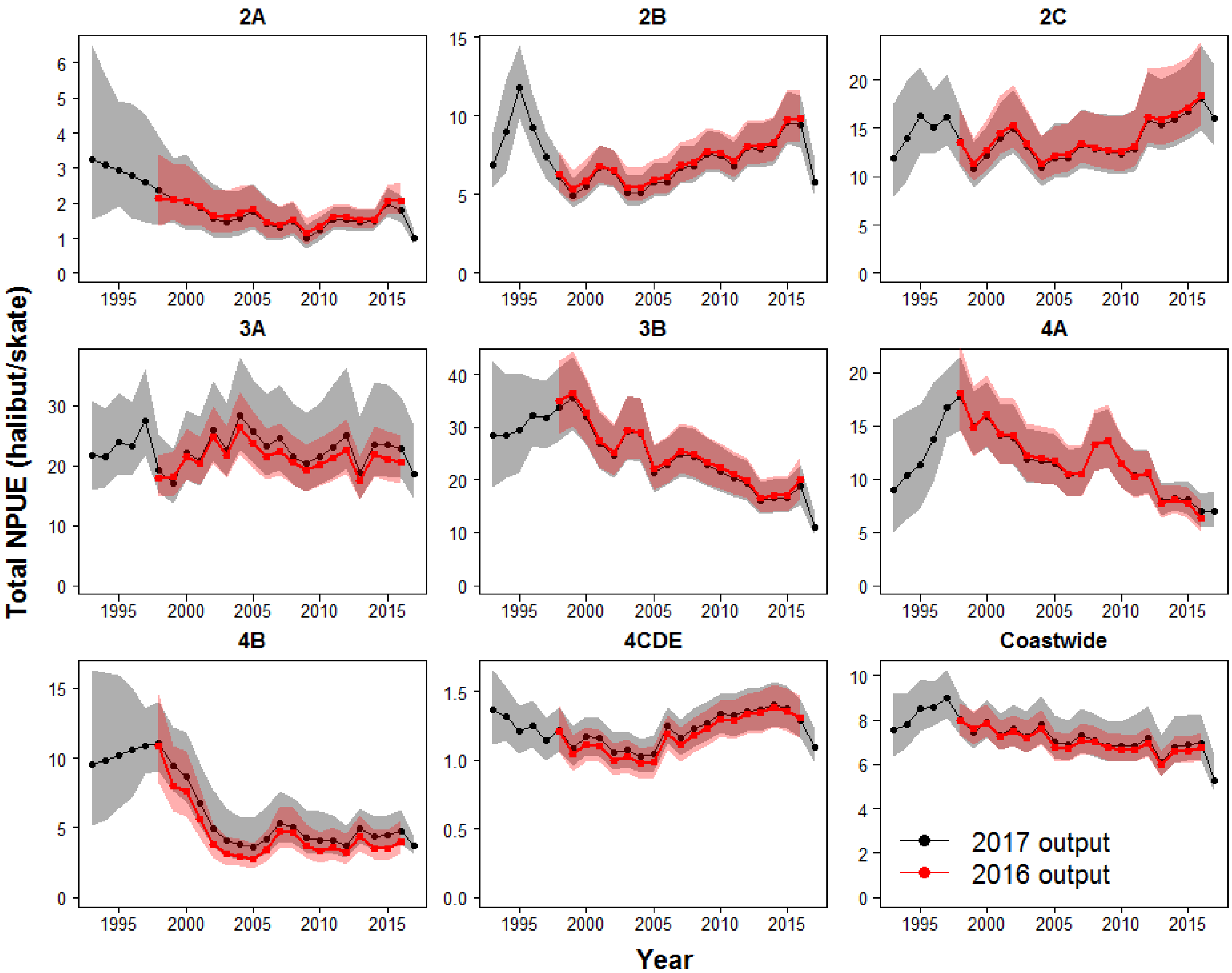

Figure 4. Posterior means (black points) and 95% posterior credible intervals (gray shaded regions) for mean total NPUE from the space-time modelling in 2017, compared with modelling output from the 2016 space-time modelling (red points and shaded regions).

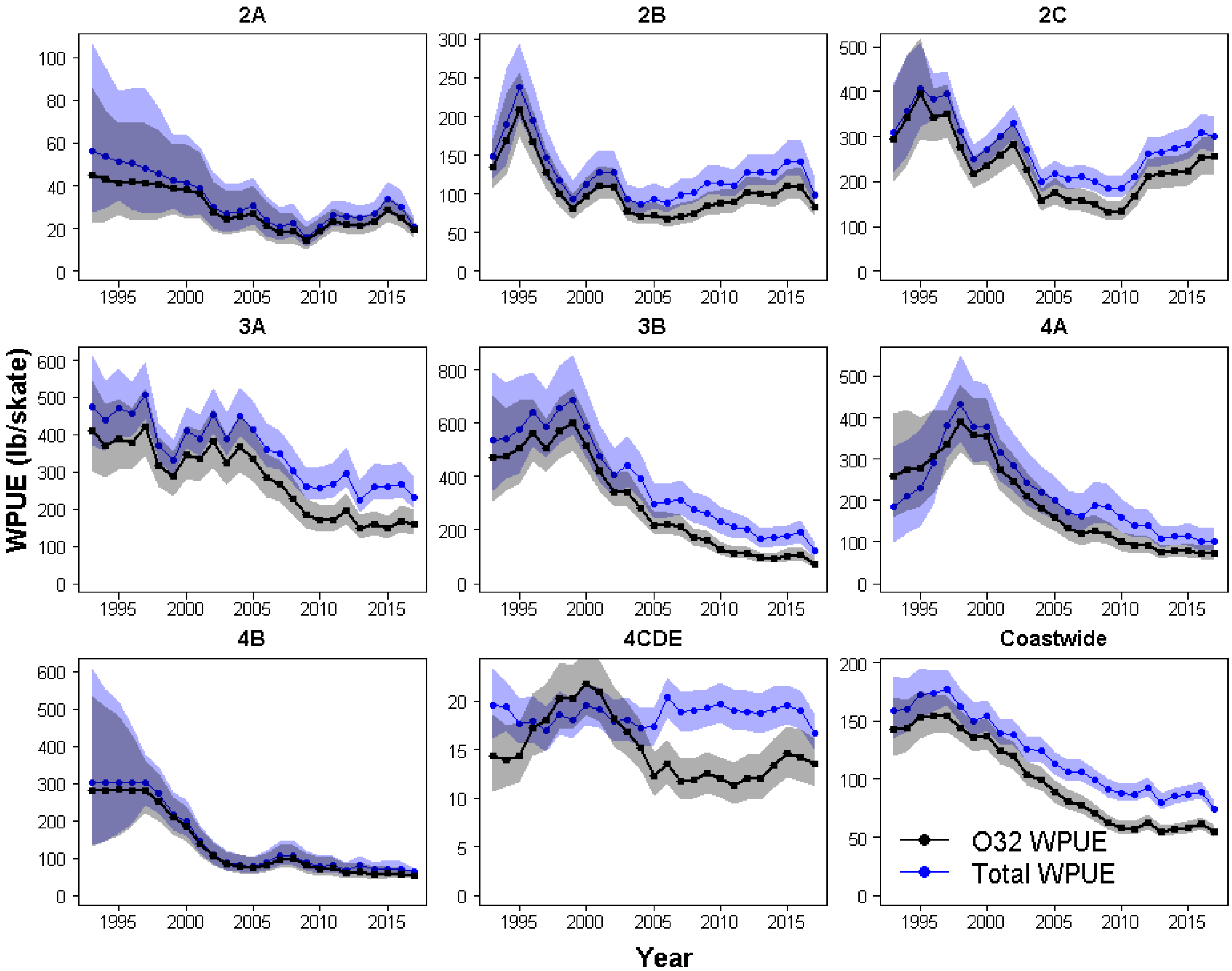

Figure 5. Posterior means (blue points) and 95% posterior credible intervals (blue shaded regions) for mean total WPUE compared with O32 WPUE (black points and gray shaded regions) from the space-time modelling in 2017.

