BO: development of spatial data analysis for (pulse) fisheries data

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Wageningen Marine Research

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Contents

Summary

Due to a decrease in the area available for fishing, competition between fishing vessels for space and resources is expected to increase. These changes are driven mainly by other human activities that take up space, such as the construction of new offshore wind parks and the designation of marine protected areas. Research on pulse fishing has led to a unique situation where detailed spatial fisheries data was collected, allowing for the study of the behaviour of an innovative fishing method with low ecological impact, especially in a setting in which space is becoming increasingly limited. This project aims to further the development of statistical tools available to analyse spatial fisheries data, using Vessel Monitoring System (VMS) data of the Dutch tickler chain (TBB) and pulse (PUL) beam trawl fleets in the period 2017-2021, when the innovative PUL gear was used by part of the Dutch beam trawler fleet and was being studied.

First, weekly fishing grounds for each vessel were identified using spatial GAMs. For these GAMs, different threshold levels of fishing activity were tested to see which level gave the most accurate representation of a fishing patch. The GAMs were then used to study fishers' behaviour, such as the number of patches exploited during a trip, the size of exploitation patches, the length of stay in a patch, and the aggregation of vessels, and to test whether the pulse fleet and traditional fleet's behaviour differ significantly. The effects of this behaviour on the efficiency of the fishery were studied, specifically on the catch per unit effort (CPUE) of the beam trawler fleet's main target species, plaice and sole.

We found that in all years TBB distribution is much more diffuse and spread out over the northern part of the North Sea, whereas PUL distribution is mostly restricted to the southern North Sea. Through the years, the PUL fishing activity dwindles. Simultaneously, the TBB activity shifts southward, towards the area where PUL fishing was previously concentrated. For TBB, we observe a strong decrease in plaice CPUE as length of stay increases, as well as when the number of vessels increases. For PUL, plaice CPUE seems less affected by length of stay and number of vessels. Sole CPUE seems in general less affected by the time spent in a patch and the number of vessels in a patch. For both TBB and PUL, CPUE decreases as the length of stay increases (though not as strongly as for plaice and TBB). For TBB, sole CPUE actually increases as the number of vessels in a patch increases. For PUL, the CPUE only slightly decreases as the number of vessels increases. An aspect that was not considered in this study, is the difference in CPUE inside and outside of a patch.

We compared the length of stay in a fishing patch for different peel levels. With higher peel levels, and thus higher threshold values, the mean length of stay, maximum length of stay, mean surface of fishing ground and mean number of cores all decrease. With the lowest thresholds, there is so much overlap between weeks that vessels are quickly identified as being in the same area (on average for 14.7 consecutive weeks).

Using the knowledge gained in this study, we recommend the use of a relatively high threshold to identify fishing grounds, where the surface area is most in line with other studies of resource patches. It would also be advisable to use a set threshold level of fishing effort, rather than a percentage of the max effort, to allow for easier comparison between vessels and weeks. Although the method is very suitable for studying spatial distributions on relatively small datasets (i.e. one vessel in one week per model), the method does not work well when applied to larger datasets (whole fleets and whole years), as information in lost when scaling up. Because of the large number of sequential calculations necessary for these analyses, this type of work is very suited for parallel computing. For the future application of this method, more detailed comparisons to other spatial fisheries analysis methods, such as the one used by Rijnsdorp et al. (2022), are needed.

The research on pulse fishing has led to a unique situation in data collection, allowing us to gain knowledge on an innovative fishing method with low ecological impact, especially in a setting in which space is becoming increasingly limited. The method developed here provides a sound and relatively easy to use analysis of fishing grounds. Such methods are increasingly important for a number of reasons:

Spatial conflict in the marine sphere is increasing due to (new) human activities at sea, the composition of the (Dutch) fleets is changing rapidly, and the distribution of (commercially relevant) fish species is likely to shift due to climate change. Gaining a detailed understanding of spatial fisheries patterns is crucial for effective management of marine resources and a sustainable fishing industry.

1 Introduction

Due to a decrease in the area available for fishing, competition between fishing vessels for space and resources is expected to increase. These changes are driven mainly by other human activities that take up space, such as the construction of new offshore wind parks, designation of marine protected areas and other types of food production such as seaweed production. This increase in competition could be detrimental to both fishers and fish stocks, as increased competition leads to less efficient fisheries and may cause local depletion of fish stocks. There is a possibility to research the extent to which these processes play out, using spatially explicit data collected by Vessel Monitoring Systems (VMS). This information was used to compare the spatial distributions of part of the Dutch demersal fleet, specifically comparing conventional tickler chain beam trawlers with innovative pulse gear beam trawlers. These two fishing techniques were chosen because in the period 2017-2021, part of the Dutch beam trawler fleet switched to the innovative PUL gear, and detailed information on the spatial distribution of the PUL vessels was collected. This offers an interesting case study to research whether processes such as resource depletion and competition play out differently for different fishing techniques with similar target species (in this case, flatfish such as sole and plaice). The aim of this research was 1) to study how the spatial distribution of tickler chain and pulse trawlers affects fisheries yields, 2) to further develop the tools available for the spatial analysis of fisheries data and 3) to advice on best practices and future developments of spatial fisheries data analysis. This can provide an indication on how fishers behave when applying (other) innovative fishing gear, such as waterspray gear.

2 Assignment

This project aims to further the development of statistical tools available to analyse spatial fisheries data. We aim to:

- Identify fishing grounds using spatial GAMs;
- Study fishers’ behaviour, such as the number of patches exploited during a trip, the size of exploitation patches, the return rate, and the aggregation of vessels, and test whether the pulse fleet and traditional fleet’s behaviour differ significantly;
- Study the effects of abovementioned behaviour on the efficiency of the fishery, specifically on the catch per unit effort (CPUE) of the beam trawler fleet’s main target species, plaice and sole;
- Develop best practices for applying GAMs to spatial fisheries data;
- Make recommendations for the further development of the methods applied in this study to analyse spatial fisheries data.

3 Materials and Methods

This work focused on developing the methods for the analysis of spatial fisheries data and applying that method to identify the fishing patterns of beam trawlers with 'traditional' tickler chains versus beam trawlers with electric pulse gear. The dataset consists of the locations of all Dutch tickler chain and pulse beam trawlers ('TBB' and 'PUL') registered through the Vessel monitoring system (VMS) in the period 2017-2021.Of this dataset, all entries where the activity was registered as fishing were selected, and where the interval between each 'ping' was smaller than or equal to 120 minutes. We excluded any entries that were outside of the latitudes 48°N and 60°N and the longitudes 6°W and 13°E.

3.1 Fishing ground analysis method

To analyse the spatial distributions of the combined fleets, as well as the individual vessels, we developed a method using generalized additive models (GAMs). First, the coordinates were transformed to UTM projection and then divided by 1000, to express them in kilometres. Next, we defined an empty grid with the desired resolution of the fishing ground raster data, depending on the processing power required (1x1km for individual vessels, 5x5km for the combined fleet). Next, each VMS entry in the dataset was projected onto the empty grid, weighted by the interval between the VMS entries (120 minutes, being the maximum interval, was assigned the maximum value of 1, all other intervals were scaled linearly to 1/120 for 1 minute intervals accordingly). Next, a binomial GAM was fitted

$$gam\left(response \sim s(x,y), familly = \text{"binomial"}, weights = \frac{1}{interval}\right)$$

where all empty grid cells, denoted by the *x,y* coordinate, had a response value of 0 and all VMS data points in the grid had a maximum value of 1, weighted by the interval. The transformed intervals were used as weights. Predictions for the entire grid were made using the 'predict' function from the 'stats' R-package. The fitted values were adjusted, so that the total of the fitted values corresponded to the Days at Sea (DaS) in the dataset, so each grid cell represented a proportional part of the total fishing effort. With these effort rasters, we could then analyse the spatial use of different fleet segments and vessels.

3.2 Visualisation

The effort rasters can be plotted in two main ways: by directly plotting the raster grid data, or by transforming the data into polygons using the 'contourLines' function from the *grDevices* R-package. This function creates a chosen number of contour lines based on longitudinal (x) and latitudinal (y) data, with a value for each grid cell (z), in our case fishing effort in DaS. To visualise the difference in total yearly fishing effort between TBB and PUL vessels, we used both methods.

3.3 Fishing ground analysis

The fishing grounds of each vessel in each week were further analysed using the polygons computed in the last step. The set peel levels allow for a straightforward method of identifying fishing grounds and resource patches, as it quickly delineates where fishing effort is concentrated. For each of these ten peels (from 10% of fishing effort to 90%), the polygons were generated. For some of the peels, several polygons were generated to make up the x% of effort (e.g. that two separated small areas at a larger fishing ground were most intensely fished and were each defined by a separate polygon). When the effort in these peels was divided over multiple polygons, these were merged to a single shapefile to represent the fishing ground of that vessel in that week. The surface of each fishing ground was saved using the ‘gArea’ function from the ‘rgeos’ R-package. The fishing ground shapefiles were then used to determine whether vessels returned to the same location in consecutive weeks, by calculating the overlap between the fishing ground in each week with the fishing ground of that vessel in the next week with the function ‘gIntersection’ from the ‘rgeos’ package. In case of overlap, a vessel was said to return. We performed this analysis with each of the ten peel levels, to assess which level (and thus size of fishing ground) gave the most appropriate representation of a fishing ground. To assess this, we compared the mean length of stay, number of cores and fishing ground area at each peel level. Next, we determined how many other vessels were at the same location during each week for each vessel, again using the ‘gIntersection’ function. Because of limits in computing power, we did this using peel level 5 as the core of the patch. For each vessel and week, the total landings for plaice and sole were aggregated from the VMS data. We also stored information on the number of patches in which fishing took place and the effort in DaS.

3.4 Data analysis

The resulting data set contained for each vessel in each week: the surface area of the fishing ground (core), fishing effort in DaS, the catch and CPUE (catch/DaS) for plaice and sole, the number of consecutive weeks spent in that location, the number of other vessels in that location in that week, and the number of separate patches exploited in that week. For each of these variables, we used standard t-tests to determine whether this differed between vessels using TBB gear and vessels using PUL gear.

