Integrating Vessel Monitoring Systems (VMS) data with daily catch data from logbooks to explore the spatial distribution of catch and effort at high resolution.

Hans Gerritsen and Colm Lordan

Abstract

Vessel Monitoring Systems (VMS) automatically collect positional data from fishing vessels. The VMS data can be linked to catch data from logbooks to provide a census of spatially resolved catch and effort data. We explore and validate the most appropriate and practical method for integrating Irish VMS and logbook data. A simple speed rule is applied to identify VMS records that correspond to fishing activity. These data are then integrated with the catch data from the logbooks using date and vessel identifier. A number of assumptions were investigated and the resulting distribution maps of catch and effort appear to be unbiased. The method is illustrated with an example of a time-series of spatially explicit catch per unit effort estimates. The proposed method is relatively simple and does not require specialist software or computationally intensive methods. It will be possible to generalise this approach to similar data sets that are available within the EU and many other regions. Analysis of integrated VMS and logbooks data will allow fisheries data to be analysed on a considerably finer spatial scale that was possible in the past which opens up a range of potential applications.

Keywords: cpue, ecosystem approach, fisheries, fishing activity, spatial distribution, vessel monitoring systems, VMS

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1. Introduction

The growing time-series of Vessel Monitoring Systems (VMS) is beginning to allow fisheries scientists to properly take into account the fine scale spatial and temporal dimensions of commercial fisheries data. This probably represents one of the most important developments in fisheries research in the last decade. The ecosystem approach to fisheries management (EAFM) increasingly requires spatially resolved fisheries data: new EAFM demands, such as the maintenance of biodiversity, spatial and temporal fisheries closures and diverse maritime resource uses, mean that the spatial and temporal scales of traditional landings and effort data are no longer adequate for many purposes.

Automatic monitoring of fishing vessels' positions is a relatively new development in European Community waters. In 1997, the European Commission (EC) introduced legislation to monitor European fishing vessels for control and enforcement purposes using a satellite-based Vessel Monitoring System (VMS) (EC, 1997a). Since 1 January 2000 all fishing vessels exceeding 24m in overall length have been required to transmit their position at least every two hours (EC, 1997b). The regulation was amended to include all vessels exceeding 18m in 2004 and 15m from 2005 (EC, 2003). Since 2006 vessels are also required to transmit vessel speed and course (EC 2003). Over the last few years VMS data have become more freely available for scientific purposes although access to such data often remains problematic because of legal and confidentiality constraints.

Skippers of all European Community vessels over 10m length are also required to record the retained catch weights by species in logbooks on a daily basis (EEC, 1983). Gear type and effort (hours fished) are also recorded. Catch locations are recorded as the ICES statistical rectangle where the fishing operations took place. These rectangles consist of a grid of 0.5° latitude by 1° longitude (approx 1100 nm^2 at 52° latitude). This is a very course resolution compared to the spatial structure that is known to exist in most fisheries.

The catch data reported in the logbooks do not include discarded fish and all catch data discussed here refers to retained catch only. The term 'landings' is often used to describe the retained catch but in the current context this can be confusing because landings only take place once per trip while catches take place throughout the trip.

VMS data have many potential applications in fisheries science, many recent publications have focussed on a description of the spatial distribution of fishing effort (e.g. Murawski *et al.*, 2005; Mills *et al.*, 2007; Fonseca *et al.*, 2008; Mullowney and Dawe, 2009; Lee *et al.*, in press; Rijnsdorp *et al.*, 1998). In some cases the effort distribution can be used to track the pattern in distribution of the target species (Bertrand *et al.*, 2008). VMS data have also been used to estimate the impact of trawling on the seabed in order to identify untrawled areas or to estimate how frequently an area is trawled (Eastwood *et al.*, 2007; Stelzenmüller *et al.*, 2008). Another current application of VMS data is the analysis of fishers' behaviour through the movement of vessels (Bertrand *et al.*, 2005; Bertrand *et al.*, 2007; Marchal *et al.*, 2007; Mullowney and Dawe, 2009)

