Falkland Islands Fisheries Department

Impact of finfish and skate trawl fisheries on benthic bycatch

2007 – 2016

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Introduction:

Commercial bottom trawl fisheries can impact marine ecosystems through their capacity to damage sessile, slow-moving, or slow-growing organisms (Freese et al. 1999, Prena et al. 1999, Hinz et al. 2009). Levels of impact vary (Kaiser et al., 2006), and are influenced by factors including the value of the target species (more valuable target species better justify the inefficiency and cost of accumulating bycatch in a trawl), the behaviour of the target species (species that move closer to the sea floor need a heavier ground-effect trawl to be caught) and the management practices that regulate any fishery.

The Falkland Islands Government licenses four finfish bottom trawl fisheries: F license; targeting skates (Rajiformes), A license (unrestricted finfish), G license (*Illex* squid and restricted finfish), and W license (restricted finfish) (FIG, 2017a). A bottom trawl fishery is also licensed for *Doryteuthis gahi* squid, but that fishery is restricted to a separate fishing area (Arkhipkin et al., 2008) and will not be considered in this study. Fishery licenses are regulated by their target species as well as area and gear restrictions. For example, vessels F-licensed to fish skates are permitted to use a tickler chain, whereas tickler chains are prohibited for vessels on A, G or W finfish licences. Trawl equipments such as tickler chains increase the yield of the target species, but are linked to greater mortalities and disturbance of benthic invertebrates (Bergman and van Santbrink, 2000).

The finfish and skate trawl fisheries provide an annual licensing revenue to the Falkland Islands of approximately £3.5 million (FIG, 2017b), of which approximately £250,000 by the skate fishery (Winter, 2015; FIG, 2017b). Falkland conservation areas trawled for skates are inhabited by invertebrate assemblages (Pompert et al., 2014), and high bycatches of benthic invertebrates have been observed in the commercial skate fishery (Boag, 2016). A preceding report examined benthic bycatch in the skate fishery (Winter and Herrera, 2016). The present report continues the analysis to compare bycatch among the four finfish bottom trawl fisheries (F, A, G and W licences) and evaluate their impact on benthic invertebrates throughout the Falklands conservation zones.

Methods:

FIG observer reports on the Falkland Islands Fisheries Department database were synthesized for F, A, G and W license catches from the last 10 years; 2007 through 2016. Only observer data or survey data are suitable for examining non-commercial bycatch, as fishing vessel operators have minimal accountability for reporting catch not kept for sale. Corresponding catches of commercial species were summarized from vessel daily catch reports over the same time period. To control the diversity of benthic bycatch taxa and varying degrees of identification for analyses, invertebrates were grouped into thirteen categories; the 12 categories defined by Winter and Herrera, (2016), plus octopus:

1. Algae
2. Anemone
3. Brittle star
4. Bryozoan
5. Coral
6. Crustacean
7. Mollusc
8. Octopus
9. Sea squirts
10. Sponges
11. Starfish
12. Urchins
13. Worms

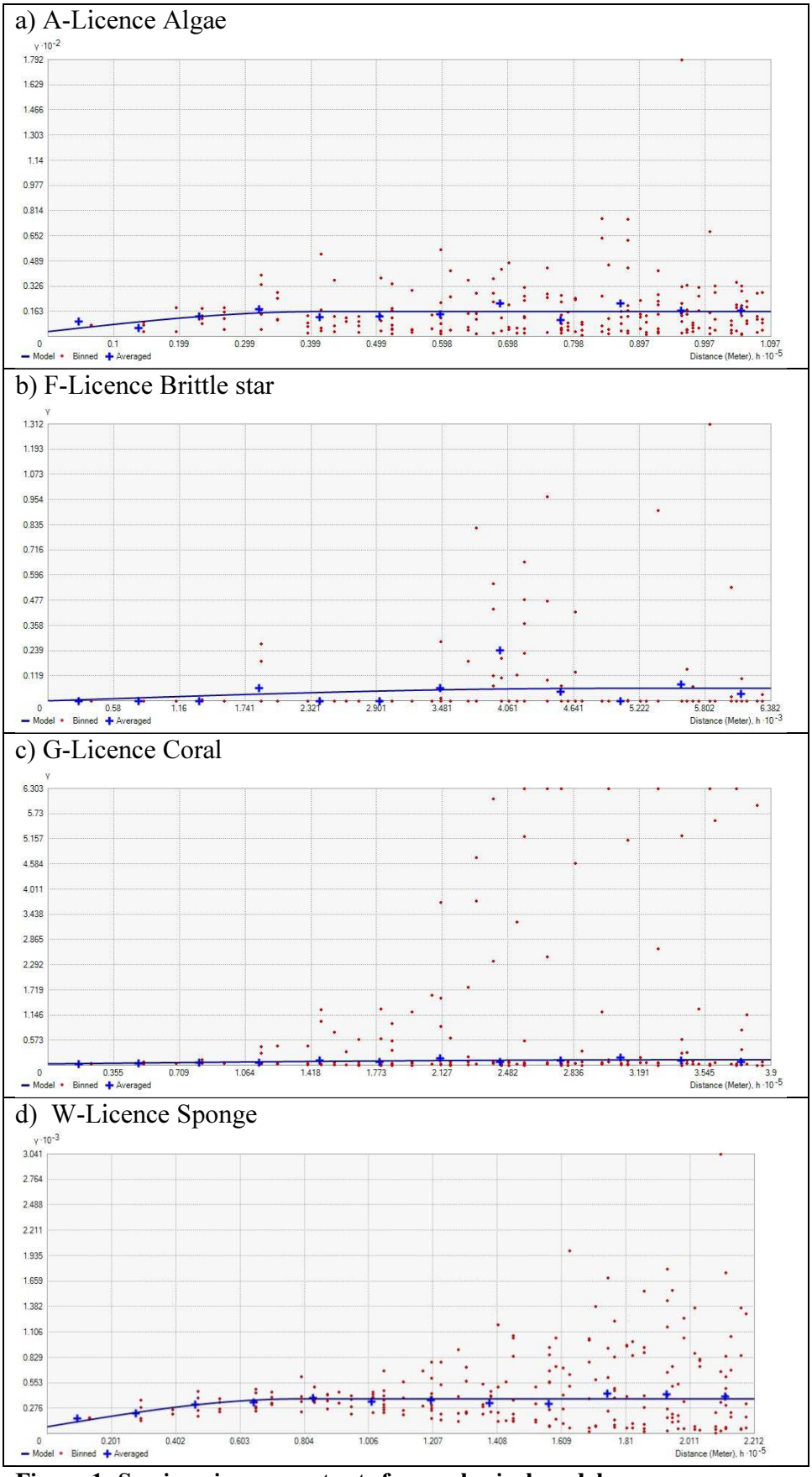


Figure 1: Semi-variogram outputs for a spherical model.

For each invertebrate category, CPUE (kg/hour) was calculated and assessed across the fishing zone per licence, using geostatistical techniques. These analyses were compiled and carried out using R software (R Core Team, 2017) and ArcMap 10.5 (ESRI, 2017).

To identify an appropriate range of years to aggregate up to the present time, generalised linear models (GLM) were calculated for each invertebrate category per licence of CPUE vs. predictor variables vessel call-sign, month, grid, and depth. Significant predictor variables were standardized and the remaining year effect was plotted over a LOESS smooth with 95% confidence intervals (Appendix 1). Inspection of the plots showed that trends in standardised CPUE of bycatch categories generally stabilised in 2010. The time-frame corresponds to substantial changes in the fisheries; rock cod (*Patagonotothen ramsayi*) reached its maximum catch in 2010 and decreased thereafter; hake (*Merluccius*) reached its highest catch in at least 10 years in 2010, decreased the next year, but has since increased even more; skate reached its maximum total catch the year after in 2011 (FIG, 2017a). Therefore, analyses were carried out using data from 2010 onwards.

To spatially identify clustering of high and low CPUE of each invertebrate category a Getis-Ord GI* Hotspot Analysis (Getis and Ord, 1992) was carried out; this identifies locations of significantly higher than average invertebrate bycatch. The Getis-Ord Gi* hotspot analysis for all licenses and categories was run using a fixed distance-band spatial relationship with a search radius of 37,040 m (the average trawl distance) from 2010 onwards. A False Discovery Rate correction was applied to adjust the statistical significance for both multiple testing and spatial dependency (most statistical tests infer values to be independent, however, spatial data usually exhibit some form of dependence in accordance with Tobler's first law of Geography) (de Castro and Singer, 2006). Points from cold and hot spots within the 95% confidence interval are mapped for each category and can be found in Appendix 2.

For each licence and invertebrate category, as well as total benthic bycatch combined, CPUE was spatially mapped using ordinary kriging with a spherical model and trawl distance search radius of 37,040 m. The spherical kriging model was found to be optimal for a broad selection of category/licence groupings (see Figure 1 for examples). Kriging results were output as two rasters, one for the estimated value and one for the standard error (SE), with a cell size of 7,408 m × 7,408 m, equivalent to one hour's trawling at average speed. To quantify benthic bycatch differences, for each invertebrate category pair-wise comparisons were examined between the 4 licences, thus 6 comparisons:

$$\binom{4}{2} = \frac{4!}{(4-2)!\ 2!} = 6$$

Significance of differences was set at $\alpha = 0.05$ (95% confidence interval) with Šidák correction for 6 parallel comparisons:

$$100 \times (1 - 0.05)^{\frac{1}{6}} = 99.14876\%$$

The 99.14876% confidence interval is equivalent to 2.63 SE on the normal distribution. Thus, for each pair-wise comparison, kriged CPUE values per spatial cell were classified as significantly different if they were separated by >2.63 × their standard errors. The krige comparisons were mapped for each of the six licence pairs:

1. F-A
2. F-G
3. F-W
4. A-G
5. A-W
6. G-W

Recommendations from this report are based on the most vulnerable invertebrate categories. The practicality of managing conservation areas for invertebrate categories (equivalent to managing fishery exclusion areas) is a function of the cost-benefit ratio of maximizing reduction of the bycatch while minimizing the forfeit of targeted commercial catch. The cost-benefit ratios for urchins, sponges and corals were examined by licence, with reference to the Getis-Ord GI* hotspots of each invertebrate category.

Following the cost-benefit analysis, a threshold is proposed that a contiguous block of grids is considerable as a conservation area if the cost-benefit ratio >6; that is the proportion of invertebrate bycatch reduced is at least 6× the proportion of target catch forfeit.

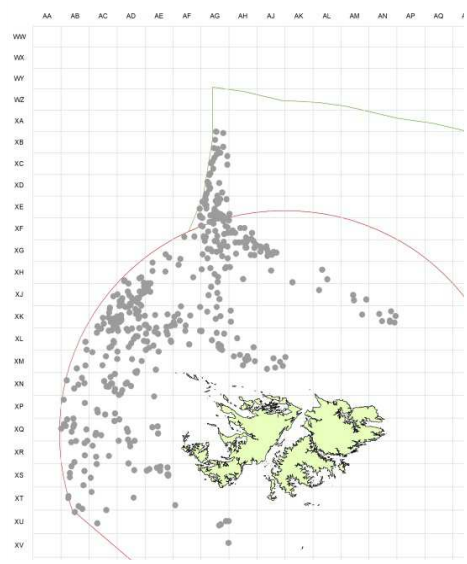
Results:

The four different licence categories varied in their observed area coverage due to a combination of fishery restrictions and distributions of target species. Observer stations taken under the different licence types are shown in Figure 2.

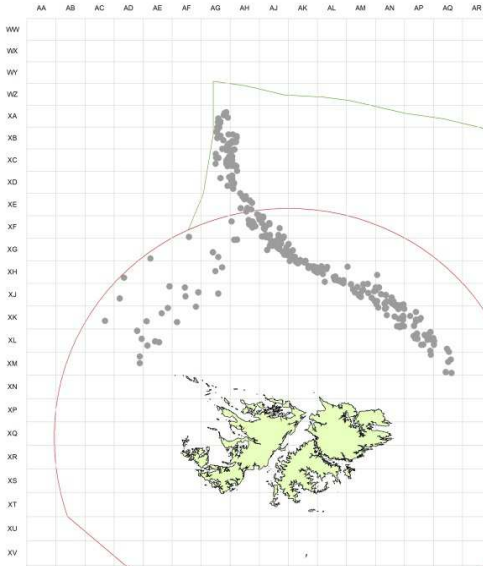
Average values of benthic bycatch across the whole area were computed to reference the deviation of hotspot areas from the mean (Table 1). Highest mean CPUE was found on F-licenced vessels for sponges with an average of 11.240 kg/hr caught.

By invertebrate category, for each licence pair significant differences across spatial cells are shown as positive numbers where the first licence had significantly greater CPUE and as negative numbers where the second licence had significantly greater CPUE. Blank spaces indicate areas of no significant difference. These comparison maps are shown in Appendix 3; areas with greater A-licence catch are red, F-licence green, G-licence blue and W-licence yellow.

a) A-Licence



b) F-Licence



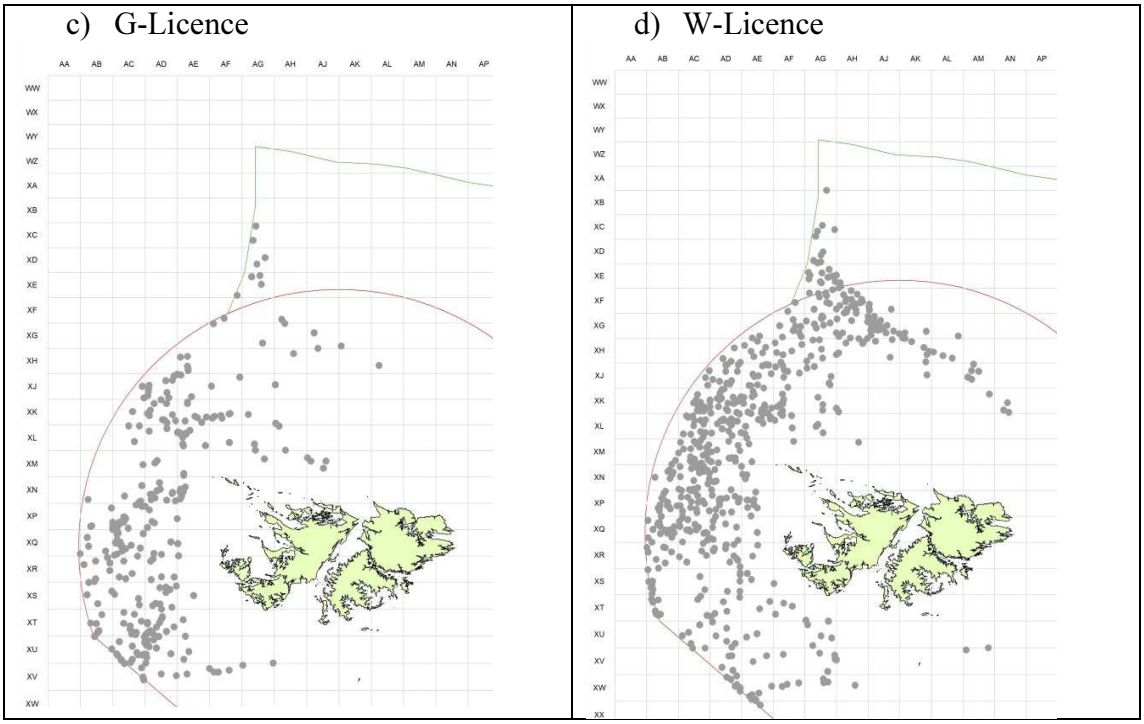


Figure 2: Spatial distribution of Observer Stations (grey) included in the analysis.

Table 1: Mean CPUE in kg/hr of benthic bycatch by licence and invertebrate category.

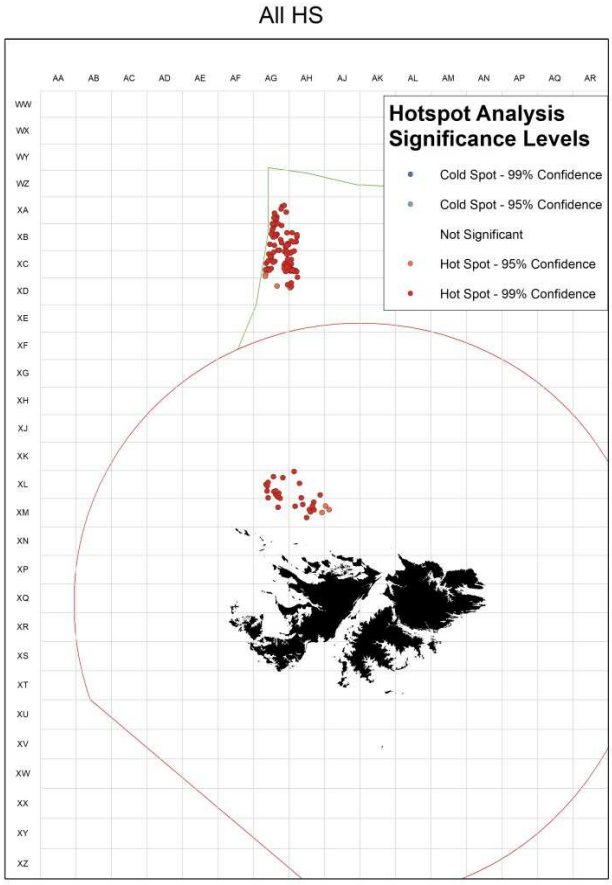
Category	A	F	G	W
Algae	0.640	2.420	0.443	0.611
Anemone	0.253	1.185	0.084	0.155
Brittle star	0.027	0.015	0.022	0.020
Bryozoan	0.075	0.049	0.001	0.012
Coral	0.292	0.331	0.042	0.114
Crustacean	0.354	0.048	0.018	0.029
Mollusc	0.307	0.314	0.178	0.153
Octopus	0.000	0.013	0.001	0.000
Sea Squirt	0.623	0.085	0.215	0.096
Sponge	6.172	11.240	2.119	4.751
Starfish	0.713	1.744	0.359	0.345
Urchin	1.085	7.301	0.156	0.363
Worm	0.003	0.057	0.001	0.001

Table 2 summarizes the occurrence of significant differences by licence / invertebrate category pairwise comparisons. Pairwise comparisons that had no significant CPUE differences at all ("N") were not plotted, as these would simply be blank maps.

Table 2 [below]: Summary of significant kriged CPUE between licences by invertebrate category. "N": no spatial cells of significant difference throughout the sample area. "S": some spatial cells of significant difference throughout the sample area.

Licence Comparison	Algae	Anemone	Brittle star	Bryozoan	Coral	Crustacean	Mollusc	Octopus	Sea Squirts	Sponges	Starfish	Urchins	Worms
F-A	N	N	S	N	N	N	S	S	S	N	N	S	S
F-G	N	N	S	N	N	N	S	S	S	N	N	S	N
F-W	N	N	S	N	N	S	N	S	S	N	N	S	S
A-W	S	S	S	S	S	S	S	S	S	S	S	S	S
A-G	N	S	S	S	S	S	S	S	S	N	S	S	S
G-W	N	S	S	S	S	S	S	S	S	S	N	N	S

Total bycatch: Total benthic bycatch for all 4 licences combined showed two distinct areas of hot spots at the 95% confidence level. One area spans the grid squares XCAG, XBAG and XAAG in the north of the FOCZ and the other is found in grid squares XLAG and XMAH of the FICZ just to the north of West Falkland (Map 1).



Map 1: Map of the overall hotspots for benthic bycatch

Algae bycatch: Both significant cold and hot spots can be found from the Getis-Ord Gi* hotspot analysis (Appendix 2, Map 2). Three hotspot clusters exist; one in grid squares XCAG/XBAG, one on the edge of the shelf in the north eastern FICZ and one

around grid square XMAH. A cold spot is found in the north western FICZ around grid square XKAD. Significant differences for algae were found only between A and W licence (Table 2; Appendix 3, Map 11). Both A and W licences are significantly catching more bycatch than each other with a peak in algal bycatch of A-licence at 69.4 kg/hr more than on W-licence found around grid square XQAC. W-Licence vessels are catching 37.0 kg/hr more algae than A-licence vessels around grid square XHAK. Some further isolated spatial cells of higher A-licence algae bycatch are found between these two grid squares and in the north of the FICZ and FOCZ.

Anemone bycatch: Distinct areas of both hot and cold spots for anemone bycatch are evident from the hotspot analysis (Appendix 2, Map 3). Along the shelf-break to the north east of the FICZ and north of the FOCZ a clear hotspot area can be identified. A second smaller hotspot is found around grid square XLAG. Coldspots are found in the majority of the western FICZ. When comparing the kriged differences between licences significant differences are noted between A, G and W-licences (Table 2; Appendix 3, Map 12 to Map 14). A higher quantity of anemone bycatch is found around grid square XMAG for A-licence in comparison to both G and W-licences with A-licenced vessels catching 4.9 kg/hr more than W and 5.6 kg/hr more than G licenced vessels. No areas exist where G and W-licenced vessels catch more than A-licenced vessels. When comparing G and W-licenced vessels, G-licenced vessels have a maximum of 1.6 kg/hr more anemone bycatch around grid square XKAH and W-licenced vessels have a maximum of 1.3 kg/hr more bycatch around grid square XHAK.

Brittle star bycatch: For brittle stars, a hotspot of bycatch is only found to the west of the FICZ around grid squares XRAB, XSAB and XTAB (Appendix 2, Map 4). Significant differences exist in interpolated CPUE of brittle stars between all four licences (Appendix 3, Map 15 to Map 20). These differences are smallest between F and G licences where F-licenced vessels caught 0.39 kg/hr more in the northern FOCZ than G-licenced vessels. A-licenced vessels had a greater maximum quantity of brittle star bycatch than F (1.8 kg/hr) and G-licenced (1.9 kg/hr) vessels in grid square XHAH and XMAH (G-licence only). In the hotspot in XSAB W-licenced vessels have a greater quantity of brittle star bycatch than both A (4.7 kg/hr) and G-licenced (4.7 kg/hr) vessels. This peak does not influence the difference between F and W-licenced vessels as there is no F-licenced fishing activity in this area. The maximum peak between these two licences is 0.5 kg/hr found in the northern most part of the FOCZ.

Bryozoan bycatch: Only a single cluster of hotspots is found for bryozoans in grid square XKAN in the eastern FICZ (Appendix 2, Map 5). Between the interpolated CPUE significant differences only exist between A, G and W licences (Appendix 3, Map 21 to Map 23). A-licenced vessels had the highest quantity of interpolated CPUE centred on grid square XLAD in comparison to G and W-licenced vessels (both at 4.3 kg/hr more catch on A-licence). Comparatively little difference exists between G and W-licenced vessels with 0.3 kg/hr benthic bycatch more in the southern FICZ. Little difference is found between the two licences elsewhere.

Coral bycatch: One single point constituting a significant hotspot of coral bycatch is found in grid square XHAH (see Appendix 2, Map 6). Here again only significant differences exist between A, G and W licenced vessels (see Appendix 3, Map 24 to

Map 26). Coral bycatch of A-licence exhibited the maximum difference from the other two licences in grid square XHAH. Here a maximum of 19.7 kg/hr more coral catch was caught on A-licence than on G licence and 16.4 kg/hr more on A-licence compared to W-licence. The largest areas of significant differences between G and W licences can be found further south and west. Here a maximum of 8.0 kg/hr more bycatch was observed on W-licenced vessels on the boundary between grid squares XRAE and XQAE. To the south of the Falklands, 3.5 kg/hr more coral bycatch is found on G-licenced vessels.