We then applied a loess smoother to see the relationships between number of weeks spent in a patch and the surface area of the patch, the number of other vessels in a patch and the surface area, and the number of weeks spent in a patch and the number of other vessels in that patch, for both TBB and PUL gear. We also plotted the distributions of the number of weeks and number of vessels in each patch for each vessel and week, and used Kolgomirov-Smirnov tests clustered by year to see if this distribution differed significantly between TBB and PUL using vessels.

Next, to gain a better understanding of the effect of length of stay and number of vessels in a patch on surface area and catch rates of plaice and sole, we created grid plots where the x and y axes represent length of stay and number of vessels, and the grid colour represents the surface area and catch rates. This was done for TBB and PUL separately to identify possible differences. To visualize these relationships between number of vessels and length of stay and CPUE of plaice and sole, we also used loess smoothers.

3.5 GLMs of CPUE

To explain the variation in catch rates for plaice and sole based on fishing behaviour and aggregation of ships, Generalized Linear Models were created, where the CPUE is explained by a linear model consisting of a set of explaining variables.

In total four global models were made: for both plaice and sole CPUE two models for vessels fishing with TBB and PUL gear. CPUE for plaice and sole of each vessel in a week was explained based on all combination of the variables: Number of vessels in patch, number of consecutive weeks in patch, number of cores, and surface of the patch.

$$glm(CPUE_{\ PLE/SOL} \sim (no.vessels + no.\ weeks + Surface\ area + no.cores)^2, familly = \text{"gaussian"})$$

Using the ‘dredge’ function from the R-package ‘MuMIn’, the best combination of these variables to explain the variation in the CPUE was selected, where the best model was that with the lowest Akaike Information Criterion (AIC). The maximum number of variables/variable combinations was set to 3, to avoid overfitting.

4 Results

In total, the dataset contained 152 vessels. On average, these vessels performed 3782 fishing trips in a year, with the most trips in 2019 (Table 1). This was also the year with the most vessels and the most VMS entries. From 2017 to 2021, the number of vessels using pulse gear dropped from 73 to 11 as a ban on pulse fishing was put into place. This also resulted in an increase in the number of vessels using tickler chains, from 59 in 2017 to 94 in 2021. The total landings of both plaice and sole decreased over the studied period. Of all trips in the dataset, 9823 used TBB gear, 8839 used PUL gear, and 155 used both TBB and PUL gear. This last is probably erroneous, with the end of one trip and the start of another taking place in the same week, and the gear being switched between those trips. These were not taken into account for rest of the analysis.

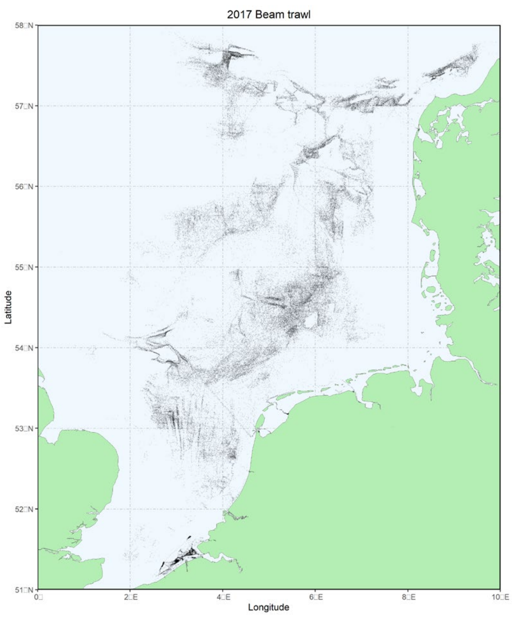
Table 1: overview of yearly number of vessels, trips, 'pings', PUL and TBB vessels, and the total landings of sole and plaice.

year	#vessels	#trips	Fishing pings	#PUL	#TBB	Landings sole (kg)	Landings plaice (kg)
2017	103	3833	282475	73	59	8284184	24206562
2018	106	4211	296917	74	60	8205361	19721324
2019	127	4396	325864	73	94	6764719	18536889
2020	114	3930	282732	29	102	6534953	15825503
2021	105	2542	197869	11	94	3772097	9309067

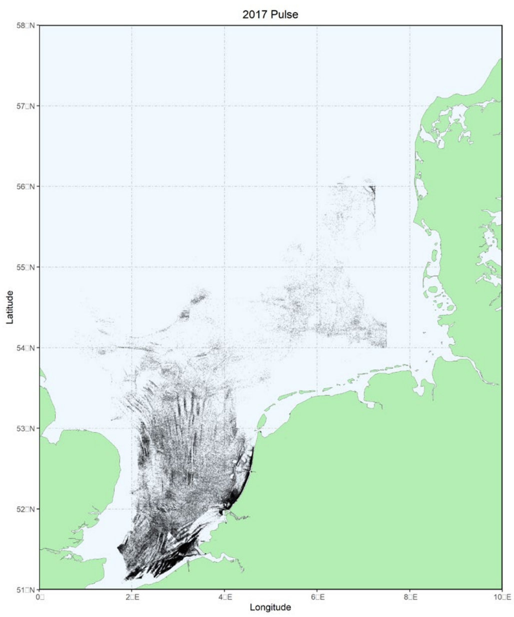
4.1 General spatial distribution

When looking at the yearly spatial distribution of the VMS entries in the dataset for TBB and PUL vessels, we see that in all years TBB distribution is much more diffuse and spread out over the northern part of the North Sea, whereas PUL distribution is mostly restricted to the southern North Sea (Figure 1). Through the years, the PUL fishing activity dwindles (with the last PUL trips taking place in 2021). Simultaneously, the TBB activity shifts southward, towards the area where PUL fishing was concentrated. This is most likely a result of vessels switching back to TBB gear around the time of the ban on pulse fishing.

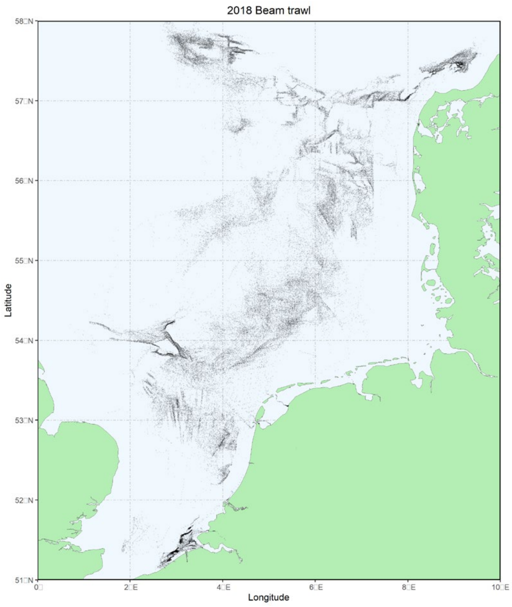
a)



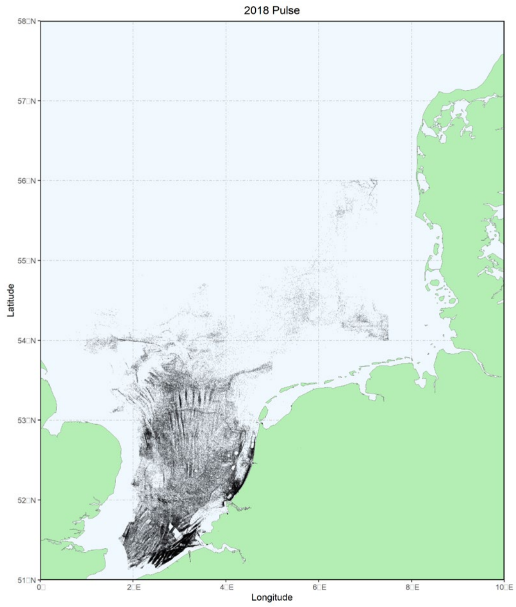
b)



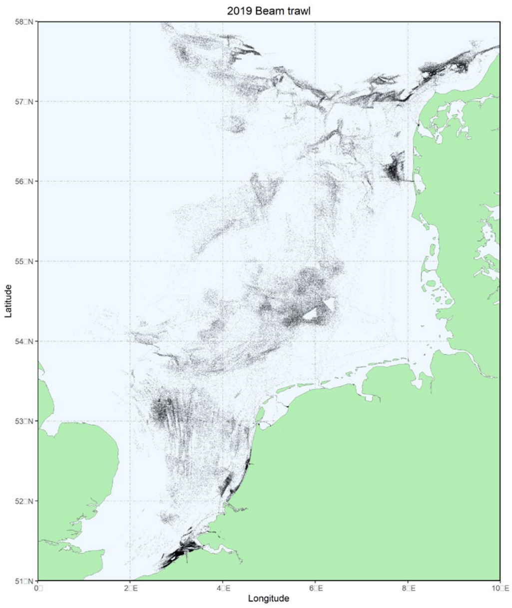
c)


2018 Beam trawl
Latitude
Longitude

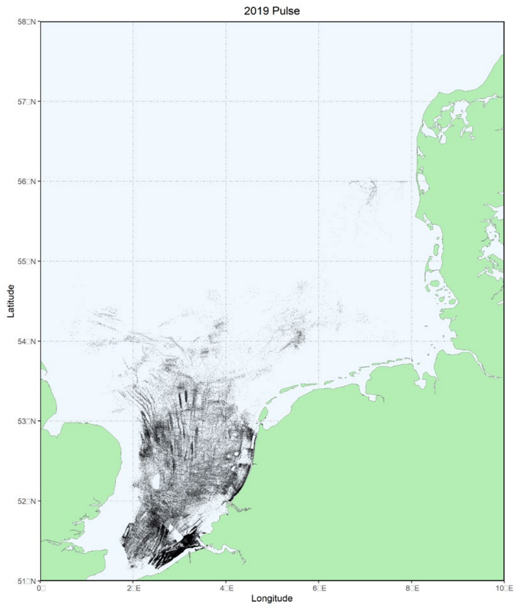
d)