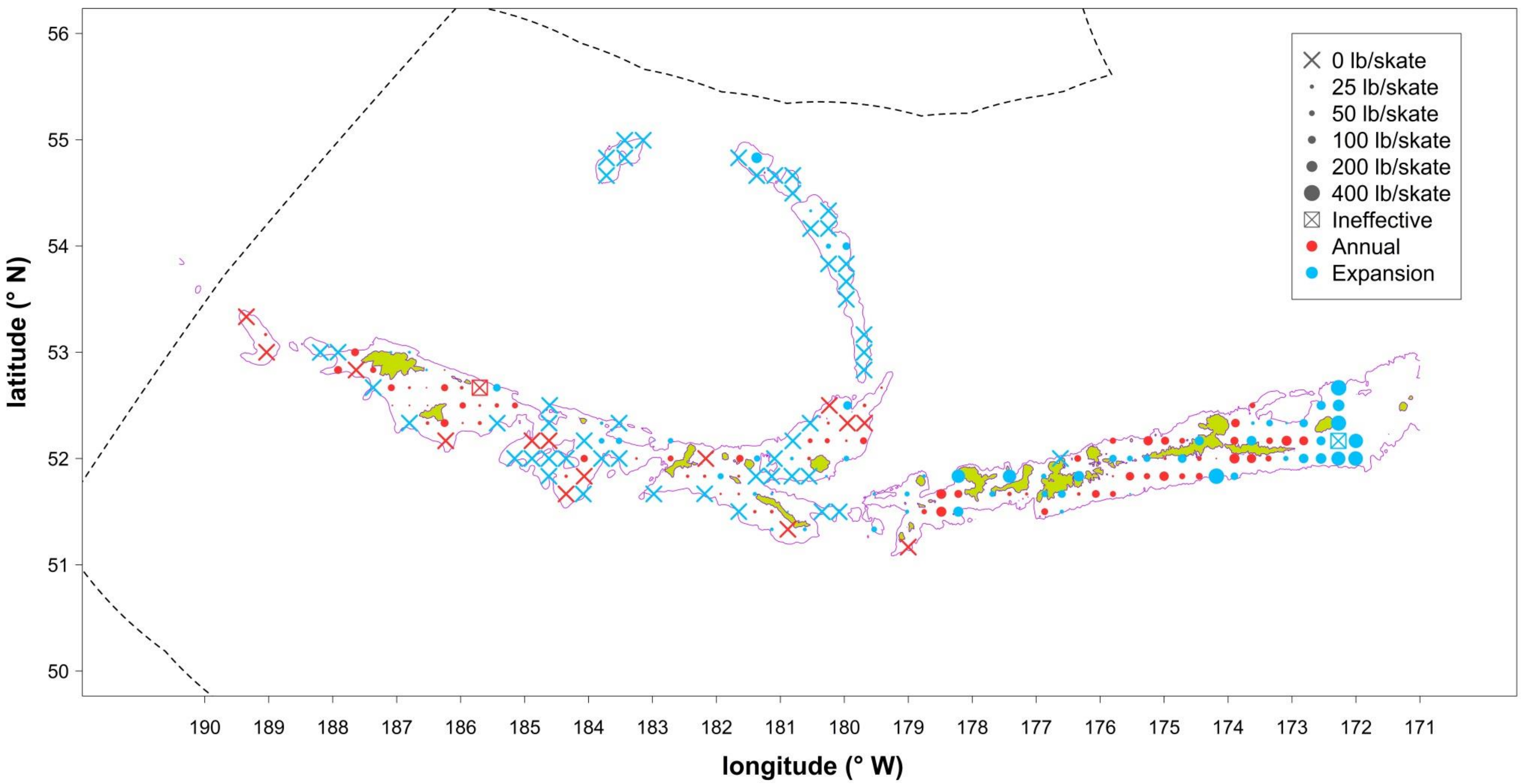

Figure 6. Map of O32 Pacific halibut WPUE by station in Regulatory Area 4B in 2017.

