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Contribution to the Symposium: '*Fishery-Dependent Information*'

Original Article

Scottish science applications of Remote Electronic Monitoring

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Part of the European Union (EU) Common Fisheries Policy revision of 2013 is a commitment to implement a land-all policy, under which the practice of discarding caught fish back into the sea will be forbidden. This measure will be applied first to the pelagic fleet in 2015, with a phased implementation for the demersal fleet between 2016 and 2019. As part of trials to determine the efficacy of a land-all policy for North Sea cod (*Gadus morhua* L.), Remote Electronic Monitoring (REM) systems were installed on seven Scottish demersal vessels in 2008. Vessels were permitted additional days-at-sea and cod quota, and were obliged to land all cod caught in the North Sea. This arrangement has been renewed each year as part of the Scottish Cod Conservation Credits scheme, and while the list of vessels involved has not remained constant, the scheme remains attractive to skippers (27 vessels in 2014), has always been oversubscribed, and is likely to remain a key part of the Scottish Government's approach to land-all enforcement. Marine Scotland Science is granted access to all REM data collected from Scottish vessels. This paper summarizes the scientific analyses carried out using these data from 2008 onwards, including the installation and operation of REM systems for scientific purposes; the programme developed to train REM analysts; systems for combining length measurements with fish counts; the potential use of REM data in management advice; and studies on such aspects as discard-rate estimation, activity mapping, estimating the relative costs of on-board and REM observation, morphometric length inference, and automated image analysis. We conclude that, while further development work is certainly needed, REM provides a rich source of fisheries information for science as well as for compliance and management. However, care will need to be taken to ensure that science monitoring and analysis resources do not become overwhelmed.

Keywords: analyst training, CCTV analysis, discard estimation, Remote Electronic Monitoring, Scottish fisheries.

Introduction

Remote Electronic Monitoring (REM) of fishing vessels consists of a number of interlinked monitoring and observing components, including CCTV video cameras to record fishing and processing activity, geographic position systems (GPS) to record vessel location, hydraulic winch pressure sensors, and drum revolution counters to determine when vessels' nets are in the water, and on-board PCs with linked, removable hard drives to record data. REM systems have been used to augment, and in some cases replace, on-board observers in many fisheries worldwide for several years (for example, see McElderry *et al*., 2003). These systems were purchased and installed on seven Scottish fishing vessels in 2008 (see Table 1). The intention of this trial period (which carried over into 2009) was to determine the potential efficacy of a land-all policy (or discard ban) for North Sea cod. Participating vessels were granted two "free" trips per year (that is, two trips which did not count towards effort or quota limits), but in return were not permitted to discard any cod while fishing in the North Sea.

During this trial period, in August 2008, the Scottish Cabinet Secretary for Rural Affairs and the Environment, Richard Lochhead MSP, met with his counterparts from the rest of the UK, Denmark, and Germany, and signed the Aalborg Statement (Scottish Government, 2009), which presented a joint position recommending the use of CCTV in fisheries monitoring. Mr Lochhead's comment at the time was as follows:

> The collection of more accurate data would undoubtedly lead to better fisheries management of our seas. Fishermen will have the chance of increasing their income whilst at the same time being able to account for all the fish they remove

Table 1. Timeline of Scottish trial and non-trial REM programmes. See text for notes on incentives offered to join.

Year	Schemes	Number of vessels	Science staff resources
2008–2009	CCTV trials	Three to four (whitefish) Three (Nephrops)	None
2010	Cod Catch Quota Scheme (CCQS)	20 (whitefish)	One summer student
2011	Cod Catch Quota Scheme (CCQS)	24 (whitefish)	One summer student
2012	Cod Catch Quota Scheme (CCQS)	24 (whitefish)	Two full-time staff Viewing rota (5 staff)
2013	Cod Catch Quota Scheme (CCQS) Firth of Forth trial	21 (whitefish) Four (Nephrops)	Two full-time staff Viewing rota (5 staff)
2014	Cod Catch Quota Scheme (CCQS)	27 (whitefish)	One full-time staff with one more to be recruited Viewing rota (10 staff)

> from the sea. In return they will receive the reward and incentive of keeping a much larger share of what they currently catch, rather than being forced to dump it into the sea. CCTV on fishing vessels provides valuable new research and data, increasing our evidence base for scientists. It can help narrow the perceived gap in science advice and what fishermen see in reality.

The next step was the Cod Catch Quota Scheme (CCQS), which commenced with 20 vessels in 2010 (Scottish Government, 2014). This still required vessels to land all cod caught in the North sea, but the incentives for joining were different: participating vessels would receive additional cod quota (initially 30% of their existing quota, relative to the average landings of the preceding 2 years), additional days-at-sea, and permission to fish within the Scottish real-time closures (Holmes *et al.*, 2009; Needle and Catarino, 2011). The application procedure consisted of a bid by the owner of the vessel for how much additional quota they thought they would need to operate the scheme, up to a maximum of 30% of their existing quota. Bids were ranked in reverse order (from low to high) and membership of the scheme was awarded to as many vessels as the national additional cod quota allowance would permit, starting from the top of the list. No specific cognizance was taken of the type of vessel or previous discard patterns, although most participating vessels turned out to be the larger and more successful demersal trawlers, which had the financial resources to lease in additional quota should it prove necessary. Applications were limited to Scottish vessels: that is, those registered in Scotland and administered at a Marine Scotland coastal office.