Crustacean bycatch: One hotspot cluster for coral within the 95% confidence interval is found in grid squares XLAG and XMAH of the FICZ (Appendix 2, Map 7). Significant differences in interpolated benthic bycatch exist in four of the six pairwise comparisons between F and W, A and W, A and G and G and W-licenced vessels (Table 2; Appendix 3, Map 27 to Map 30). Only one area where a significant difference between A and G/W licenced vessels was found is located on the boundary of grid squares XMAG and XMAH. Here A-licenced vessels had higher benthic bycatch than G (133.5 kg/hr) and W-licenced (133.9 kg/hr) vessels. Significant differences between G and W licences are lower but more wide spread. Here a maximum of 10.5 kg/hr more crustacean bycatch is found on W-licenced vessels in grid square XKAG. F-licenced vessel bycatch is only significantly different from W-licenced crustacean bycatch in one location found in grid square XKAG where there is 10.4 kg/hr more bycatch on W-licenced vessels. No other licences are significantly different from F-licences.

Mollusc bycatch: Two hotspot clusters within the 95 % confidence interval are evident from the Getis-Ord Gi* hotspot analysis (Appendix 2, Map 8). One of these clusters is located in grid squares XKAC, XLAC, XKAD and XLAD in the western FICZ and the other cluster is located in grid squares XLAG and XMAH. Based on interpolated CPUE significant differences are found in all pairwise comparisons except between F and W-licenced vessels (Appendix 3, Map 31 to Map 35). In general the areas over which differences exist are fairly small. When comparing A and G licenced vessels, a maximum difference of 5.0 kg/hr of molluscan bycatch is found on G-Licenced vessels in grid squares XRAC and XNAD. The same is true in comparison with W-licenced vessels except here the maximum difference is slightly higher at 5.1 kg/hr. Significant differences between F and G licences are restricted to two pixels, one with slightly higher F-licence bycatch and the other with slightly higher G-licence bycatch varying maximum of 0.89 kg/hr. The only areas of significant difference in mollusc bycatch found between F and A-licence at the higher CPUE on A-licence (7.5 kg/hr) in the north of the FOCZ in grid squares XCAH and XBAH. The same trend is evident when comparing A and W-licenced molluscan bycatch. Here a maximum difference of 3.8 kg/hr is seen.

Octopus bycatch: A cluster of hotspots within the 95% confidence interval from the Getis-Ord Gi* hotspot analysis is found in grid squares XHAK and XGAJ of the northern FICZ (Appendix 2, Map 9). Differences in the interpolated CPUEs are found between all licence comparisons (Appendix 3, Map 36 to Map 41). When compared to both G and W-Licenced Vessels the same area of significant difference is found to be greater for A-licence. This is located in the southern FICZ and is 0.08 kg/hr greater than W and G-licenced vessels. An area of approximately equal size to the west of this point serves as a maximum difference for G-licenced vessels in comparison to A.

In the comparison on A and W-licenced vessels a maximum difference is seen in grid square XGAK where there is 0.15 kg/hr more octopus bycatch on W-licenced vessels. Significant differences of octopus bycatch between F and A-licenced vessels and F and G-licenced vessels are limited to a few spatial cells in the northern FICZ. In both cases, bycatch is higher on F-licence reaching a maximum difference of 0.1 kg/hr. The same is also seen for the comparison with W-licenced vessels however, here there is an added spot of significant difference in grid square XGAK where 0.17 kg/hr more octopus is caught on W-licence. This spot is also seen in the comparison between G and W-licenced vessels where the bycatch is 0.15 kg/hr higher on W-licence than G.

Sea Squirt bycatch: One single cluster of hotspots within the 95 % confidence interval exists for sea squirts in grid squares XLAG, XMAH and XMAJ (Appendix 2, **Error! Reference source not found.**). As with octopus significant areas were found between all licence comparisons (see Appendix 3, Map 42 to Map 47). Similar trends are seen between A and G-licenced vessels and A and W-licenced vessels. In both cases a maximum difference of more sea squirt bycatch is seen on A-licence between grid squares XMAG to XMAJ. This area has a benthic bycatch of 38.9 kg/hr more on A than G-licenced vessels and 48.4 kg/hr more on A than W-licenced vessels. Differences between F and A licenced bycatch are limited to a small area in grid square XMAE where 15.6 kg/hr more sea squirts are caught on A-licenced vessels. Differences between F and G licenced vessels are most apparent further northwest in the FICZ where a maximum of more bycatch in F-licenced vessels of 5 kg/hr is found in grid square XGAE and a maximum difference on G-licenced vessels compared to F-licenced vessels of 4.5 kg/hr in grid square XKAG. The above area of greater benthic bycatch around grid square XGAE on F-licenced vessels is also observed in the comparison with W-licenced vessels where a maximum difference of 5.0 kg/hr is noted. A maximum difference of 13.1 kg/hr is noted in grid square XLAF where more benthic bycatch is found on W-licenced vessels. Finally, differences are also observed between G and W-licenced vessels. Benthic bycatch on G-licenced vessels is higher than on W-licenced vessels in grid square XMAG varying by 20.2 kg/hr. Slightly to the west in grid square XMAF sea squirt bycatch is higher on W-licenced vessels than on G-licenced vessels by 18.2 kg/hr.

Sponge bycatch: Both hot and cold spot(s) can be found in the Getis-Ord Gi* hotspot analysis for sponges (Appendix 2, **Error! Reference source not found.**). Only one cold spot is found within the 95% confidence interval in grid square XPAC. Hotspots are more numerous than cold spots and can be found in three clusters. The first of these is found in grid squares XJAN and XKAN and comprises points within the 95% and 99% confidence interval. This is also true for another cluster which can be found predominantly in grid squares XSAB and XRAB and consists of spots within both confidence interval levels. A third smaller cluster of hotspots is found in grid square XLAG consisting of points within the 95% confidence interval. Amongst the pairwise comparisons areas of significant difference can only be found in the comparison of A and W licences and G and W licences (Appendix 3, Map 48 and Map 49). In both comparisons the area of maximum difference can be found in grid square XRAB where there is an interpolated CPUE of 271.8 kg/hr more sponge bycatch found on W-licence than A-licence and 273.1 kg/hr more bycatch on W-licence than on G-licence vessels. In the comparison between G and W-licenced vessels some other isolated spatial cells of significant difference exist across the northern FICZ.

Starfish bycatch: Clusters of both hot and cold spots exist for the hotspot analysis of starfish bycatch (Appendix 2, **Error! Reference source not found.**). Three clusters of hotspots are found for starfish. These are found in the northern FOCZ in grid squares XAAG to XCAG and in the FICZ, where one cluster is found in the eastern part in grid squares XMAQ to XKAP and further to the west in grid squares XMAH to XLAG. Cold spots are found predominantly in the FICZ and constitute of one large cluster around grid squares XJAD, XKAC, XKAD, XKAE and XLAD and smaller clusters in grid squares XFAG and XPAC. In the comparison of interpolated catches significant differences were only noted between A and G-licenced vessels and A and W-licenced vessels (Appendix 3, Map 50 and Map 51). Here the maximum difference between A and G-licenced vessels is found in between grid squares XMAG and XMAH where 22.4 kg/hr more starfish are caught on A-licence than on G-licence. This is the only area where significant differences are observed between A and G-licenced vessels. In the comparison between A and W-licenced vessels this area is also the area of maximum difference in bycatch with 23.1 kg/hr more caught on A-licenced vessels. Some further areas of significant difference exist throughout the fishing areas mostly with higher bycatch on A-licenced vessels.

Urchin bycatch: From the Getis-Ord Gi* hotspot analysis a single cluster of bycatch hotspots can be found in the northern FOCZ in grid XAAG to XCAG (Appendix 2, **Error! Reference source not found.**). Significant differences in kriged urchin bycatch can be found in some areas between most licences apart from G and W licences (Appendix 3, Map 52 to Map 56). In both the comparisons between A and G-licences and A and W-licences, the area of maximum significant difference is found in the northern FOCZ in grid squares XBAG to XDAH where more urchin bycatch is found on A-licenced vessels. 114.8 kg/hr more urchins are found on A-licenced vessels than on W-licenced vessels and 88.9 kg/hr more on A-licenced vessels than on G-licenced vessels. In both of these pairwise comparisons another area of significant difference is found around grid square XMAH where more benthic bycatch is found on A-licenced vessels. CPUE of urchins on F-licenced vessels is significantly more than on G and W-licenced vessels in northern FOCZ around grid squares XBAG to XEAG. Here 29.3 kg/hr more urchin are caught on F-licence than on G-licence and 46.3 kg/hr more urchin are caught in this locality on F-licence than on W-licenced vessels. No other areas of significant differences exist between these two pairings. Differences between F and A-licenced vessels are less one-sided. Here two areas of significant difference exist beside each other in the northern FOCZ. In grid squares XBAH and XCAH 82.6 kg/hr more urchins are caught on A-licenced vessels than on F-licenced vessels. In grid squares XBAG to XEAG significantly more urchin are caught on F-licenced vessels than A-licenced vessels with a maximum difference of 29.1 kg/hr. Here again no other areas of significant differences than those described above exist.

Worm bycatch: One cluster of Getis-Ord Gi* hotspots for worms can be found around grid square XLAG (Appendix 2, Map 10). In the comparison of interpolated worm bycatch significant differences exist between all pairwise comparisons apart from F and G-licenced vessels (Appendix 3, Map 57 and Map 61). Differences between A and G-licenced vessels show a maximum difference of 1.1 kg/hr in grid square XMAG with more worm bycatch on A-licence. Surrounding this other areas of significant difference exists with some areas of higher bycatch on G-licence. Grid-square XMAG also boosts significantly higher quantities of worm bycatch on A-licence compared to W-licenced vessels with a maximum difference of 1.14 kg/hr. In

this comparison there are again other areas to the north of this point with significant differences in worm bycatch. Differences between F and A-licenced vessels were smaller in quantity with a maximum difference in bycatch of 0.11 kg/hr found in grid square XHAG. Other areas of both higher bycatch of F and A-licenced vessels are found further east and north of this area. Significant differences between F and W and G and W-licenced vessels are smaller yet. A maximum of 0.06 kg/hr more benthic bycatch is found in the northern FICZ on W-licenced vessels. In the northern FOCZ more bycatch is found on F-licenced vessels compared to W-licenced vessels. The area of significantly greater benthic bycatch on W-licenced vessels compared to F-licenced vessel is also seen in the comparison between G and W-licenced vessels. Here a difference of 0.02 kg/hr worm bycatch is observed. Further south-west in grid square XTAB and extrapolated out of the zone, a maximum difference of 0.03 kg/hr more worm bycatch are caught on G than on W-licenced vessels.

Fisheries Catches:

Fisheries catch data reported by vessels during observation periods were analysed to show trends of where main catches per target species were found, both in terms of per unit effort and as total catch. These catch figures are found in Appendix 4.

Illex *catches:* Catches of *Illex* were greatest overall on G-licenced vessels with main catches located to the west of the FICZ. The same was true for CPUE of *Illex* where greatest CPUE was found in grid square XUAB, XUAC and XUAD. Some catches of *Illex* were also noted on other licence types but these were comparatively small.

Hake catches: Catches of hake were greatest overall on A-licenced vessels with the greatest quantity of catches located in the north western FOCZ. Smaller but still significant catches of hake were noted for W-licence in the same area however, smaller catches were also noted in the central FICZ on G-licenced vessels. When comparing catch per unit effort, greatest CPUE was found ranging from grid squares XMAH to XMAK in the south to XBAG in the north.

Other finfish catches: Greatest catches of finfish were noted on A, G and W licenced vessels with highest aggregate catches found in grid square XKAD and surrounding grid squares across all three fleets. Catch per unit effort varied greatly across the fleet with highest CPUE found near grid square XKAD across all fleets, however, between the different fleets, other areas of high CPUE varied greatly.

Ray catches: Greatest catches of ray were noted in the F-licenced fishery where highest catches are noted along a diagonal line of grid squares ranging from XEAG to XLAP. Catch of ray on other licence types was minimal with CPUE highest again on F-licenced vessels with highest values of CPUE in grid square XKAH and along the diagonal of XEAG to XLAP.

Table 3 [below]. Percentages of total bycatch / catch accounted by various hotspots in the Falkland Islands fishing zone, 2010-2016. Fields under-shaded grey are hotspots that could be considered cost-effective conservation areas by the criterion that the % of invertebrate bycatch reduced is at least 6× the proportion of target catch forfeit.

Invertebrate Hotspot	Licence	Grids	% Total Bycatch / Catch 2010 - 2016				
			Urchin	Sponge	Coral	Primary Target*	All Commercial
Urchin	F	XAAG, XBAG, XCAG, XBAH, XCAH	72.3	18.8	14.6	10.1	8.2
Urchin	A	XBAG, XCAG	66.3	11.3	<0.1	3.9	3.7
Urchin	G	XAAG, XBAG, XCAG, XBAH, XCAH	0.0	0.1	0.0	0.7	0.7
Urchin	W	XBAG, XCAG	0.4	0.2	0.1	1.5	1.4
Sponge	F	XJAM, XJAN, XKAN	4.6	30.0	42.7	22.3	19.0
Sponge	A	XKAG, XLAG, XLAF	5.9	14.0	9.7	2.1	2.0
Sponge	G	XKAG, XLAG, XMAG	1.6	7.9	0.0	2.7	2.8
Sponge	W	XRAB, XRAC, XSAC, XTAC	2.8	26.0	3.7	2.5	3.2
Coral	F	XGAG, XHAG, XHAH	0.2	2.0	0.0	1.3	1.6
Coral	A	XHAG, XHAH	0.2	4.2	20.5	1.0	1.1
Coral	G	XGAG, XHAG, XHAH	0.3	0.6	0.0	0.5	0.6
Coral	W	XHAH, XHAJ, XHAK	3.7	8.5	23.8	3.1	3.0

* Primary catch is skate for F licence, rock cod, hake and hoki for A and W licences, and rock cod, *Illex* and hoki for G licence.

Cost-benefit analysis:

Urchin bycatch was concentrated in one hotspot north in the FOCZ (Map 13). For F licence, five grids centred on this hotspot (XAAG, XBAG, XCAG, XBAH, XCAH) accounted for 72.3% of urchin bycatch between 2010 and 2016, vs. 10.1% of

skate catch and 8.2% of all commercial catch (Table 3). For A licence, two grids on this hotspot (XBAG, XCAG) accounted for 66.3% of urchin bycatch (Table 3), while adjacent grids added little benefit. For both F and A licences, this hotspot also accounted double-digit sponge proportions higher than the commercial catches. G and W licences had trivial to nil urchin bycatch proportions on this hotspot, as well as commercial catch proportions, indicative that these licences don't fish there anyway (Table 3).

Sponge bycatch was concentrated in three hotspots; one at the western edge of the Falklands fishing zone, a smaller one just north of West Falkland, and a larger one further north of East Falkland (Map 11). For F licence, three grids on the hotspot north of East Falkland accounted for 30.0% of sponge bycatch and 42.7% of coral bycatch. However, the proportion of skate target catch on these same grids was 22.3%, rendering the area too costly as an exclusion zone. For A licence, three grids on the hotspot north of West Falkland (XKAG, XLAG, XLAF) accounted for 14.0% of sponge bycatch as well as 5.9% of urchin bycatch and 9.7% of coral bycatch. As the proportion of finfish target catch in these three grids was only 2.1% (Table 3), the area of these three grids could be considered cost-effective (14.0% / 2.1% > 6.5×) as a fishing exclusion zone for A licence. For W licence, four grids on the hotspot north of East Falkland (XRAB, XRAC, XSAC, XTAC) accounted for 26.0% of sponge bycatch vs. 2.5% of finfish target catch (> 10×) (Table 3), suggesting this area as a cost-effective W exclusion zone. For G licence, 7.9% of sponge bycatch were accounted by three grids partially overlapping the A licence sponge hotspot but this was not enough to be considered cost-effective for conservation.

Coral showed in one small hotspot north of the Falkland Islands (Map 6). For A licence, two adjacent grids on that hotspot (XHAG, XHAH) accounted for 20.5% of coral bycatch, and for W licence, three partially overlapping grids on that hotspot (XHAH, XHAJ, XHAK) accounted for 23.8% of coral bycatch (Table 3). These percentages were respectively 20.5× and 7.7× higher than primary target catches in this hotspot for A and W licences, indicating potentially cost-effective exclusion zones. F and G licences caught little to no coral on this hotspot, and very little commercial target species (Table 3).

A further calculation was undertaken to determine if cost-effective fishing exclusions for urchins could be restricted temporally. Winter and Herrera (2016) had found that F-licence urchin bycatch was particularly concentrated during the month of October. This concentration may be related to the seasonality of urchin settlement (Balch and Scheibling, 2000; Hereu et al., 2004; Tomas et al., 2004). For the present study, examination of other licences' urchin bycatch showed that A licences had the highest CPUEs in September, while W licence also peaked in October, and G licence did not fish in either September or October (Figure 3). The temporal trend peaking in September / October (CPUE vs. Month; LOESS smooth with degree = 2, span = 0.75) was significant at $p < 0.001$ for F licence, and marginally significant at $p < 0.10$ for A licence. It was not statistically significant for W licence, although the trend was visibly deflected upwards in October. Therefore, the percentages of bycatch / catch shown in Table 3 for urchin were re-calculated but taking data only in September and October as proportions of the totals.

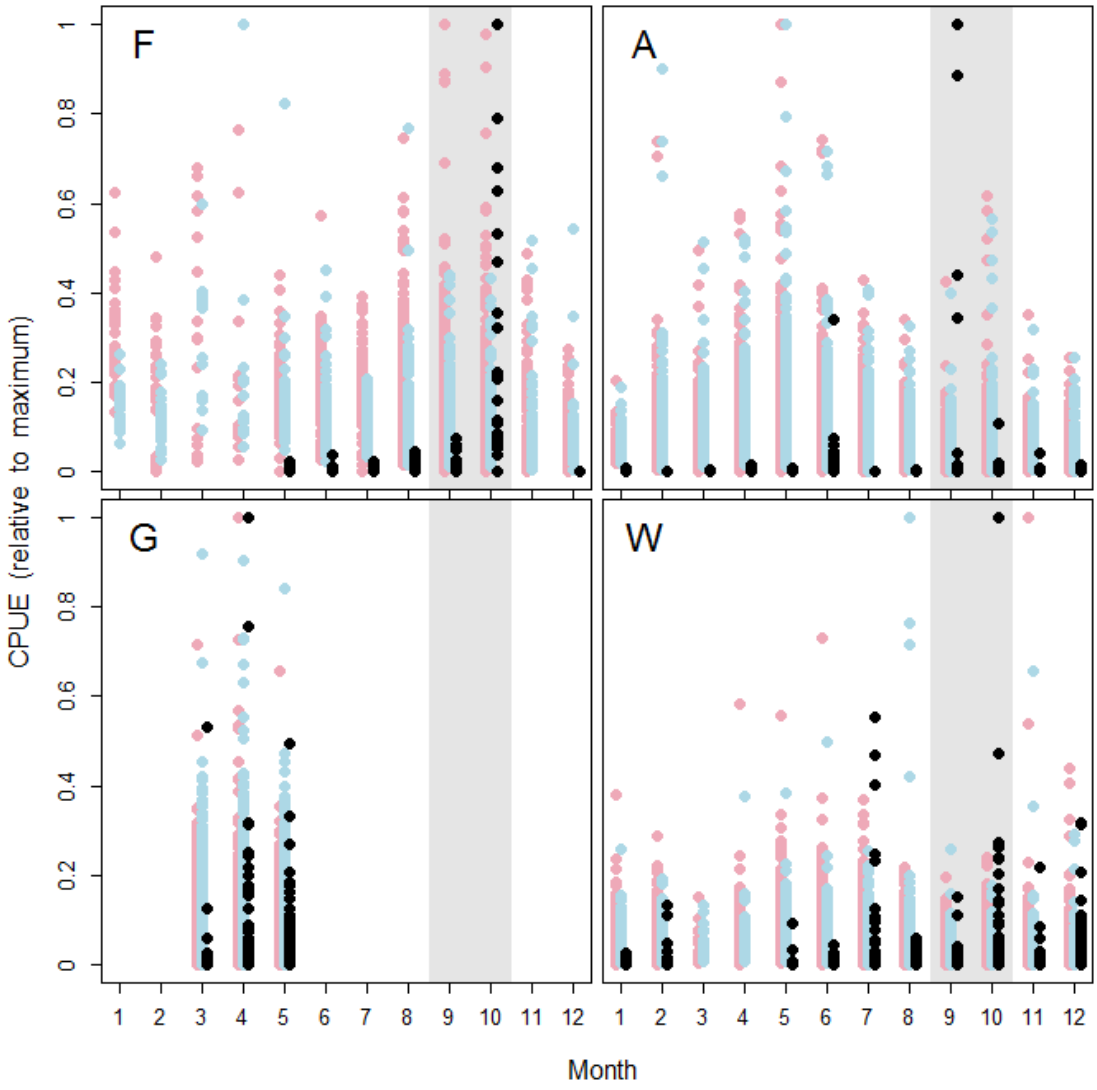


Figure 3. Relative CPUE by month of primary target catch (red), total commercial catch (blue), and urchin catch (black), for F, A, G and W licences, 2010 – 2016. Months September and October are under-shaded grey.

For F licence, the five grids on the urchin hotspot accounted for 69.7% of urchin bycatch between 2010 and 2016 in just September / October, vs. 7.3% of skate catch and 5.7% of all commercial catch (Table 4). Thus the cost-benefit ratio with respect to target skate catch improved compared to the full year: from 72.3% / 10.1% = 7.2× to 69.7% / 7.3% = 9.5×, and with respect to all commercial catch from 72.3% / 8.2% = 8.8× to 69.7% / 5.7% = 12.2×. For A licence, the two grids on the urchin hotspot accounted for 66.2% of urchin bycatch in just September / October, vs. 2.4% of primary target catch and 2.2% of all commercial catch (Table 4). Likewise, this represented an improvement in the cost-benefit ratios; from 66.3% / 3.9% = 17.0× to 66.2% / 2.4% = 27.6×, and from 66.3% / 3.7% = 17.9× to 66.2% / 2.2% = 30.1×. G and W licences, which had minimal urchin bycatch proportions on the urchin hotspot for the whole year, likewise had minimal proportions for September / October.

Table 4. Equivalent to Table 3 for urchins, but with percentages catch / bycatch restricted to those taken in September and October (as a proportion of the whole year). Note that the composition of grids in Table 4 was not predetermined to be exactly the same as in Table 3; it was re-examined separately for substantial contributions to the bycatches / catches, but turned out to be the same.

Invertebrate Hotspot	Licence	Grids	% Total Catch / Bycatch 2010 - 2016				
			Urchin	Sponge	Coral	Primary Target*	All Commercial
Urchin	F	XAAG, XBAG, XCAG, XBAH, XCAH	69.7	14.5	12.1	7.3	5.7
Urchin	A	XBAG, XCAG	66.2	11.1	<0.1	2.4	2.2
Urchin	G	–	–	–	–	–	–
Urchin	W	XBAG, XCAG	0.4	<0.1	<0.1	0.8	1.1

* Primary catch is skate for F licence, rock cod, hake and hoki for A and W licences, and rock cod, *Illex* and hoki for G licence.

Recommendations:

Our analyses have found significant, but varied, impacts of Falkland Islands trawl fisheries on 13 categories of invertebrates. Management recommendations will focus on three invertebrate categories: urchins, sponges, and corals, which had the highest bycatch quantities (Table 1) and are indicators of hard ground (Fewkes, 1890; Cabioch et al., 1995; Yoklavich et al., 2016).

The data reveal that an efficient benthic bycatch conservation area could be established on the urchin hotspot in the north-western part of the FOCZ, even if this conservation area was only closed to commercial fishing in months September and October. Minor conservation areas should be considered for the sponge and coral hotspots that, although not comprising majority proportions of sponge and coral bycatch, would achieve substantial reductions of these bycatches for relatively little commercial catch forfeited. As noted by Winter and Herrera (2016), the bycatch / catch ratios reviewed in this type of analysis do not anticipate effects of how trawl effort might shift to other areas as fishers compensate for closures. The implementation of any conservation area must therefore gauge potential shifts in commercial fishing strategy. Notwithstanding, the results of this study have demonstrated significant heterogeneities in the distribution of benthic invertebrate bycatch distributions, which can be utilized to improve management for the environmental impacts of these fisheries.