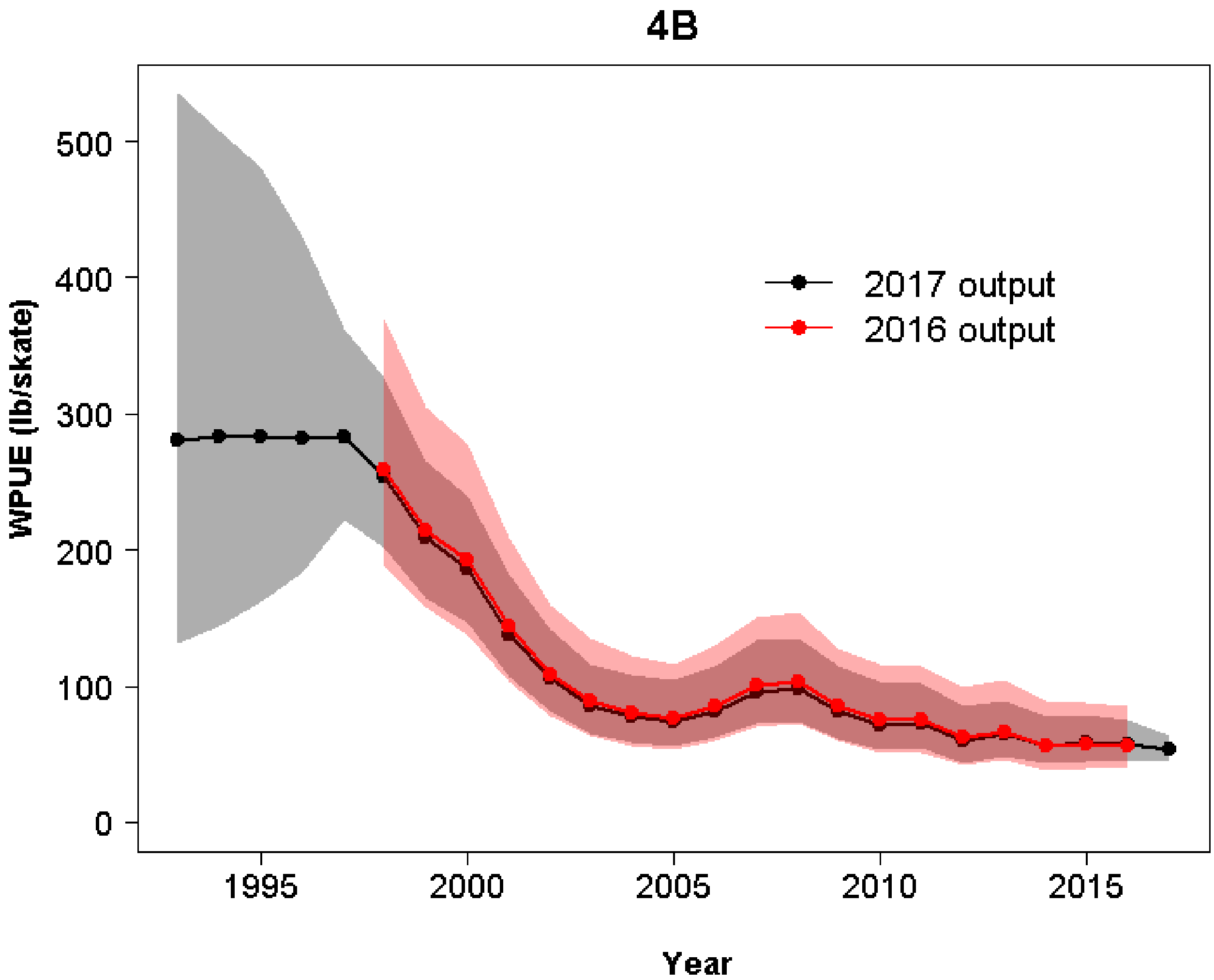

Figure 7. Comparison of the time series of estimated mean O32 Pacific halibut WPUE in Regulatory Area 4B from the 2017 modelling with the output from the 2016 modelling.

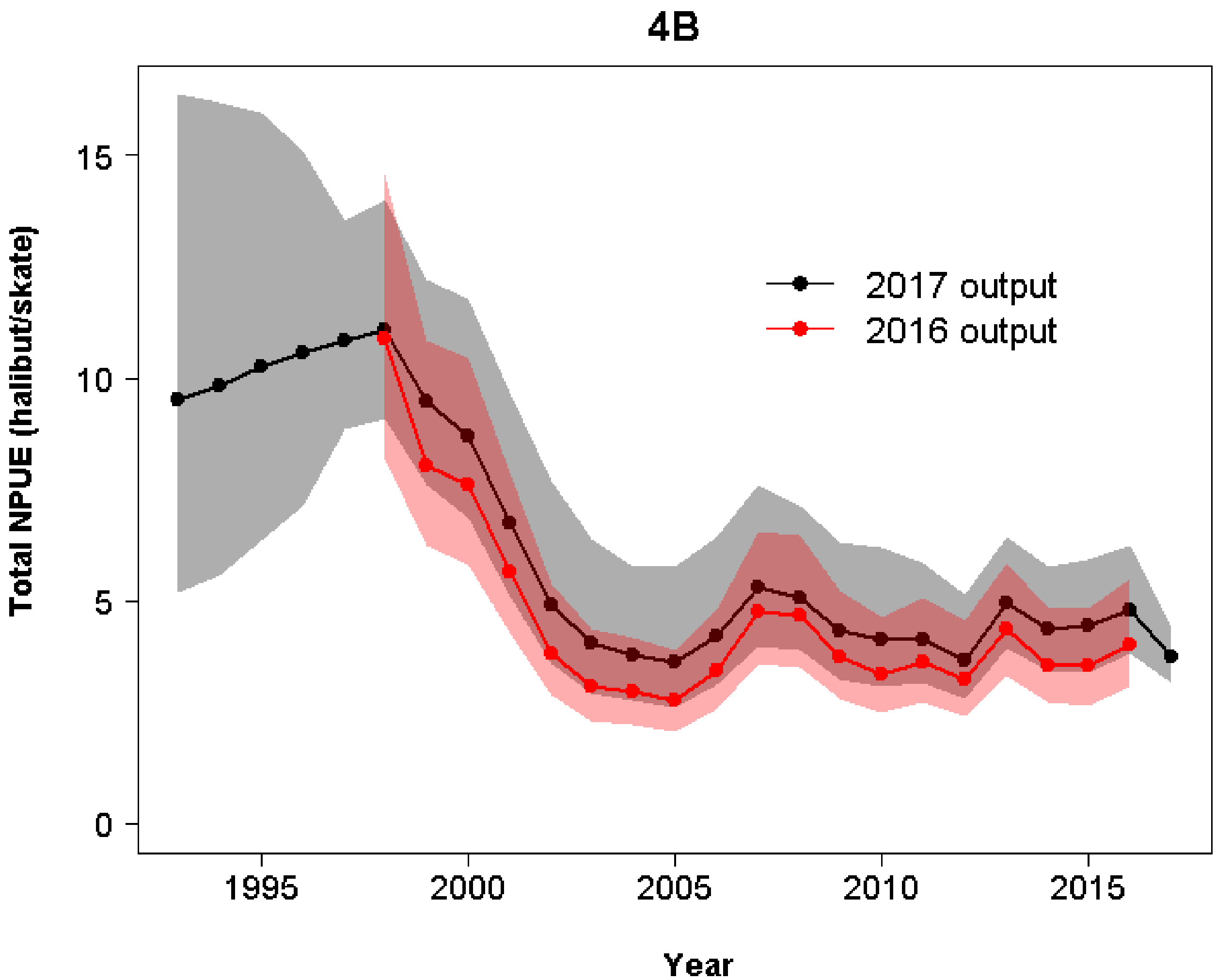

Figure 8. Comparison of the time series of estimated mean total Pacific halibut NPUE in Regulatory Area 4B from the 2017 modelling with the output from the 2016 modelling.