2018 Pulse
Latitude
Longitude

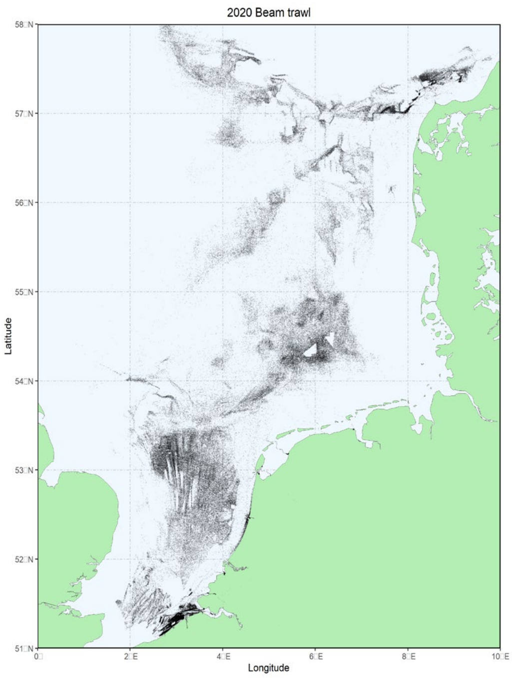
e)


2019 Beam trawl
Latitude
Longitude

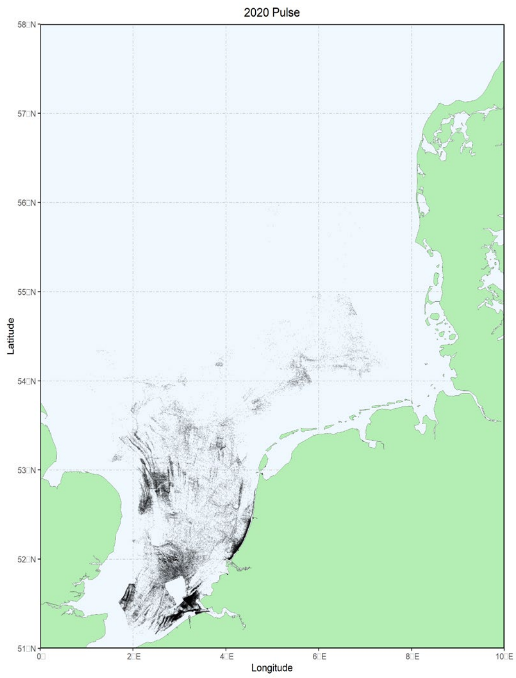
f)


2019 Pulse
Latitude
Longitude

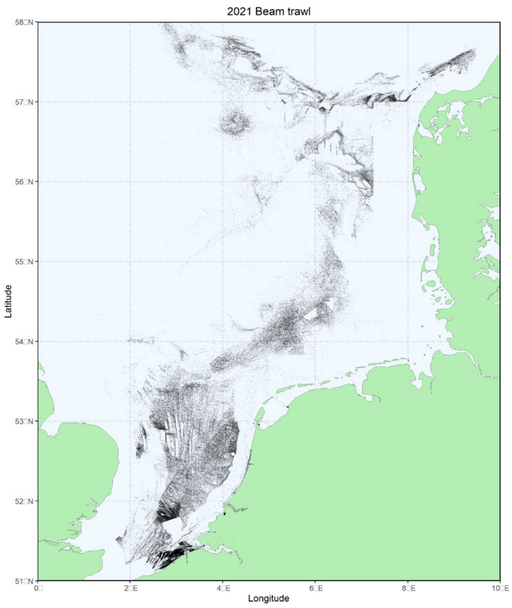
g)


2020 Beam trawl
Latitude
Longitude

h)


2020 Pulse
Latitude
Longitude

i) j)



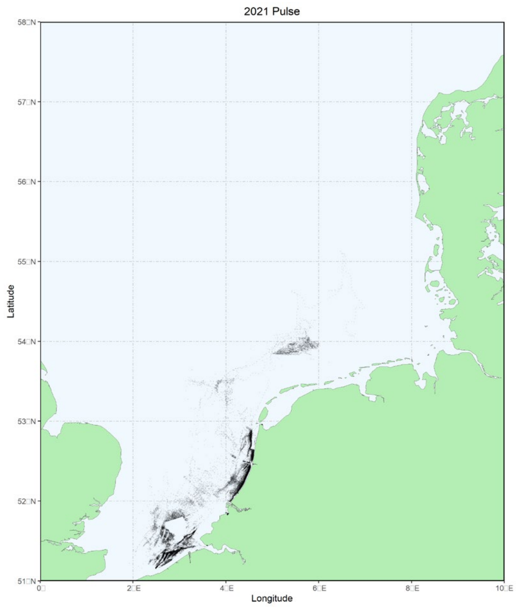
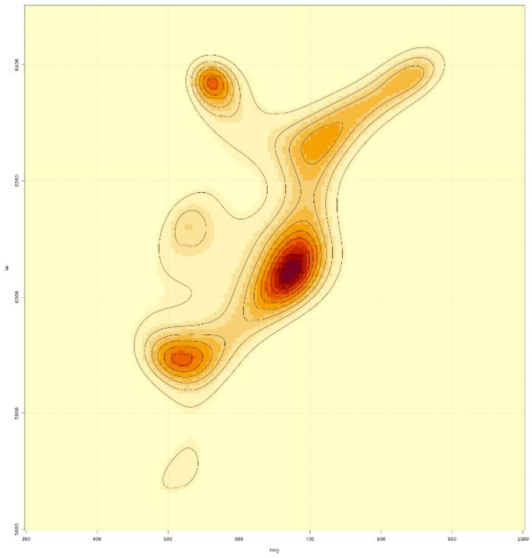


Figure 1a-j: Spatial distribution of 'pings' where behaviour is fishing for pulse and bream trawlers from 2017-2021.

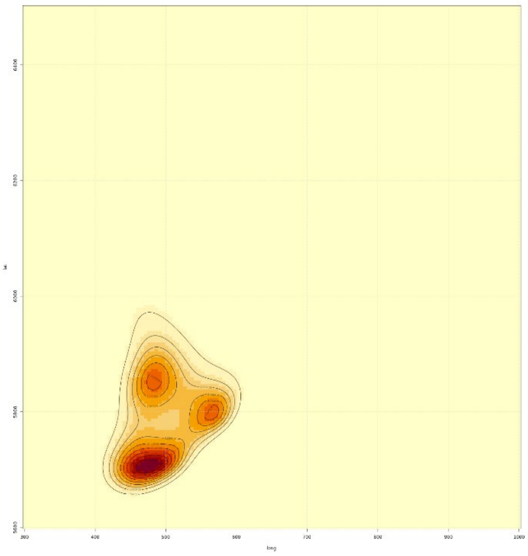
4.2 Total yearly effort

For these yearly spatial distributions, we then made spatial GAM models to further analyse spatial distribution of the fleets in the studied period. Figure 2 shows the output of these models, which were made on a 5x5km grid. The grid cells are coloured based on the effort in that year, and the contour lines represent proportions of the maximum effort (from 10% to 90% of maximum effort). The absolute effort values can therefore not be compared between figures, since they are relative to each year and gear's maximum effort. The threshold values of effort are written in the contour lines. In general, we observe the same distribution as the points data, where the distributions of TBB vessels is more diffuse and north-easterly, and the PUL vessels are concentrated in the southern North Sea. We can also observe the shrinking of the PUL fleet's fishing grounds and the subsequent southwardly shift of the TBB fleet in the latter half of the studied period.