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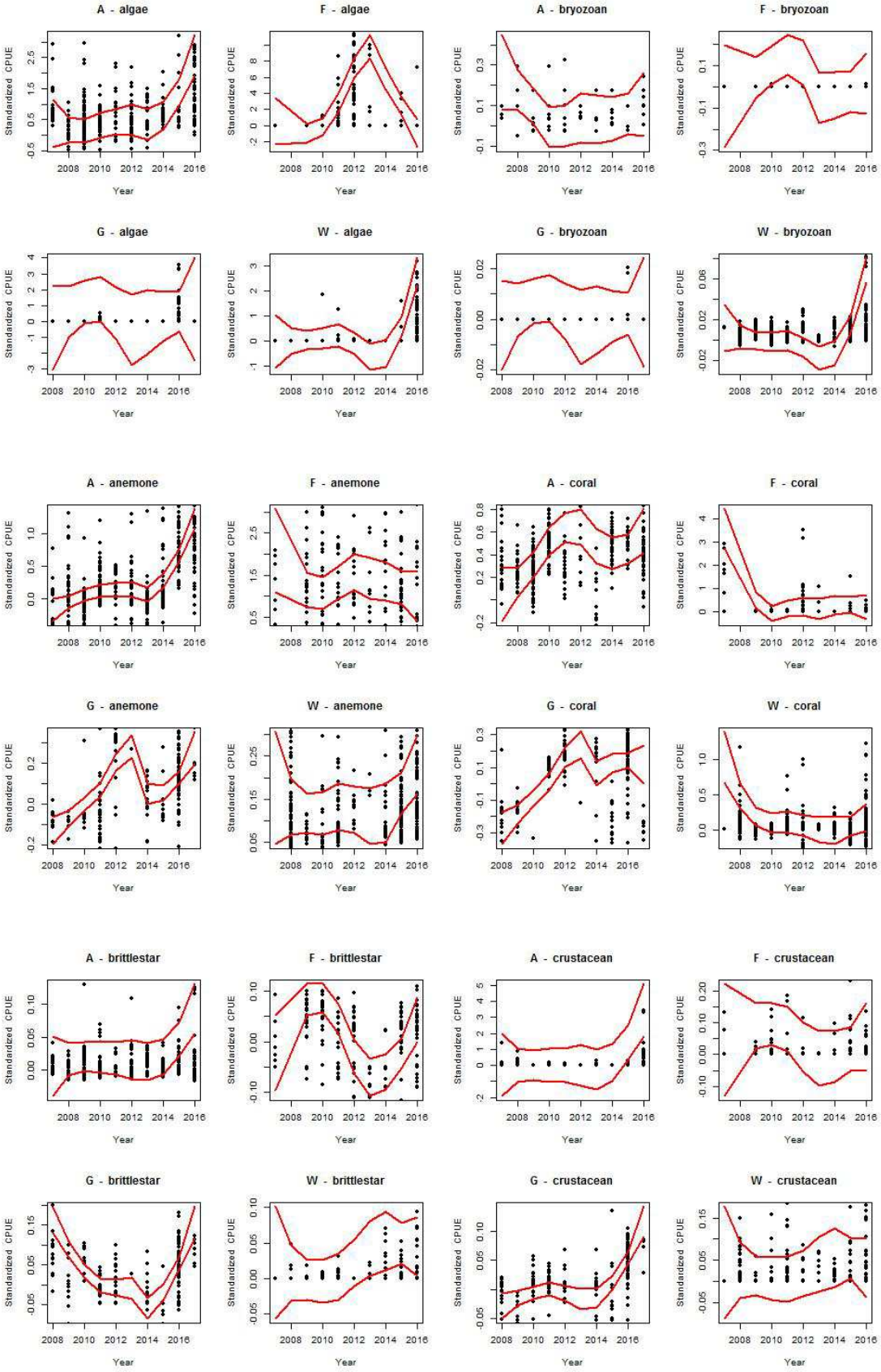
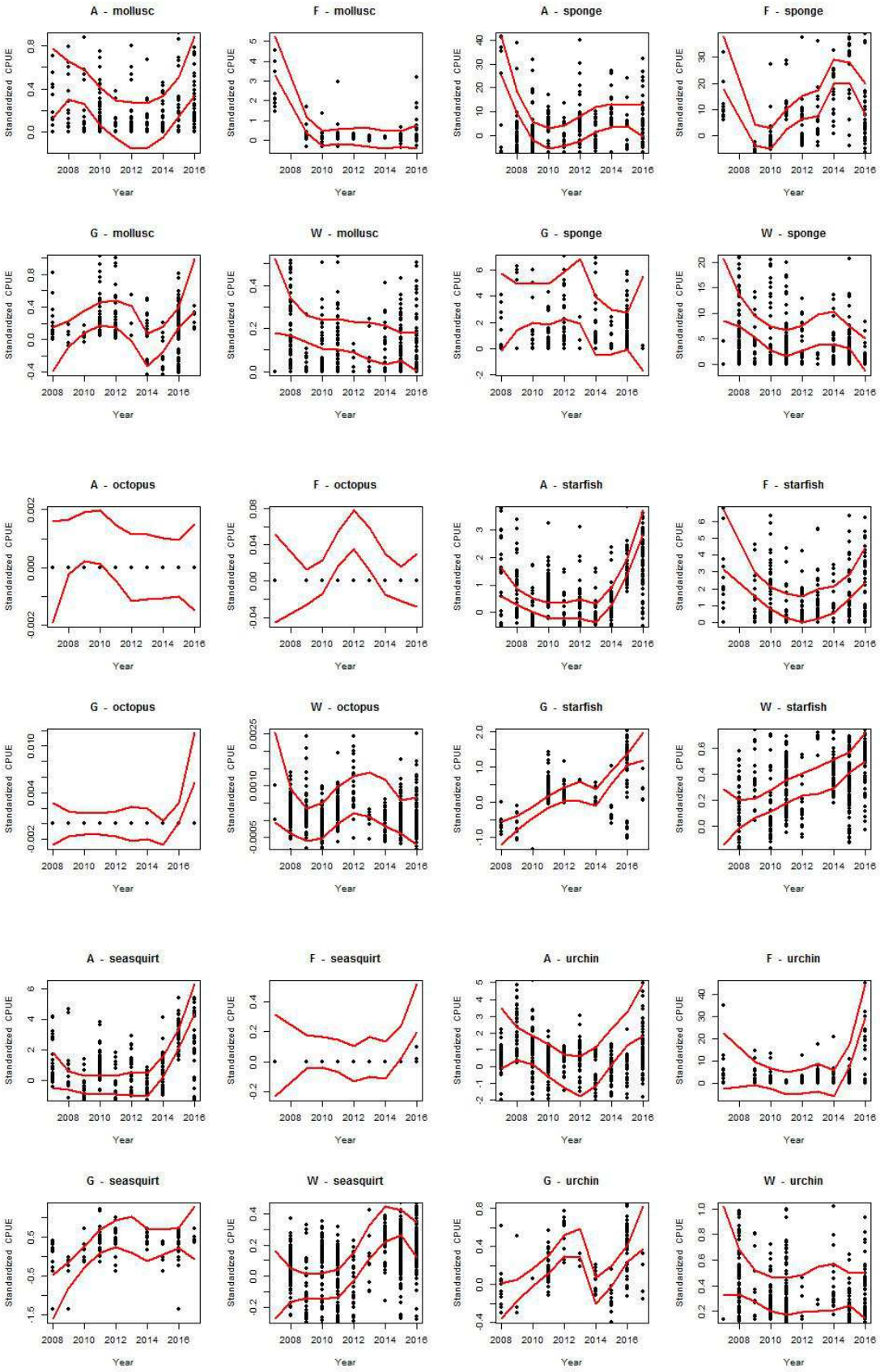
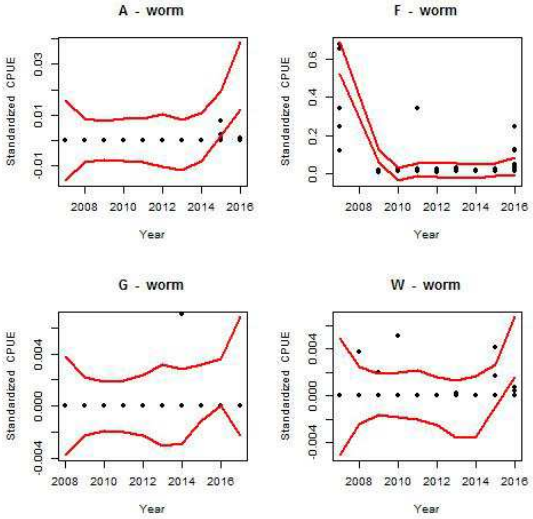
Appendix 1:

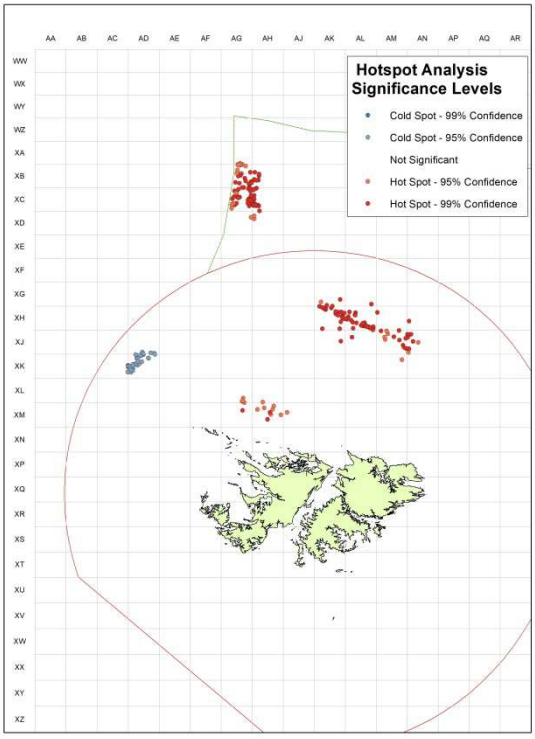

A - algae
F - algae
A - bryozoan
F - bryozoan
G - algae
W - algae
G - bryozoan
W - bryozoan
A - anemone
F - anemone
A - coral
F - coral
G - anemone
W - anemone
G - coral
W - coral
A - brittlestar
F - brittlestar
A - crustacean
F - crustacean
G - brittlestar
W - brittlestar
G - crustacean
W - crustacean
Standardized CPUE
Year


A - mollusc
F - mollusc
A - sponge
F - sponge
G - mollusc
W - mollusc
G - sponge
W - sponge
A - octopus
F - octopus
A - starfish
F - starfish
G - octopus
W - octopus
G - starfish
W - starfish
A - seasquirt
F - seasquirt
A - urchin
F - urchin
G - seasquirt
W - seasquirt
G - urchin
W - urchin
Standardized CPUE
Year


A - worm
F - worm
G - worm
W - worm
Standardized CPUE
Year
2008
2010
2012
2014
2016

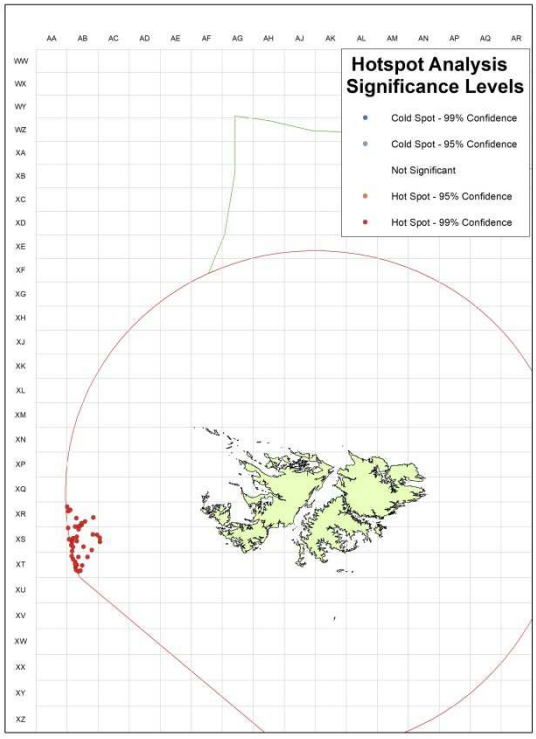
Appendix 2: Getis-Ord GI* hotspots of bycatch CPUE, by invertebrate category.