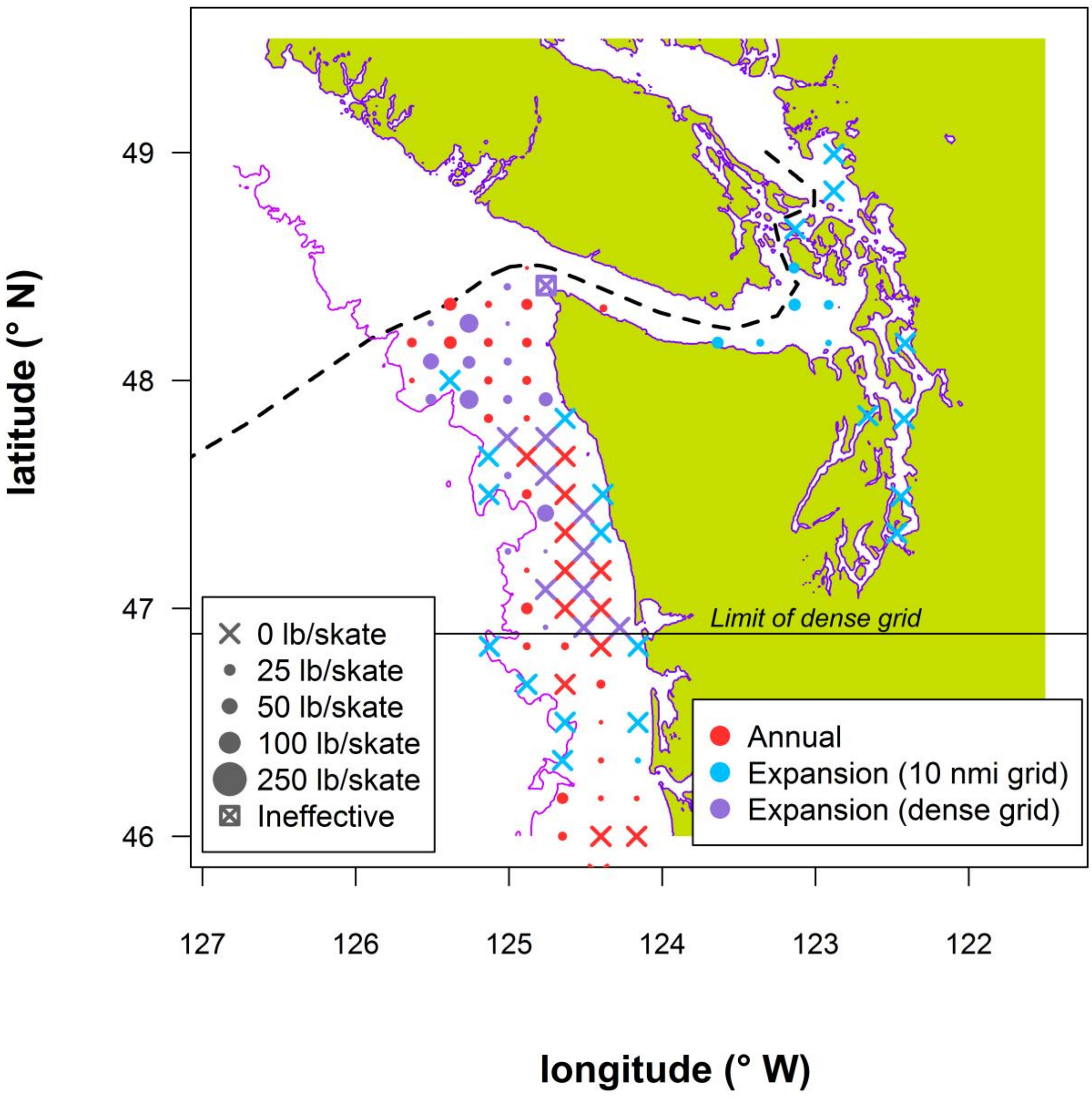

Figure 9. Map of O32 Pacific halibut WPUE by station in northern Regulatory Area 2A in 2017.

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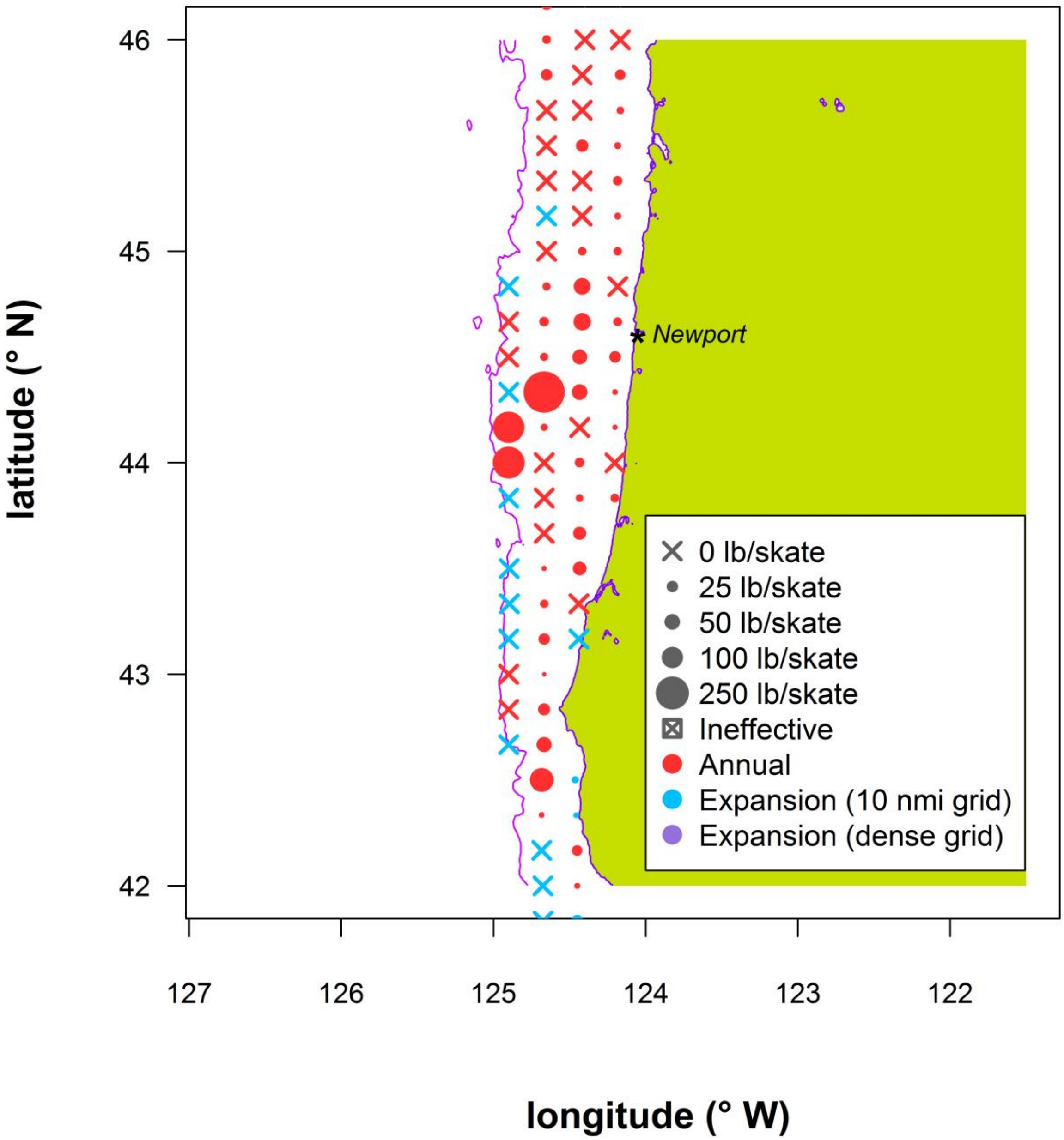

Figure 10. Map of O32 Pacific halibut WPUE by station in central Regulatory Area 2A in 2017.