The explanatory power of the VMS data can be greatly increased by linking the data to catch data from fishers logbooks. Some of the applications of integrated VMS and catch data that have been investigated include: the use of maps of catch per unit effort (cpue) to estimate fish density (Afonso-Dias et al., 2002); quantifying of misreporting (Palmer and Wigley, 2009) and population-depletion estimates (Deng et al., 2005; Walter et al., 2007). However there are a large number of other possible applications to integrated VMS and logbook datasets, particularly in a mixed-fisheries context. Management of mixed fisheries can be particularly challenging but it may be assisted by the use of integrated VMS and logbook data in a number of ways, for example:

- More accurate cpue time-series can be provided by taking into account changes in fishing locations for fleets that may switch between target species.
- By comparing the spatial distribution of effort and cpue data, the intended target species of each trip may be identified, allowing trips to be characterised into métiers more accurately.
- Distribution maps of catches of vulnerable species can be used to identify areas for fisheries closures and to monitor their effectiveness.
- Track records of vessels can be established; derogations from closures may be obtained for vessels that can be shown to avoid catches of certain species inside proposed closed areas.
- Sampling locations can be compared with the distribution of catches or effort to investigate whether the samples are representative of the catches or effort of a fleet.

The VMS data do not indicate whether a vessel is fishing, steaming or inactive. It is important to know this to avoid assigning catches or effort to locations where the vessel was not actually engaged in fishing operations. The most common approach to this problem is to use vessel speed criteria to infer whether a VMS record corresponds to fishing activity (e.g. Murawski *et al.*, 2005; Eastwood *et al.*, 2007; Palmer and Wigley, 2009; Walter *et al.*, 2007; Mullowney and Dawe, 2009; Lee *et al.*, in press).

Some authors have reported a significant number of false-positive results (where vessels were travelling at ‘fishing’ speeds but were not actually engaged in fishing operations) but false-negative results tend to be rare (vessels travelling at speeds outside the range of ‘fishing’ speeds that were actually engaged in fishing). Mills *et al.* (2007) developed rules for speed and directionality but they only resulted in a very small improvement on speed alone. Borchers and Reid (2008) used hidden Markov models based on vessel speed but it was not clear whether this method performed better than a simple speed rule. Bertrand *et al.* (2008) used artificial neural networks to identify sets of seine netters using speed, time, change in direction and change in speed. They were able to correctly identify 83% of fishing operations which was not possible using speed alone.

Logbook data are collected on a different temporal scale to the VMS data which creates a problem for linking the two datasets. Pedersen *et al.* (2009) combined landings data of all vessels by gear type and ICES statistical rectangle and weighted these landings by the spatial distribution of the VMS effort data. This method can lead to biased estimates as skippers are not required to record all statistical rectangles in which they fished but may only record the rectangle in which most of the catches were made (EEC, 1983). In the Irish logbook database, less than 2% of all daily logbook entries contain entries for more than one statistical rectangle per vessel per day while the matching VMS data suggests that more than 50% of all daily fishing operations cover more than one rectangle. Therefore, the reported statistical rectangles are not useful for linking VMS and logbook data. Others have assigned the landings from each trip to the VMS fishing locations for the matching trip (Afonso-Dias *et al.*, 2002; Palmer and Wigley, 2009). While this may be a valid approach, the catch data are often available on a daily basis and linking data by date, rather than by trip, will produce more accurate results if the variability in catches within each day is lower than the variability within each trip.

An example will be provided here to illustrate the use of integrated VMS and logbook data to estimate a time-series of cpue for monkfish to the west of Ireland. Monkfish (*Lophius piscatorious* and *L.budegassa*) are mainly caught by otter trawlers in a mixed fisheries, often together with hake and megrim. The spatial distribution of effort the otter trawl fleet may change over time; for example vessels may shift between targeting *Nephrops* and demersal fish, or fuel prices might dictate their range. Raw cpue signals can therefore be masked by these changes. The integrated VMS and logbook data can be used to identify an area where monkfish are targeted and to estimate the cpue for this area alone. This will provide a more reliable index of abundance which could be used for stock assessment and advice.

The objective of the current paper is to explore and validate the most appropriate method for integrating Irish VMS and logbook data and to provide a worked example of an application that is relevant to fisheries science. It will be possible to generalise this approach to similar data sets that are available within the EU and many other regions where catches are reported on a daily basis.