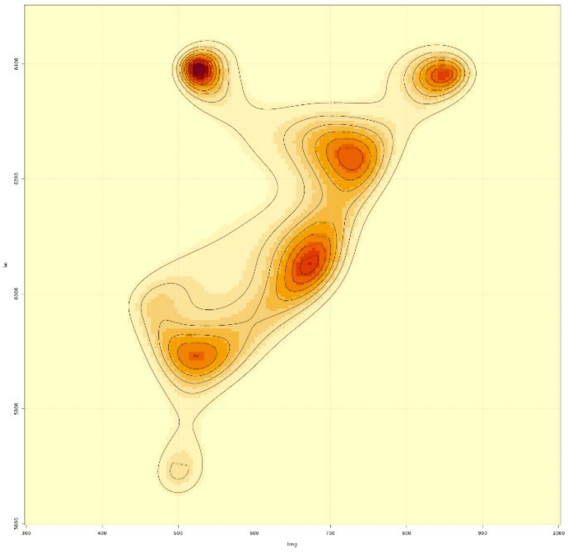
a) TBB 2017



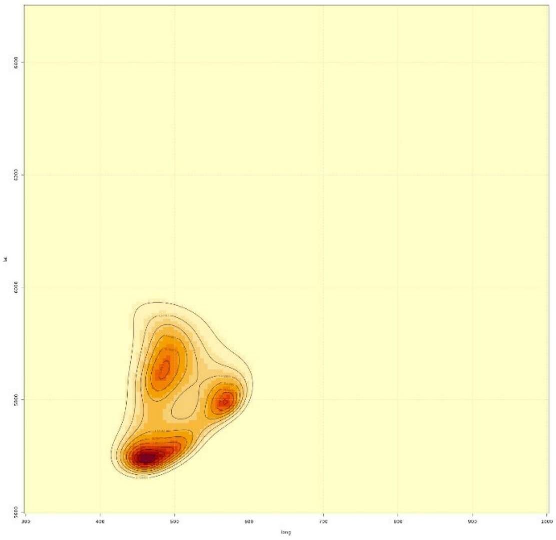
b) PUL 2017



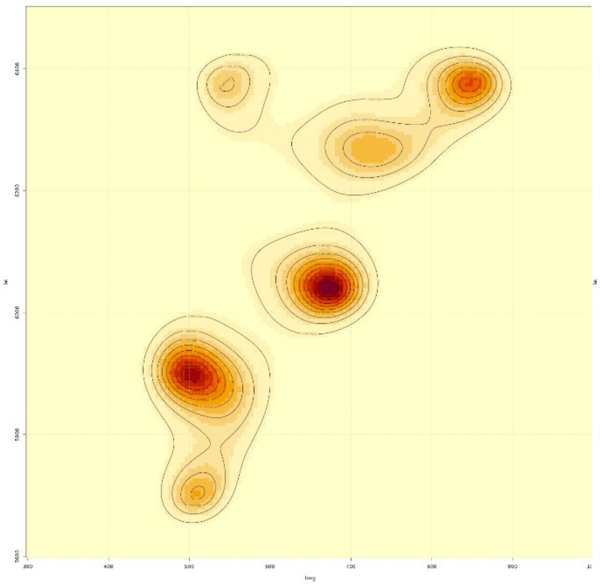
c) TBB 2018



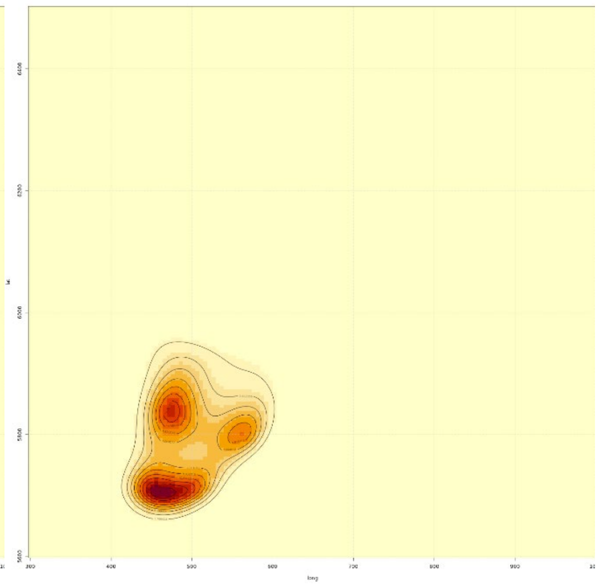
d) PUL 2018



e) TBB 2019



f) PUL 2019



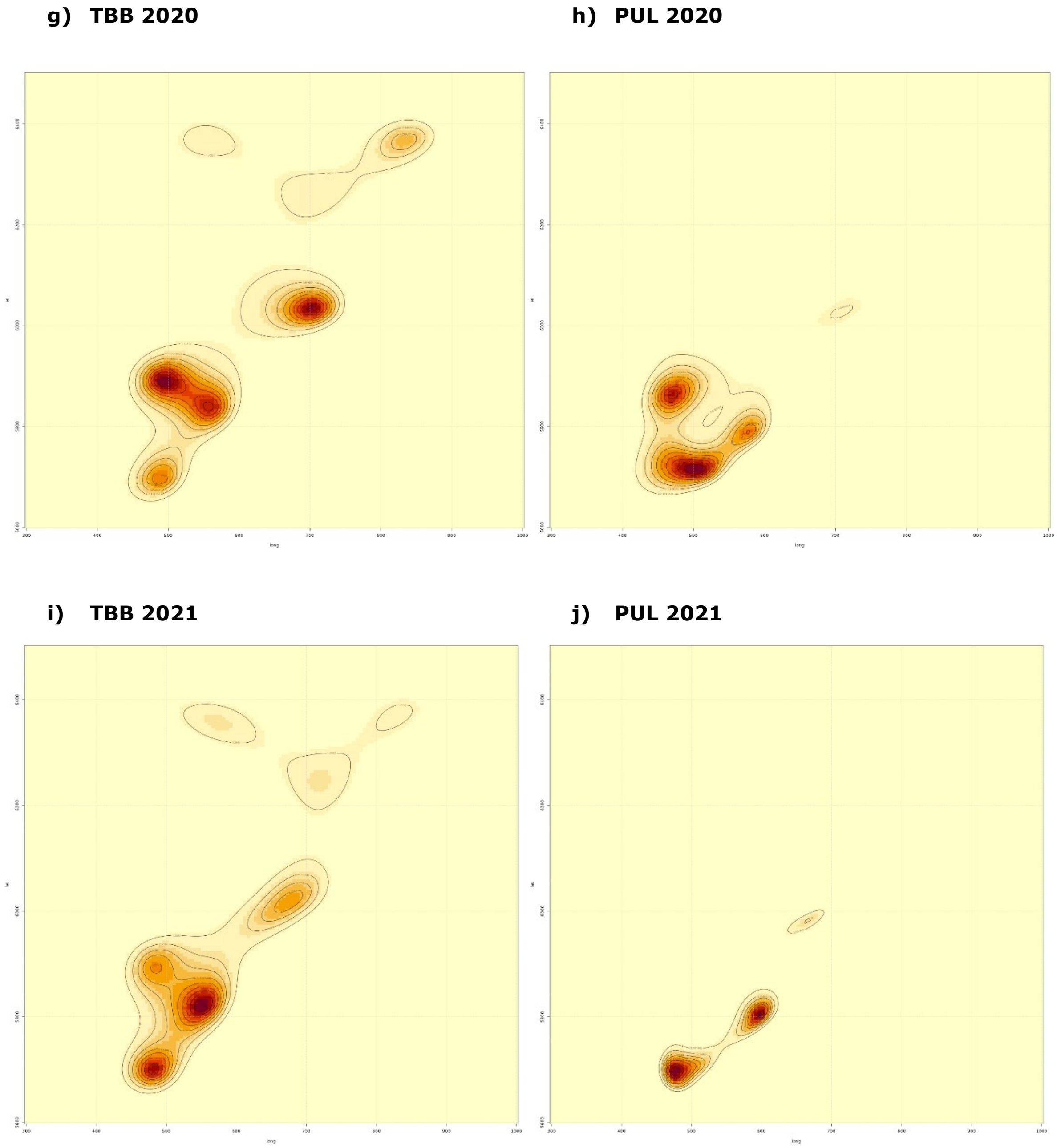


Figure 2a-j: GAM model output for yearly spatial effort of TBB and PUL trawlers in the period 2017-2021. The background grid used was 5x5 km. The colour scheme used is relative to the maximum effort for that year and gear combination, so it is not comparable between figures but scales with the maximum effort. Threshold values are shown in the contour lines.

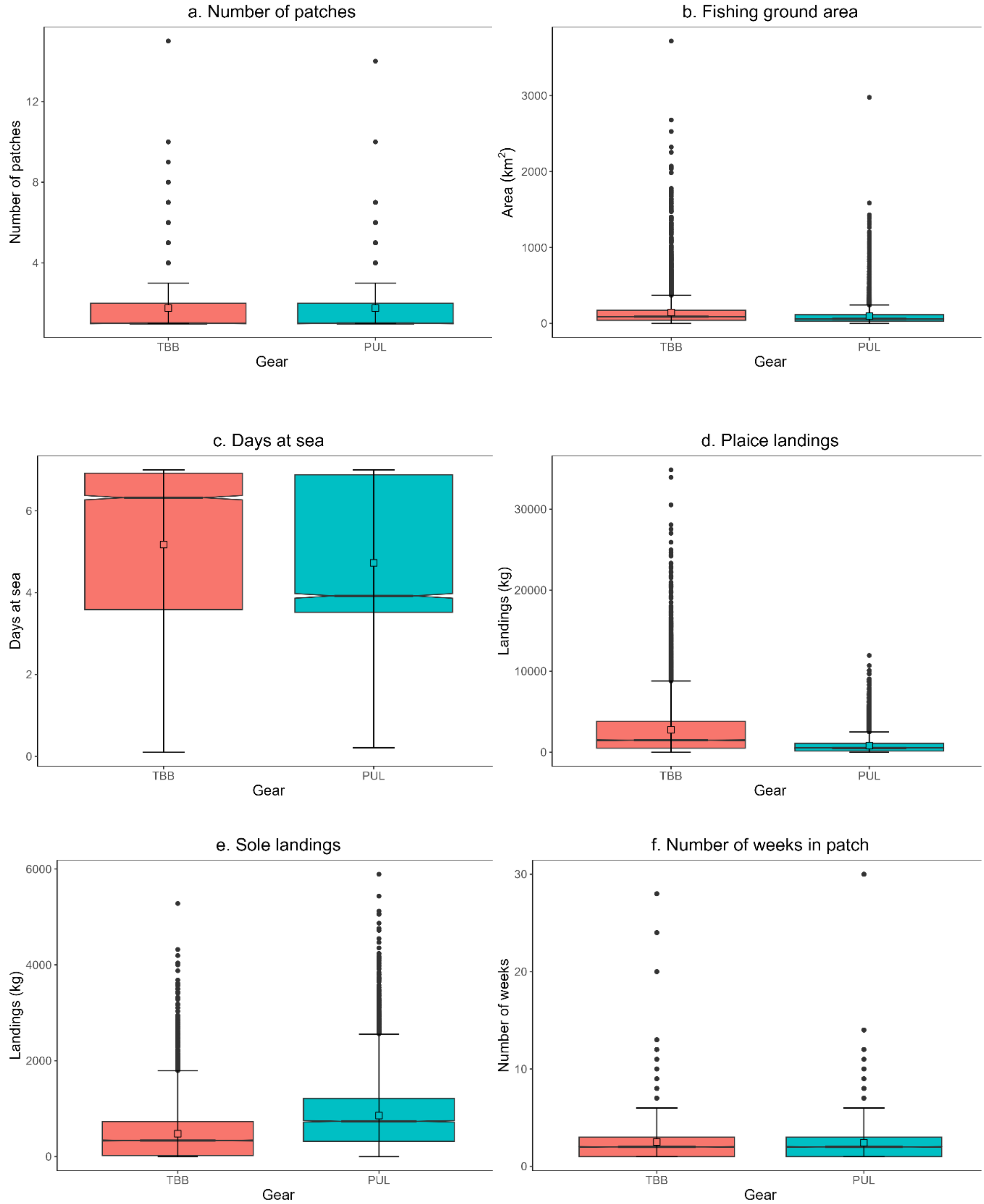
4.3 Development of fishing grounds method

We aimed to determine which peel level (and thus which fishing ground size) would be the most appropriate for analysing overlap between fishing grounds. For this, we compared the length of stay in a patch for different peel levels (Table 2). With higher peel levels, and thus higher threshold values, the mean length of stay, maximum length of stay, mean surface of fishing ground and mean number of cores all decrease. With the lowest thresholds, there is so much overlap between weeks that vessels are quickly identified as being in the same area (on average for 14.7 consecutive weeks). The surface area of fishing grounds with this peel level is very large. For the last peel level (or highest threshold), there is hardly ever any overlap between consecutive weeks (mean length of stay = 1 week). The fishing ground is only 0.001 km^2 and always consists of a single core.