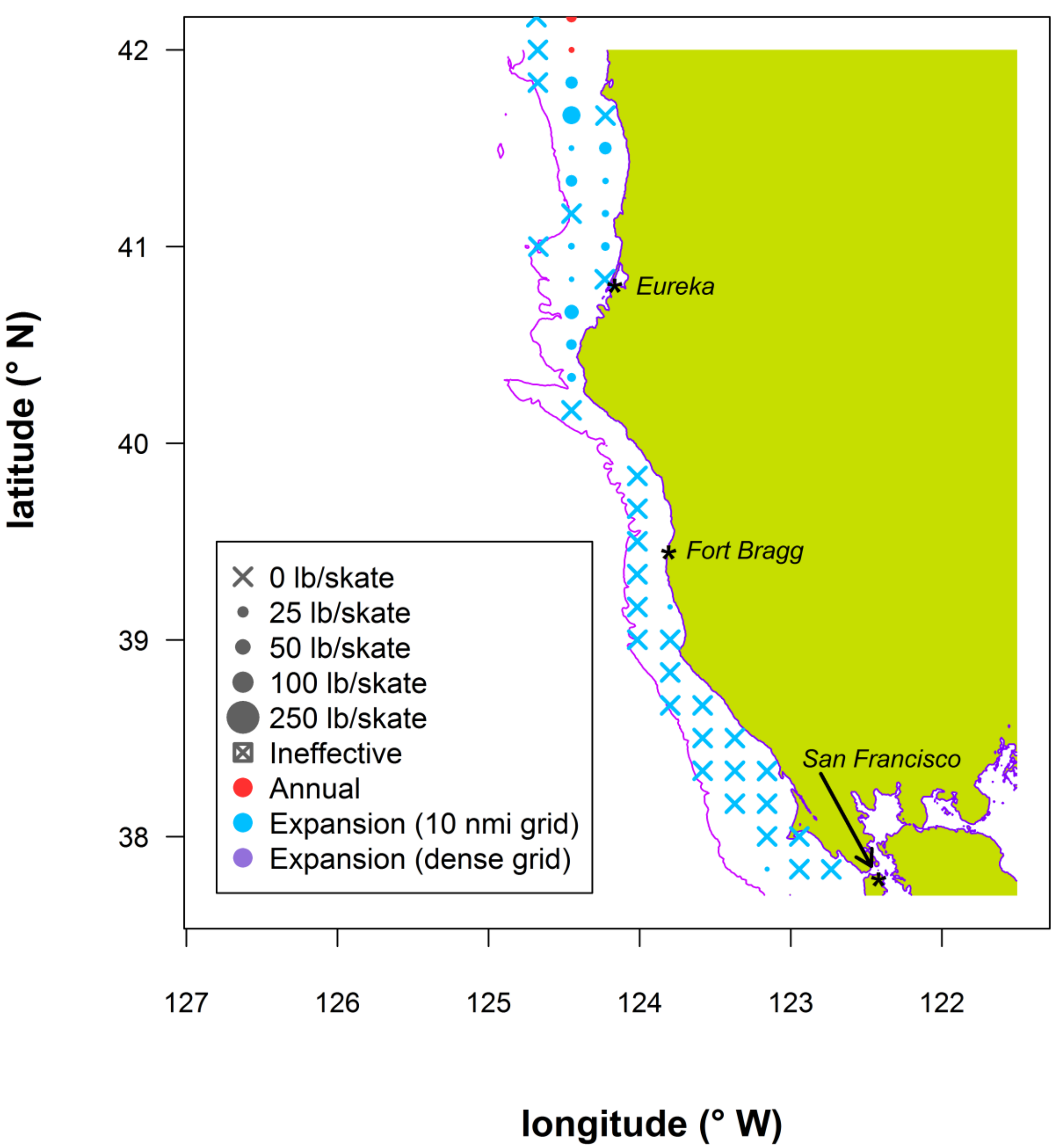

Figure 11. Map of O32 Pacific halibut WPUE by station in southern Regulatory Area 2A (California) in 2017.

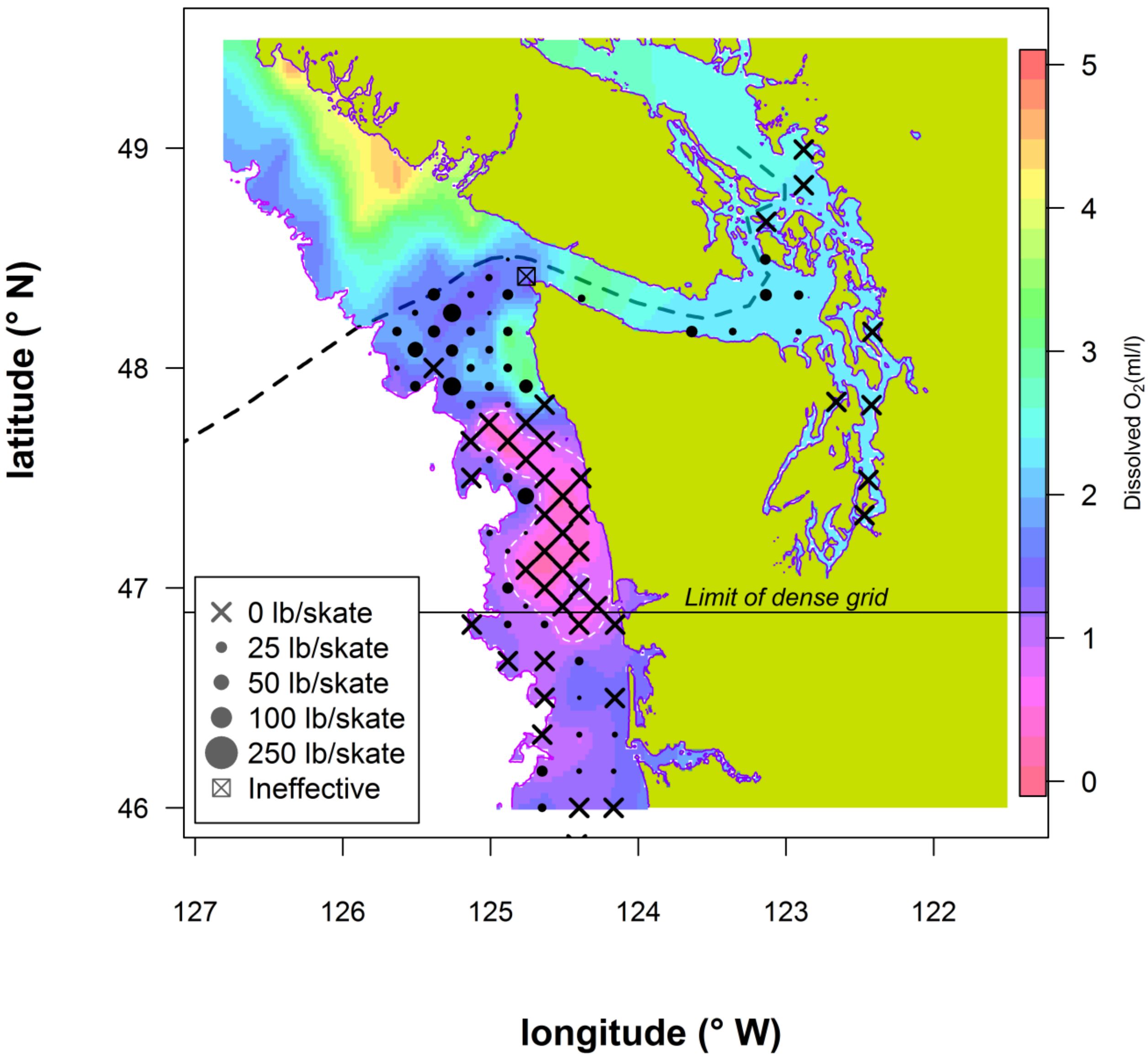

Figure 12. Estimated dissolved oxygen in northern Regulatory Area 2A in 2017. Values are model predictions from a spatial model fitted to the 2017 IPHC water column profiler data. O32 WPUE values from the setline survey are overlaid with black symbols.