2. Methods

All data were held in a SQL Server 2008 database. Initial data manipulation took place in SQL and further analyses were performed in the R environment (R-Development Core Team, 2009). The data were screened for duplicate records and outlying values of position, speed, catch and effort.

Speed criteria

Since 2006, the instantaneous vessel speed and course have been transmitted with the positional information for most VMS records (the instantaneous speed is the speed at the instant the data are recorded). In cases where the instantaneous speed is unavailable the vessel speed is generally calculated from the orthodromic distance and time interval between consecutive VMS records under the assumption that the vessel travelled in a straight line at a constant speed. (e.g. Mills *et al.*, 2007; Walter *et al.*, 2007).
Speed rules may be validated by checking the results of a rule against a dataset with known fishing times and locations (e.g. Palmer and Wigley, 2009). Ireland has conducted a fisheries observer programme aimed at estimating discards since 1993. During the observer trips all fishing times and locations are recorded and these trips can therefore be used to investigate and validate the most appropriate speed thresholds. Most observer trips take place on bottom otter trawlers, therefore the analysis will be limited to this gear type. After removing trips with ambiguous vessel names or obvious data entry errors, a total of 153 observer trips could be matched up with the VMS data corresponding to 845 days at sea and 2109 valid hauls.

Estimating effort
Effort was estimated for each VMS record as the time interval since the previous record. Any time intervals of more than 4 hours were removed and substituted with the daily average time interval of the remaining records in order to avoid assigning a disproportionate amount of effort to records that follow a period of missing data. Speed criteria were then applied to remove all records where the vessels were inactive or steaming.

Allocating catch data to VMS positions
The Community Fleet Registration (CFR) number was used to link vessels in the VMS and logbook databases. This number is unique to each vessel. For each vessel and date there are usually a number of VMS records that correspond to fishing activity and the catches were assigned equally to all fishing locations for each vessel on each day (following Deng *et al.*, 2005). For example: if a vessel with 5 VMS 'fishing' records on a day catches 100kg of cod, then 20kg of cod will be allocated to each of the 5 VMS fishing positions. This approach requires the assumption that the catches made in a single day are uniformly distributed. This important assumption will be tested using the fisheries observer dataset.
Once the catch or effort data have been assigned to each VMS location, the point data can be aggregated to an appropriate grid for mapping.

Monkfish cpue time series
Irish VMS and logbook data from 2003-2009 were used in the area between 9°-15°W and 49°-54°30'N. Vessels using otter bottom trawls, (including twin rigs and pair bottom trawls) were selected. The catch and effort data were aggregated to a grid of 0.6° longitude by 0.04° latitude (approx 2.2 x 2.4nm).

3. Results
Speed criteria
In order to establish the optimum speed criteria for distinguishing fishing operations, the fisheries observer dataset was used (otter bottom trawlers only). The proportion of VMS records that were correctly assigned to fishing and non-fishing activity was calculated for a range of minimum and maximum fishing speeds. Figure 1 shows that

when using the instantaneous speed, the highest proportion (88%) of correctly assigned VMS records resulted from speed criteria that set the minimum fishing speed around 1.5 knots and the maximum fishing speeds around 4.5 knots. Vessels travelling at less than 1.5 knots are assumed to be inactive (e.g. sheltering, waiting for the tide or mending gear). Vessels travelling at speeds over 4.5 knots are assumed to be steaming. Figure 1 also shows that if the calculated speed is used, the optimum speed criteria are lower (minimum fishing speed of around 0.5kn and a maximum fishing speed of around 4kn). The proportion of correctly assigned VMS records is slightly lower when using the calculated speed (83%). Various attempts were made to include instantaneous, calculated speed and / or course changes into an algorithm to identify fishing operations but the proportion of correctly assigned records could not be significantly improved.

In order to investigate when the speed criteria might fail to correctly identify whether a vessel is fishing, a number of trips were examined in detail. Many trawlers shoot their gear very soon after hauling it and during this period they are likely to travel at 'fishing speeds' while not actually engaged in fishing. Figure 2 illustrates that many of these false-positive results occur between consecutive hauls. Trip 1 (Figure 2) shows an example where the vessel was inactive for a number of hours at a time and this was generally reflected in the vessel speed. Trip 2 shows an example where the vessel travelled for a considerable period between fishing operations and this was also clearly reflected in the vessel speed. However, this trip also shows a few false-negative results where the vessel was reported to be fishing but the vessel speed was below the threshold of 1.5 knots. This occurred most frequently at the very start and end of a tow. Trip 3 illustrates that many false-positive results occur if a VMS transmission falls in the period between hauling the gear and shooting it again.

