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Integrating vessel monitoring systems (VMS) data with daily catch data from logbooks to explore the spatial distribution of catch and effort at high resolution

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Vessel monitoring systems (VMS) automatically collect positional data from fishing vessels, and the data can be linked to catch data from logbooks to provide a census of spatially resolved catch-and-effort data. The most appropriate and practical method for integrating Irish VMS and logbook data is explored and validated. A simple speed rule is applied to identify VMS records that correspond to fishing activity. The VMS data are then integrated with the catch data from logbooks using date and vessel identifier. Several 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 estimates of catch per unit effort. The proposed method is relatively simple and does not require specialist software or computationally intensive methods. It will be possible to generalize this approach to similar datasets that are available within the EU and many other regions. Analysis of integrated VMS and logbook data will allow fisheries data to be analysed on a considerably finer spatial scale than was possible previously, opening up a range of potential applications.

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

Introduction

The growing time-series of vessel monitoring systems (VMS) is beginning to allow fisheries scientists to take into account the fine-scale spatial and temporal dimensions of commercial fisheries data, an important development in fisheries research. 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 vessel 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 satellite-based VMS (EC, 1997a). Since 1 January 2000, all fishing vessels >24 m overall length have been required to transmit their position at least every 2 h (EC, 1997b). The regulation was amended to include all vessels >18 m in 2004 (EC, 2003) and >15 m from 2005, and since 2006, vessels have also been required to transmit vessel speed and course information. Over the past few years, VMS data have become more widely available for scientific purposes, although access to such data often remains problematic because of legal and confidentiality constraints.

Skippers of all EC vessels >10 m long are also required to record the retained catch weight by species in logbooks on a daily basis (EEC, 1983). Gear type and effort (hours fished) are also recorded. Catch locations are recorded as ICES statistical rectangles where the fishing operations took place. These rectangles consist of a grid of 0.5° latitude by 1° longitude (~1100 nautical miles^2 at 52°N), a low resolution compared with the spatial structure known to exist in most fisheries.

Catch data reported in logbooks do not include discarded fish, so all catch data discussed here refer 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, whereas catches take place throughout the trip.

VMS data have many potential applications in fisheries science, and many publications have focused on a description of the spatial distribution of fishing effort (e.g. Rijnsdorp *et al.*, 1998; Murawski *et al.*, 2005; Mills *et al.*, 2007; Fonseca *et al.*, 2008; Mullowney and Dawe, 2009; Lee *et al.*, 2010). In some cases, the effort distribution can be used to track the distribution of the target species (Bertrand *et al.*, 2008). VMS data have also been used to estimate the impact of trawling on the seabed 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 fisher behaviour through the movement of vessels (Bertrand *et al.*, 2005, 2007; Marchal *et al.*, 2007; Mullowney and Dawe, 2009).

The explanatory power of VMS data can be increased by integrating the catch data from 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 misreporting (Palmer and Wigley, 2009), and population depletion estimates (Deng *et al*., 2005; Walter *et al*., 2007). However, there are many other possible applications of 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 many ways, for example:

(i) more accurate cpue time-series can be provided by taking into account changes in fishing locations for fleets that may switch between target species;

(ii) the intended target species of each trip may be identified by comparing the spatial distribution of effort and cpue data, allowing trips to be characterized into métiers more accurately;

(iii) distribution maps of catches of vulnerable species can be used to identify areas for potential fisheries closure and to monitor their effectiveness;

(iv) track records of vessels can be established, and derogations from closures may be obtained for vessels that can be shown to avoid catches of certain species inside proposed closed areas;

(v) 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.

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. The most common approach to this problem is to use vessel-speed criteria to infer whether a VMS record corresponds to fishing activity (Murawski *et al*., 2005; Eastwood *et al*., 2007; Walter *et al*., 2007; Mullowney and Dawe, 2009; Palmer and Wigley, 2009; Lee *et al*., 2010). 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). However, 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, and changes in direction and speed. They were able to identify 83% of fishing operations correctly, an outcome not possible using speed alone.