Critically, all participating vessels had to carry REM systems, installed by Marine Scotland (MS), and the resulting data had to be useable and made available to MS Compliance and Science divisions for analysis. Vessels joining the CCQS were required to remain on the scheme for the full fishing year, unless they were found to be breaking the terms and conditions (by discarding fish out of camera view, for example, or persistently refusing to keep cameras clean): such vessels were removed from the scheme and their benefits revoked. Vessels were required to stop fishing once their cod quota had been exhausted, although they were permitted to lease in additional quota. Participating vessels were also not permitted to lease out any cod quota or transfer days-at-sea.

The CCQS has continued to the present day (2014), and while the vessels included have changed from year to year, the scheme has always been oversubscribed. The incentives available have been deemed valuable enough by skippers to discount the potential extra costs of joining the scheme, including (but not limited to) the following: not being allowed to discard cod, other compliance issues (such as increased detection of highgrading of other species), the obligation to make the vessel accessible for hard drive retrievals and REM system maintenance, duty-of-care responsibilities for the REM systems, and privacy concerns. As of September 2014, there have been a total of 46 vessels in the CCQS, of which 27 are currently members. Of the rest, 12 left for unknown reasons and have not reapplied; 3 were expelled for refusing to record discards; 2 were expelled for other breaches of terms and conditions; 1 was sold; and 1 sank.

The CCQS was implemented partly as a directed measure to access cod quota and effort derogations for Scotland, but also as a test case for the forthcoming EU landings obligation (EU, 2013). This commences in 2015 for pelagic vessels (fishing for herring and mackerel), with a phased introduction for demersal vessels (fishing for mixed demersal species) from 2016 (target species) to 2019 (all quota species). For the landings obligation to be effective, it is essential that it be appropriately enforced. It is also very important that the existence of a measure which (effectively) criminalizes discarding does not reduce the quality and reliability of discard data for the scientific assessment process (Condie *et al.*, 2014). For these reasons, among others, it is vital that a monitoring system be developed, which is unobtrusive, difficult to avoid, yet does not impinge on fishers' personal and commercial rights. In this paper, we focus on the science that can be achieved with an REM system including CCTV cameras, but we also suggest that this may be a preferable system for monitoring the landings obligation (rather than alternatives such as on-board observers).

Mr Lochhead's comments following the Aalborg Statement emphasized that the intention of the Scottish CCTV (or more properly, REM) scheme was twofold: to facilitate monitoring of fishing and discarding activity for Compliance purposes, but also (and equally) to provide valuable data to fisheries scientists to increase our understanding of fleet dynamics, population distribution and structure, and ecosystem components. The potential for REM data to achieve this was thought to be high, though following much development work. This paper summarizes the work that has been undertaken at the MS Science Marine Laboratory in Aberdeen from 2008 to the present, and reports on initial findings. We include such aspects as installation of REM systems, sampling schemes, analyst training, discard-rate estimation, activity mapping, relative costs of different observation platforms, and morphometric length inferences. We conclude with comments on the potential use of REM data in management advice, and ongoing developments in automated image analysis.

Scientific input to installation and operation of REM systems

The installation and maintenance of REM systems on Scottish vessels has been operated principally by the MS Compliance division. The on-board monitoring (and control) of fish discarding was the key initial driver in the implementation of the Scottish REM programme, along with science analysis, and the proximity of two main MS Compliance offices to the fishing harbours in Fraserburgh and Peterhead was also an important consideration. However, MS Science staff have played an important role in the development of improved camera and analysis systems, and regularly assist in many tasks.

The first of these is the determination of the appropriate location and orientation of cameras to facilitate both Science and Compliance analyses (particularly of the discard area). A standard four-camera set-up would usually include one camera positioned high up (often on the wheelhouse) looking aft to help determine when the vessel is fishing, and also to detect any instances of slippage (the codend being opened while still in the water). There would also be a camera directed at the hopper where the codend is suspended before being opened, and two in the fish-processing area (one looking over the full processing sequence, and one focused on the discard chute). More recently, REM systems have been able to store data from up to eight cameras, and the additional slots have been used to attempt to ensure that there are no points of potential discarding from the vessel which cannot be seen. Alternative set-ups have been used in different circumstances. For example, cameras were positioned on one demersal vessel to cover the entire sorting belt, and these were used to estimate cod catch (rather than just discards). On pelagic vessels fishing for mackerel (*Scomber scombrus* L.) and herring (*Clupea harengus* L.), there are no sorting belts as the fish are pumped aboard directly from the net into holding tanks below deck. Here, the external camera covering the area where the net is drawn alongside the vessel is of most interest, although catch estimation is also possible using a camera that covers an open part of the fish-pumping tube (if one exists). Cameras have been trialled on smaller vessels fishing for species such as queen scallops (*Aequipecten opercularis* L.) and langoustines (*Nephrops norvegicus* L.), but these often use different sorting and processing systems (such as sorting tables or open areas on deck) and thus far it has proved difficult to analyse such footage.

The main camera used for determining demersal discard rates is that directed towards the discard chute. On the demersal vessels included in the CCQS, the principal problem is the positioning of this camera. The working space in these vessels is generally extremely cramped with low ceilings, and it can be difficult to locate a camera in such a way as to enable a clear, undistorted view of the discard chute without running the risk of water and fish waste splashing up onto the camera casing, or of the view being obscured by fishers working. Lighting can be problematic below decks, and water droplets often collect on the lowest point of the camera casing dome which obscures the centre of the image. Skippers have a duty of care in the CCQS to ensure that cameras are kept clean, but this has not always been fulfilled.