Table 2: Characteristics of fishing grounds at the different peel levels (i.e. fishing effort threshold): mean and maximum length of stay (consecutive weeks), mean surface area, and mean number of cores.

Peel level	Mean length of stay (weeks)	Max.	Mean surface area (km^2)	Mean number of cores
1	14.7	114	718.28	2.79
2	7.5	59	410.48	2.51
3	4.6	30	264.24	2.22
4	3.2	30	177.70	1.97
5	2.5	30	121.28	1.76
6	2.0	30	81.62	1.57
7	1.6	28	52.42	1.41
8	1.3	13	30.05	1.28
9	1.1	8	12.77	1.16
10	1.0	2	0.001	1

For several important fishing behaviour characteristics (Figure 3), we tested whether these differ significantly for TBB and PUL vessels. We found that the TBB and PUL fleet show different behaviours in many aspects (Table 3). TBB fishing trips were significantly longer than PUL fishing trips, 5.17 days against 4.73 days ($p < 0.001$). The fishing grounds identified for TBB were also larger than those identified for PUL vessels, 143 km^2 against 95.48 km^2 ($p < 0.001$). On average TBB vessels spent more consecutive weeks in a patch than PUL vessels, 2.5 weeks against 2.4 weeks ($p = 0.012$), and there were often more other vessels in the same area as TBB vessels compared to PUL vessels, 3.6 against 3.0 vessels ($p < 0.001$). Both plaice landings and plaice CPUE were higher for TBB vessels (landings 2761 kg against 808 kg, CPUE 595 kg/DaS against 196 kg/DaS), while sole landings and CPUE were higher for PUL vessels (landings 856 kg against 478 kg, CPUE 199 kg/DaS against 97 kg/DaS) ($p < 0.001$).



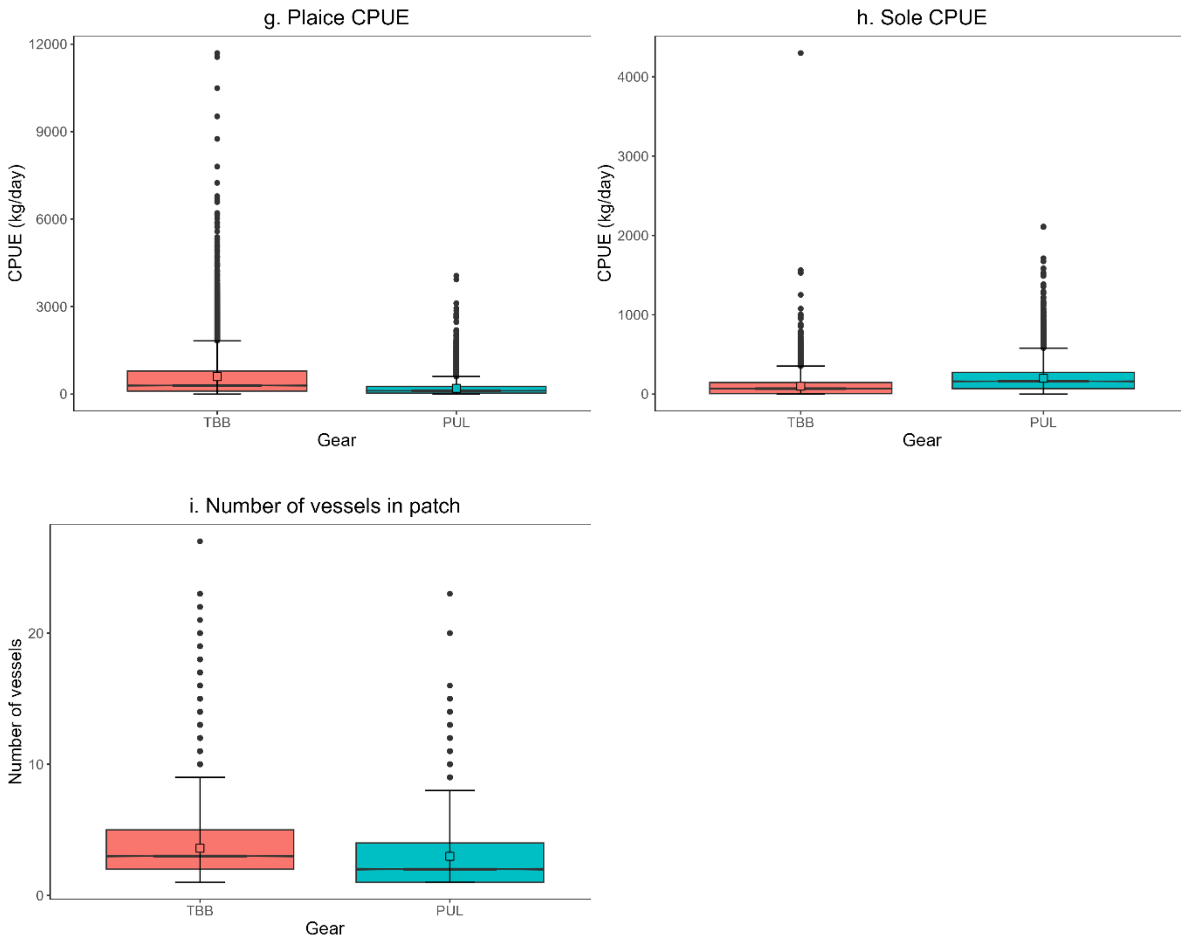


Figure 3a-i: Distributions of important variables for each fishing trip for both gear types, TBB and PUL. a) Number of patches, b) Fishing ground area in km^2, c) Days at sea, d) Plaice landings in kg, e) Sole landings in kg, f) Number of consecutive weeks in a patch, g) Plaice CPUE in kg/DaS, h) Sole CPUE in kg/DaS, i) Number of other vessels in a patch. The boxes show the 25th, 50th and 75th percentiles, the lines show the 5th and 95th percentiles. Notches represent the 95% CI around the median. The mean percentage is given by the square. Outliers are given by points.

Table 3: Mean values of several important variables for weeks and vessels, for both TBB and PUL gear, with the alternative hypothesis of the standard t-test used, and the resulting p-value (significant results in bold).

Variable	TBB mean	PUL mean	$H_{alternative}$	p-value
Days at sea	5.17	4.73	Greater	**< 0.001**
Fishing ground area (km^2)	143.45	95.48	Greater	**< 0.001**
Number of patches	1.76	1.76	Greater	0.451
Number of weeks in patch	2.51	2.42	Greater	**0.012**
Number of vessels in patch	3.59	2.98	Greater	**< 0.001**
Plaice landings (kg)	2761.35	808.47	Greater	**< 0.001**
Sole landings (kg)	477.92	856.45	Less	**< 0.001**
Plaice CPUE (kg/DaS)	595.46	195.77	Greater	**< 0.001**
Sole CPUE (kg/DaS)	97.43	199.06	Less	**< 0.001**

When plotting the relationships between number of weeks spent in a patch, number of vessels present in a patch and size of that patch, and applying a loess smoother, we can observe multiple trends (Figure 4): Firstly, fishing grounds of beam trawlers with tickler chains tend to be smaller when vessels return to them for more consecutive weeks. This effect is less pronounced for pulse trawlers. Secondly, fishing grounds tend to be larger when more vessels are present in a patch (this makes sense, as the number of vessels in a patch is determined by overlap with other vessels' fishing grounds, and larger fishing grounds result is more overlap). Last, the number of other vessels in a patch is negatively correlated with the number of weeks spent in that patch. In other words, if a vessel return to a patch for multiple weeks in a row, other vessels are less likely to go there. These effects are mostly consistent over for TBB and PUL gear, though the size of the fishing ground seems to stabilize for PUL gear when they return to a patch for a longer period, in which case the fished surface increases. This could also be because of the limited data available for such long stays, which would be in line with the shorter average return time in a patch for PUL gears (Table 3). Furthermore, the size of a fishing ground seems to increase more strongly with an increasing number of vessels for PUL vessels than for TBB vessels.