Algae



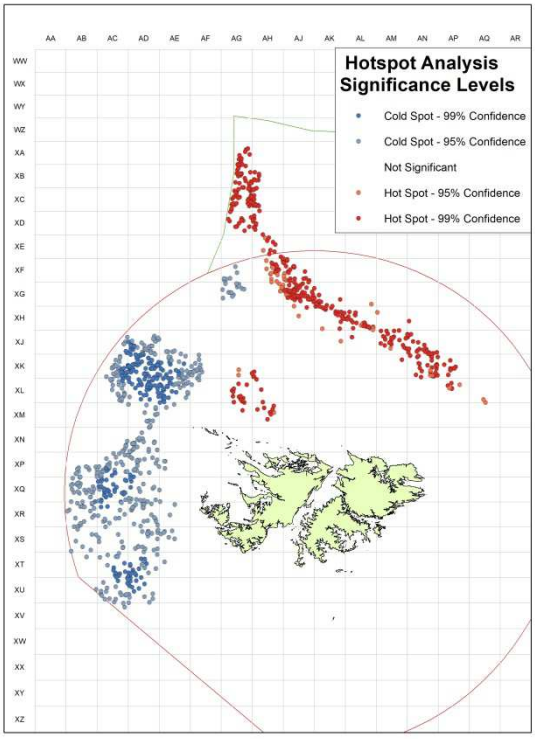
Map 2: Algae

Brittlestar



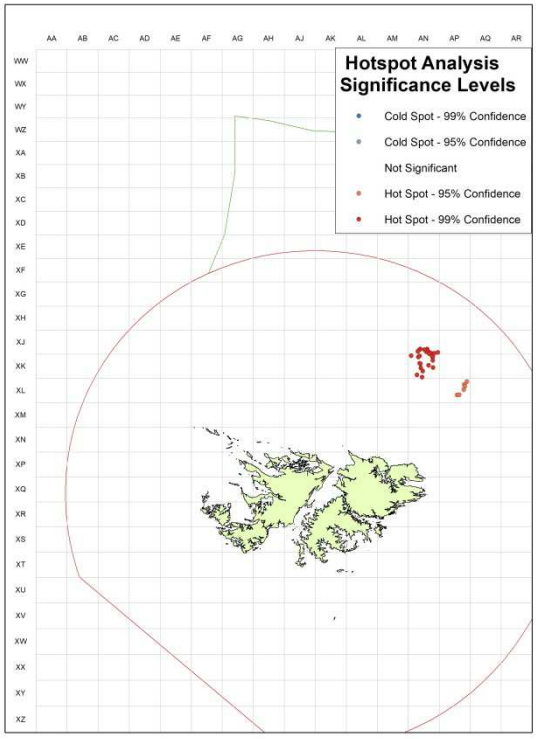
Map 4: Brittle star

Anemone



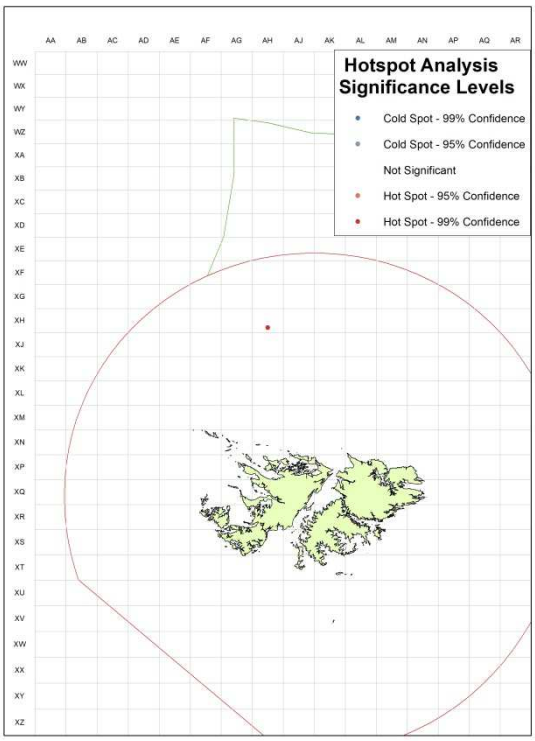
Map 3: Anemone

Bryozoan



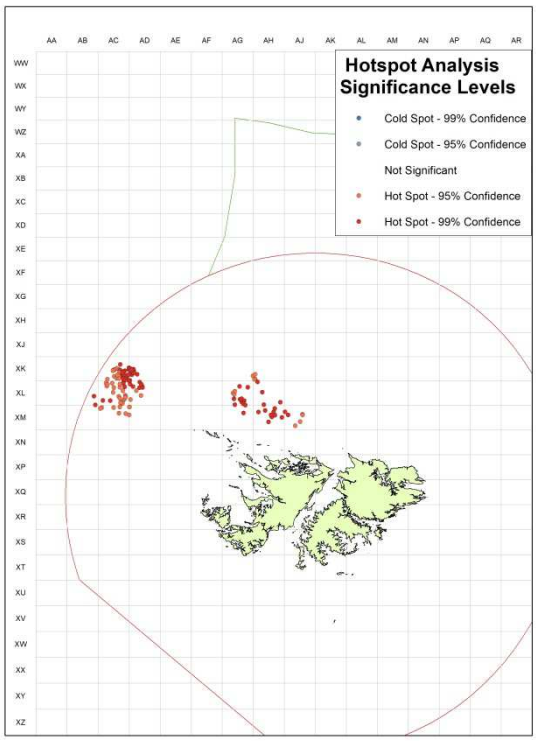
Map 5: Bryozoa

Coral



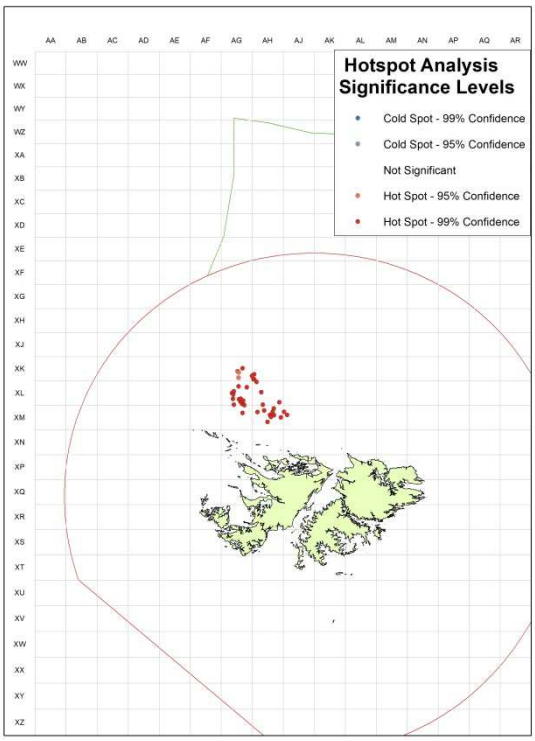
Map 6: Coral

Mollusc



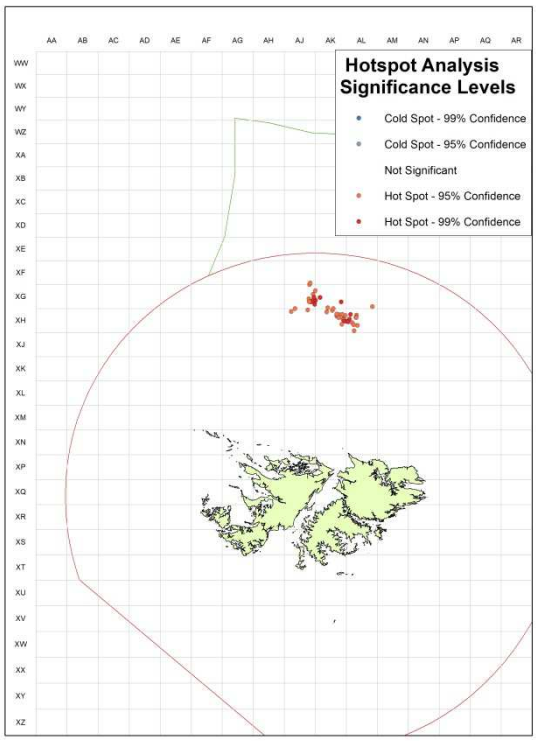
Map 8: Mollusc

Crustacean



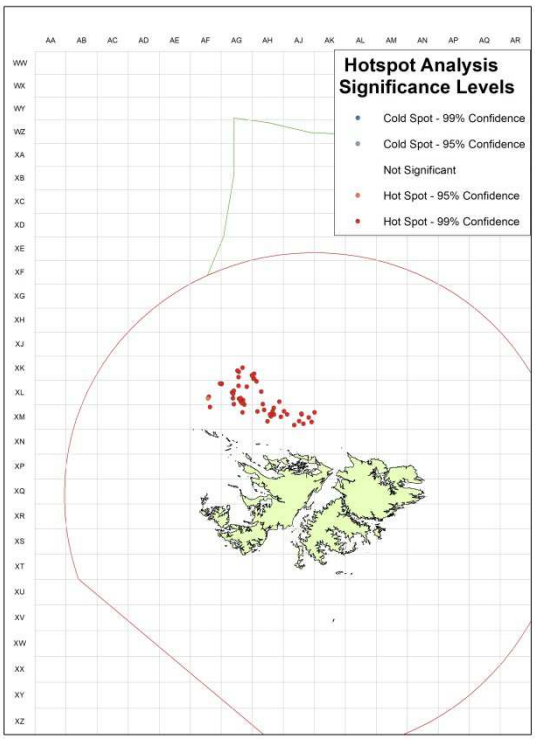
Map 7: Crustacea

Octopus



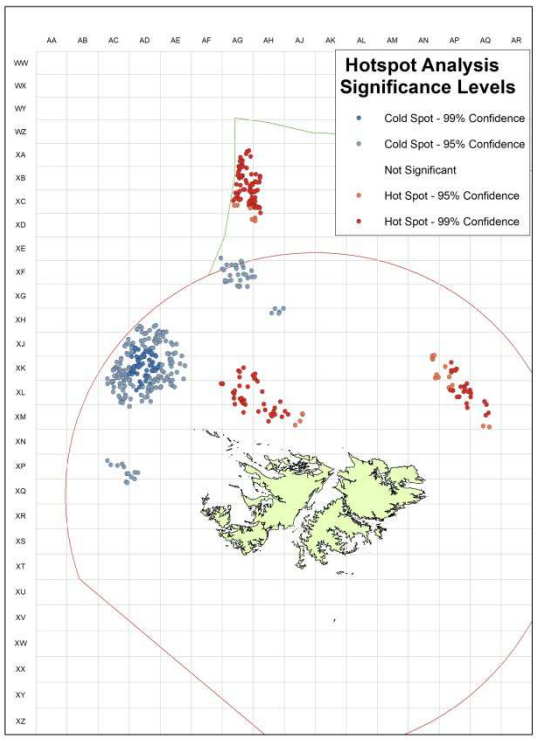
Map 9: Octopus

SeaSquirt



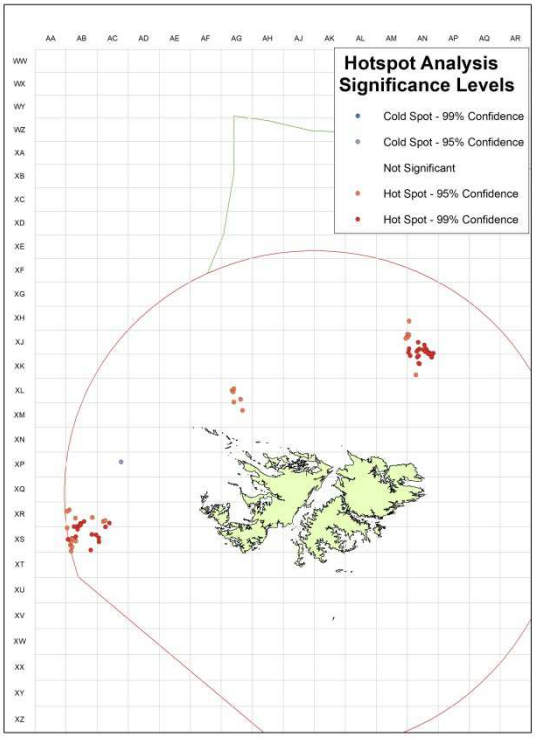
Map 10: Sea squirt

Starfish



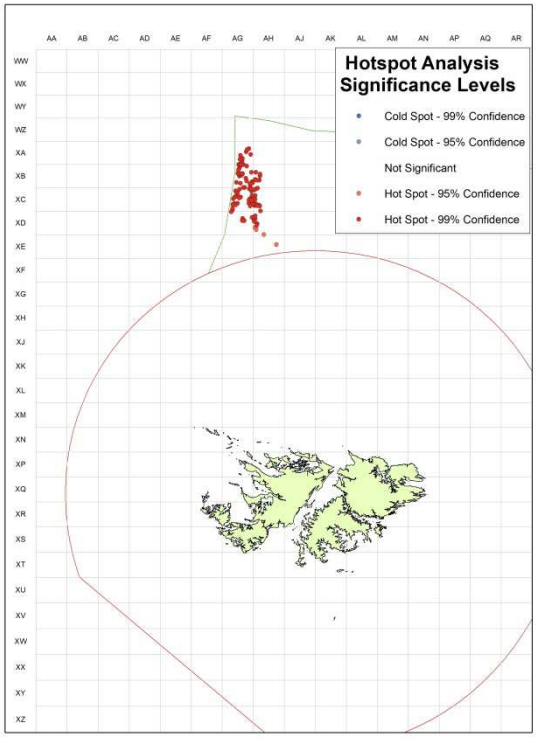
Map 12: Starfish

Sponge



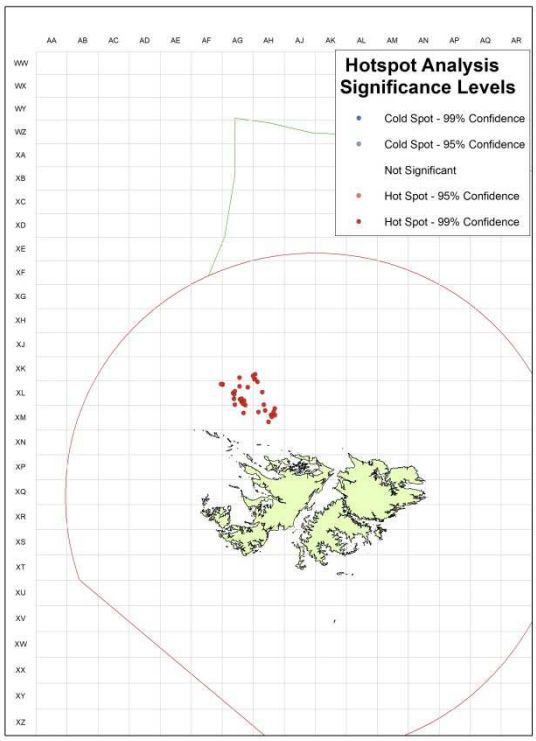
Map 11: Sponge

Urchin



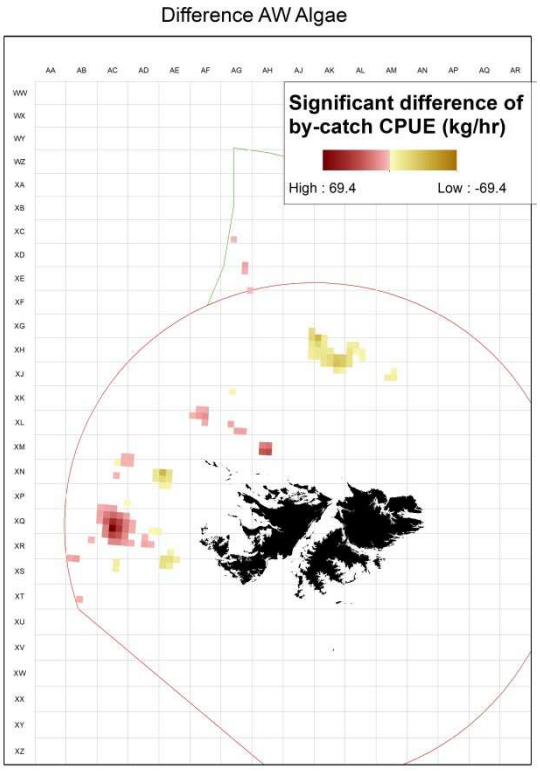
Map 13: Urchin

Worm

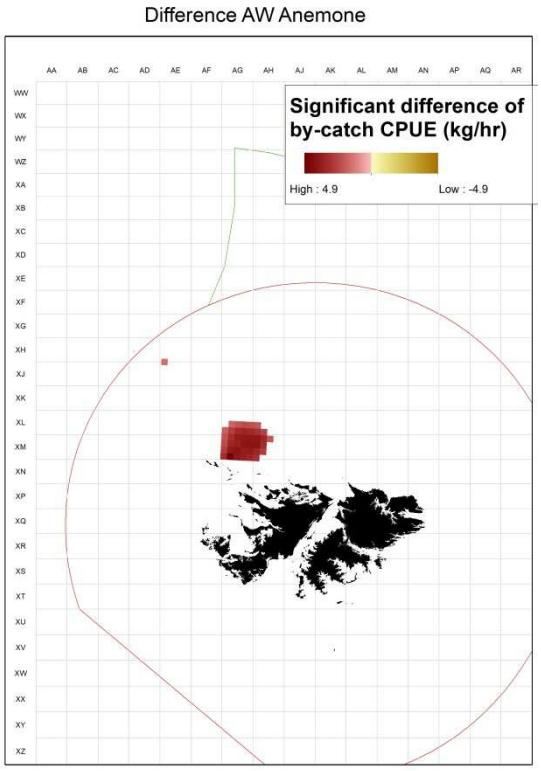


Map 10: Worm

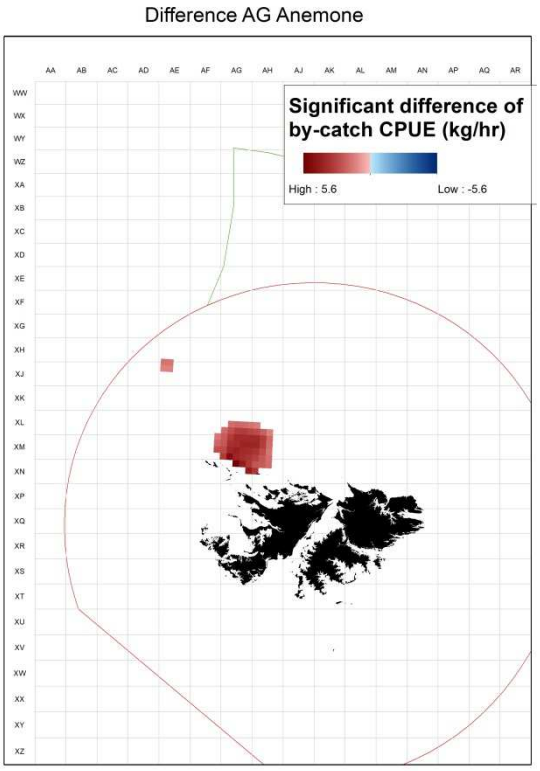
Appendix 3: Pairwise significant bycatch CPUE differences between licences.



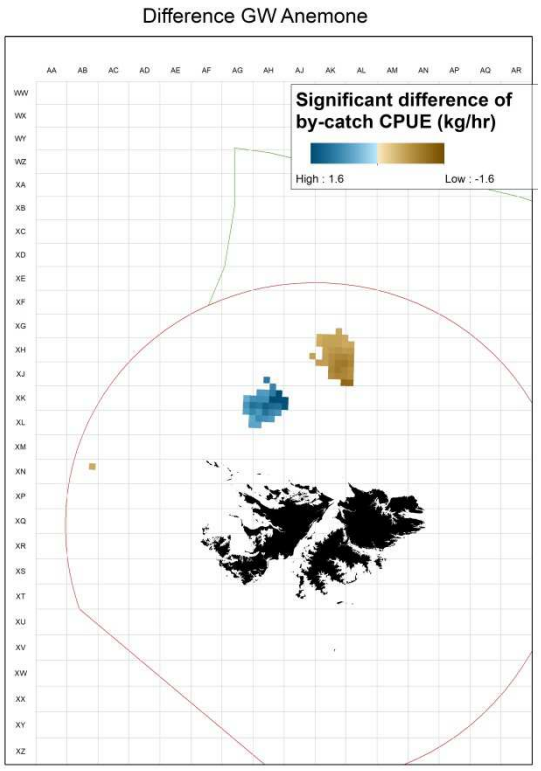
Map 11: Algae - A and W licences



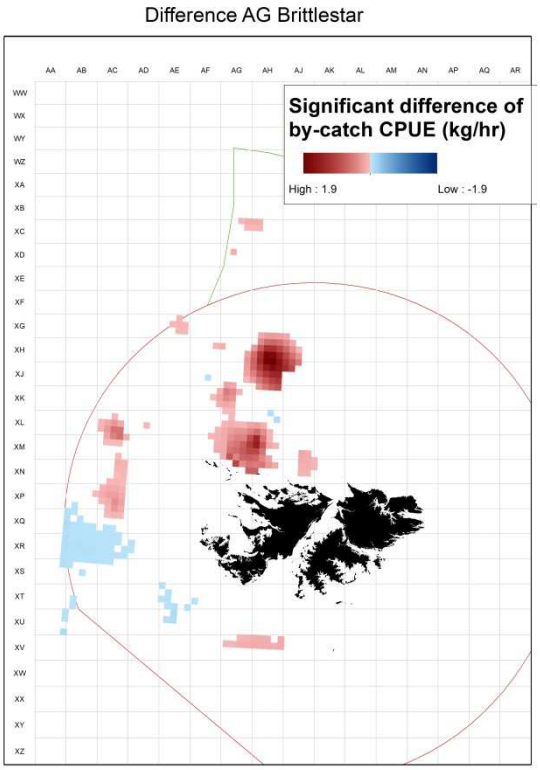
Map 13: Anemone - A and W licences



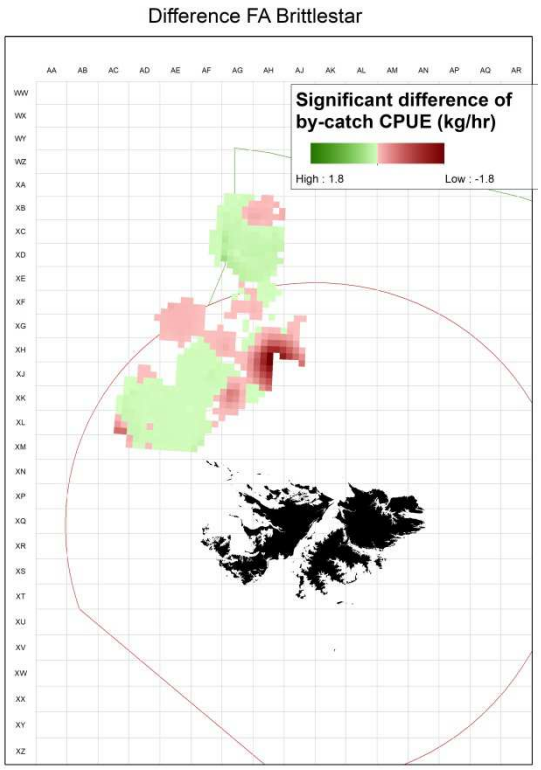
Map 12: Anemone - A and G licences



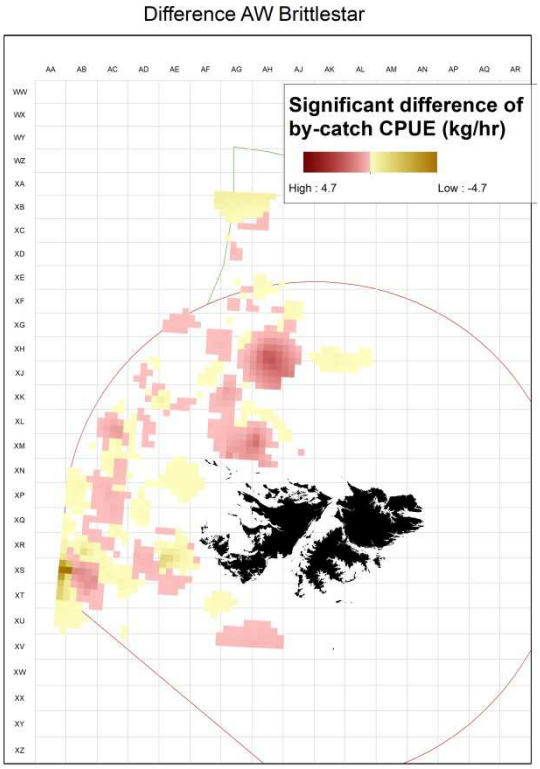
Map 14: Anemone - G and W licences



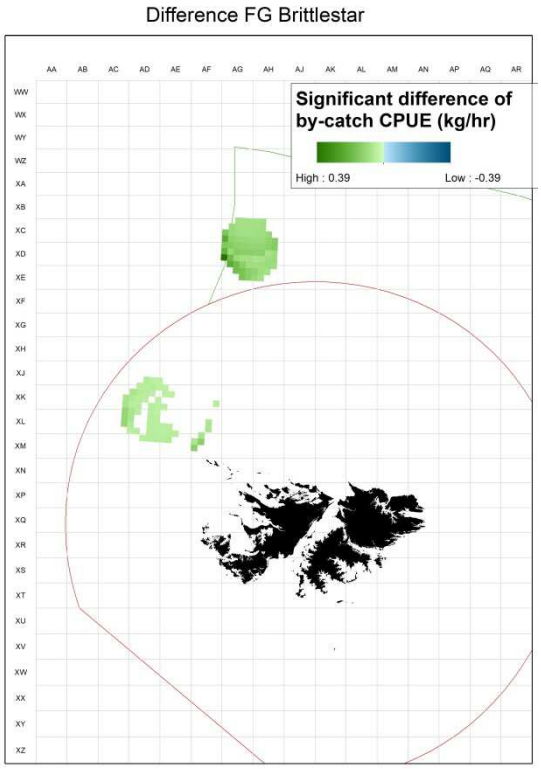
Map 15: Brittle star of A - G licences



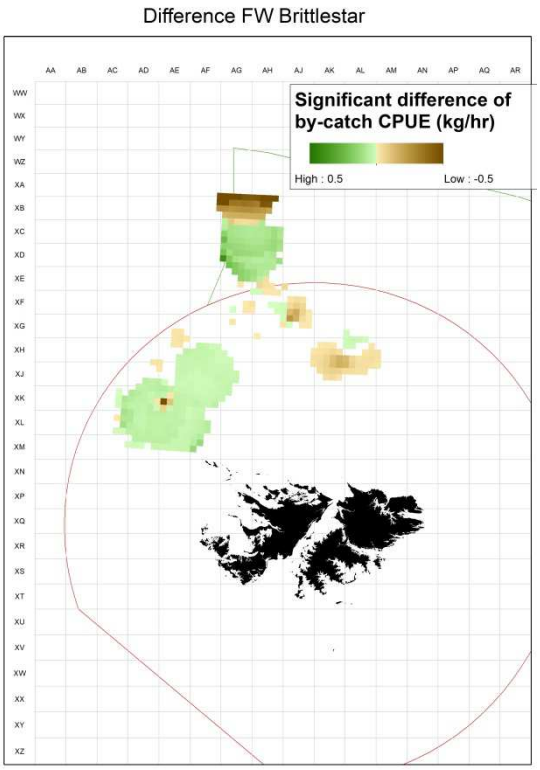
Map 17: Brittle star - F and A licences



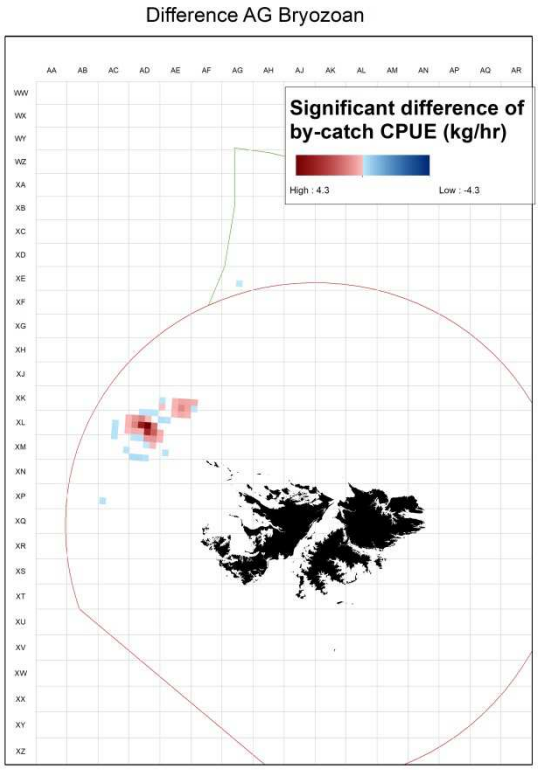
Map 16: Brittle star - A and W licences



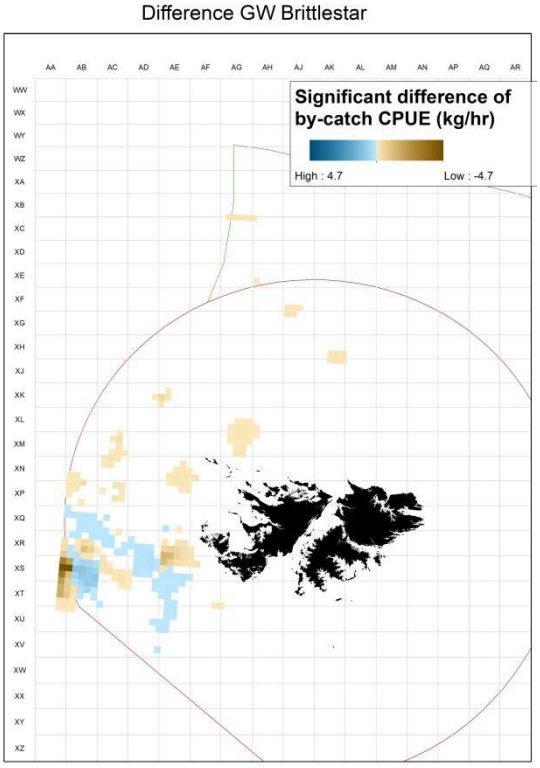
Map 18 : Brittle star - F and G licences