As well as camera position, MS Science staff are involved in the calibration of video images using checkpoints such as screws, bolts, or other fixed points in the image. Such calibration is essential to subsequent length determination. We also assist in the positioning and calibration of REM-related sensors such as GPS and winch pressure readers, and this involvement improves the scope for subsequent analysis. For example, winch pressure can be either high while fishing and low while not fishing, or *vice versa.* The difference is caused by the particular positioning of the sensor in the vessel's hydraulic power system, and could hinder analysis if the physical layout of the system was not known beforehand.

Sampling schemes for REM data

The initial users of REM data were MS Compliance staff, acting in a monitoring and enforcement role. The approach taken by MS Compliance was generally intelligence-led, in that a perception of potential illegal activity (obtained through observation at sea or in port, or through other information channels) would lead to increased surveillance of particular vessels. While this approach is still followed in cases that warrant it, a focus on specific vessels is clearly not appropriate for a scientific sampling scheme that is intended to be randomized and unbiased. MS Science staff have therefore developed a more suitable sampling programme that is now used by both MS Compliance and MS Science. Although the results of this do not yet contribute to the ICES data collation process for assessment working groups due to the impossibility of age reading using CCTV video, they have been used to develop illustrative, unraised discard estimates for REM vessels (see the Discard-rate estimation section). Hard drives are collected from vessels by MS Compliance staff in Peterhead. Twenty percent of trips are randomly sampled (as a rule of thumb, each hard drive contains data and video from one sampling trip), and a randomly selected 20% of the hauls on these trips are analysed by MS Science staff for discards of six key species: cod (*Gadus morhua* L.), haddock (*Melanogrammus aeglefinus* L.), whiting (*Merlangius merlangus* L.), saithe (*Pollachius virens* L.), hake (*Merluccius merluccius* L.), and monkfish (*Lophius piscatorius* L. and *Lophius budegassa* S.). As a minimum, counts are collated for these species. Lengths are also measured for those fish for which this is possible in the sampled hauls, although (as we discuss in the Morphometric length inference section) many fish will be occluded or distorted in some way and for these fish lengths will be inferred following the procedure outlined in Section 5c. Selection of both trips and hauls to be sampled is random, and such *post hoc* random sampling of fishing activity is a unique benefit of REM-based monitoring. Discard rates can then be estimated from these data using the procedure summarized in Discard-rate estimation section.

Analyst training and evaluation

While camera and storage systems are improving, the available REM video footage from fishing vessels is recorded with a relatively low frame rate (around two frames per second) using cameras considered to be low definition by most current standards. Other impediments to analysis are that cameras are not always regularly cleaned, fishers can inadvertently obstruct the view, and fish often lie on top of each other or are occluded by waste products while on the sorting belt. It should also be noted that many fish in temperate waters tend to look quite similar at a distance, a problem not faced when undertaking analyses of tropical systems (Spampinato *et al.*, 2008). Projects are underway in Aberdeen and elsewhere to develop automated image analysis algorithms, but in the meantime it remains that case that all REM video analyses must be carried out by trained human analysts.

Initial studies in Aberdeen were conducted with one or two analysts, but it quickly became apparent that people could not be expected to analyse footage for more than about an hour in a single session. Viewing can become tedious and tiring quickly, leading to mistakes and staff dissatisfaction, and the decision was taken to develop a pool of analysts who could be called upon to analyse footage in a rota system, fitting this into their principal scientific work. To enable this, we produced a programme through which all analysts would be trained to use Archipelago EMI software (McElderry and Turris, 2008) to analyse footage. The training programme consists of the following five steps, usually including a total of 15 one-hour sessions of which six are supervised by an experienced analyst.

1. Introduction to REM video analysis (one supervised hour), including the set-up and background of the REM scheme, types of vessels, and how samples are selected. A brief introduction to the species for which the footage is to be analysed is given, along with instruction on how to load sensor data, add data annotations and a description of software features.
2. Fish identification skills (one supervised hour), which will train the analyst to be familiar with the target species, including recognition at all possible angles. An identification sheet was produced for each species with images showing different angles and light conditions. These slides are used to point out specific features that will help identify a species when seen on footage, even if it is only partially visible or upside-down. A range of screenshots showing the sorting belt are then presented twice, the second time with labels clearly identifying the visible fish, thus allowing initial testing of identification skills. The ID sheets (see Figure 1) include one page for each species with images and helpful tips on how to identify the target species. Images used are mainly screenshots taken from REM video footage, supplemented with images taken at a fish market. One hour was found to be sufficient for this stage, but it must be emphasized that the analysts being trained were experienced at-sea or market observers and were thus already familiar with the species concerned: the task here was to learn how to identify fish from video footage, rather than to identify fish *per se*. The training was also limited to six species: the ability to identify correctly all species commonly caught by the Scottish camera vessels would take longer to acquire.
3. Practice runs (4 h, one or two supervised). This stage consists of four 1-h sessions analysing video clips of graded and increasing difficulty, although the quality of all clips in this stage should be high to allow for the trainee to focus on species identification and the analysis process. Each clip is analysed by experienced analysts in advance. The first two training sessions should consist of a selected haul being analysed for counts under supervision, while the following two are without supervision. When a haul has been analysed, the counts can be compared with those of the experienced analysts. The comparisons of counts should help to highlight any problems with species identification. The length of this stage will depend on the progress of the trainees. When it is completed, the trainees should be able to identify target species from REM footage, they should be able to notice fish that are partially occluded, and they should be able to use the software independent of guidance from an experienced analyst.
4. Species identification tests (4 h, all unsupervised). In this stage, the trainee carries out unsupervised count analysis of four 10-min segments of REM footage from three different vessels, chosen to illustrate different observations set-ups, species mixes, and fish densities. This exercise tests the ability of the trainee to produce counts of sufficient reliability and accuracy.
5. Finally, a further series of exercises (occupying around 5 h in total) is undertaken to extend the abilities of the trainee to measure and record fish lengths as well as counts. The training programme will normally take around 15 h, with 7–8 h being supervised by experienced analysts, although more time may be required.