Figure 3 shows that fishing operations are generally identified with a high level of accuracy (overall 94%) however in the period just after shooting and just before hauling the proportion of correctly identified records is lower. The proportion of records that are correctly identified as steaming or inactive is quite low just before shooting and after hauling (around 50%; Figure 3) but this improves if the vessel is steaming or inactive for longer periods (overall 68% correct). So the highest proportion of false-positive errors appears to occur close to fishing operations, in which case the distribution pattern of fishing effort will not be strongly biased by these errors.

Allocating catch data to VMS positions

By allocating daily catches equally to all 'fishing' records for that day, one makes the implicit assumption that the catch rate of each species does not vary between hauls in a single day. In order to test whether the results are sensitive to this assumption, the catch data from the observer trips was examined. During observer trips, the catches for individual hauls are recorded by the observer which allows us to estimate the true spatial distribution of the catches and compare this to the distribution of the catches that would be result from assigning the total daily catches equally to all hauls for each vessel (which reflects the way the catches are assigned to the VMS data). The catches were allocated to the mid-point of each tow and aggregated on a grid of 0.1° longitude x 0.15° latitude to create distribution maps. The grid with the true catches was compared to that of the daily catches by plotting the corresponding values in each cell of the two grids against each other (Figure 4). The figure shows that allocating the average daily catch weights to each haul position gives nearly identical results to using the actual catch weights from each haul. So even though the catches may vary within a single day, this variation does not appear to cause bias or poor precision in the distribution maps (the results are highly correlated with a slope of 1).

Monkfish cpue time series

Figure 5 shows the otter trawl effort of Irish vessels during 2003-9 and the proportion of monkfish, megrim and hake in the catches. Monkfish are caught throughout the area but they appear in the highest proportion in the catches between 225m and 450m depth. A polygon was drawn to take in the area between 225m and 450m depth to the east of 12°30'W which corresponds to the main area where monkfish appear to be targeted. Monkfish are often landed with hake and megrim, however Figure 5 shows that megrim are mainly caught in shallower areas than monkfish (to the east of the polygon) while hake are mainly caught in deeper areas (west of the polygon). The catches and effort within the polygon were estimated on a yearly basis to produce a cpue time-series (Figure 6). For comparison, the cpue for the whole area was also estimated. Both trends show an increase over time but the increase in cpue within the polygon is more pronounced and is likely to provide a more accurate index of abundance because it is insensitive to changes in the spatial distribution of effort. The cpue for the whole area was also estimated directly from the logbooks (vessels >15m only). These values are slightly lower than the VMS estimates, suggesting a small bias in the effort estimate from the VMS.

4. Discussion

Speed criteria

There can be considerable differences between the instantaneous vessel speed and the calculated speed. The calculated vessel speed is based on the assumption that the vessel travelled in a straight line at a constant speed between VMS positions. When a vessel is steaming this assumption seems reasonable and the calculated speed is expected to agree well with the instantaneous speed. On the other hand, when vessels are fishing they rarely follow straight lines and are likely to change their speed around the start and end of each fishing operation. Therefore the calculated speed will be less accurate when a vessel is fishing. In the current case, the instantaneous speed performed slightly better at distinguishing fishing operations than the calculated speed, but it appears reasonable to use the calculated speed if the instantaneous speed is not available.

The speed criteria that were applied resulted in a low proportion of false negative results; when a vessel was travelling at less than 1.5kn or more than 4.5kn it was rarely engaged in fishing activity (94% correct). However there was a significant proportion of false-positive results (only 68% correct); there could be a number explanations for this. Firstly it is possible that not all shoot and haul times were (correctly) recorded in which case the true proportion of false-positive results is unknown. Secondly while a vessel is engaged in shooting or hauling the gear, this is not recorded as fishing activity but the vessel is likely to travel at a speed that corresponds to fishing activity. Alternatively, a vessel might steam slowly while waiting for the right tide or mending gear, the speed at which a vessel is steaming may be also reduced due to bad weather.