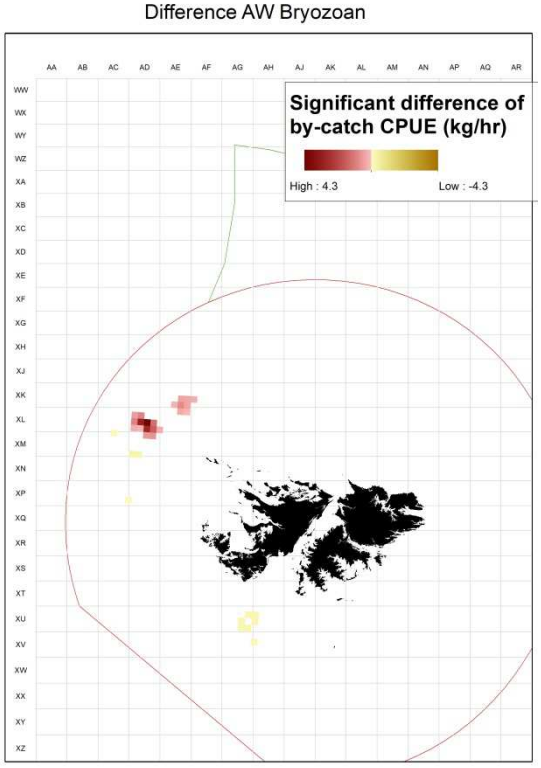
Map 19: Brittle star - F and W licences



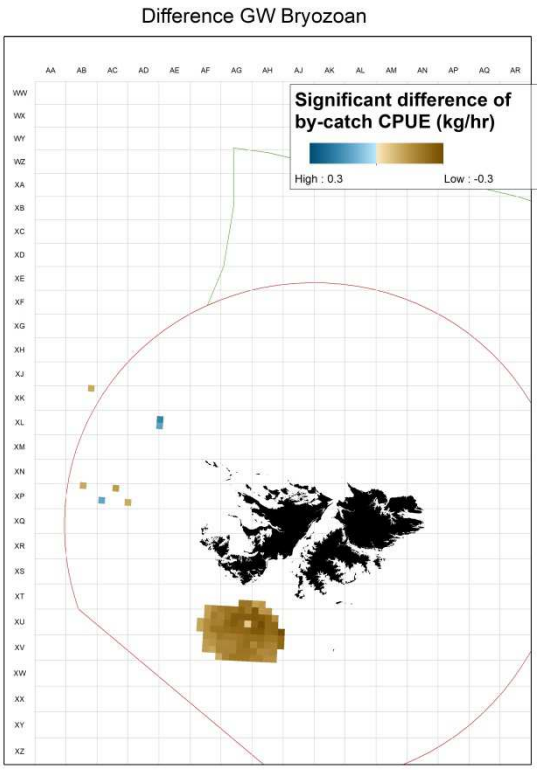
Map 21: Bryozoan - A and G licences



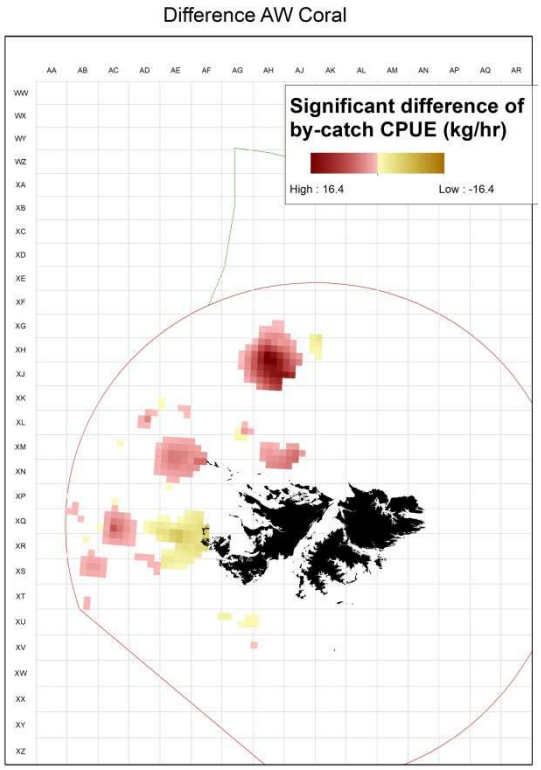
Map 20: Brittle star - G and W licences



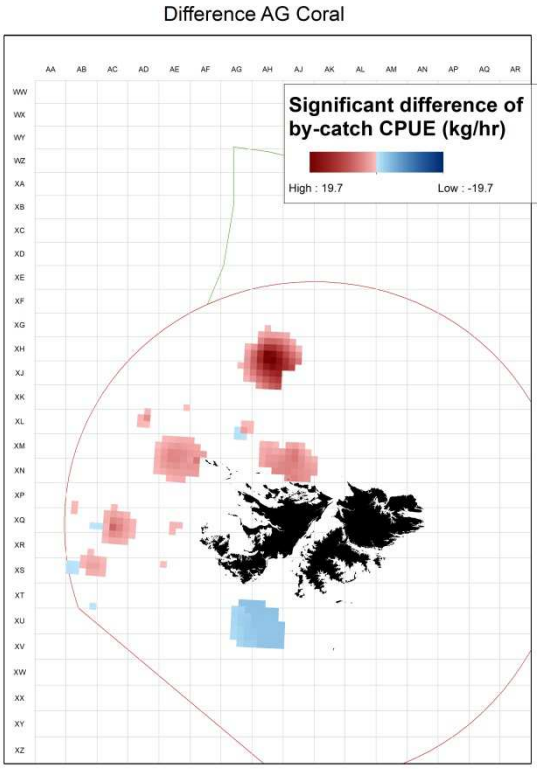
Map 22: Bryozoan - A and W licences



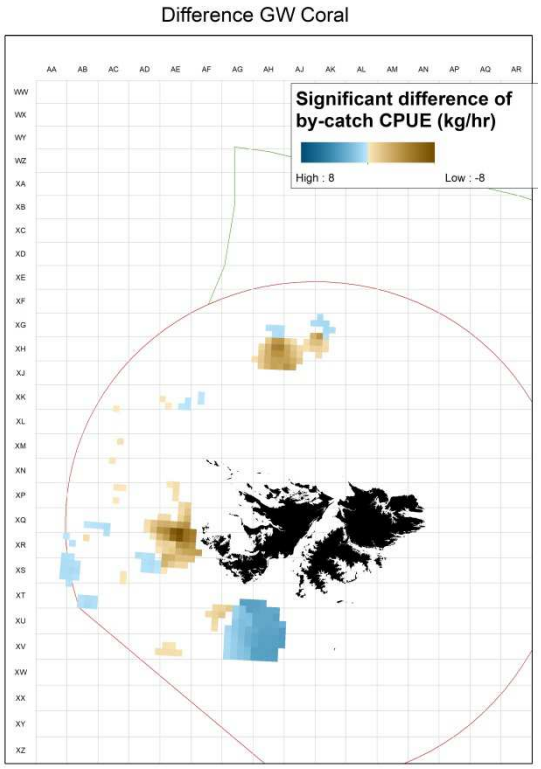
Map 23: Bryozoan - G and W licences



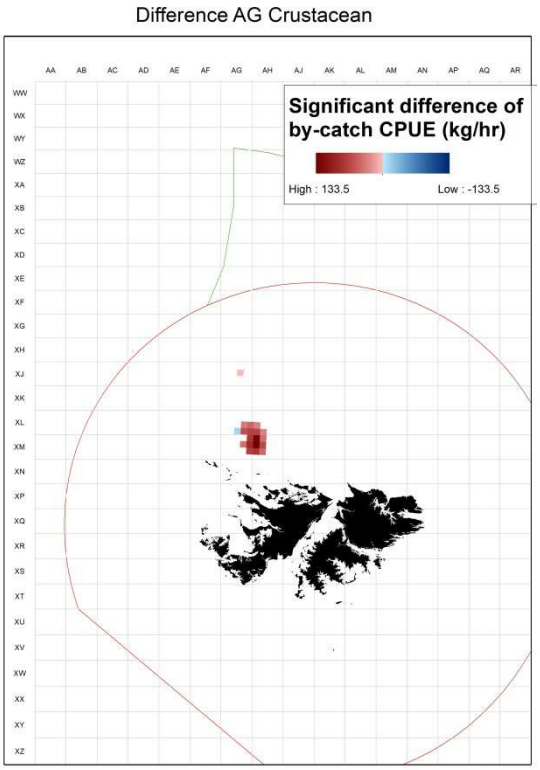
Map 25: Coral - A and W licences



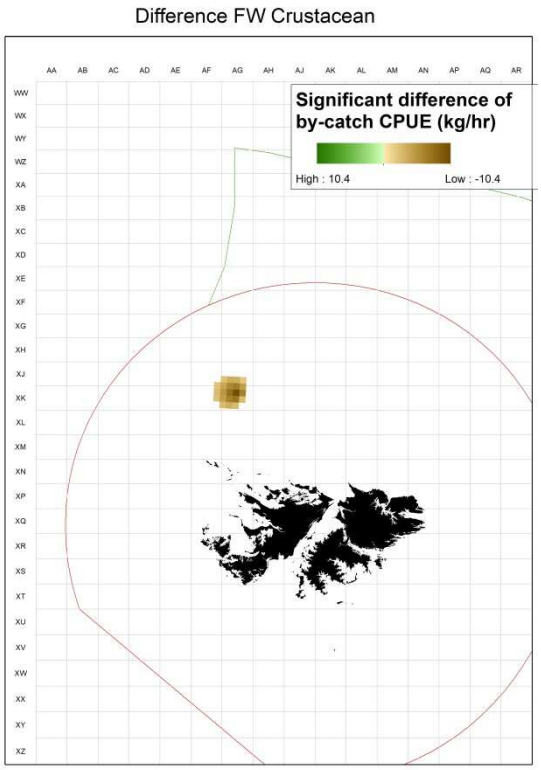
Map 24: Coral - A and G licences



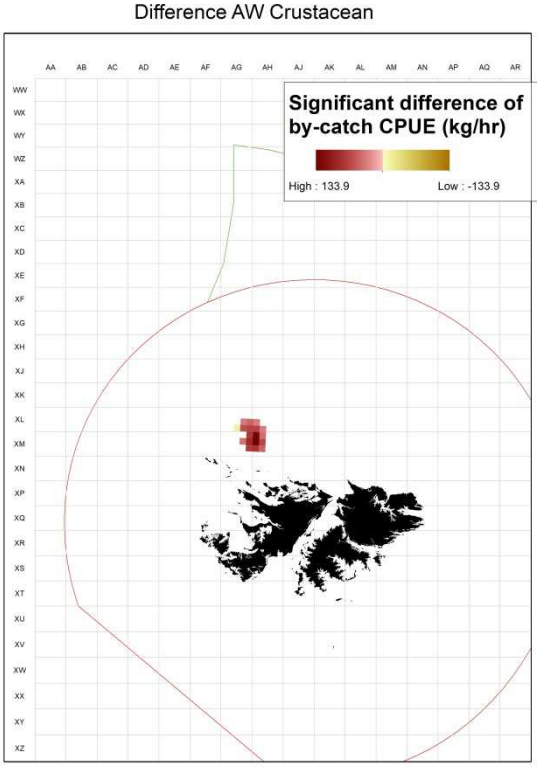
Map 26: Coral - G and W licences



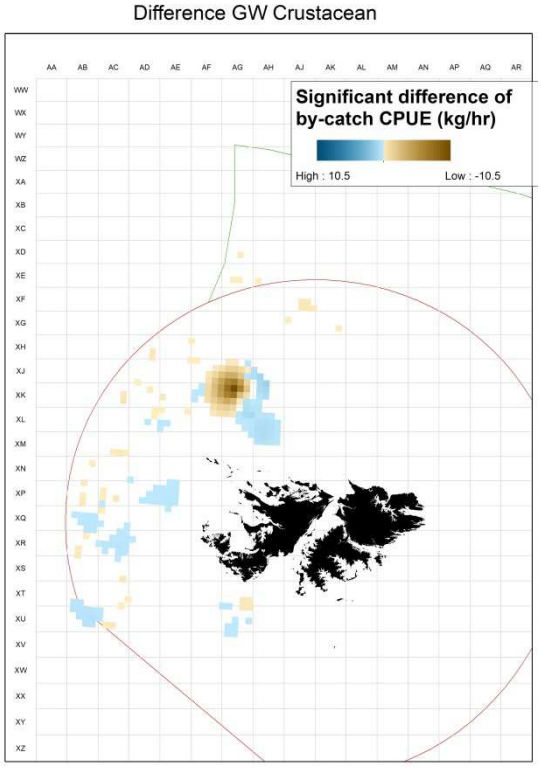
Map 27: Crustacean - A and G licences



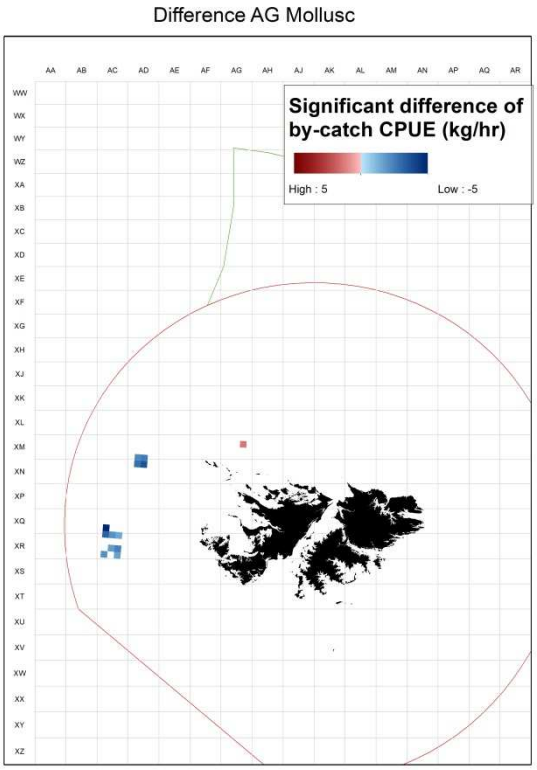
Map 29: Crustacean - F and W licences



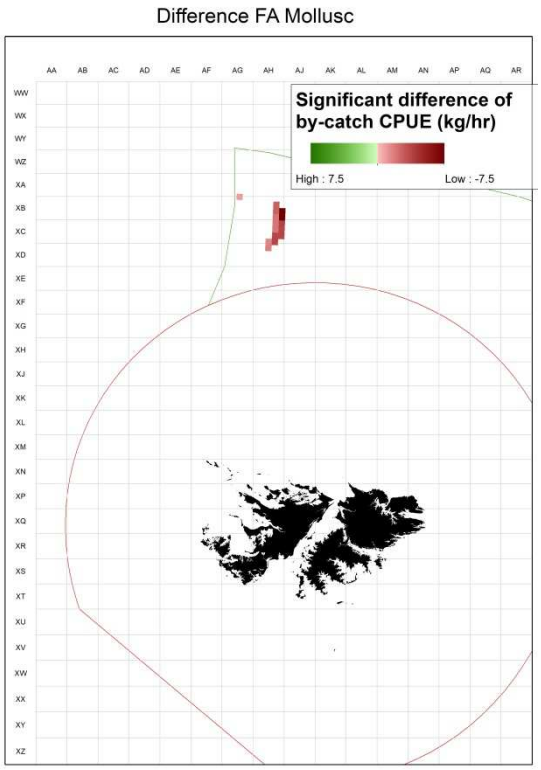
Map 28: Crustacean - A and W licences



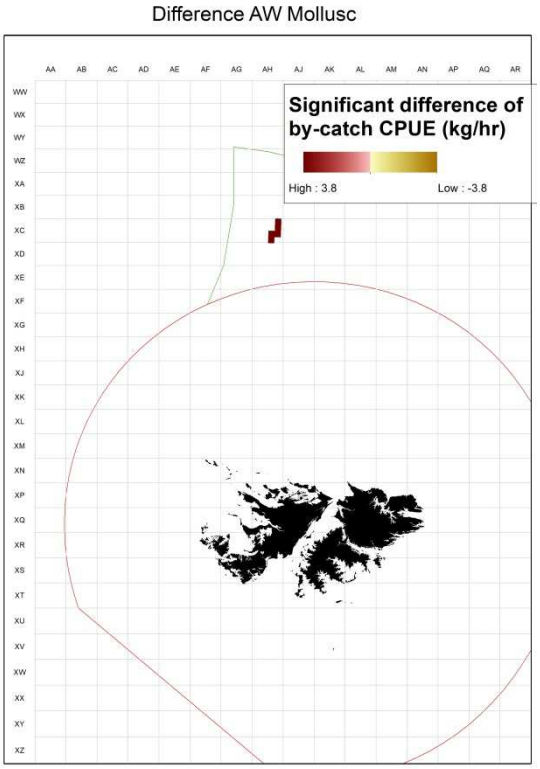
Map 30: Crustacean - G and W licences



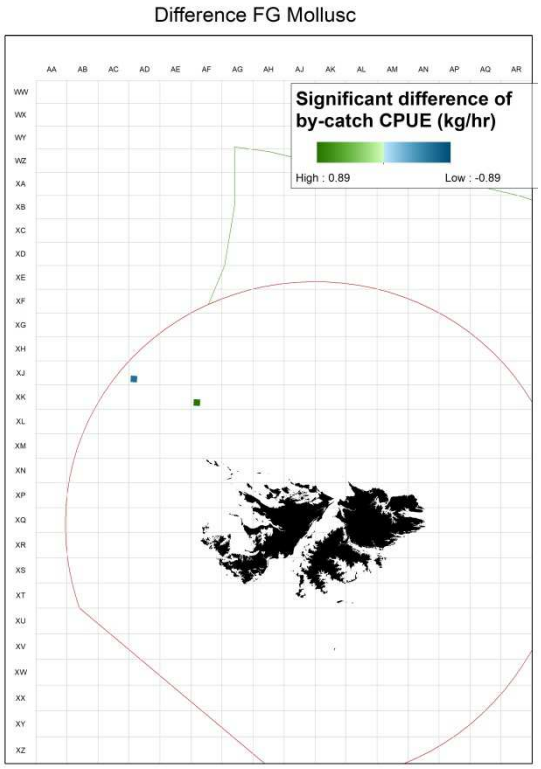
Map 31: Mollusc - A and G licences



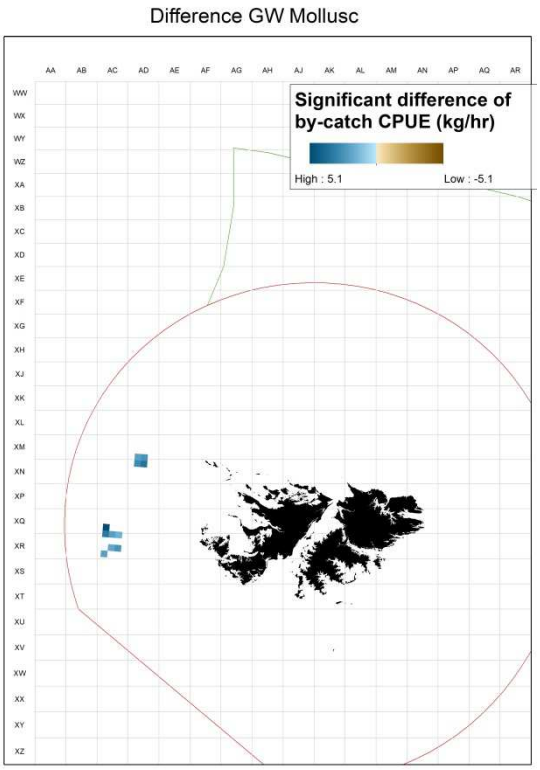
Map 33: Mollusc - F and A licences



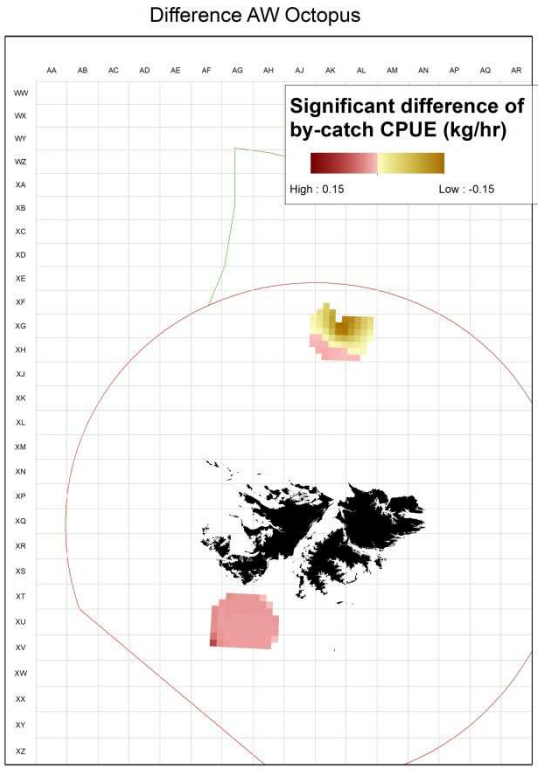
Map 32: Mollusc - A and W licences



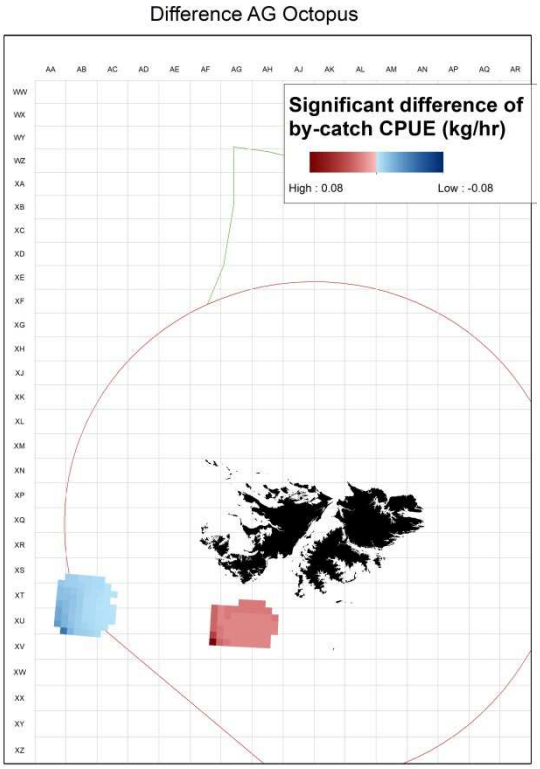
Map 34: Mollusc - F and G licences



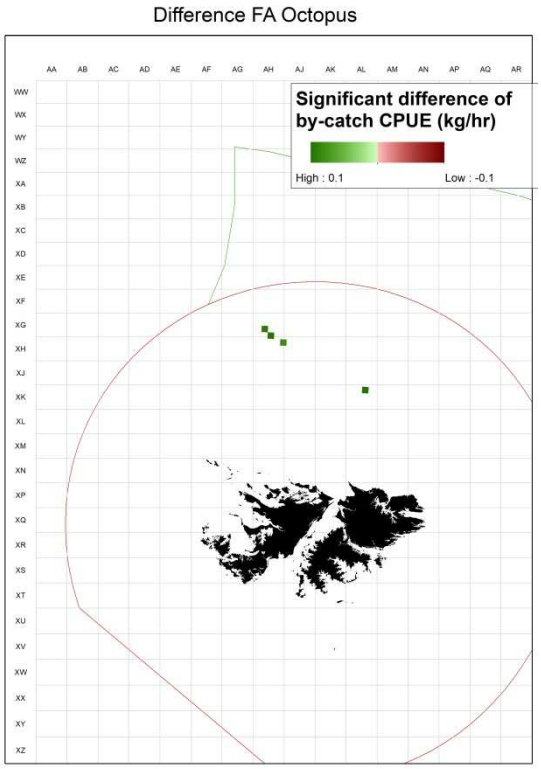
Map 35: Mollusc - G and W licences



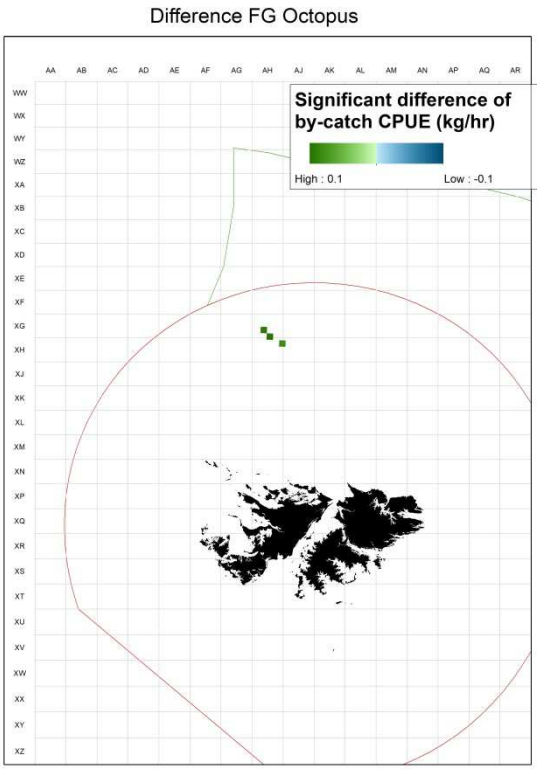
Map 37: Octopus - A and W licences



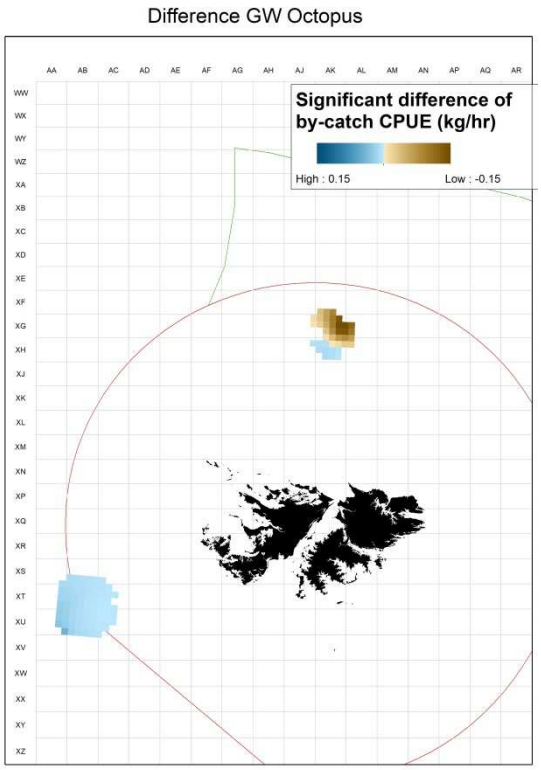
Map 36: Octopus - A and G licences



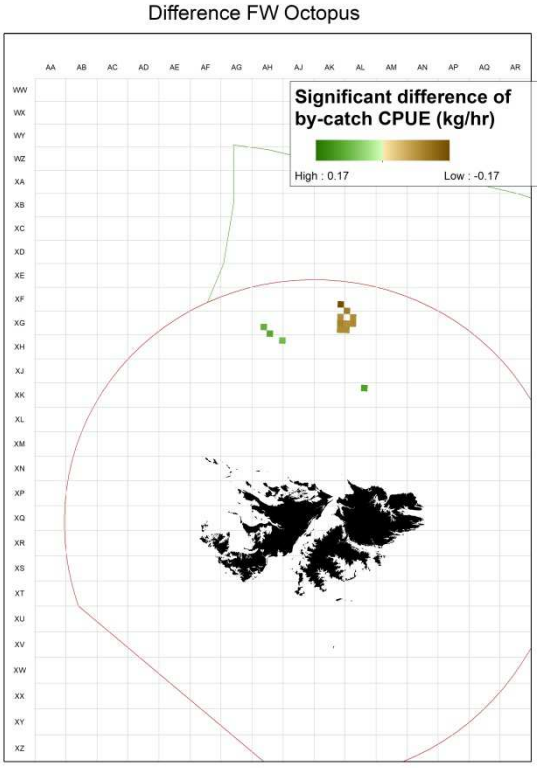
Map 38: Octopus - F and A licences



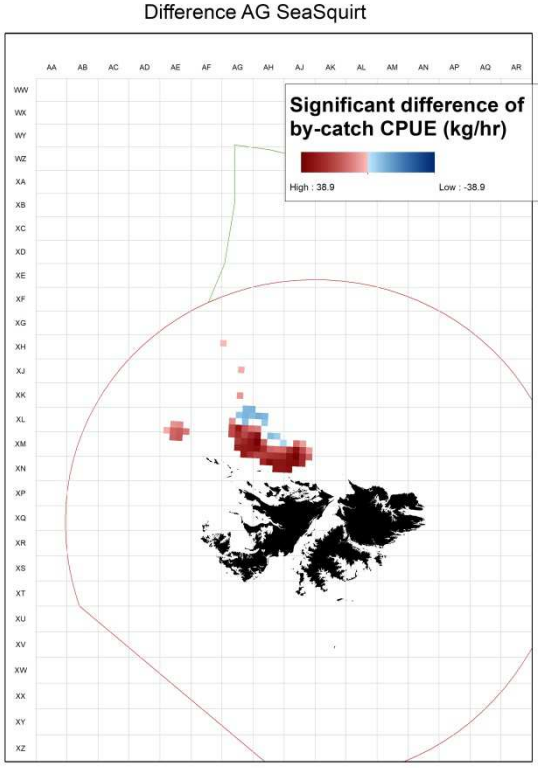
Map 39: Octopus - F and G licences



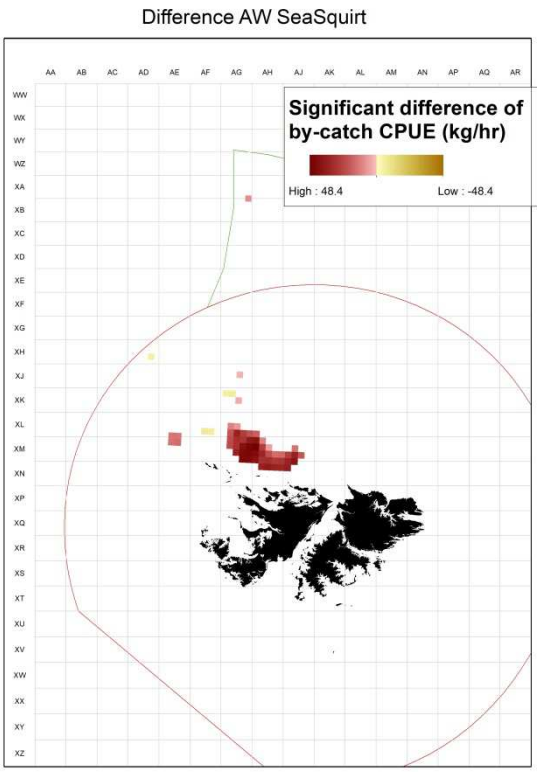
Map 41: Octopus - G and W licences