Count training acceptance thresholds

As described above, in Step 4 the trainee is asked to count the number of fish of each of the six relevant species in four 10-min clips, using REM video footage from three vessels. This acts as a test to ensure that, following the training process, the trainee is able to determine fish numbers to a sufficient level of precision. However, the true numbers of fish in these clips are unknown. We can determine the relative precision of different analysts, but we cannot yet ascertain how close those counts are to reality. Work is planned to conduct tests of analysts using footage from research-vessel surveys of groups of fish of known numbers and lengths, but this has not yet been possible.

In lieu of true tests of the accuracy of the survey method, a procedure was devised to determine precision—that is, whether a particular trainee's counts are sufficiently similar to those of the trainers, and to all the other trainees. Our approach is to summarize the available counts for each species in each video clip using the boxplot function in R (R Core Team, 2014). This generates box-and-whisker plots for each dataset, and designates as outliers those counts which lie outside the whiskers which extend to the most extreme data point which is no more than 1.5 times the length of the box away from the box (R Core Team, 2014). This method is non-parametric, and therefore does not require assumptions about the underlying statistical distribution of the counts data, which would be difficult to justify. Once outliers for each vessel and analyst have been determined in this way, they are tabulated for comparison. Although each case is judged on its merits, our rule-of-thumb is that an analyst with more than one outlier is likely to benefit from further training. The approach assumes that most counts will on average be approximately correct, and does not consider that any analyst is more likely to be correct than any other. This requires that there are a reasonable number of counts available for comparison, and the comparison must be updated after every analyst has viewed the relevant footage. For example, suppose three analysts counted 50 haddock in one sample. The median count would be 50, and there would be no outliers. If the following 20 analysts all counted 10 haddock in the sample, the median would be 10, and the first three counts would now appear to be outliers. If most analysts are incorrect for some reason, then this approach will give a biased conclusion.

Results for the application of this method during 2013 to MS Science training data are given in Figure 2 and Table 2 (note that analysts' names have been anonymized), from which we see that analysts C, D, and H may require additional training. The analysts began the training with different levels of experience and knowledge of fish identification, so some variation in relative precision would be expected. We can also note from Figure 2 that the footage from some vessels (for example, Vessel C) permits a more consistent count of fish than on others (for example, Vessel A), although this is too small a sample size to reach any firm conclusions. Without further tests, it is difficult to know which characteristic of Vessel C leads to these results—it could be the camera set-up, the image quality, the catch quantity, whether more or less catch occluded, or a combination of these. The tests have also indicated some of the more common mistakes, including misidentifying small haddock as whiting and *vice versa*, and omitting to count smaller haddock, whiting and hake because they closely resemble non-target species such as poor cod (*Trisopterus minutus* L.), and Norway pout (*Trisopterus esmarkii* N.) Although not a focus of our analyses, it is also clear that species of flatfish that are presented belly-up can be very difficult to differentiate.

Scientific analyses using REM data

Activity mapping

Vessel monitoring system (VMS) data consist of vessel speeds, headings, and locations, with one reading (known as a "ping") being transmitted to a central repository via a satellite link every 2 h. The data are actually generated at a much higher frequency (as much as once in every 10 s), but the limitation to one ping every 2 h reduces the cost of satellite transmissions. Although intended principally for use by the coastguard and fishery enforcement organizations, VMS data have a clear utility for scientific analyses of fleet dynamics and population distribution. Permission for Scottish fishery scientists to access VMS data was granted by the Scottish fishing industry in 2007 (Gatt and Reid, 2007), and they have been used extensively since the modelling of vessel movements and the generation of advice (see Needle and Catarino, 2011; Needle, 2012).