Although the rate of false-positive results is quite high, otter trawlers tend to spend much more time fishing then steaming or being inactive, therefore the total proportion of errors was relatively small (88% correct). Lee *et al.* (in press) found for a number of gear types that the distribution patterns of fishing effort was relatively insensitive to actual speed criteria. The reason for this may be that many of the false-positive errors occurred just before shooting or just after hauling the gear while the vessel is still in the same area where the fishing operations took place. One may wish to change the speed criteria to minimise either the false-positive results or the false-negative results, depending on the purpose of the analysis.

Linking VMS and logbook data

Linking VMS and logbook data by date and vessel identifier, requires the assumption that the catches are uniformly distributed over all VMS positions that correspond to fishing activity. This is an important assumption because catches might vary within a day due to tides, diurnal cycle or fishing location and a vessel can cover a relatively large area in a day. Most fishing operations take place within a 5 nautical mile radius on any particular day, but 5% of operations take place in a radius of 30 nautical miles or more (VMS data of Irish vessels). However, it is clear from Figure 4 that once a large number of observations are aggregated, the overall errors resulting from variability in the catches within each day do not appear to affect the distribution pattern of catches. The most likely explanation is that these errors are random and tend to cancel each other out as long as each grid cell has a sufficient number of observations. Therefore, patterns in catches can be clearly discerned on scales much smaller than the daily range of the fishing vessels.

Due to imperfections in both the VMS and logbooks databases, it is not possible to match all records. For the Irish otter trawl data, 71% of 93827 of logbook vessel-days could be matched up with their VMS records. Of the remaining vessel-days, 15% were from vessels which have no VMS requirement (under 15m). The other 14% could not be matched up for various reasons including ambiguous vessel names and data entry errors. If these mismatches occur randomly, they will not affect the distribution patterns but in some cases it might be necessary to raise the effort or catch data to the total reported effort or catches from the logbooks.

Monkfish cpue time series

The monkfish cpue analysis indicated that considerable spatial structure can exist, even within the catches of species that are generally landed together as monkfish, hake and megrim are. This allowed an area can be identified where a single species appears to be the main target. This could then be used to estimate cpue time-series that is insensitive to changes in the spatial distribution of effort.

Because most (96%) of the monkfish landings were taken by vessels exceeding 15m in total length, the vast majority of the vessels in the fishery were covered by VMS since 2005. However for 2003 and 2004 the estimates might be biased because only larger vessels (>24m and >18m respectively) were required to carry VMS in those years. The cpue estimates are also contingent on accurate reporting of the catches.

Conclusions

Catch data were assigned to VMS positions on a daily basis and this approach appears to result in unbiased distribution patterns although a small proportion of the catches could not be linked to VMS data. The proposed method is relatively simple and does not require specialist software or computationally intensive methods and can be generalised to a large number of datasets. Analysis of integrated VMS and logbooks data will allow fisheries data to be analysed on a considerably finer spatial scale that was possible in the past.