Logbook data are collected on a different temporal scale from 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, then weighted those landings by the spatial distribution of the VMS effort data. This method can lead to biased estimates, however, because skippers are not required to record all statistical rectangles in which they fished; they only need to record the rectangle in which most of the catches were made (EEC, 1983). In the Irish logbook database, fewer than 2% of all daily logbook entries contain entries for more than one statistical rectangle per vessel per day, whereas the matching VMS data suggest that >50% of all daily fishing operations cover more than one ICES rectangle. Therefore, the statistical rectangles reported are not useful for linking VMS and logbook data. Other workers 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). Although this may be a valid approach, catch data are often available daily, 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 (*Lophius piscatorius* and *L. budegassa*) west of Ireland. Monkfish are caught mainly by otter trawlers in mixed fisheries, often together with hake (*Merluccius merluccius*) and megrim (*Lepidorhombus whiffiagonis*). The spatial distribution of effort by 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 that area alone, providing a more reliable index of abundance for use in stock assessments and management 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 generalize this approach to similar datasets that are available within the EU and many other regions where catches are reported daily.

Material and 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, instantaneous vessel speed and course have been transmitted with positional information for most VMS records (instantaneous speed is the speed at the instant the data are recorded). In cases where instantaneous speed is unavailable, 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 (Mills *et al*., 2007; Walter *et al*., 2007).

Speed criteria may be estimated and validated by checking the results of a rule against a dataset with known fishing times and locations (Palmer and Wigley, 2009). Ireland has conducted a fisheries observer programme since 1993 aimed at estimating discards, and during such trips, all fishing times and locations are recorded, so these trips can be used to estimate and validate the most appropriate speed thresholds. Most observer trips take place on demersal otter trawlers, so our analysis is limited to that gear. After removing trips with ambiguous vessel names or obvious data-entry errors, 153 observer trips could be matched with VMS data, corresponding to 845 days at sea and 2109 valid hauls.

Estimating effort

Effort was estimated for each VMS record as the interval since the previous record. Any intervals of >4 h were removed and substituted with the daily average time interval of the remaining records to preclude 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 number was used to link vessels in the VMS and logbook databases. The 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 five VMS fishing records in a day catches 100 kg of cod (*Gadus morhua*), then 20 kg of cod will be allocated to each of the five VMS fishing positions. This implies the assumption that the catches made in a single day are uniformly distributed. This important assumption is 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 to 2009 were used in the area between 9 and 15°W and between 49 and 54°30′N. Vessels using demersal otter trawls (including twin rigs and pair bottom trawls) were selected. The catch-and-effort data were aggregated to a grid of 0.06° longitude by 0.04° latitude (~2.2 × 2.4 nautical miles).

Results

Speed criteria

To establish the optimum speed criteria for distinguishing fishing operations, the fisheries observer dataset was used (demersal otter 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 greatest proportion (88%) of correctly assigned VMS records resulted from speed criteria that set the minimum and maximum fishing speeds at ~1.5 and ~4.5 knots, respectively. Vessels travelling at <1.5 knots are assumed to be inactive (e.g. sheltering, waiting for the tide, or mending gear). Vessels travelling at speeds >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 ~0.5 knots, maximum fishing speed ~4 knots), and the proportion of VMS records assigned correctly 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 records assigned correctly could not be improved significantly.

To investigate the circumstances under which the speed criteria might fail to identify correctly whether a vessel is fishing, several trips were examined in detail. Many trawlers shoot their gear soon after hauling, and during this period they are likely to be travelling at fishing speeds while not actually engaged in fishing. Figure 2 demonstrates that many of these false-positive results occur between consecutive hauls. Trip 1 (Figure 2) is an example of a vessel that travelled for a number of hours, which was generally reflected in the vessel speed. Trip 2 is an example where the vessel travelled for a considerable period between fishing operations, a situation clearly reflected in the vessel speed. However, that trip also yielded a few false-negative results; the vessel was reported to be fishing, whereas the vessel speed was below the threshold of 1.5 knots. This was identified most frequently at the very start and the end of a tow. Trip 3 illustrates a number of false-positive results where VMS transmissions fall in the period between hauling and shooting.