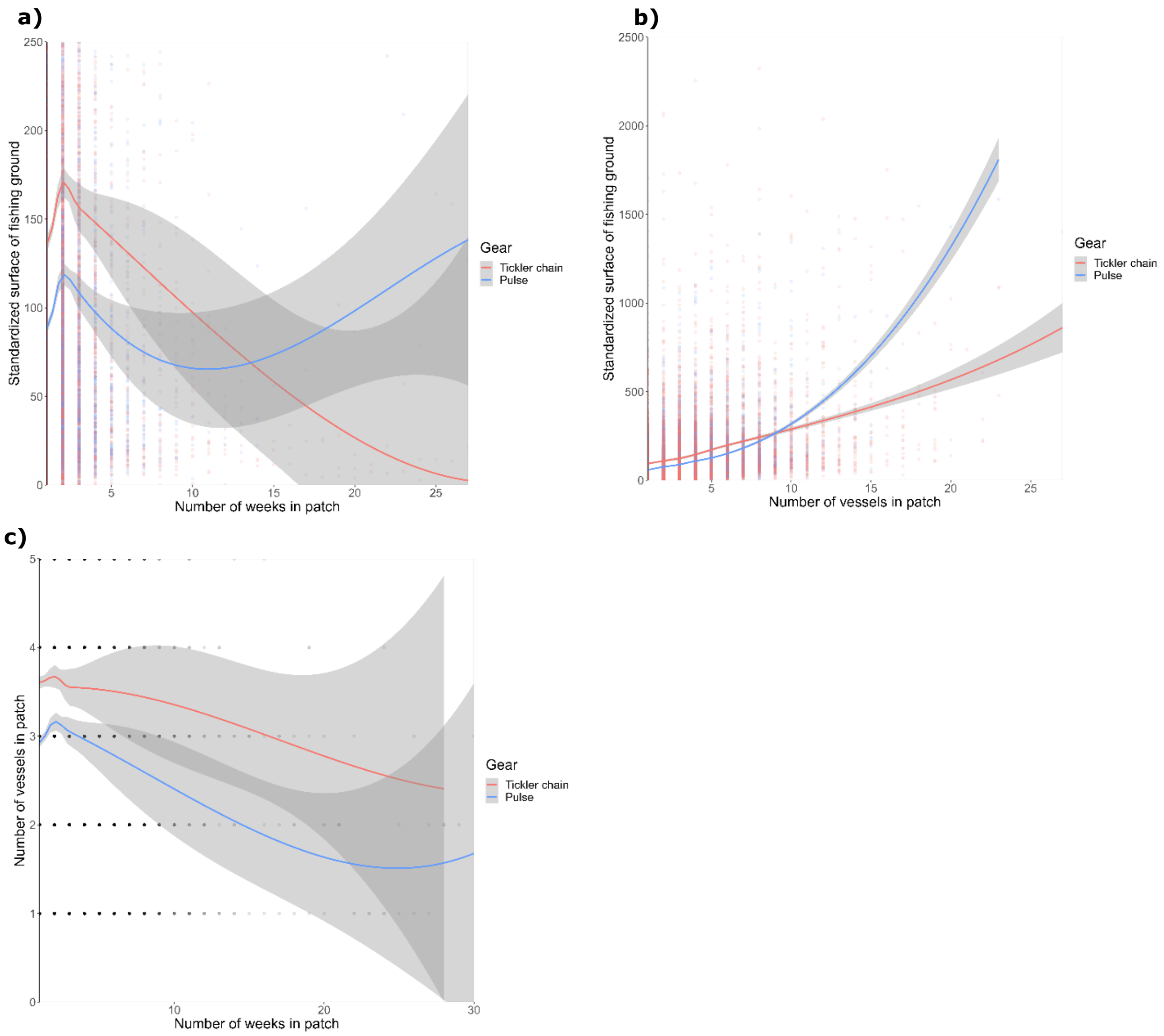


Figure 4: Relationships between a) number of consecutive weeks spent in a patch and the size of the patch, b) number of other vessels present in a patch and the size of the patch, c) number of consecutive weeks spent in a patch and the number of vessels present in a patch, to which a loess smoother was applied. The grey areas represent the 95% CIs. Note: not all the data points are shown. Note the different scales on the y-axes.

The distributions of length of stay and number of vessels in a patch are similar for TBB and PUL vessels (Figure 5), and no significant differences were found. TBB vessels seem to aggregate with more ships than PUL vessels.

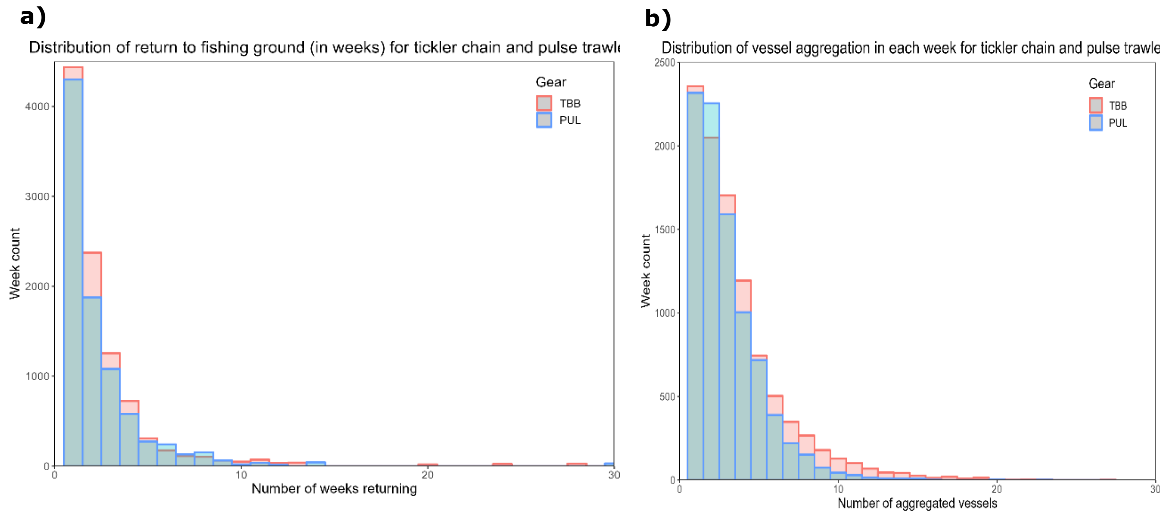
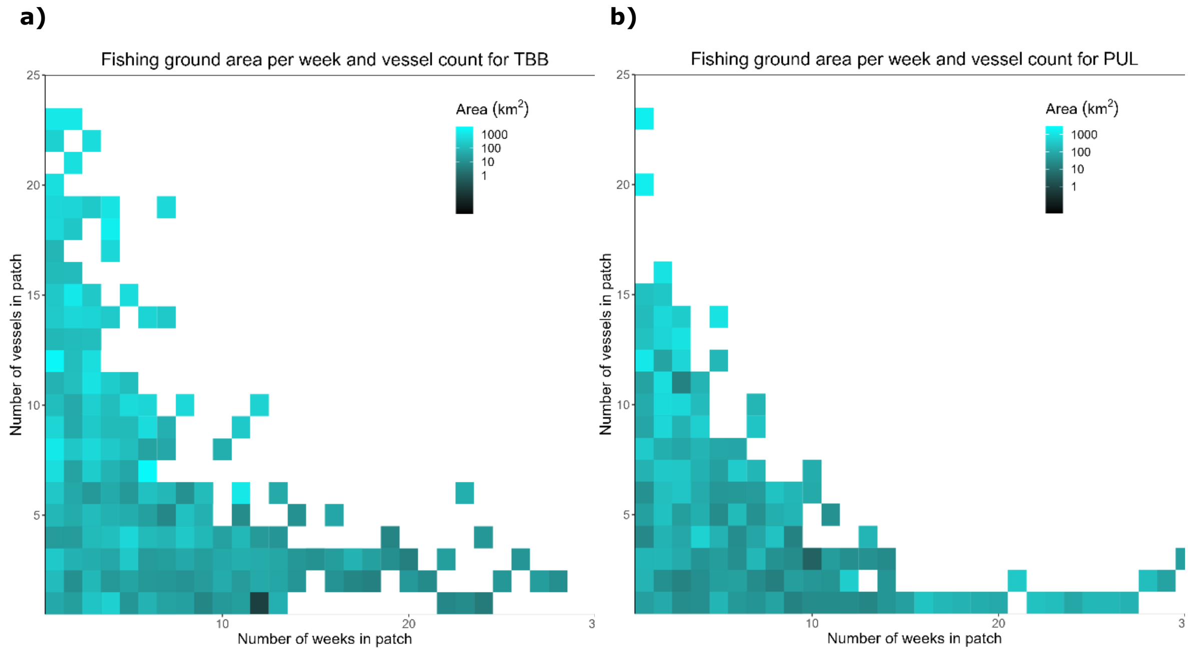


Figure 5: Distributions of a) the number of weeks spent in a patch and b) the number of other vessels present in that patch for each vessel and week. The data is split up into vessels using TBB and PUL gears to show the differences in distribution. Vessels using TBB gear seem to spend less time in a patch and seem to aggregate with more vessels.

The grid plots in Figure 6 show the mean surface area, plaice CPUE and sole CPUE for different combinations of length of stay and number of vessels, separated for TBB (left) and PUL (right). We observe that the size of the fishing ground seems to be highest when there are more vessels in a patch (as explained above), for both TBB and PLE. CPUE of plaice for TBB seems to be highest when many vessels are present in a patch and when the length of stay is short. For PUL this effect seems less pronounced. For sole, the CPUE again seems higher in the first weeks in a patch and when many vessels are aggregated. For TBB, CPUE of sole seems lowest when few vessels are aggregated.