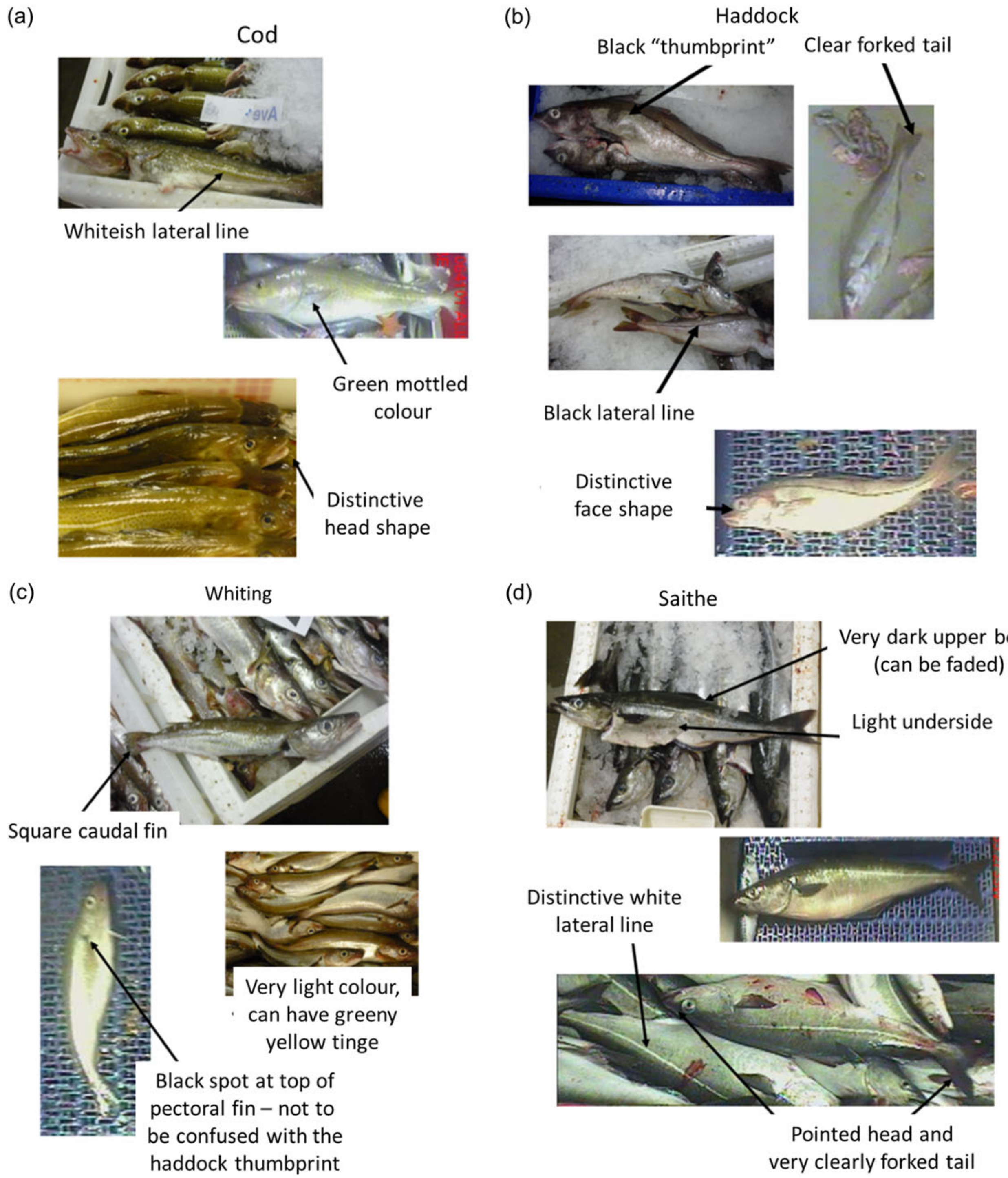

Figure 1. REM analyst training sheets, used in step 2 of the training programme.