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Figures

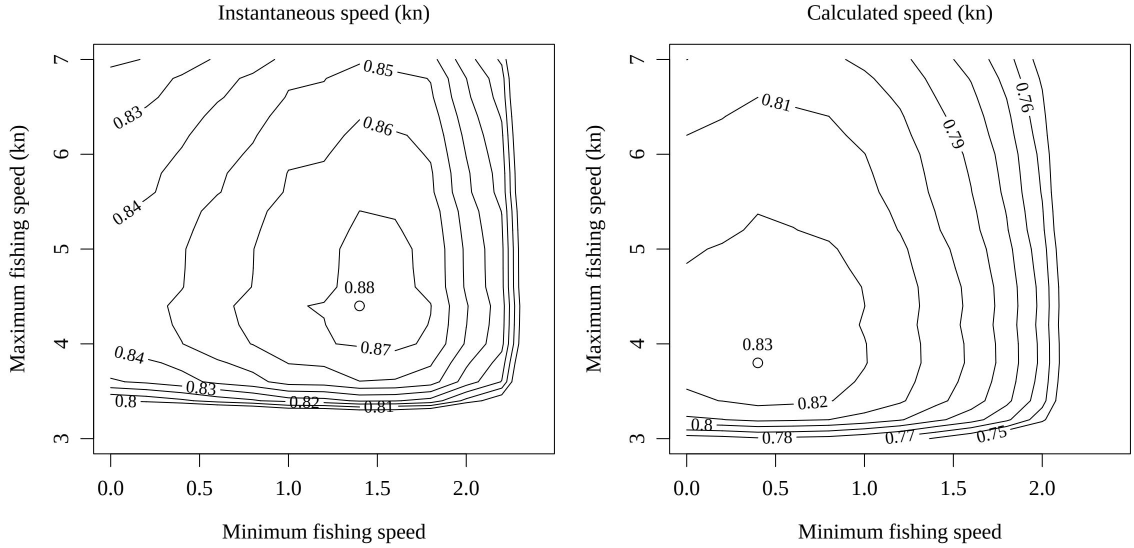

Figure 1. The minimum and maximum speed at which otter bottom trawlers were assumed to be fishing. The contour lines show the proportion of VMS records that were correctly identified as fishing or non-fishing activity during observer trips. The left panel shows the results for the instantaneous speed recorded by VMS and the right panel shows the results for the calculated speed.

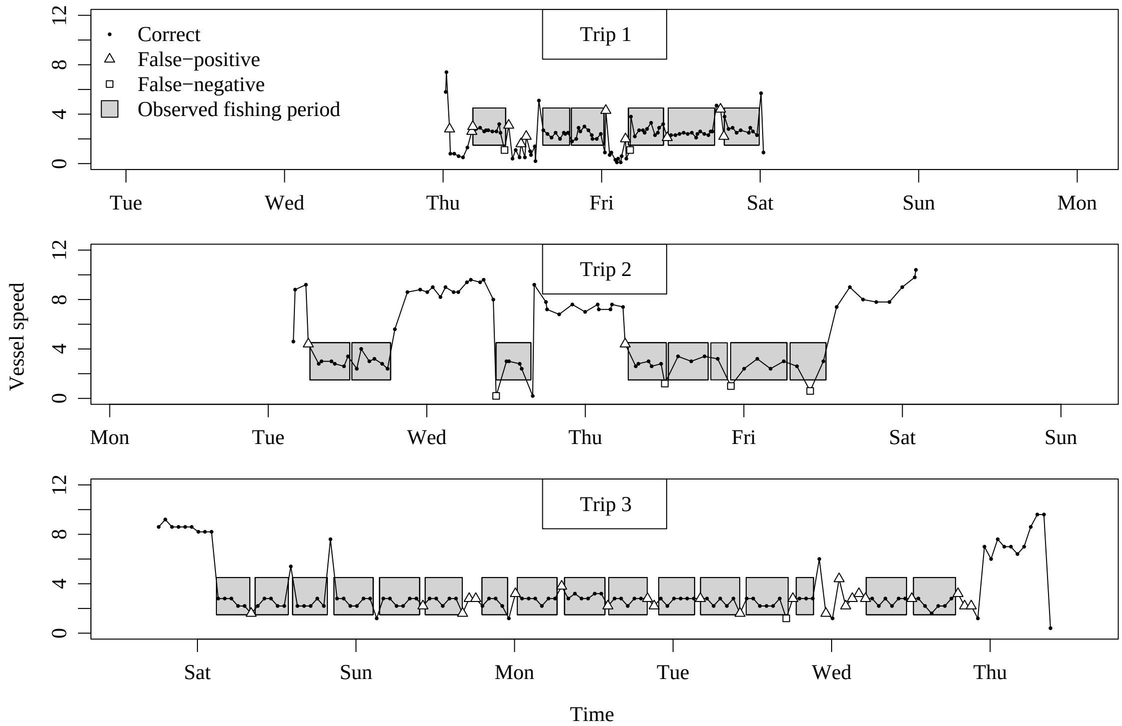

Figure 2. Three examples VMS data from observer trips. Each symbol represents one VMS record. The grey boxes represent the fishing activity recorded by the observer. Instantaneous vessel speeds between 1.5 and 4.5 knots were assumed to correspond to fishing. False-positive results are VMS records which fall within the speed criteria for but for which no fishing activity was recorded. False-negative results are VMS records that fall outside the speed criteria for fishing but which took place during fishing operations.