Fishing operations are generally identified with a high level of accuracy (overall 94%; Figure 3), but in the period just after shooting and just before hauling, the proportion of records identified

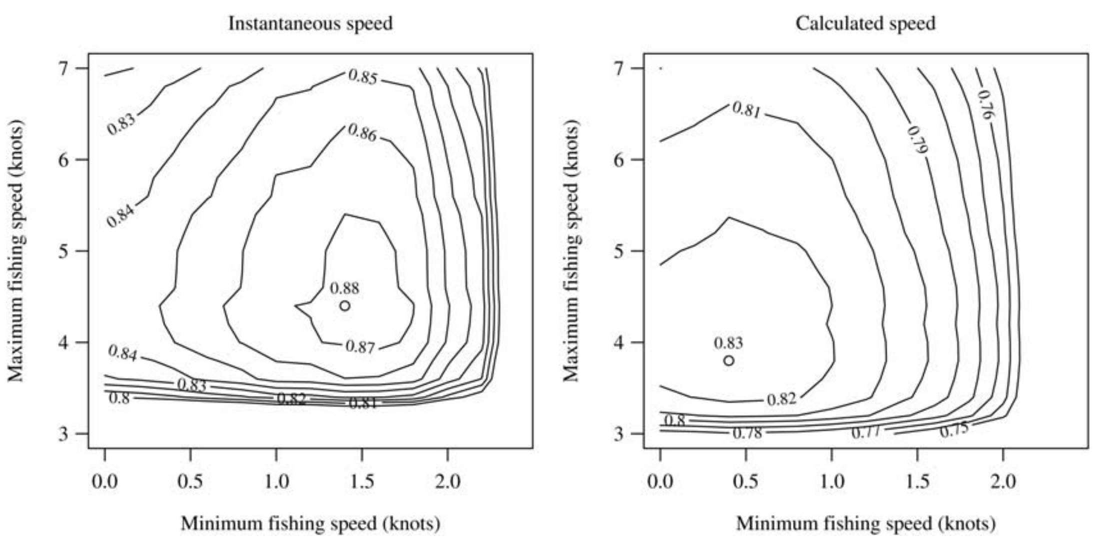

Figure 1. Minimum and maximum speeds at which bottom otter trawlers were assumed to be fishing. The contour lines show the proportion of VMS records that were correctly identified as fishing or non-fishing activity during observer trips. The left panel shows the results for instantaneous speed recorded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