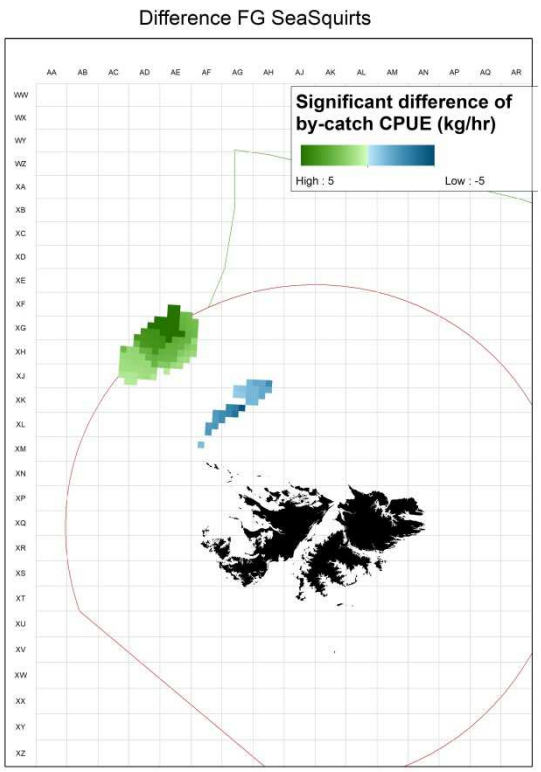
Map 40: Octopus - A and W licences



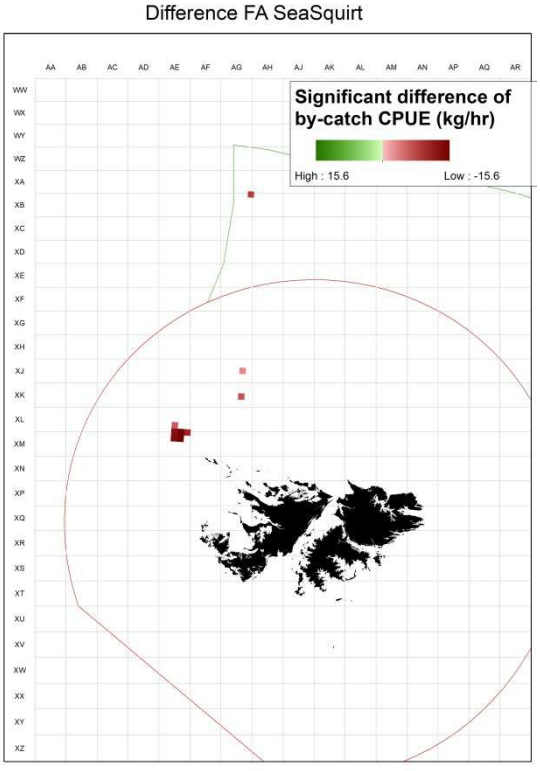
Map 42: Sea Squirt - A and G licences



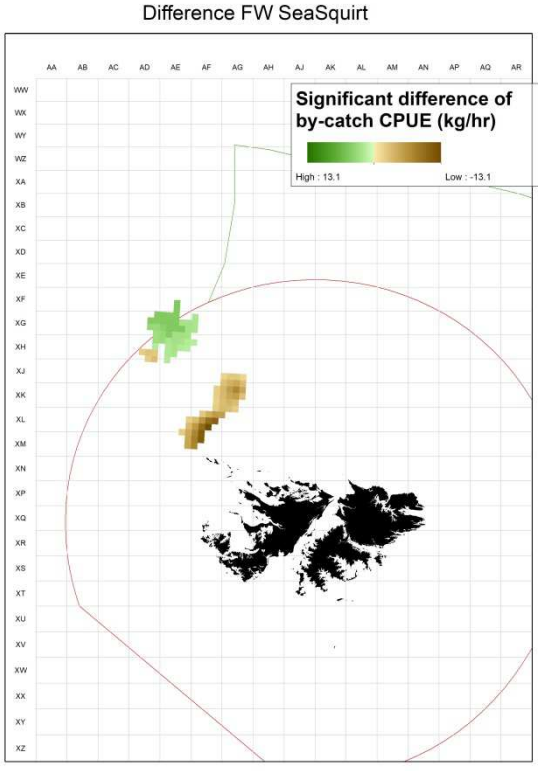
Map 43: Sea Squirt - A and W licences



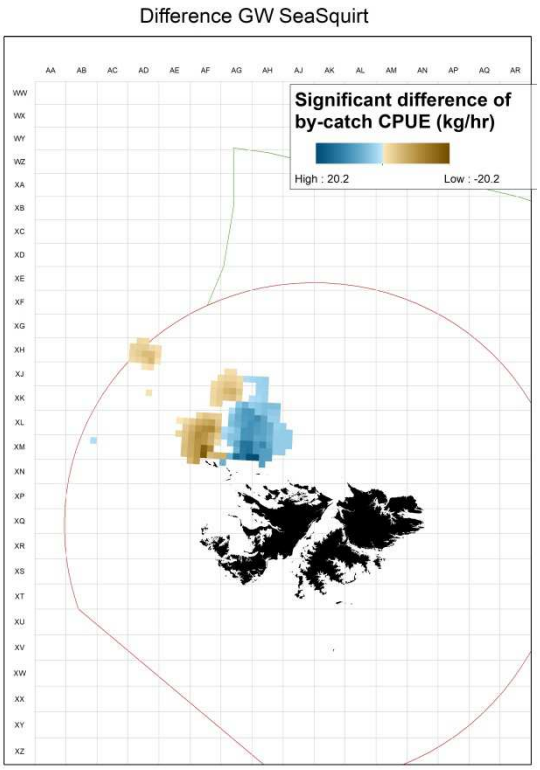
Map 45: Sea Squirt - F and G licences



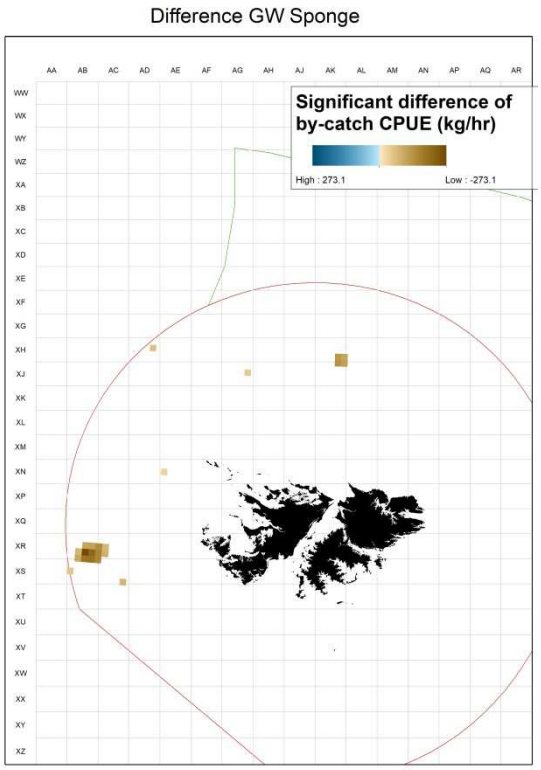
Map 44: Sea Squirt - F and A licences



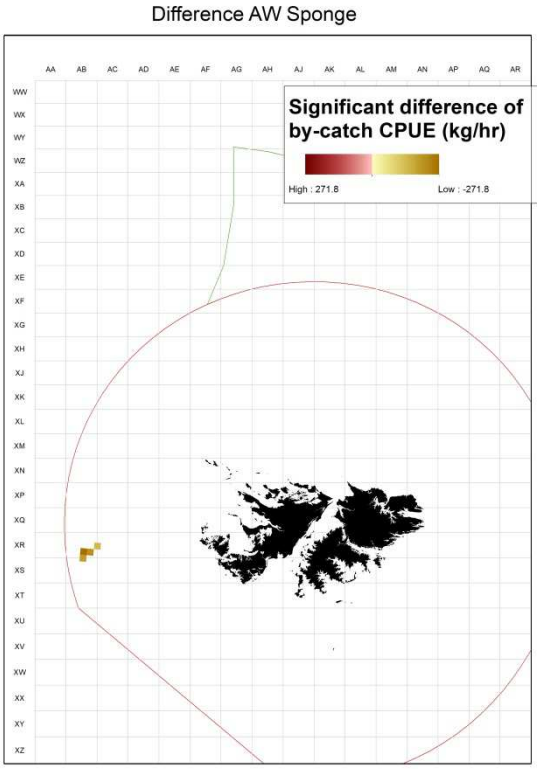
Map 46: Sea Squirt - F and W licences



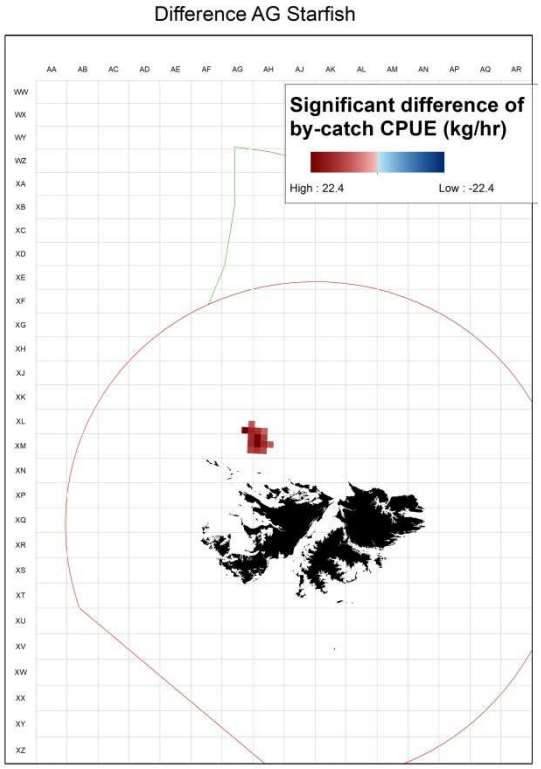
Map 47: Sea Squirt - G and W licences



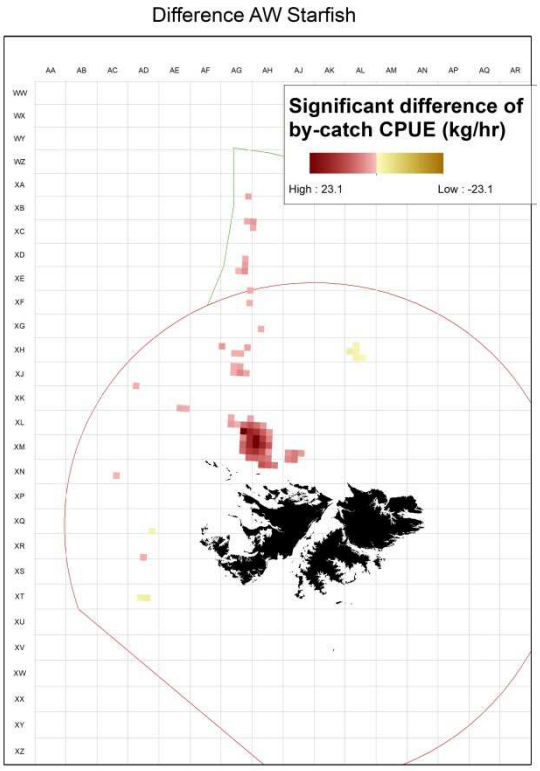
Map 49: Sponge - G and W licences



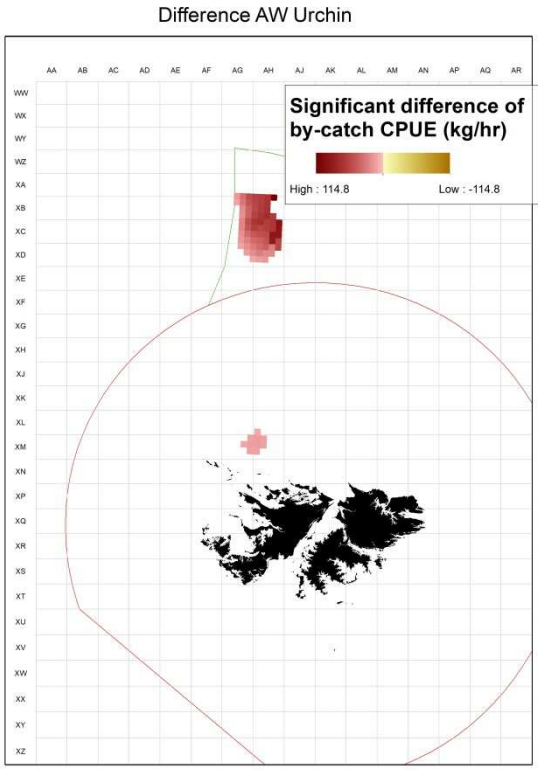
Map 48: Sponge - A and W licences



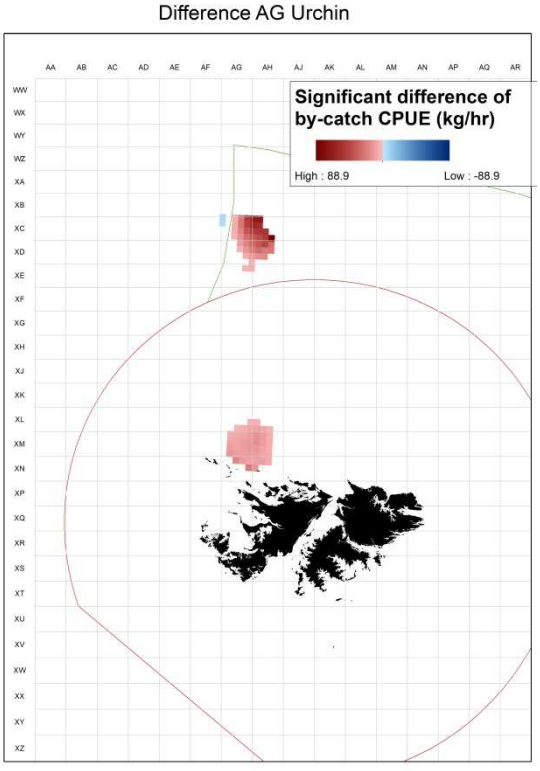
Map 50: Starfish - A and G licences



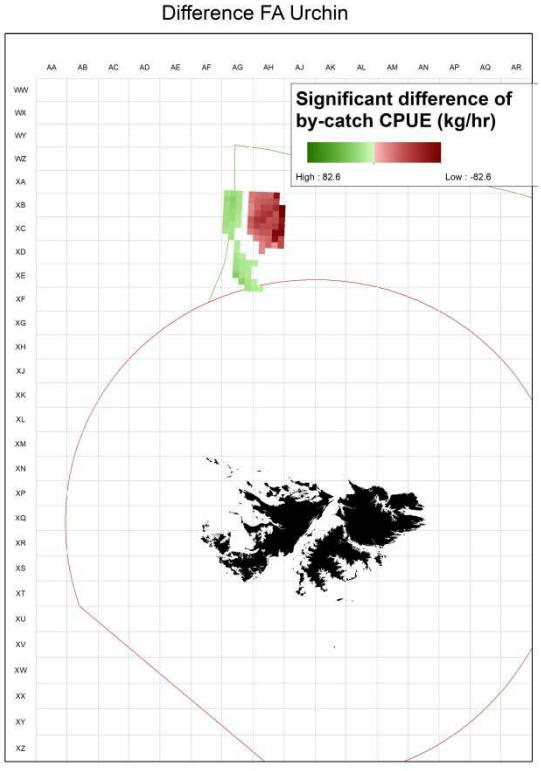
Map 51: Starfish - A and W licences



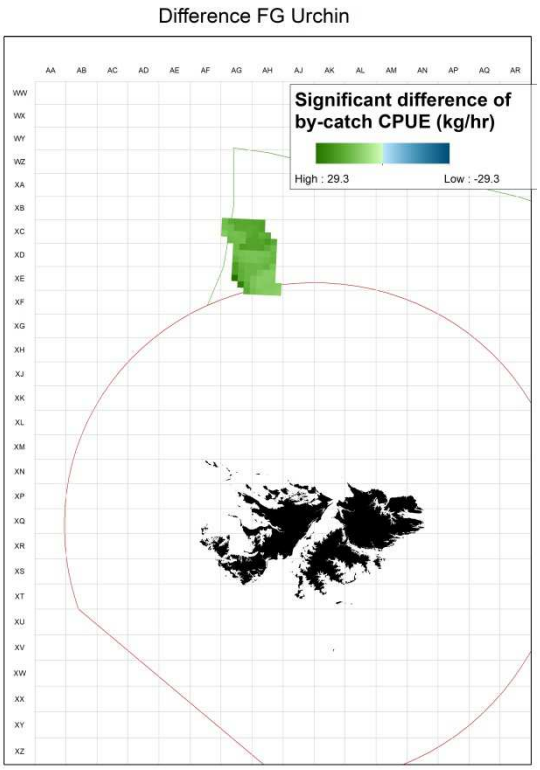
Map 53: Urchin - A and W licences



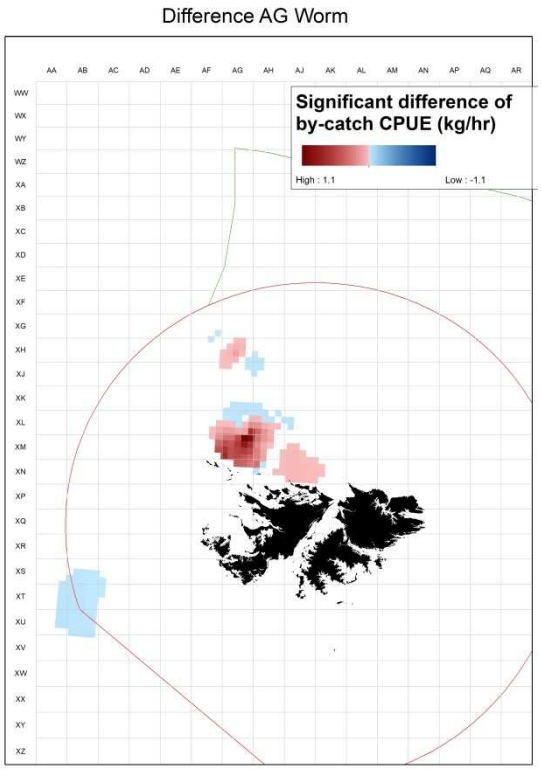
Map 52: Urchin - A and G licences



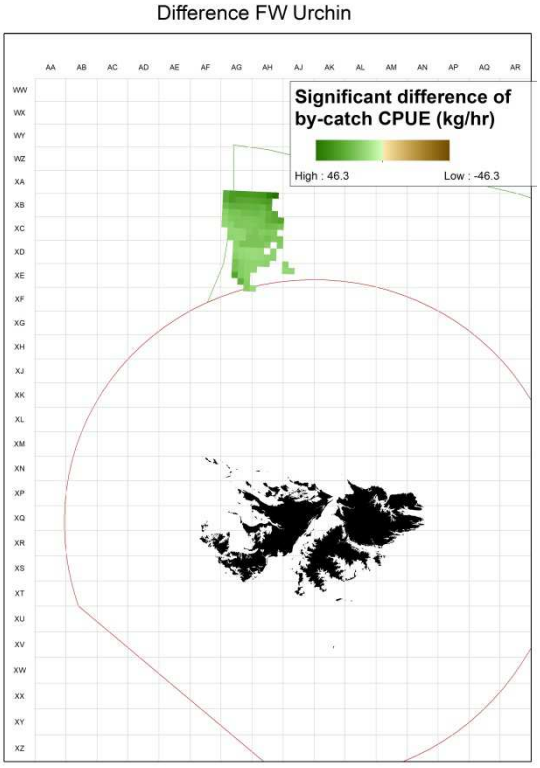
Map 54: Urchin - F and A licences



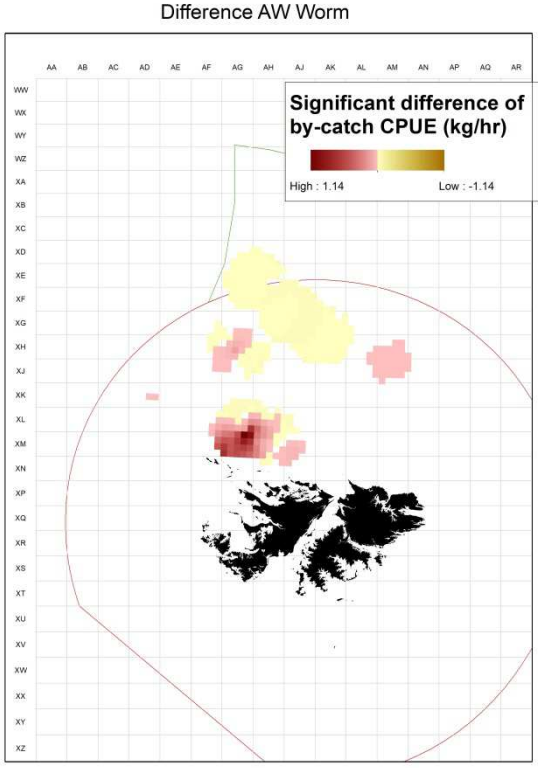
Map 55: Urchin - F and G licences



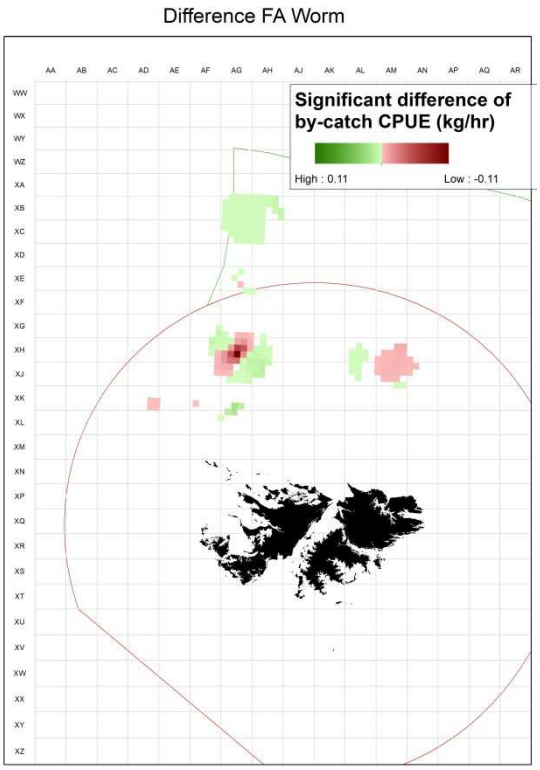
Map 57: Worm - A and G licences



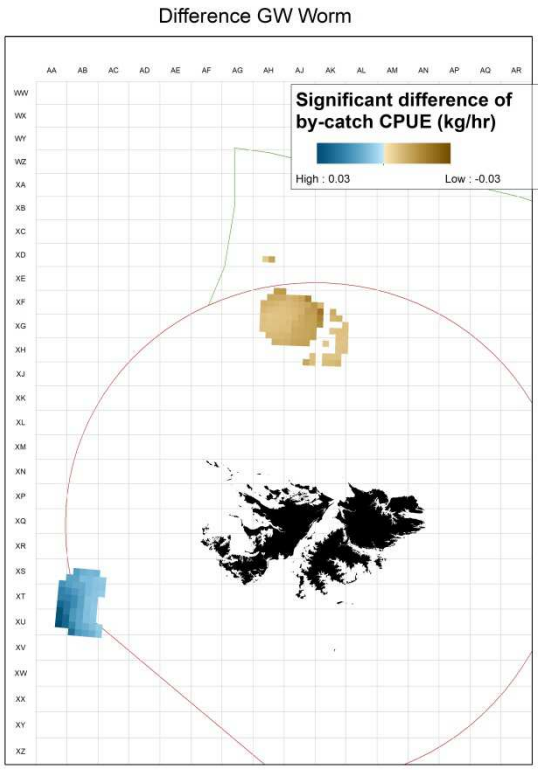
Map 56: Urchin - F and W licences



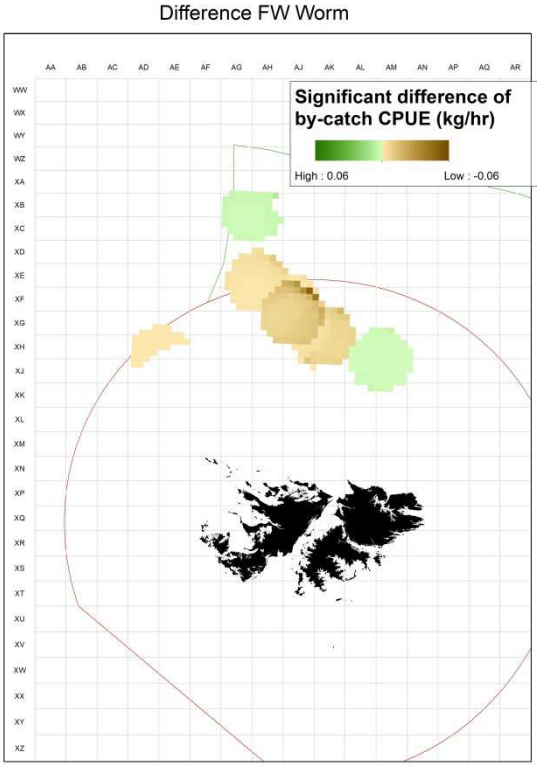
Map 58: Worm - A and W licences



Map 59: Worm - F and A licences

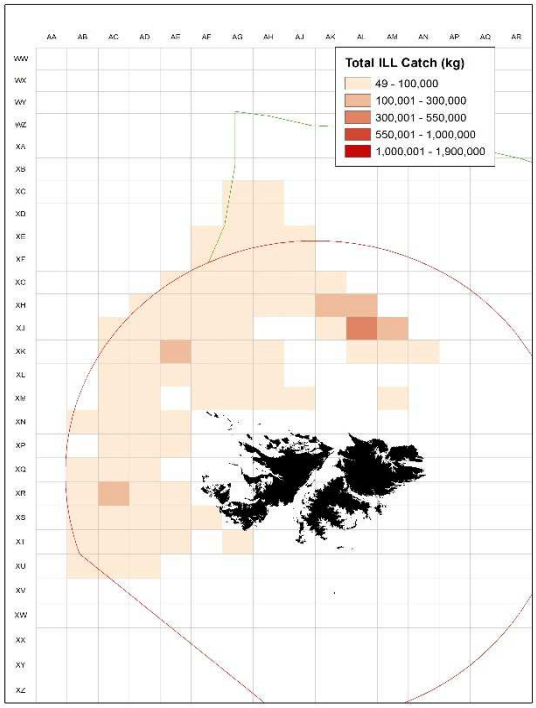


Map 61: Worm - G and W licences

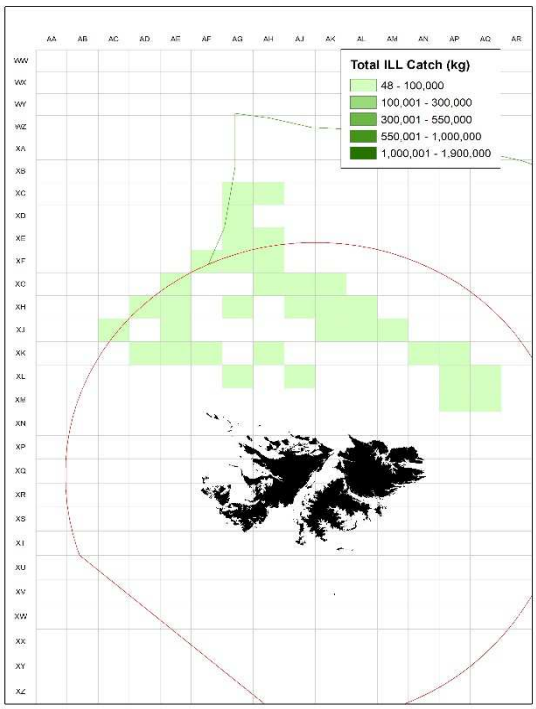


Map 60: Worm - F and W licences

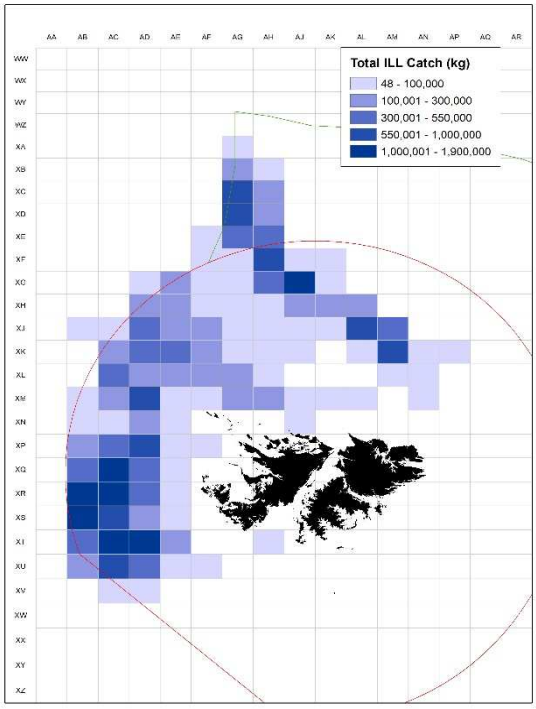
Appendix 4: Target species catches / CPUE by licence, 2007 to 2016