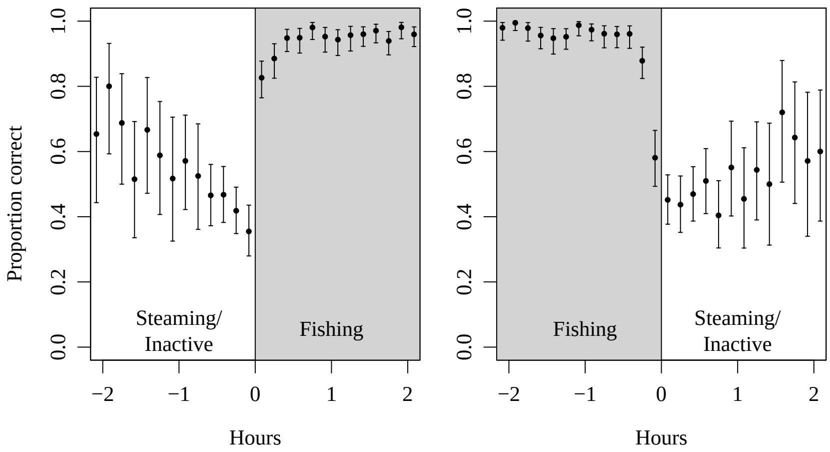

Figure 3. The proportion of VMS records from observer trips that were correctly identified as fishing or non-fishing activity plotted against the time before the gear is shot (left panel) and the time before the gear is hauled (right panel). The error bars represent the 95% confidence intervals of the proportions.

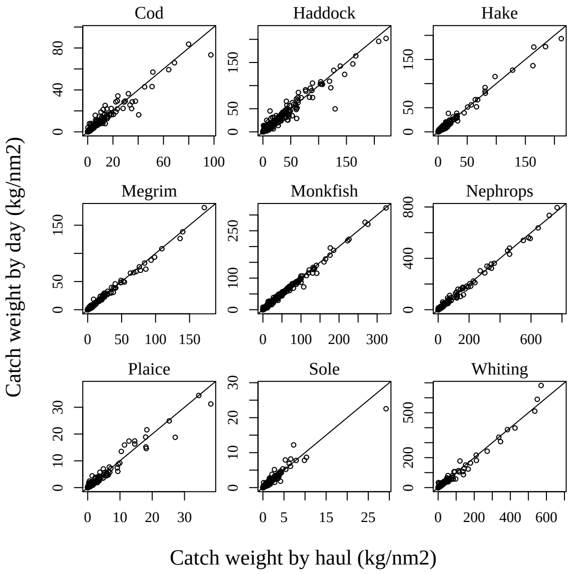

Figure 4. Comparison of two methods of assigning catch weights to fishing positions for nine main species caught on observer tips of bottom otter trawlers. Assigning catch weights to the actual haul position (catch weight by haul) resulted in very similar results to assigning the average daily catch to each haul position (catch weight by day) after aggregating the data to a grid of 0.1° x 0.15°. Each point in the plots represents a grid cell.