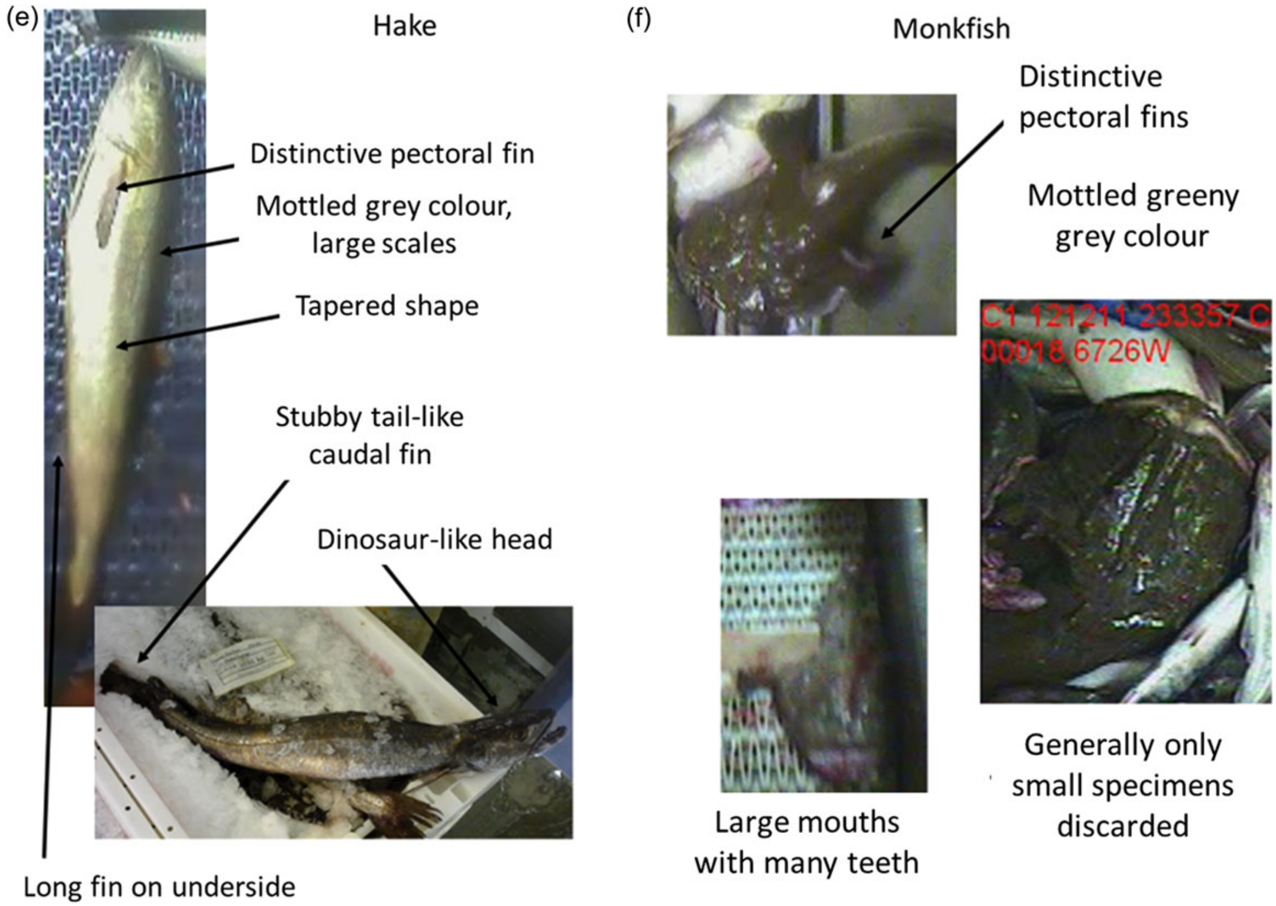

Figure 1. Continued

There are two principal drawbacks with VMS data as made available from European fisheries. First, the 2-hourly transmission provides relatively sparse data on where a vessel has been, when compared with REM GPS position data, which can be recorded every 10 s. Second, unlike REM data for which video and winch pressure readings indicate fishing activity, VMS data do not directly indicate what a vessel is doing at a particular location. Borchers and Reid (2008) used probabilistic activity models to conclude, for demersal trawlers, that only those moving at speeds of 0.5–5.0 knots were likely to be fishing. This is generally a reasonable approximation, but can be seriously misleading as illustrated by Figure 3, which gives a comparison of perceived fishing activity as indicated by VMS and REM data for a Scottish seine vessel. Here we can see that the VMS-derived fishing path underestimated the area impacted by the vessel, the true path of which (with the characteristic triangular pattern of seine fishing) is given by the REM data.

REM data are therefore likely to provide more reliable and accurate spatial distributions of fishing activity, both at vessel and fleet levels, than has been available to date using VMS data. Work is continuing in Aberdeen and elsewhere on methodologies to implement the use of REM data in the evaluation of spatial management strategies, for example, and we believe this will be a key use of REM data in the future.

Relative costs of on-board and REM observation

In situ monitoring of fisheries by on-board observers has, until recently, been used as the primary method for collecting biological fisheries data. However, the quantity of data that can be collected by such means is extremely limited. Difficulties such as lack of spare berths and trips that leave at very short notice make it difficult to provide sufficient coverage. These problems, combined with the high cost of sending an observer to sea, means that there are relatively few trips covered each year, even in well-established observer programmes such as that run in Scotland since 1978 (which covers, on average, around 75 trips per year: Fernandes *et al.*, 2011). Although the data collected are of great importance for fisheries management, their limited availability could result in bias, uncertainty, and subsequently inappropriate scientific advice (Benoît and Allard, 2009).

As well as considerations of scientific accuracy and reliability, it is also important to consider the costs and efficiency of any alternative observation scheme: a highly accurate and reliable remote sampling programme is of little use if its costs are prohibitive. To date, there have been a number of studies suggesting that REM provides a lower-cost (yet still valid) observation platform than on-board human observers. McElderry and Turris (2008) state that REM can be provided at a quarter of the daily cost of observers. Ames *et al.* (2005) suggest that in the Alaskan longline fishery, REM systems could operate between a third and a half of the cost of observer programmes. Meanwhile, in Denmark, it has been estimated that an REM system could offer much the same data as the observer scheme at as little as one-tenth of the cost (Kindt-Larsen *et al.*, 2011).

During 2012, we conducted a study to consider the costs involved in both observer and REM-based monitoring, to determine whether REM can be cheaper while also producing more extensive data