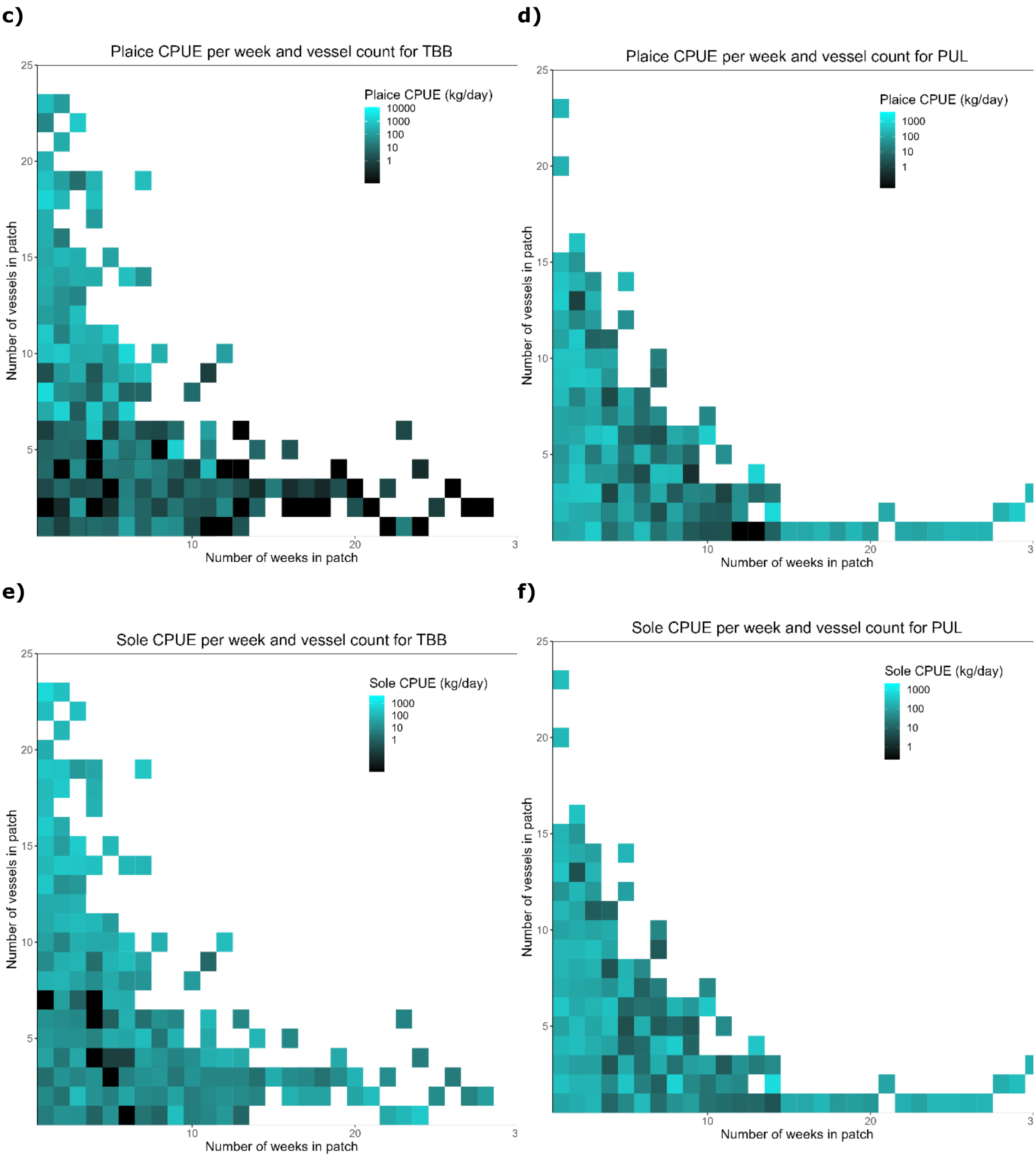


Figure 6: Grid plots showing for each combination of number of consecutive weeks spent in a patch and number of vessels present in that patch a-b) the patch area in km², c-d) the CPUE for plaice in kg/days, e-f) the CPUE for sole in kg/days, for TBB (left) and PUL (right). Lighter shades represent higher values. Black represents zeroes. Colouring is logarithmic.

Figure 7 shows the CPUE of plaice and sole as a function of the number of weeks spent in the patch and the number of other vessels in a patch, for TBB and PUL separately. For TBB, we observe a strong decrease in plaice CPUE as length of stay increases, as well as when the number of vessels increases: When a vessel exploits a new patch for the first time and/or is the only ship there, average CPUE is around 600 kg/DaS. This decreases sharply when a vessel stays in a patch for longer. When the number of vessels in a patch increases, plaice CPUE drops and stabilizes around 400 kg/DaS. For PUL, plaice CPUE seems less affected by length of stay and number of vessels. Sole CPUE seems in general less affected by the time spent in a patch and the number of vessels in a patch, remaining around 200 kg/DaS throughout a vessel's stay and with an increasing number of other vessels in the area. For both TBB and PUL, sole CPUE decreases as the length of stay increases (though not as strongly as for plaice and TBB). For PUL vessels, it starts around 200 kg/DaS in the first week and drops to around 120 kg/DaS around the fifteenth week in a patch. For TBB, sole CPUE starts around 100 kg/DaS in the first week and decreases to around 30 kg/DaS around week 15. For TBB, sole CPUE actually increases as the number of vessels in a patch increases, starting around 90 kg/DaS if a vessel is alone, and increasing up to 200 kg/DaS. For PUL, the CPUE only slightly decreases as the number of vessels increases, but stays rather stable around 200 kg/DaS.

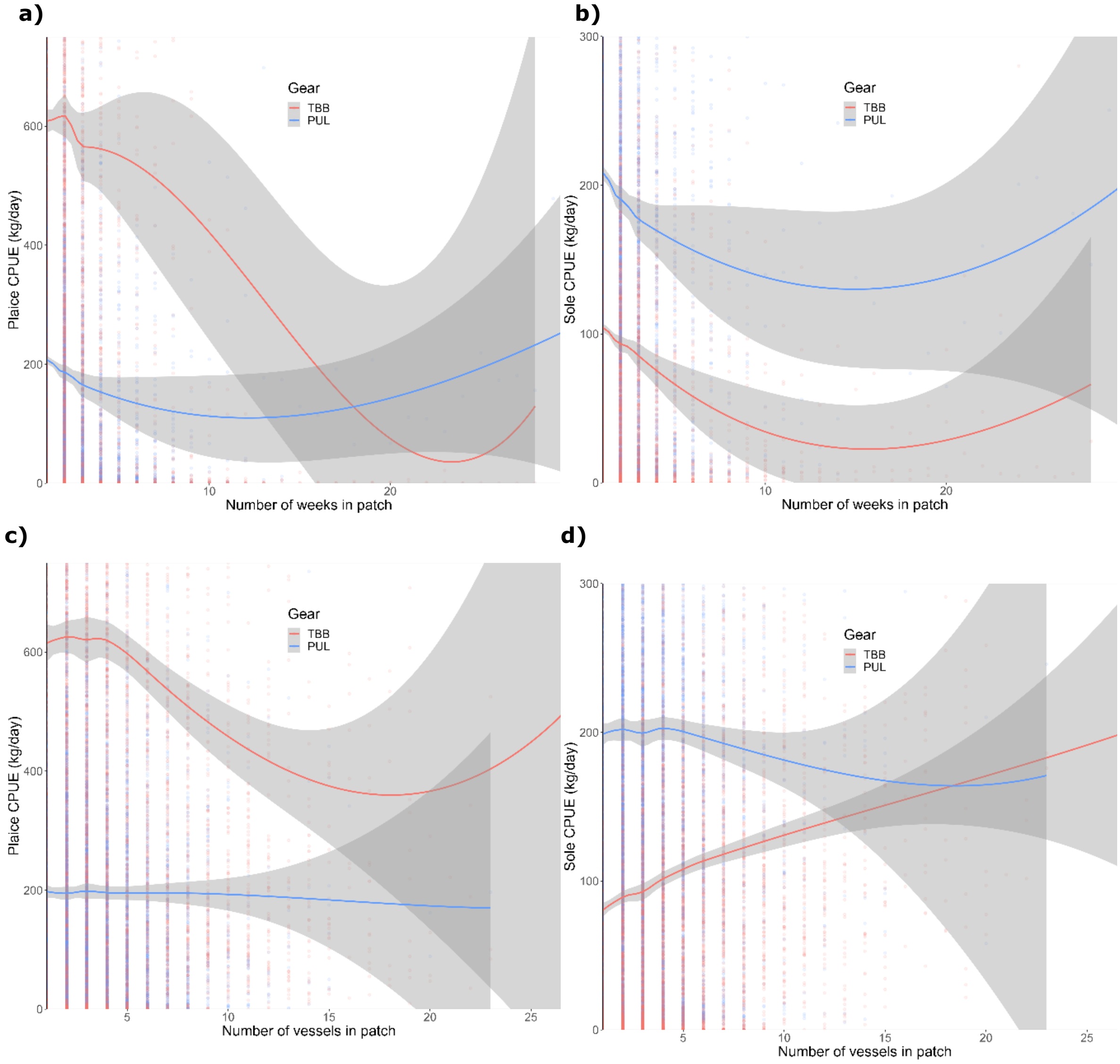


Figure 7: Relationships between a-b) number of consecutive weeks spent in a patch and plaice and sole CPUE, and c-d) number of aggregated vessels in a patch and plaice and sole CPUE, for vessels with TBB and PUL gear separately, with a loess smoother applied to the data. The grey areas represent the 95% CIs. Note: not all the data points are shown. Note the different scales on the y-axes.

4.4 GLMs of CPUE

For both species and both gear types, CPUE was analysed with GLMs as a function of the number of vessels, number weeks, fishing ground surface and the number of patches. Table 4 shows the different models and their AIC values. For all four combinations of species and gear type, the best model was the one where CPUE was explained as a function of the number of vessels in that patch (N_{ves}), the number of consecutive weeks in that patch (N_{wk}) and the surface area of that patch (S). None of the interaction effects were selected.

Table 4: Different model configurations with CPUE for plaice and sole explained as a function of of the covariates: number of vessels in that patch (N_{ves}), number of consecutive weeks in that patch (N_{wk}) and surface area of that patch (S), and interaction effects between those covariates. For each model, the degrees of freedom (df) are shown, as well as the Akaike Information Criterion (AIC) for each combination of species and gear. AIC is used to assess the model with the best fit (in bold).