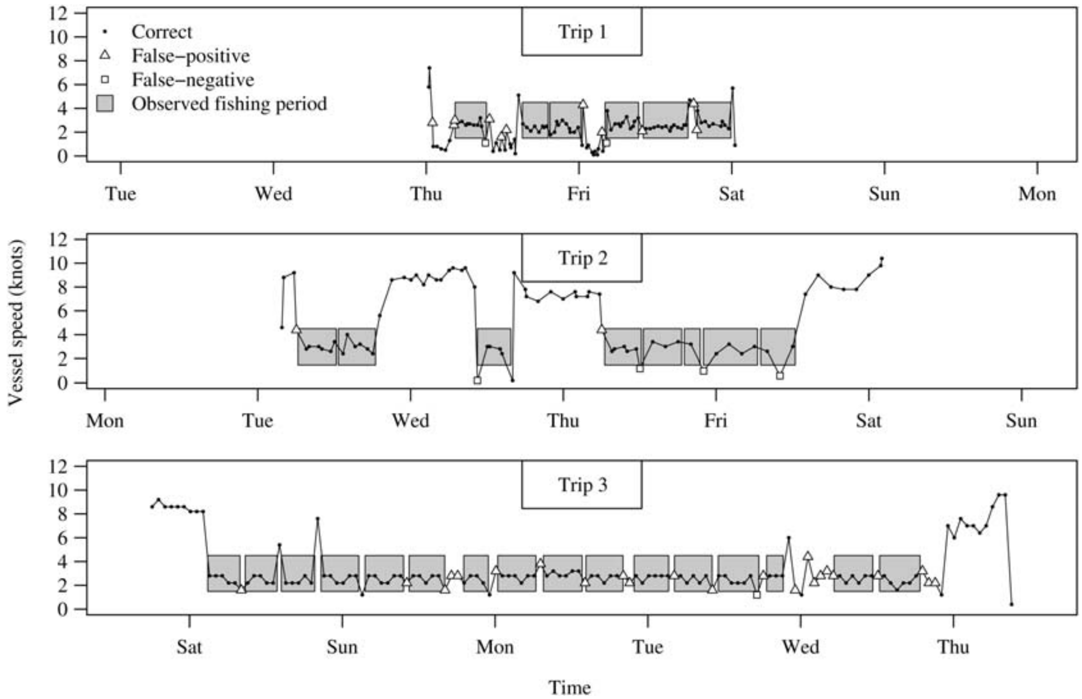

Figure 2. Three examples of VMS data from observer trips, each symbol representing one VMS record. The grey boxes represent the fishing activity recorded by the observer. Instantaneous vessel speeds between 1.5 and 4.5 knots were assumed to correspond to fishing. False-positive results are VMS records that fall within the speed criteria for fishing, 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.

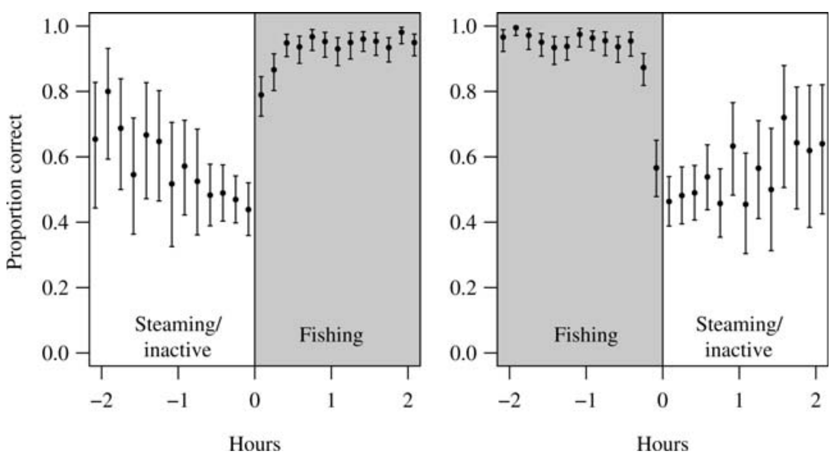

Figure 3. The proportion of VMS records from observer trips that were correctly identified as fishing or non-fishing activity plotted against the time before the gear was shot (left panel) and the time before the gear was hauled (right panel). The error bars represent the 95% confidence intervals of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

correctly is lower. The proportion of such records correctly identified as steaming or inactive is low just before shooting and after hauling (around 50%; Figure 3), but the accuracy improves if the vessel is steaming or inactive for longer periods (overall 68% correct). Therefore, the highest proportion of false-positive errors occur close to fishing operations, in which case the spatial distribution pattern of fishing effort will not be strongly biased by the 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. To test whether the results were sensitive to this assumption, catch data from observer trips were examined. During observer trips, catches from individual hauls are recorded by the observer, which allows us to estimate the true spatial distribution of the catches and to compare this with the distribution of catches that would result from assigning the total daily catches equally to all hauls for each vessel/day (which is the manner in which catches are assigned to VMS data). Catches were allocated to the midpoint of each tow and aggregated on a grid of 0.1° longitude $\times$ 0.15° latitude to create distribution maps. The grid with true catches was compared with that of daily catches by plotting the corresponding values in each cell of the two grids against each other (Figure 4). Clearly, allocating average daily catch weights to each haul position yields nearly identical results to using actual catch weights from each haul (the results are highly correlated, with a slope of 1). Therefore, although catches may vary within a single day, the variation does not appear to cause bias or poor precision in the distribution maps.