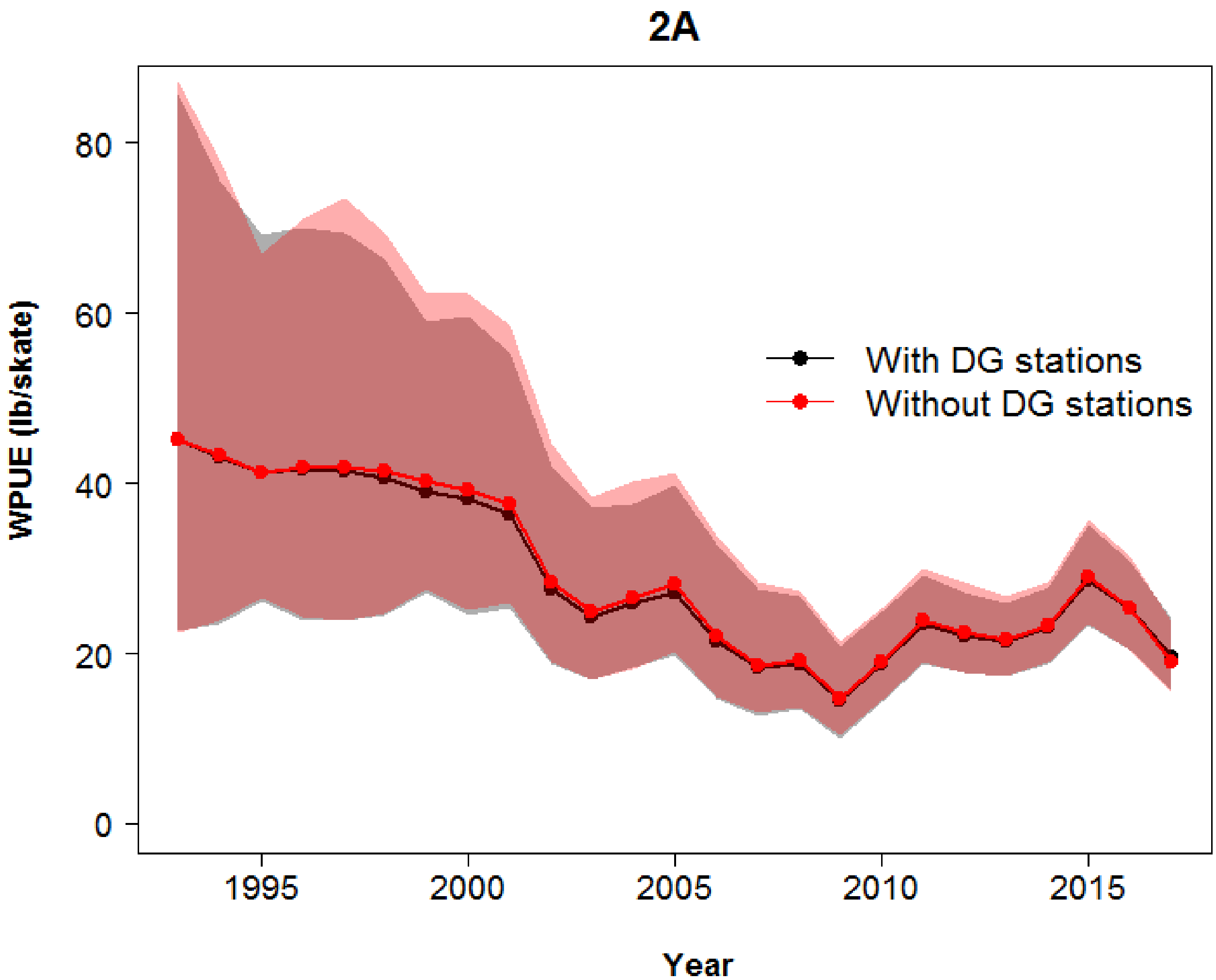

Figure 13. Posterior means (points) and 95% posterior credible intervals (shaded regions) for mean O32 WPUE from the space-time modelling for Regulatory Area 2A from models fitted with data from the dense grid stations (black) and without those data (red).