	Variable(s)							AIC-TBB		AIC-PUL	
Model	N_{ves}	N_{wk}	S	$N_{ves}\times N_{wk}$	$N_{ves}\times S$	$N_{wk}\times S$	df	PLE	SOL	PLE	SOL
M1	X	X	X				5	**159139.1**	**121798.6**	**123876**	**117077.1**
M2	X		X				4	159192.2	121880	123910	117127.1
M3	X	X		X			5	159191.3	121819.7	123953.6	117087.5
M4	X		X		X		5	159191.8	121879.7	123893.4	117123.9
M5	X	X					4	159190.3	121819.1	123957.7	117094.9
M6	X						3	159244	121899.5	123986.8	117142
M7		X	X			X	5	159223.3	121963.6	123892	117085.8
M8		X	X				4	159222	121967.8	123892.4	117088.7
M9			X				3	159270.8	122054.8	123924.8	117137
M10		X					3	159240.6	121966.1	123956.2	117097.2

Table 5 gives the summaries of these four models, where it is indicated whether the effects of the covariates are negative or positive, and whether the effects are significant. The effects for all covariates are significant ($p << 0.001$). When comparing plaice CPUE between TBB and PUL using vessels, we see that the CPUE is influenced in a similar manner: the CPUE is reduced when the stay in the patch becomes longer (negative effect of N_{wk}) and when the number of vessels in a patch increases (negative effect of N_{ves}). The CPUE of plaice is higher in bigger patches (positive effect of S) for both vessels using TBB and PUL. In general, the CPUE for TBB vessels is higher than for PUL vessels (larger intercept), and responds more strongly to longer stays and more vessels. Sole CPUE is influenced differently by the number of vessels in a patch and the size of a patch for TBB than for PUL vessels: For TBB, CPUE increases when the number of vessels in a patch increases, while it decreases for PUL vessels. CPUE for TBB is also higher in smaller patches, while for PUL CPUE is higher in larger patches. For both TBB and PUL, CPUE decreases with the length of stay in a patch. In general, sole CPUE is higher with PUL gear than with TBB gear.

Table 5: Coefficients of the fixed effects of the selected models for plaice and sole CPUE for TBB and PUL gear. Variables given are: the intercept (0), number of vessels in the patch (N_{ves}), number of consecutive weeks in the patch (N_{wk}) and surface area of patch (S). Significance is indicated in bold p-values.

		PLE			SOL		
	Variable	**Estimate**	**SE**	**P**	**Estimate**	**SE**	**P**
TBB	$\beta\ 0$	705.5	15.6	< 0.001	92.5	2.3	**p < 0.001**
	$\beta\ N_{ves}$	-27.0	2.9	< 0.001	5.7	0.4	**p < 0.001**
	$\beta\ N_{wk}$	-34.4	4.6	< 0.001	-6.3	0.7	**p < 0.001**
	$\beta\ S$	0.3	0.05	< 0.001	-0.03	0.006	**p < 0.001**
PUL	$\beta\ 0$	210.9	5.8	< 0.001	217.7	4.0	**p < 0.001**
	$\beta\ N_{ves}$	-6.4	1.5	< 0.001	-3.7	1.0	**p < 0.001**
	$\beta\ N_{wk}$	-10.6	1.8	< 0.001	-8.7	1.2	**p < 0.001**
	$\beta\ S$	0.2	0.02	< 0.001	0.08	0.02	**p < 0.001**

5 Conclusions and recommendations

5.1 Discussion

This work presents a first attempt to analyse fishing grounds using relatively simple GAM models of spatial fishing effort. Overall, the method used identified a number of significant behavioural differences between vessels using TBB and vessels using PUL gear. TBB and PUL vessels are distributed differently, especially in the earlier years of the studied period before the ban on pulse fishing. As the pulse ban went into effect, these vessels often switched back to TBB gear, which means the overall TBB effort shifted to the former PUL grounds. TBB vessels fished for longer and had larger fishing grounds than PUL vessels. This could be due to the larger range of TBB vessels, which in turn is probably caused by the higher fishing speed of TBB vessels. This difference in fishing ground could be, among other things, what led to the longer stay at a fishing ground and the higher number of vessels in the same area. TBB vessels had higher catch rates of plaice and lower catch rates of sole compared to PUL vessels. This is in line with the target species of both fleets: TBB gear can be used for targeting both plaice and sole, however because of the efficiency of PUL gear for catching sole, the majority of TBB vessels in this period would have targeted plaice in more northern waters.

Some effects of surface area of the patch, length of stay and number of vessels are visible and were selected in the GLMs. These effects differed between gears and species: plaice CPUE was negatively associated with both length of stay and number of vessels, while for TBB vessels, sole CPUE was positively associated with the number of vessels (sole CPUE was negatively associated with number of weeks and vessels for PUL and with number of weeks for TBB). Plaice CPUE was higher at larger fishing grounds, while for sole the effect was the opposite for TBB (negative) and PUL (positive). In general, we see an effect of resource depletion when vessels return to the same fishing ground for a longer period. We also mostly see a competition effect in CPUE when many vessels aggregate. These effects are always more pronounced for the target species of the fleet (sole for PUL, mostly plaice for TBB). This makes sense, as the patches that are being targeted are probably abundant with the target species.

An aspect that was not taken into account in this study, was the possible variation in target species, especially within the TBB fleet: These vessels can target both plaice and sole, and may use mesh sizes more appropriate for these species. In this study, all TBB vessels were considered collectively, without a regard for the differences within that fleet. We also did not consider whether vessels switched from TBB to PUL, and if that changed their behaviour and/or target species. This is especially interesting when studying a time period when many vessels were forced to switch from PUL to TBB fishing due to ban on pulse fishing.

5.2 Recommendations for further analyses

We also evaluate the possibilities and limitations of the methods used. One of the main issues to address is how we determine a fishing ground. When comparing the different peel levels (or effort thresholds) in table 2, we observe that the chosen peel has a large impact on the resulting fishing ground characteristics. Rijnsdorp et al. (2022) estimate the size of a core to be 24 km^2 for PUL and 34 km^2 for TBB vessels and their analysis uses more detailed information on a resource patch, looking at the distance between individual hauls. Comparing our results to Rijnsdorp et al., it seems peel level 8 may be the most appropriate effort threshold to categorize fishing grounds. It must be noted that Rijnsdorp et al. (2022) consider exploitation patches on smaller (time) scales, of several days, while here we only considered total weekly fishing behaviour (including catches and CPUE). For the vessel return rate, we used the 5^{th} peel, which seemed a good compromise between fishing grounds being too large and too small. We recommend to update this analysis with higher a threshold (e.g. peel level 8) and study the relationships between length of stay, number of vessels and surface area. Another possibility would be to set an absolute effort threshold for all vessels in all weeks. That way, comparisons between fishing grounds can be made more easily.

To be able to compare between vessels in the same week, we used week numbers to define a fishing trip. Although this has its benefits, it will have led to problems with trips that occurred in multiple weeks (for example, Wednesday to Wednesday). Because these trips would then have been considered two trips, this may have led to a higher assessment of return rate. To more accurately define fishing trips, information on the departure and return date of vessels is needed. To Another improvement that could be made to the calculation of the return rate, is to see how significant the overlap with the previous week actually is: Here, we assumed vessels to return when there was any overlap at all. However, it could be more appropriate to consider a vessel as returning when the overlap was a certain proportion of the fishing ground.

The grouping of vessels was also done straightforward, not taking into account whether vessels were actually in the same location at the same time (rather, in the same week). This made the computing relatively simple because only one shapefile had to be created for each vessel in each week, it may have led to an overestimation of aggregating behaviour. Another effect of this was that the groups were not discrete units, as the only information available was what other vessels overlapped with each vessel. Because of this, it was not possible to aggregate landings over the clustered groups. Perhaps the use of higher effort threshold would lead to the formation of more discrete groups.

An aspect that was not considered in this study, is the difference in CPUE inside and outside of a patch. This was due to the fact that we did not have a value of CPUE at each 'ping', but rather the catches over multiple 'pings'. A way around this would be to calculate the CPUE from the interval and the catch over that ping (and others).

The GAM method of analysing fishing grounds is relatively straightforward, however, it still required significant processing power and thus computing time. Due to the repetitive nature of analysing many vessels over many weeks, this task is ideally suited for parallel computing. This cut back the computing time significantly and made it an appealing method for analysing spatial data.

Although the GAM method seems to accurately translate VMS data into spatial density maps for a vessel in a week, the method did scale well to the larger datasets of all entries in a year for each gear. Due to computational restraints, we had to use a less fine raster to aggregate the data entries to: The whole (square) area in which fishing was about 750x750 km, which led to around 500.000 grid cells if the cells were 1x1km (as in the analysis per vessel per week). Therefore, the cells were set to 5x5km, resulting in around 20.000 grid cells. The resolution of these models is rather low, and does not allow for the presentation of fishing grounds in the same detailed manner as the models for one vessel in one week.

The GAM method for analysing spatial fisheries data allows for many different types of fishing behaviour studies. One aspect that was not researched in this work, is the behaviour of individual vessels. It would be interesting to see if certain types of consistent behaviour can be identified (for example, 'explorers vs. residents' or 'pioneers vs. followers'), and to test which of these behaviours resulted in the highest catch rates.

For the GLM models, we set the maximum number of covariates to three. This led to the exclusion of all interaction effects from the best models. Given the interactions visible in the grid plots (Figure 6), the inclusion of some interaction effects would seem likely. When the maximum number of covariates was increased beyond what was used in this study, interaction effects were selected for several models. The role of the maximum number of covariates allowed in each model should be critically examined, as to not be overzealous with excluding or including covariates. For the GLM models, the Gaussian distribution was used. This does not seem to be the most appropriate method, as values of 0 are possible (and indeed, prevalent), leading to a 0-truncated dataset. However, other, more appropriate model distributions did not return functional models. In future, the chosen distribution should be examined more carefully.

Lastly, to assess the use this method for analysing fishing behaviour, we recommend comparing the output of this method to the output of Rijnsdorp's (2022) more accurate method on the same data, to see if the GAM model outputs actually accurately represent exploitation patches. All in all, we feel this method has great potential as an easy-to-use, accessible way of analysing spatial fisheries data.

6 Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2015 certified quality management system. The organisation has been certified since 27 February 2001. The certification was issued by DNV.

References

Rijnsdorp, A. D., Aarts, G., Hintzen, N. T., van Rijssel, J. C., Winter, A. M., & Poos, J. J. (2022). Fishing tactics and the effect of resource depletion and interference during the exploitation of local patches of flatfish. ICES Journal of Marine Science, 79(7), 2093-2106.

Justification

Report C031/23
Project Number: 4318100252

The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

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