Monkfish cpue time-series

Figure 5 shows the otter-trawl effort of Irish vessels during the years 2003–2009 and the proportion of monkfish, megrim, and hake in the catches. Monkfish are caught throughout the area, but their proportion in the catches is highest at bottom depths of 225–450 m. A polygon was drawn to encompass the area between 225 and 450 m deep 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, but Figure 5 shows that megrim are caught mainly shallower than monkfish (east of the polygon) and that hake are caught mainly deeper (west of the polygon). Catches and effort within the polygon were estimated yearly to produce a cpue time-series (Figure 6). For comparison, the cpue for the whole area was also estimated. Both sets of estimates 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 of vessels >15 m. These values are slightly lower than the VMS estimates, suggesting a small bias in the effort estimate from the VMS.

Discussion

Speed criteria

There can be considerable differences between instantaneous and calculated vessel speed. 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 calculated speed is expected to match instantaneous speed. On the other hand, when vessels are fishing, they rarely follow a straight line and are likely to change speed around the start and the end of each fishing operation. Therefore, calculated speed will be less accurate when a vessel is fishing. In our case, instantaneous speed performed slightly better at distinguishing fishing operations than calculated speed, but it still appears reasonable to use calculated speed if instantaneous speed is not available.

The speed criteria applied resulted in a small proportion of false-negative results. When a vessel was travelling at <1.5 or >4.5 knots, 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 of explanations for this. First, it is possible that not all shooting

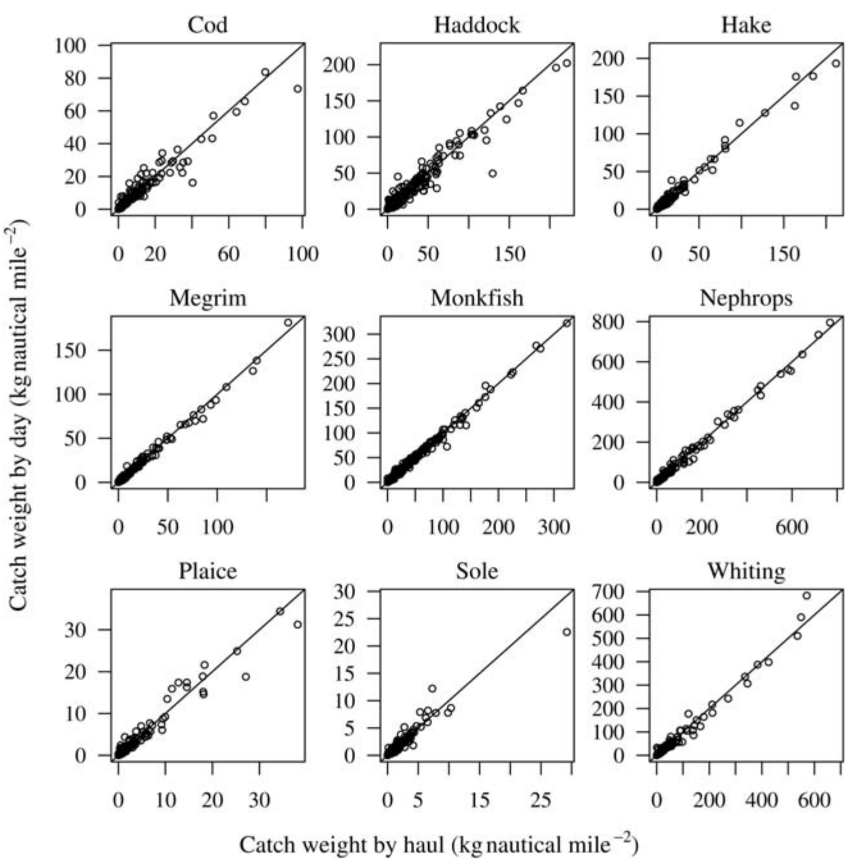

Figure 4. Comparison of two methods of assigning catch weights to fishing positions for nine main species caught on observer trips of demersal otter trawlers. Assigning catch weights to the actual haul position (catch weight by haul) resulted in similar results to assigning the average daily catch to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