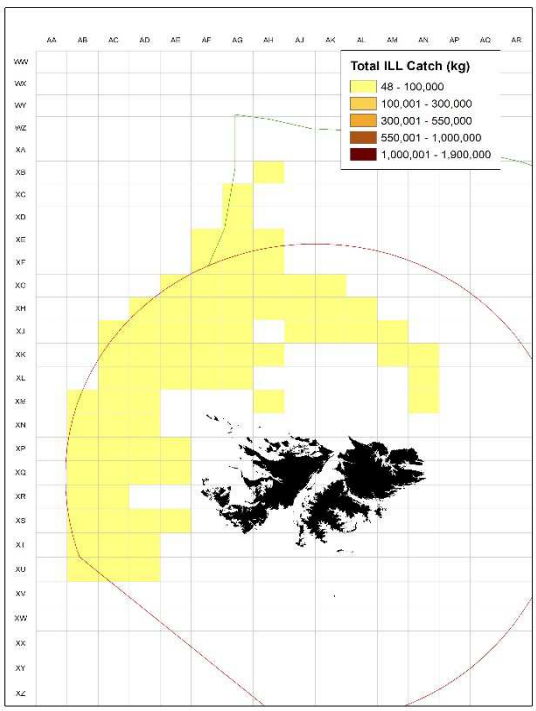
Map 62: *Illex* total catch, A licence



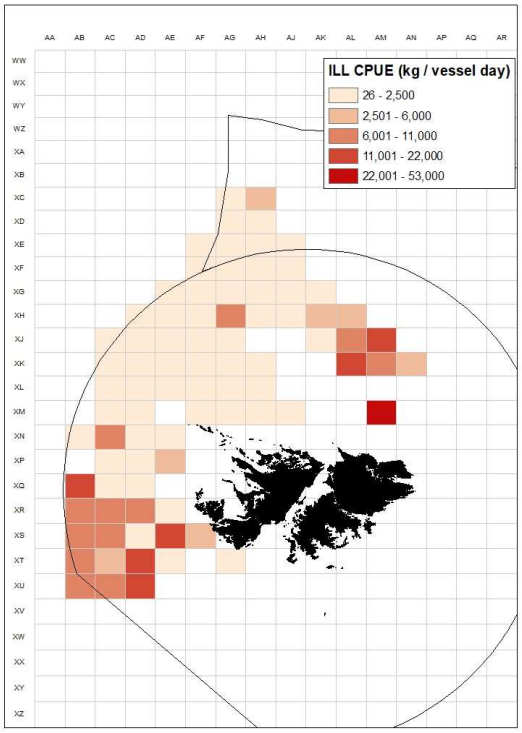
Map 63: *Illex* total catch, F licence



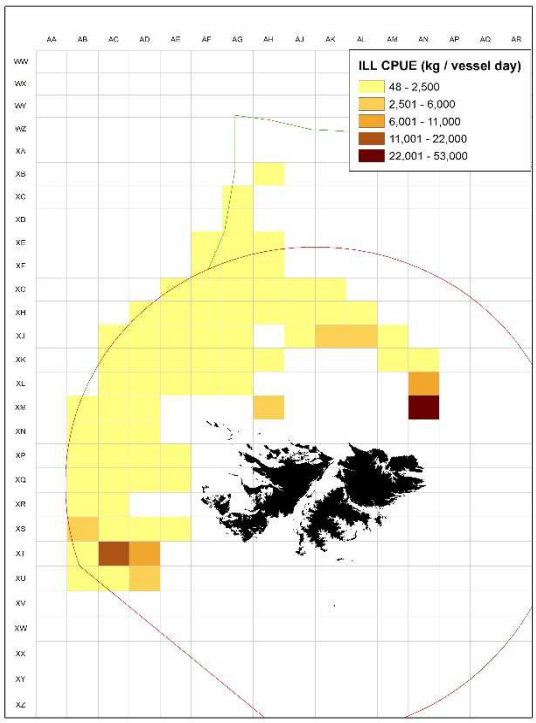
Map 64: *Illex* total catch, G licence



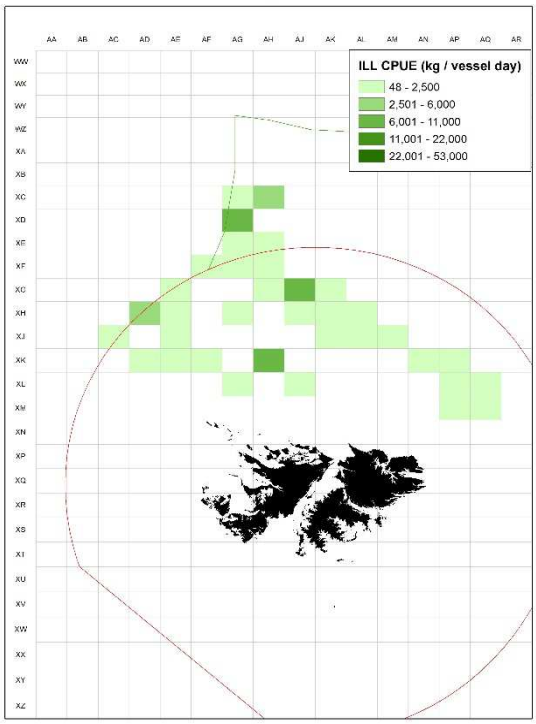
Map 65: *Illex* total catch, W licence



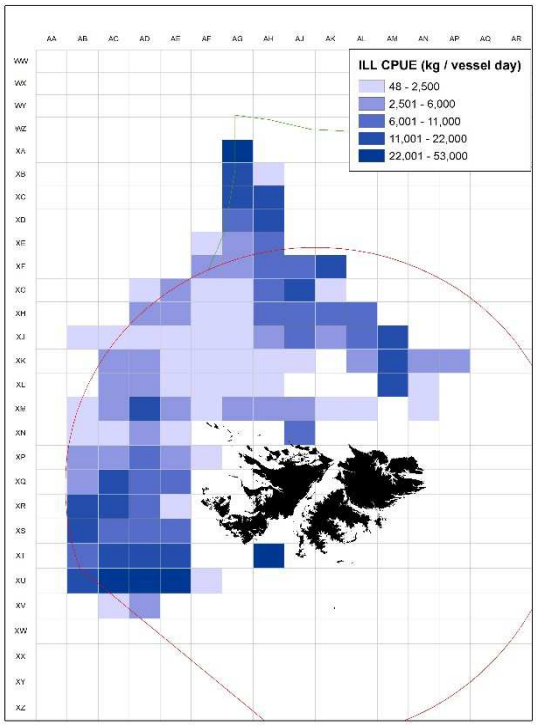
Map 66: *Illex* CPUE, A licence



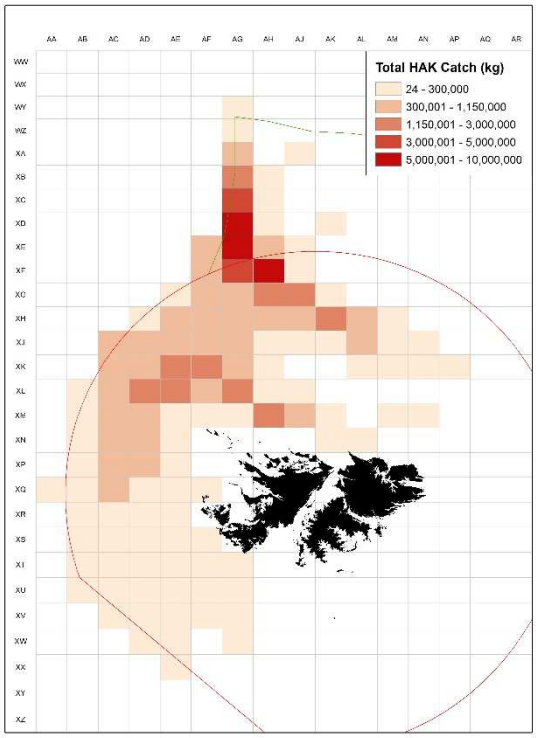
Map 68: *Illex* CPUE, W licence



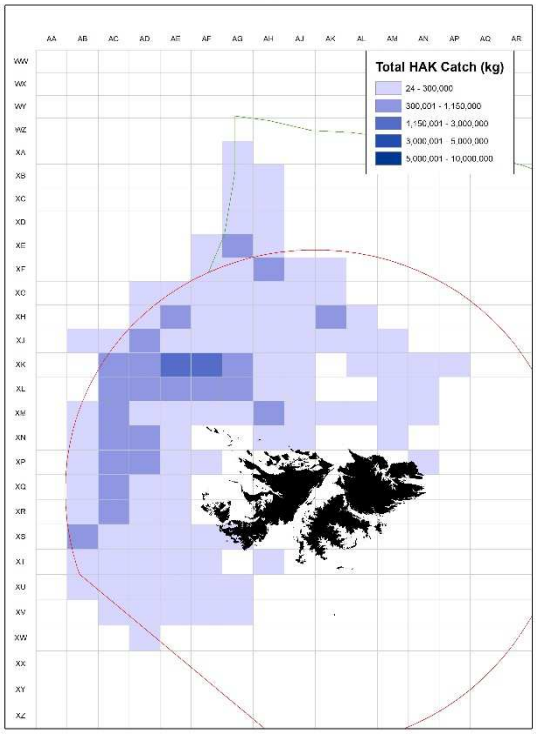
Map 67: *Illex* CPUE, F licence



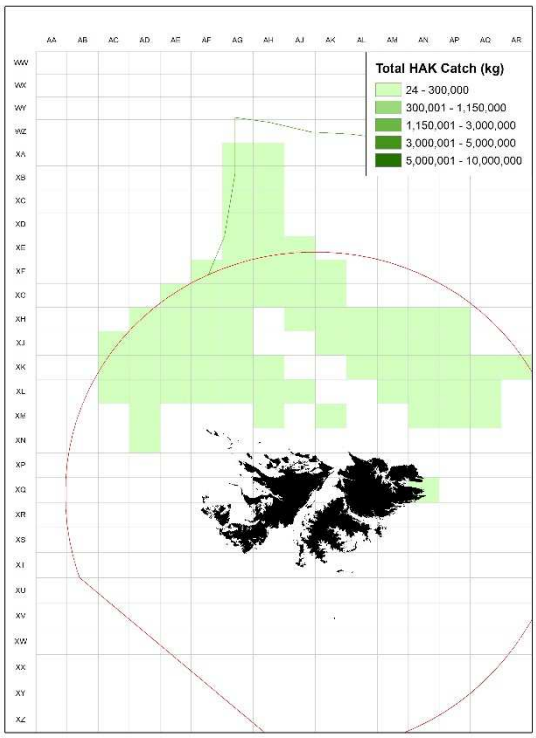
Map 69: *Illex* CPUE, G licence



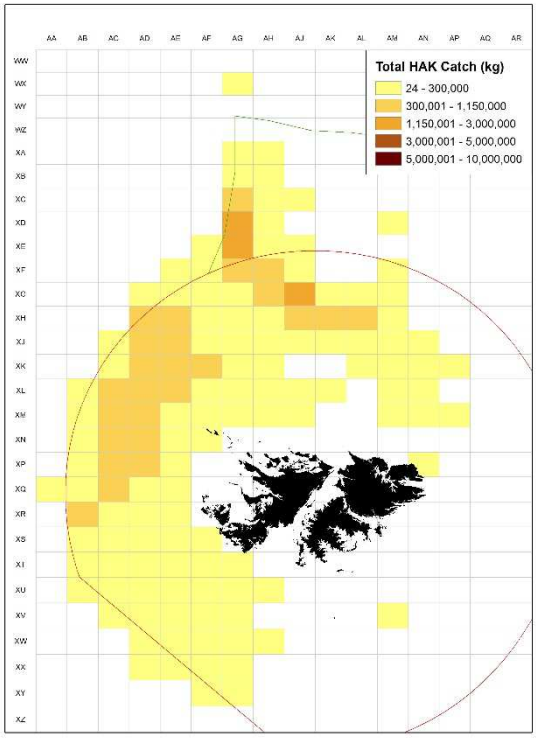
Map 70: Hake total catch, A licence



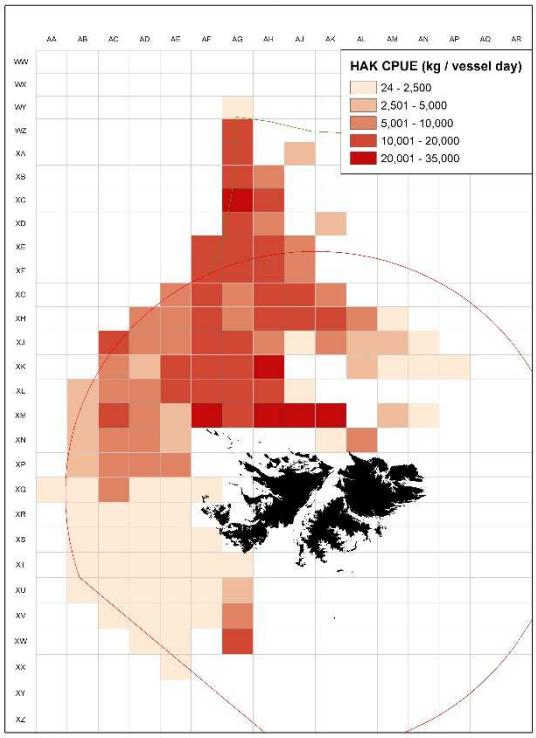
Map 72: Hake total catch, G licence



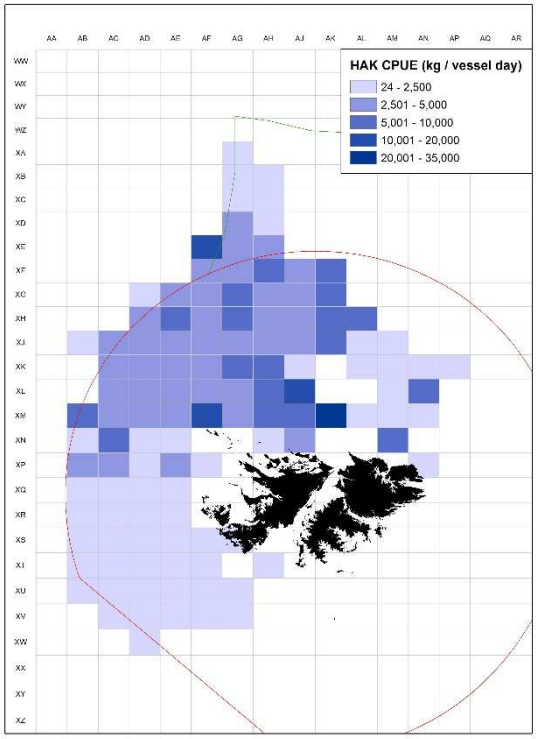
Map 71: Hake total catch, F licence



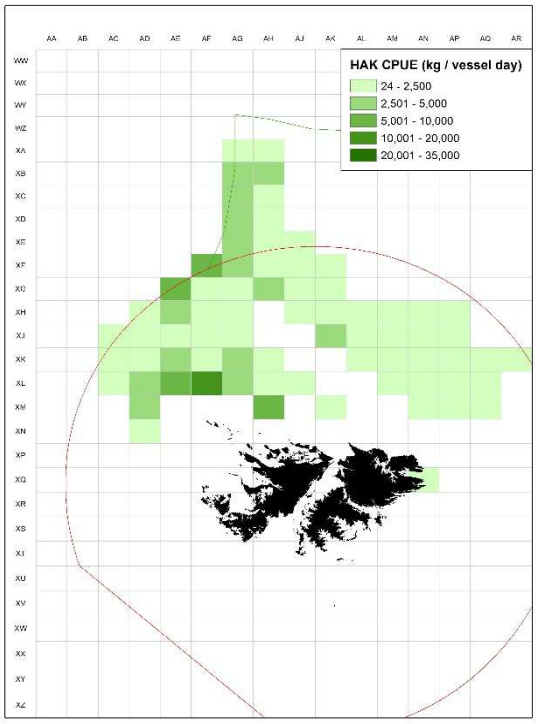
Map 73: Hake total catch, W licence



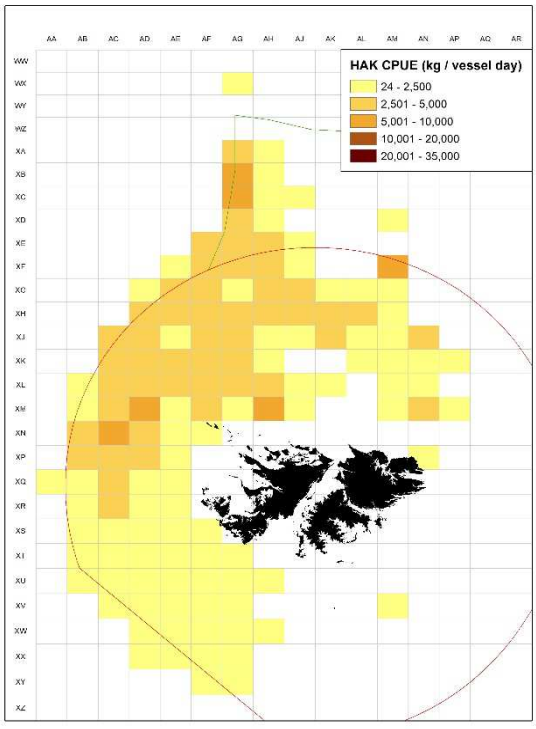
Map 74: Hake CPUE, A licence



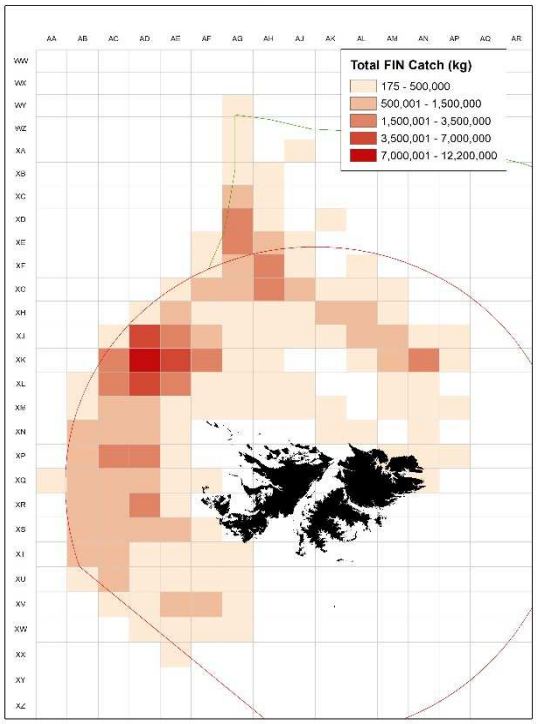
Map 76: Hake CPUE, G licence



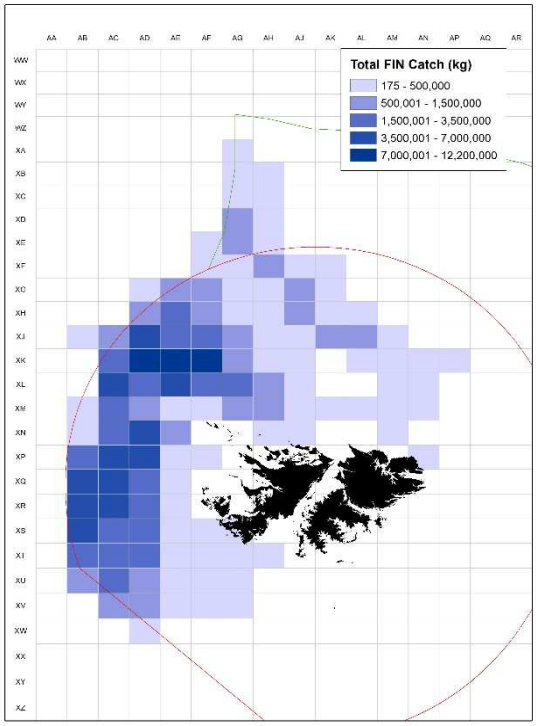
Map 75: Hake CPUE, F licence