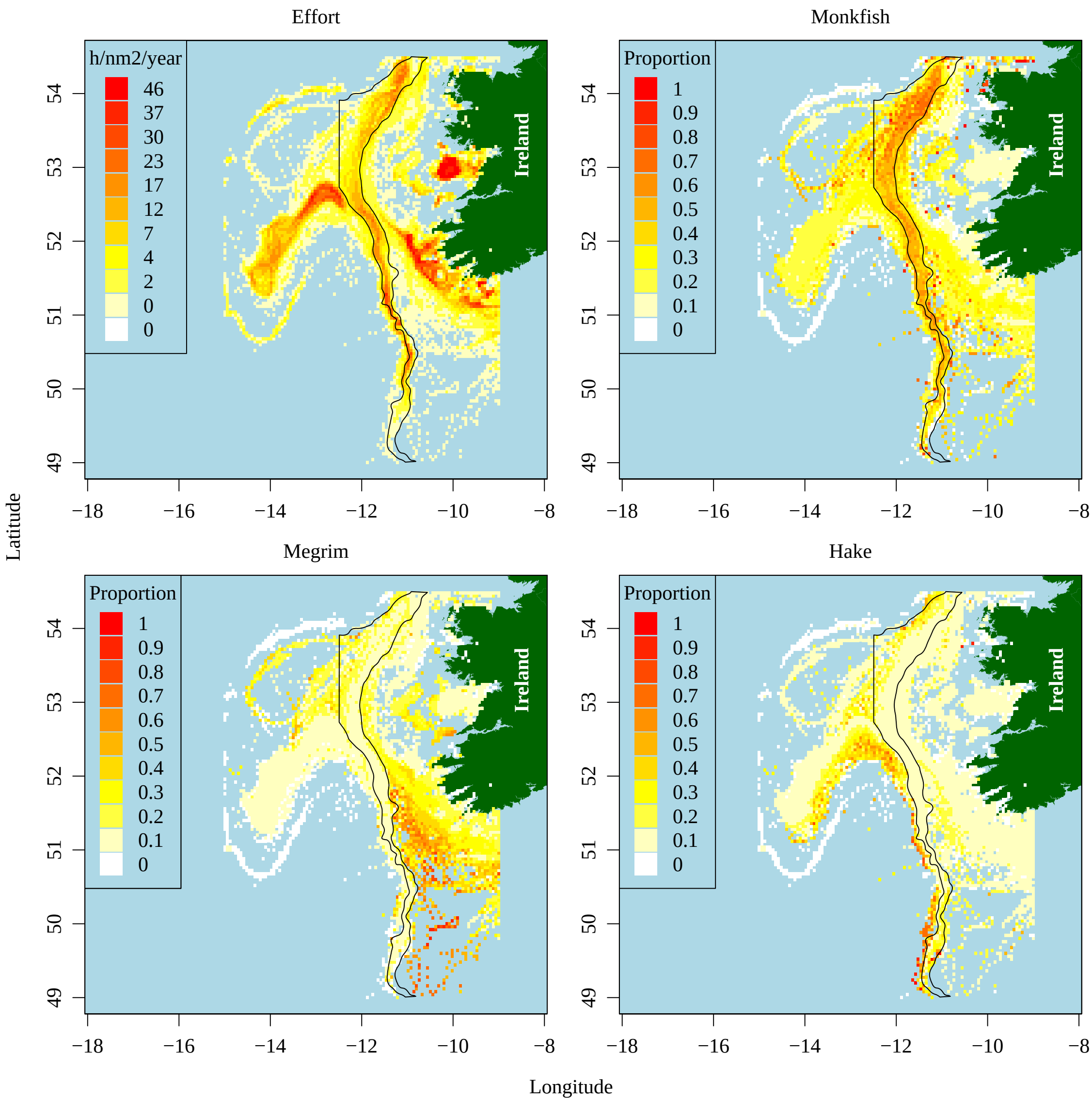

Figure 5. The otter bottom trawl effort to the west of Ireland during 2003-9 (top left). The proportion of monkfish (top right), megrim (bottom left) and hake (bottom right) in the retained catches. The polygon in which the catches are generally dominated by monkfish is defined as the area between 225m and 450m bottom depth to the east of 12° 30’W.

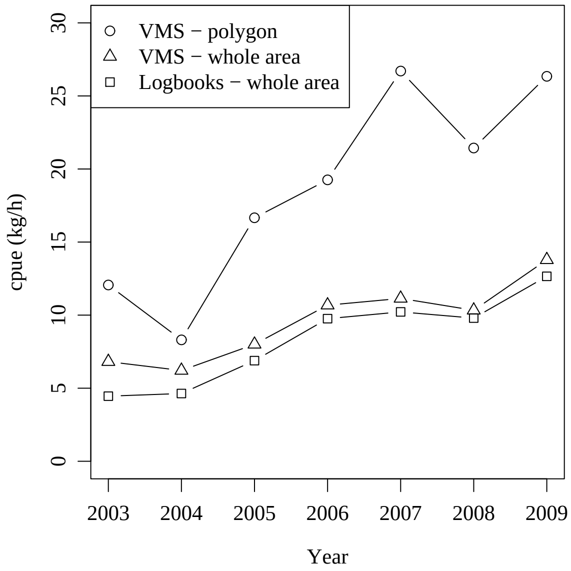

Figure 6. Cpue estimates for monkfish. The cpue inside the polygon is considerably higher than the cpue in the whole area (9° to 15°W and 49° to 54°30’N). The cpue estimate from logbooks data is shown for comparison.