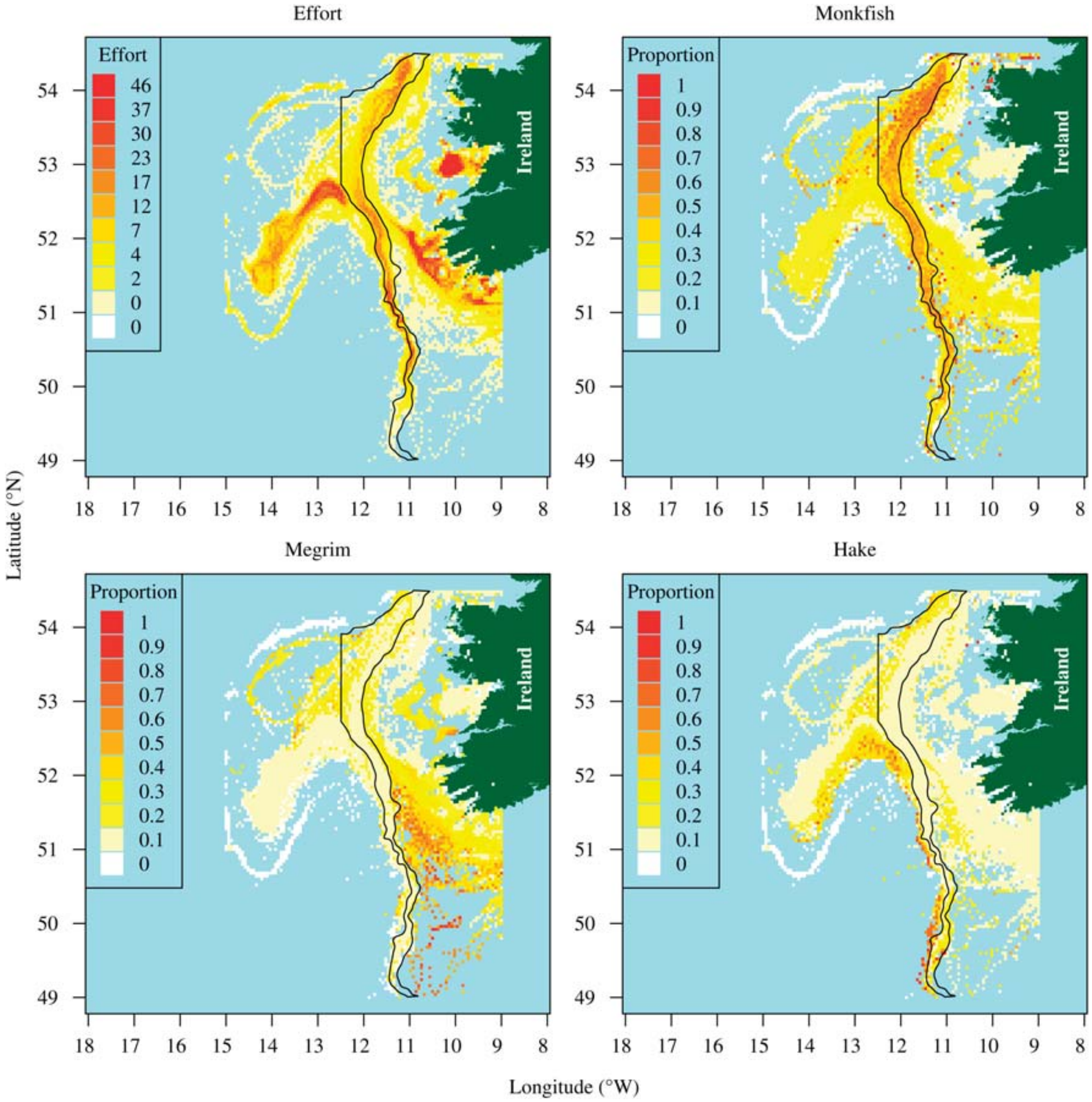

Figure 5. Otter bottom-trawl effort west of Ireland during the years 2003–2009 (top left; in h nautical mile^{-2} year^{-1}), and the proportion of monkfish (top right), megrim (bottom left), and hake (bottom right) in the retained catches. The polygon in which catches are generally dominated by monkfish is defined as the area between 225 and 450 m bottom depth east of 12°30′W.