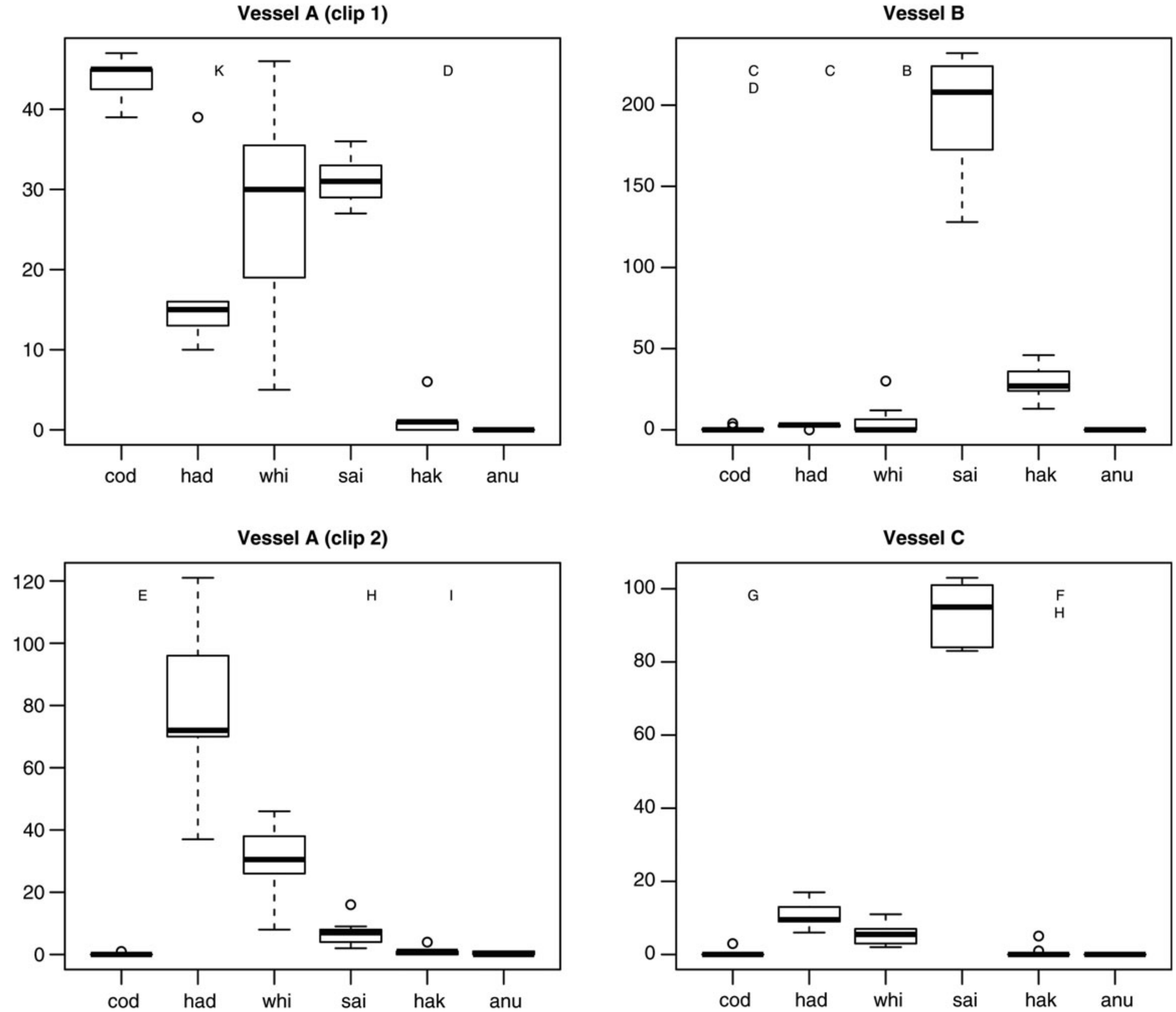

Figure 2. Boxplot summaries of fish counts from 10-min video clips for six species (cod, haddock, whiting, saithe, hake, and monkfish) from three vessels by 11 Marine Scotland Science analysts (both trainers and trainees). Each outlier has a letter printed above it which refers to the analyst. For example, saithe from Vessel A (clip 2) was overcounted by analyst H. The thick line denotes the median, the boxes the interquartile range, and the whiskers extend to the most extreme data point, which is no more than 1.5 times the length of the box away from the box.

Table 2. The number of outlying counts for each analyst across four video clips.

Analyst	Outliers
A	0
J	0
B	1
E	1
F	1
G	1
I	1
K	1
C	2
D	2
H	2

through the ability to subsample from more trips (Dinsdale *et al.*, 2013). In our first analysis, costs were calculated for the entire monitoring process for one vessel with an on-board observer and one

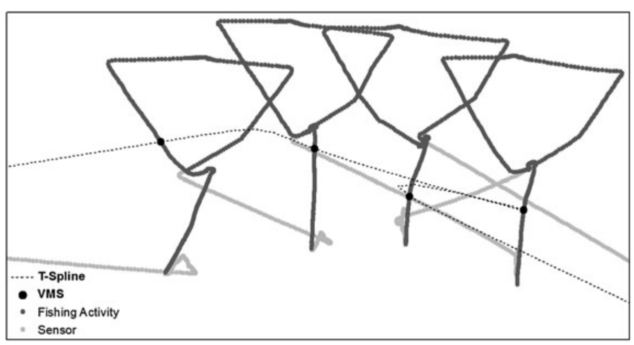

Figure 3. Comparison of fishing locations as inferred from two-hourly VMS "pings" with speed <5 knots (large points) and 10-s position records from a GPS linked to an REM system (dark grey for fishing, light grey for non-fishing) on a Scottish seine vessel. The dotted line gives a T-spline curve fitted through the VMS points, which would be the best estimate of the area impacted by the vessel in the absence of REM data.

Table 3. Assumed expenses for an analysis comparing costs of on-board and REM monitoring. Values are based on Marine Scotland expenses during 2012.