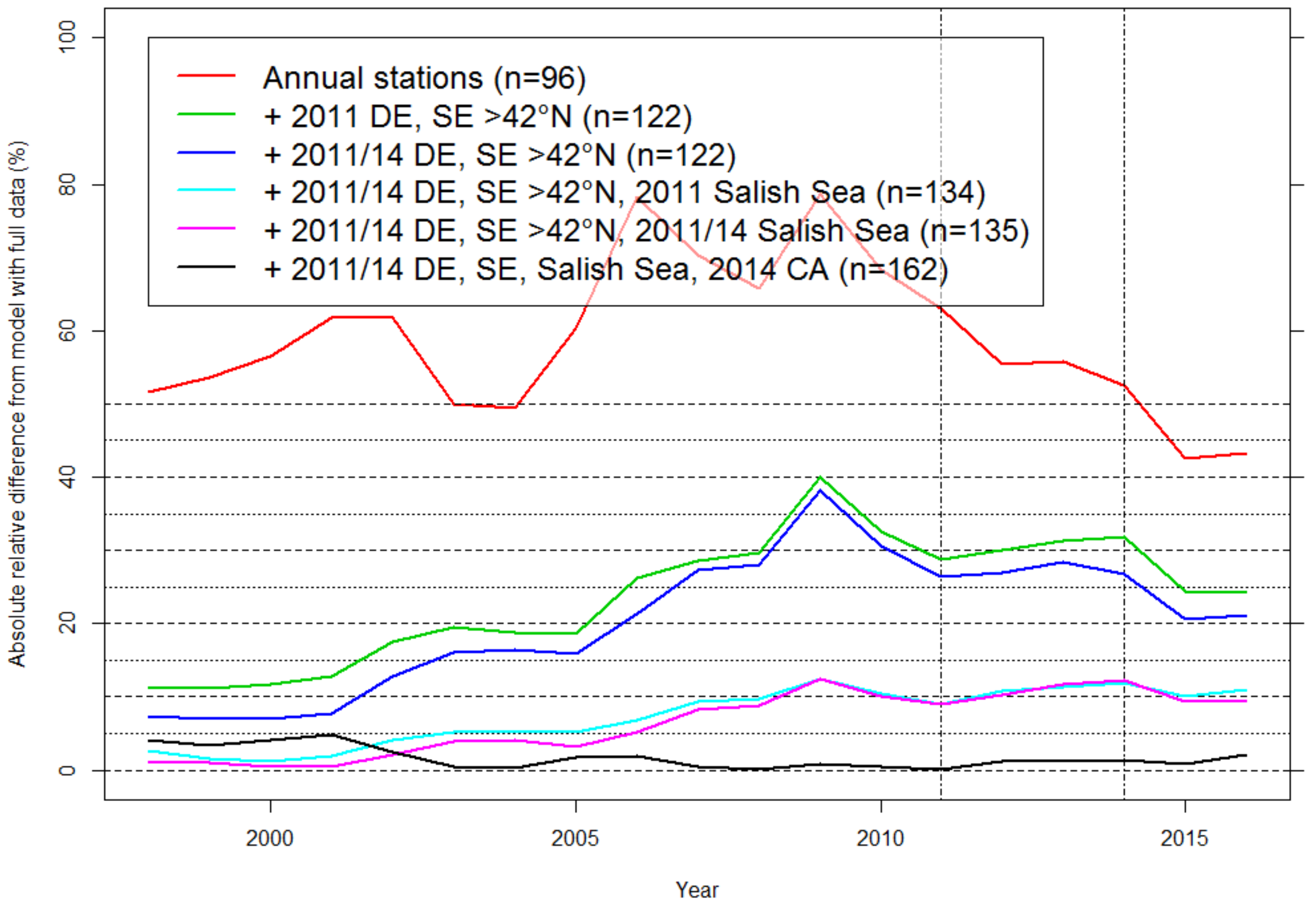

Figure 14. Absolute relative difference in estimated mean WPUE between models fitted to subsets of the Regulatory Area 2A data, and the model using all available data. The vertical lines show the 2011 and 2014 setline survey expansion years in Regulatory Area 2A.

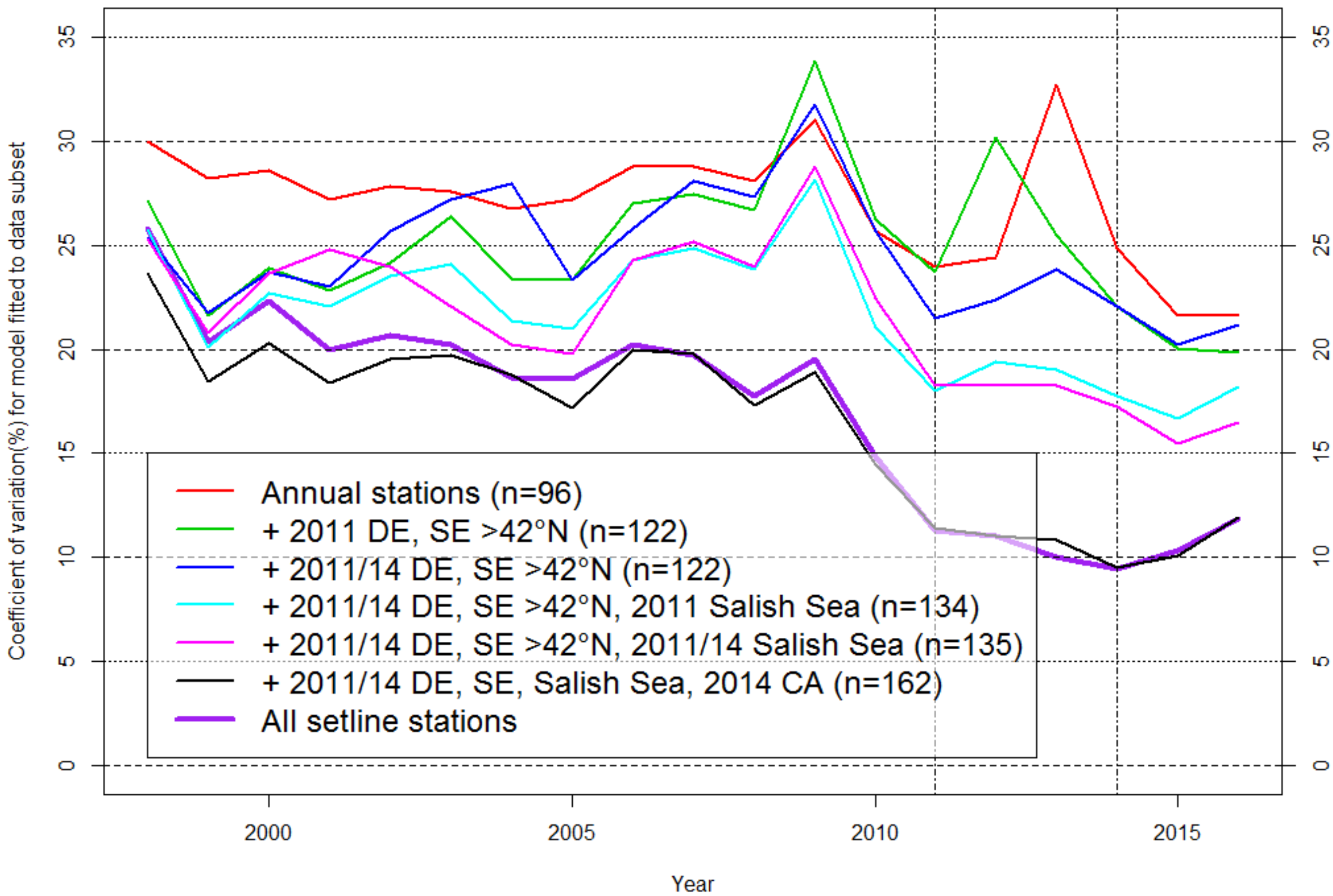

Figure 15. Coefficient of variation of estimated mean WPUE for models fitted to subsets of the Regulatory Area 2A data and the model using all available data. The vertical lines show the 2011 and 2014 setline survey expansion years in Regulatory Area 2A.