and hauling times were (correctly) recorded, in which case the true proportion of false-positive results is unknown. Second, when a vessel is engaged in shooting or hauling the gear, this is not recorded as fishing, but the vessel is likely to travel at a speed corresponding to fishing activity. Alternatively, a vessel might steam slowly while waiting for the right tide or mending gear, and the speed at which a vessel is steaming might be reduced too as a consequence of bad weather.

Although the rate of false-positive results is quite high, otter trawlers tend to spend more time fishing than steaming or being inactive, so the total proportion of errors was relatively small (88% correct). Lee *et al*. (2010) found that the distribution patterns of fishing effort for a number of gear types were relatively insensitive to the actual speed criteria. The reason for this may be that many of the false-positive errors were derived from just before shooting or just after hauling the gear while the vessel was still in the same area as that in which fishing took place. One may wish to adjust the speed criteria to minimize 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 catches are uniformly distributed over all VMS positions corresponding to fishing activity. This is an important assumption because catches might vary within a day as a result of 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 radius of 5 nautical miles on any particular day, but 5% of operations take place within 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 have been aggregated, the overall errors resulting from variability in the catches within each day do not appear to affect the

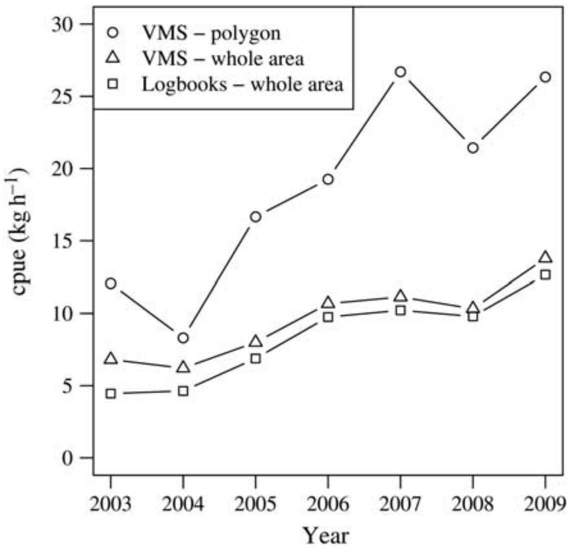

Figure 6. Cpue estimates for monkfish. The cpue inside the polygon is considerably higher than the cpue in the whole area (9–15°W 49–54°30′N). Cpue estimates from logbook data are shown for comparison.

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 enough observations. Therefore, patterns in catches can be discerned clearly on scales much smaller than the daily range of fishing vessels.

Because of imperfections in both VMS and logbook databases, it is not possible to match all records. For Irish otter-trawl data, 71% of 93 827 logbook vessel-days could be matched with their VMS records. Of the remaining vessel-days, 15% were from vessels having no VMS requirement (<15 m). The other 14% could not be matched for various reasons, including ambiguous vessel names and data-entry errors. If these mismatches are random, 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 considerable spatial structure, even within the catches of species generally landed together, such as monkfish, hake, and megrim. This allowed an area to be identified in which a single species appeared to be the primary target. This knowledge could then be used to estimate cpue time-series that are insensitive to changes in the spatial distribution of effort.

As most (96%) monkfish landings were taken by vessels >15 m long, the vast majority of vessels in the fishery have been covered by VMS since 2005. However, for 2003 and 2004, the estimates might be biased because only larger vessels (>24 and >18 m, respectively) were required to carry VMS then. 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 it can be generalized 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 than was possible in the past.

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