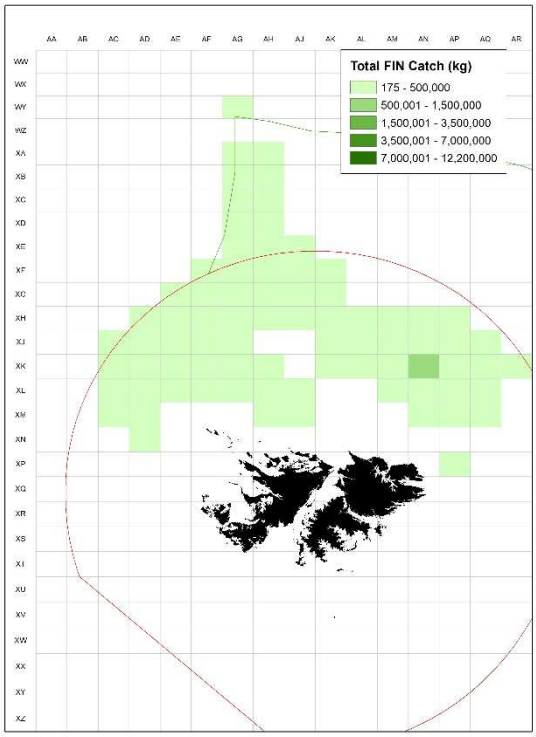
Map 77: Hake CPUE, W licence



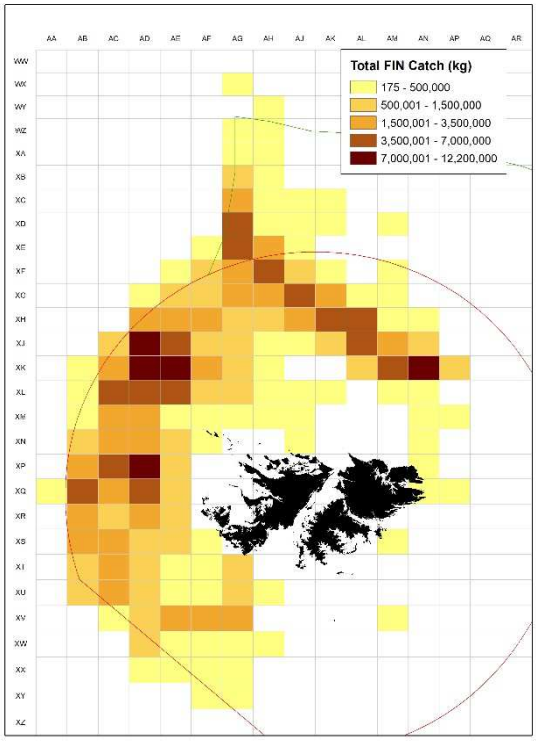
Map 78: Finfish total catch, A licence



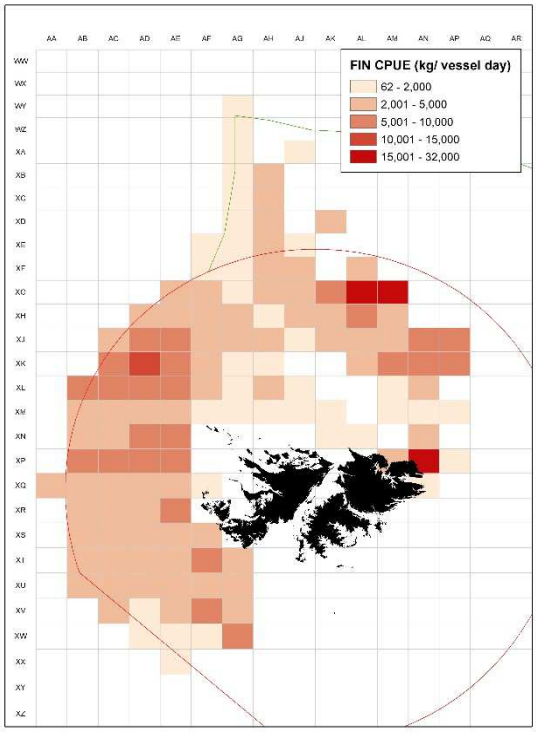
Map 80: Finfish total catch, G licence



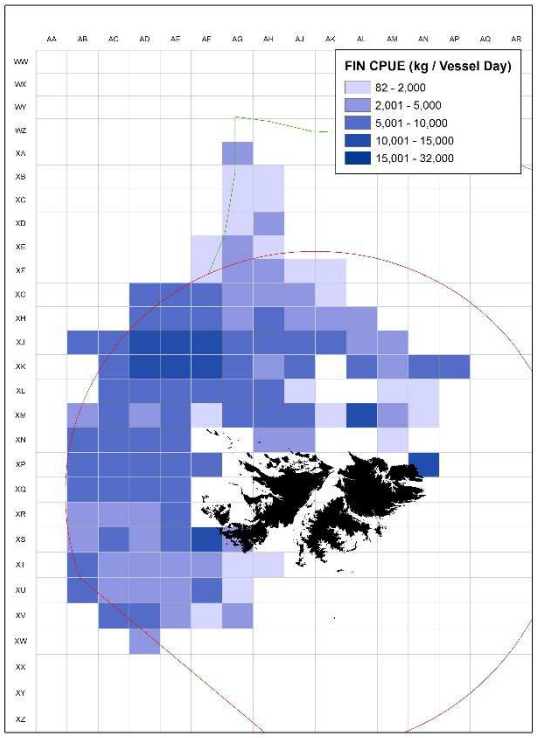
Map 79: Finfish total catch, F licence



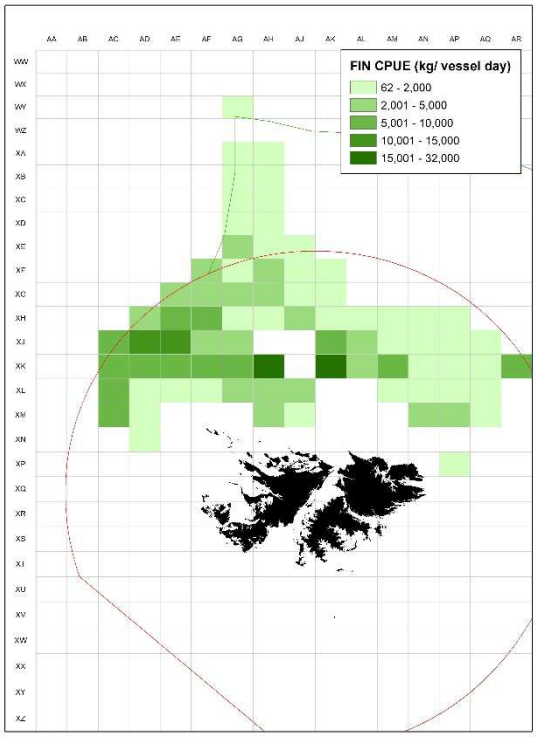
Map 81: Finfish total catch, W licence



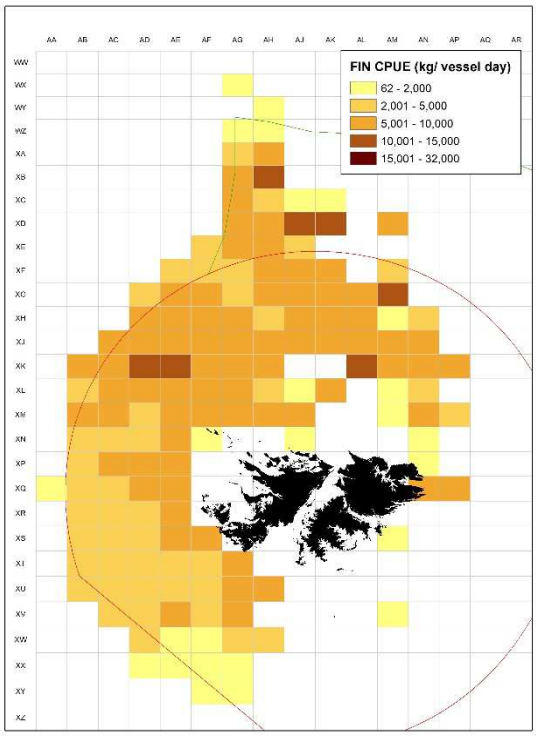
Map 82: Finfish CPUE, A licence



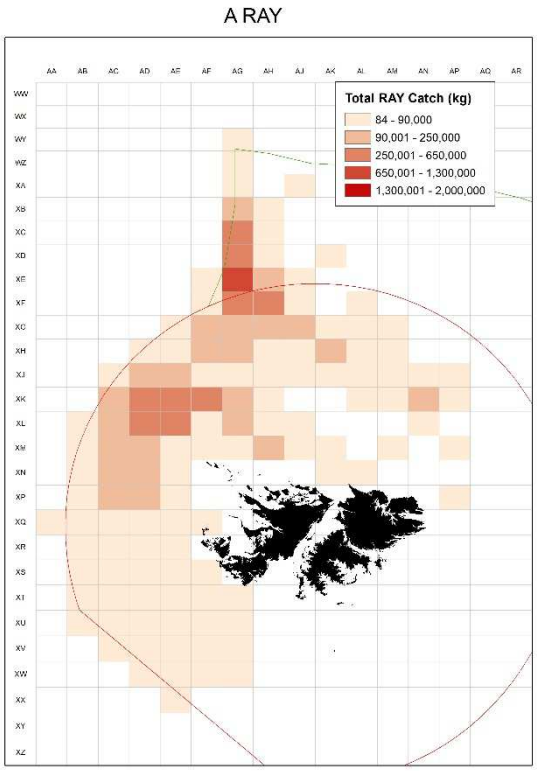
Map 84: Finfish CPUE, G licence



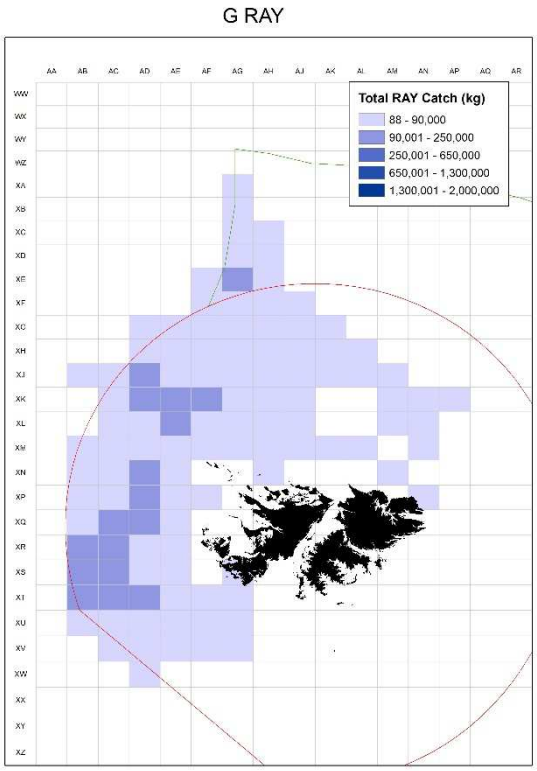
Map 83: Finfish CPUE, F licence



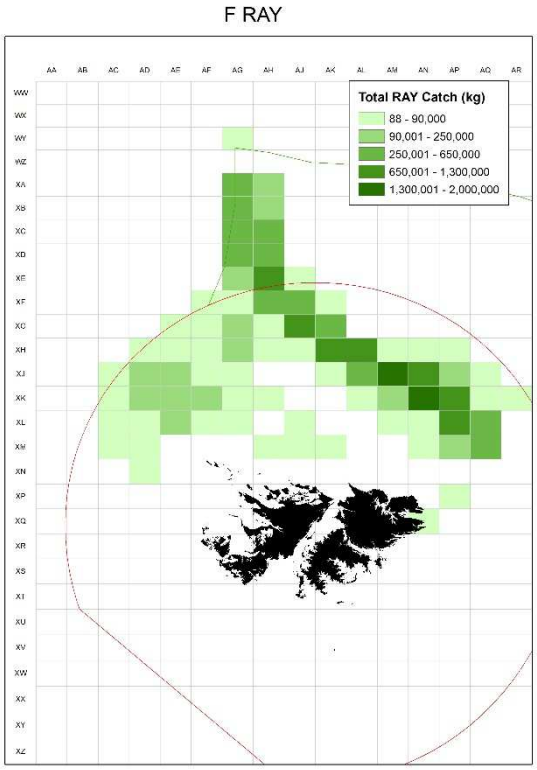
Map 85: Finfish CPUE, W licence



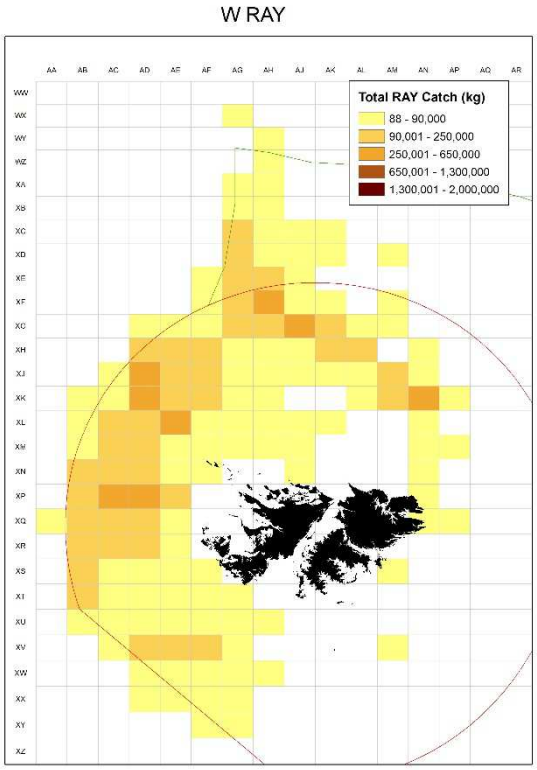
Map 86: Ray total catch, A licence



Map 88: Ray total catch, G licence

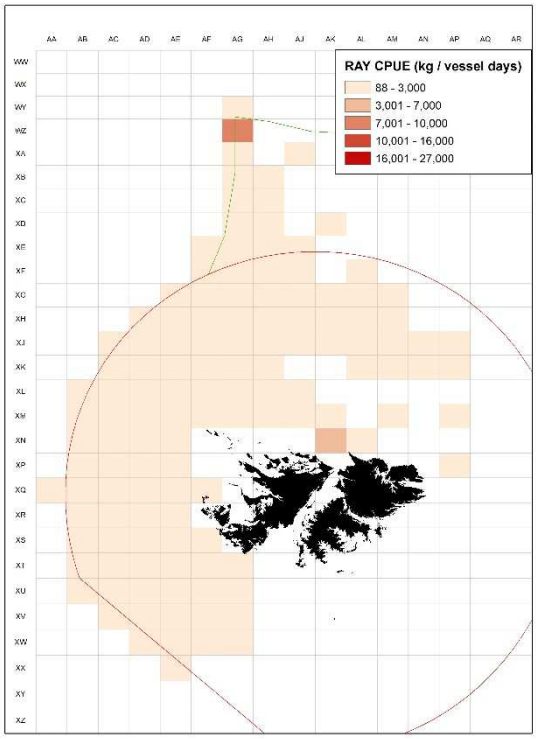


Map 87: Ray total catch, F licence



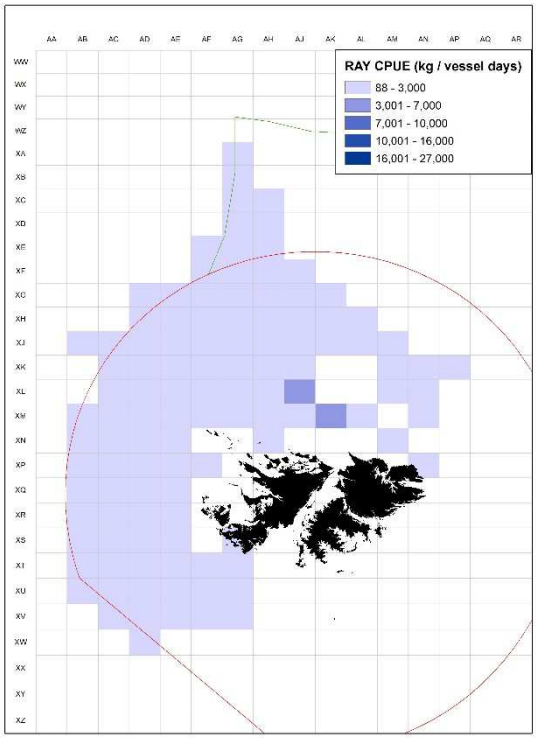
Map 89: Ray total catch, W licence

A RAY



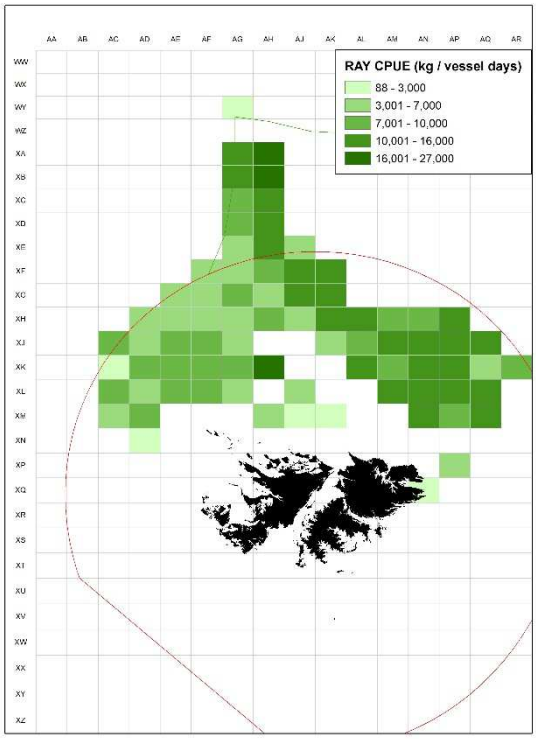
Map 90: Ray CPUE, A licence

G RAY



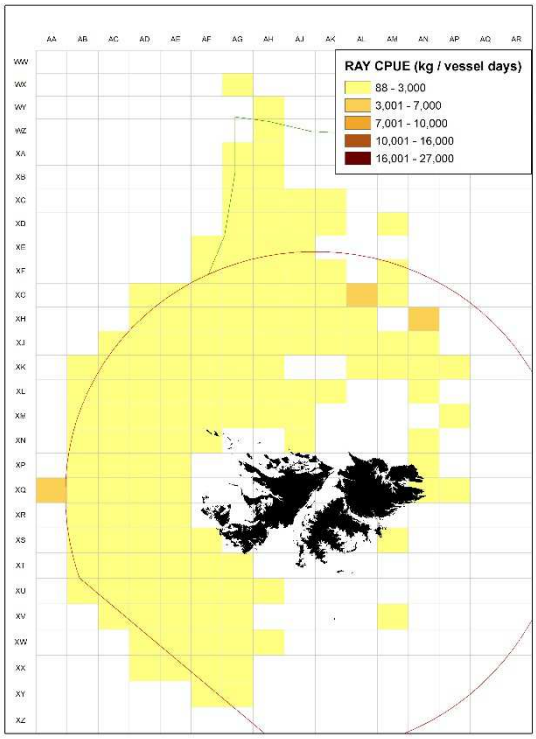
Map 92: Ray CPUE, G licence

F RAY



Map 91: Ray CPUE, F licence

W RAY



Map 93: Ray CPUE, W licence