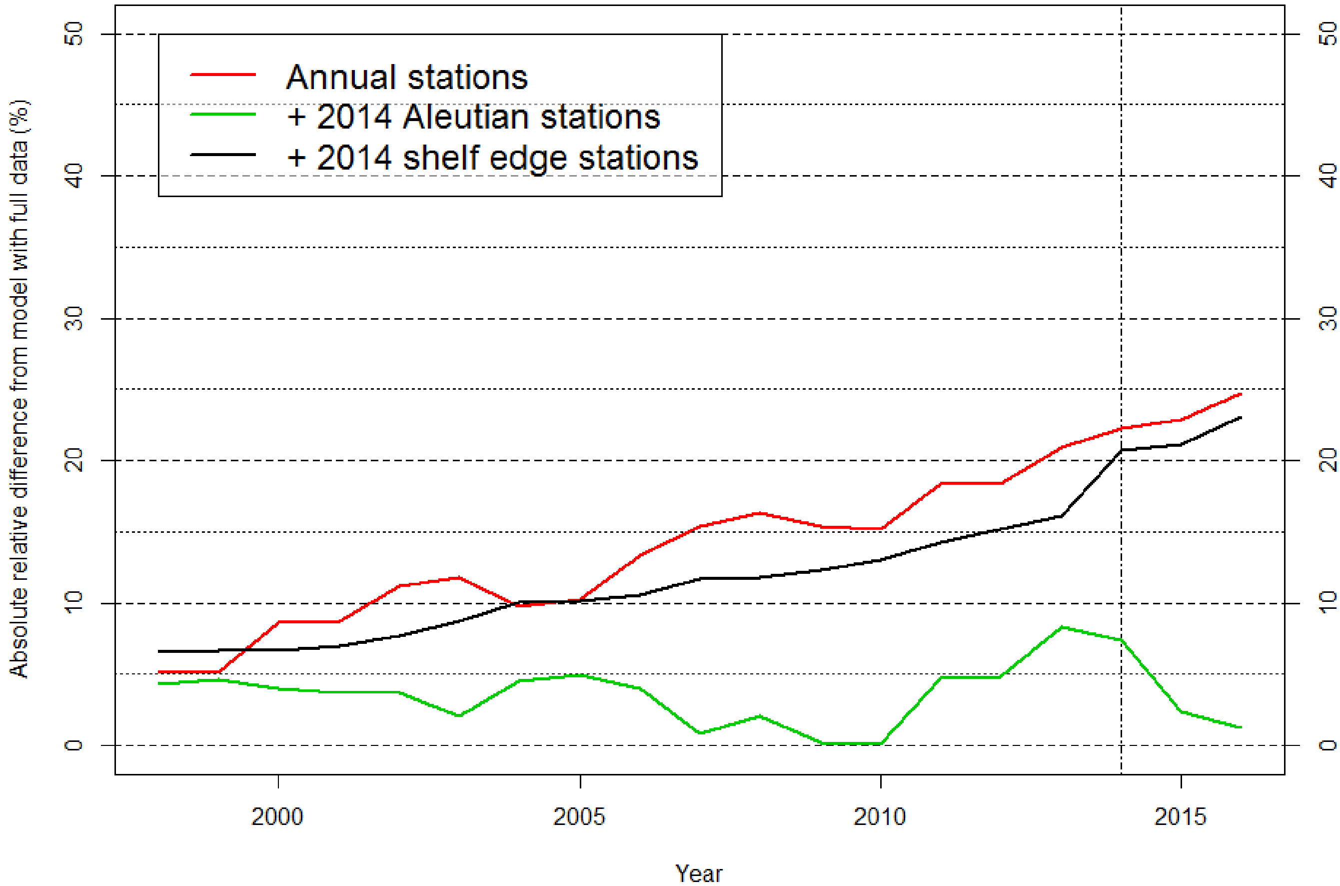

Figure 16. Absolute relative difference in estimated mean WPUE between models fitted to subsets of the Regulatory Area 4A data, and the model using all available data. The vertical line shows 2014, the year of the Regulatory Area 4A setline survey expansion.

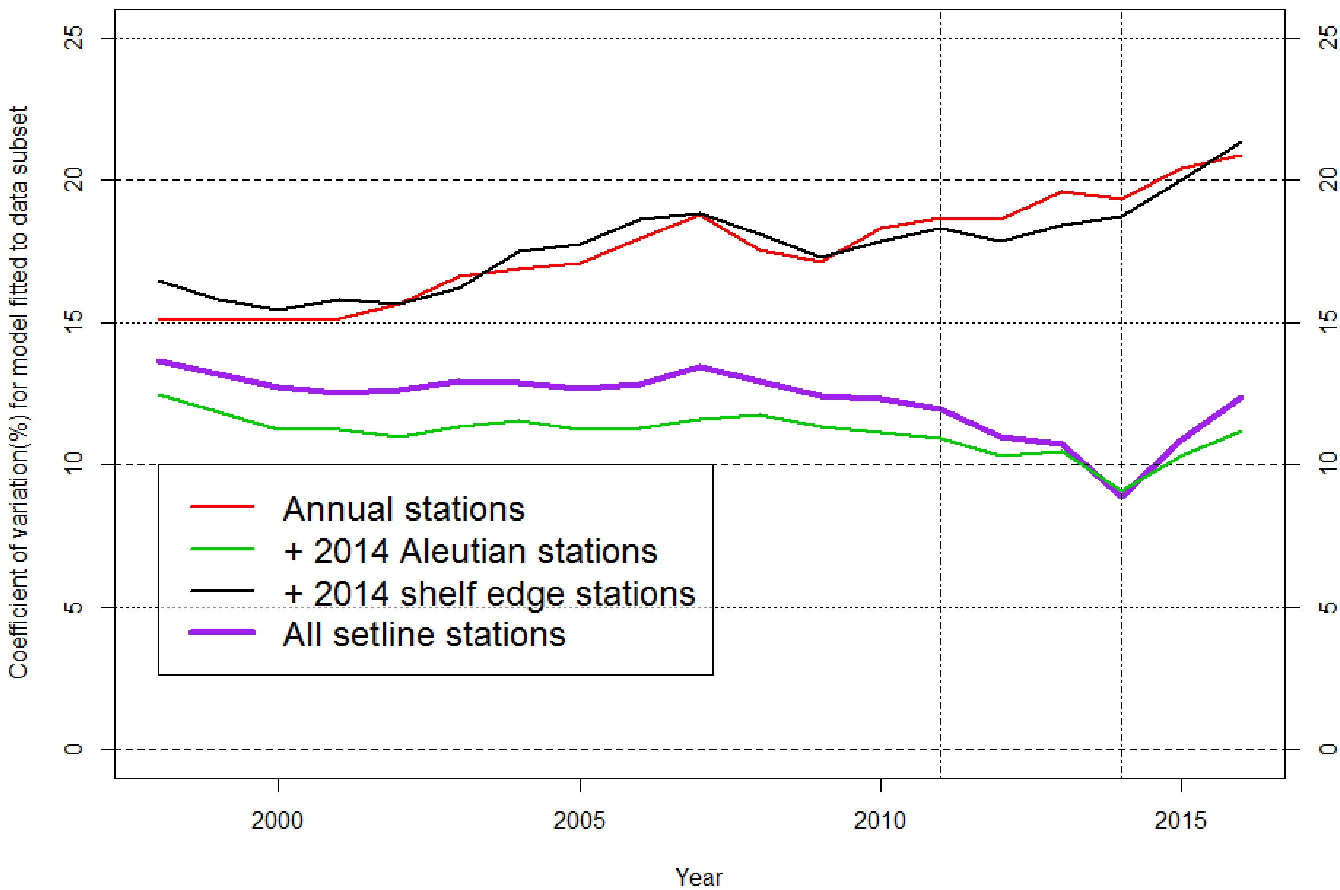

Figure 17. Coefficient of variation of estimated mean WPUE for models fitted to subsets of the Regulatory Area 4A data and the model using all available data. The vertical line shows 2014, the year of the Regulatory Area 4A setline survey expansion.