	Observer	REM	Recurring
Salary	£18 556	£18 556	annual
Training	£1 890	£189	once
REM equipment		£9 000	once
Administration PC	£1 500	£1 500	annual
Analysis PC		£4 896	5 years
Transport	£50		trip
Vessel payment	£25		daily
Sea allowance	£175		daily
Sea gear	£200		annual
Medical	£80		2 years
Sea survival training	£150		5 years
Courier		£40	weekly
Software licence		£2 675	annual
System installation		£2 400	once
Equipment maintenance		£1 200	annual
Hard drive replacement		£70	4 years
Camera replacement		£500	3 years

with REM over the course of a year. Table 3 summarizes the costs assumed in the model when applied to one vessel, for both observers and REM monitoring, and indicates the frequency with which each cost would be incurred (including an estimate of the operating lifetime of equipment). Costs mostly relate to those actually incurred by Marine Scotland during 2012.

The salary costs for both the observer and REM programmes were calculated assuming one scientist in each case, employed at the entry level for Marine Scotland (Grade A4). The observer was assumed to be able to work at sea for 180 days per year, covering 26 trips and measuring 4 hauls per day. The REM analyst was assumed to be able to work for 225 days per year, analysing 7 hauls per day (each haul taking 39 min on average to analyse).

Training costs for the observer were assumed to equal the cost of one observer trip (thereby assuming that this would be sufficient), and were calculated as

$$\begin{aligned}\text{observer training} = {} & \text{average trip length (days)} \\ & \times (\text{daily salary} + \text{daily sea allowance} \\ & + \text{daily vessel payment}).\end{aligned}$$

Here we follow the Marine Scotland practice of paying the vessel a daily fee (£25 in 2012) to cover the costs of housing the observer on-board, while the observer is paid a sea allowance (£175 per day in 2012) to compensate for hard working conditions. In addition, the observer would be required to undergo basic sea survival training every 2 years. Training costs for the REM analyst assumed a 20-h training programme, and hence were calculated as the hourly REM analyst salary multiplied by 20. REM equipment costs are taken from the outlay required in 2012 to purchase Archipelago REM equipment on one vessel (one PC, four cameras, sensors, and associated wiring), and we stipulate separate costs for REM equipment installation, maintenance, and replacement. Each observer and REM analyst would be required to have access to one Marine Scotland computer for administration purposes, while the REM analyst would also require a graphically high-powered PC on which to conduct analysis (renewed every 5 years on average). The remaining costs for the observer programme are relatively minor and cover aspects such as land transport, sea gear purchasing, and regular

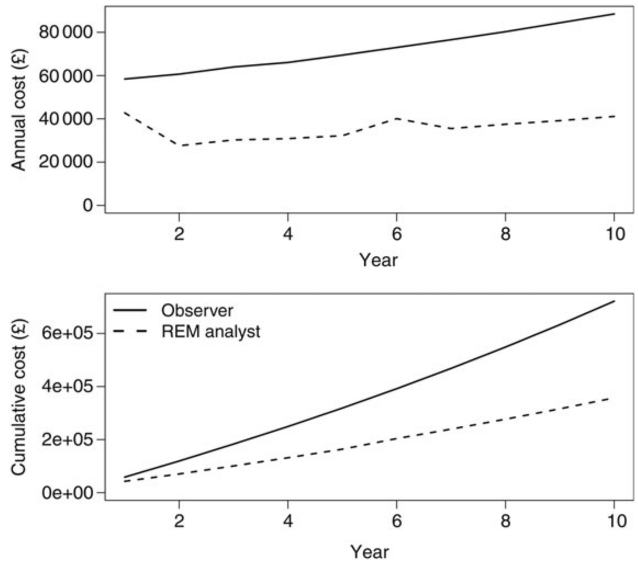

Figure 4. Summary of annual costs for simulation study of discard monitoring using at-sea observers or the CCTV component of an REM system. The simplified illustrative scenario given here is for one vessel, one observer, and one REM analyst.

medical fitness checks. Aside for courier costs for transporting hard drives from Peterhead to Aberdeen and back again, the remaining REM cost covers the annual software licence from Archipelago.

The cost calculations were carried out for the case of a single vessel over a 10-year simulation period, assuming a 5% interest rate. Here we allow one observer (with the capability to cover up to 720 hauls) and one REM analyst (to cover up to 1575 hauls)—the difference in the potential hauls covered arises from the fact that the observer must work through hauls in real time (including breaks between hauls), whereas the REM analyst is not restricted in this way. Figure 4 shows the expected annual and cumulative costs for each programme on this basis. Despite relatively high initial start-up costs, due to the purchase of equipment and software, the REM programme is always cheaper than the observer programme and becomes increasingly so as time goes on. Figure 5 shows a more representative example of 21 REM vessels, 4 observers (covering up to 2880 hauls), and 2 REM analysts (covering up to 3150 hauls), which replicates the situation at Marine Scotland in 2012. Here we see that the REM programme is initially more expensive, but becomes more economical after just 1 year.

We conclude that although the initial costs of REM are high, in the mid-to-long term these costs reduce to make it a more cost-effective method for monitoring than on-board observers. However, we also note that the comparisons conducted to date have been relatively simplistic, as we do not yet consider the fact that CCTV monitoring is likely to be insufficient to estimate discard rates without more direct additional biological sampling (for age, sex, maturity, weight, etc.). It is unlikely that we have managed to capture all the costs involved in each programme, and the comparison could be refined further as the REM analysis approach matures. For example, it may be that occasional on-board observers will be required to validate the results of REM analysis, in which case the costs of these observers would need to be factored into the REM analysis cost estimate.

In future work, it may be more appropriate to consider the relative costs of using observers or CCTV to determine discard rates with a particular *variance*. For example, the possible sampling

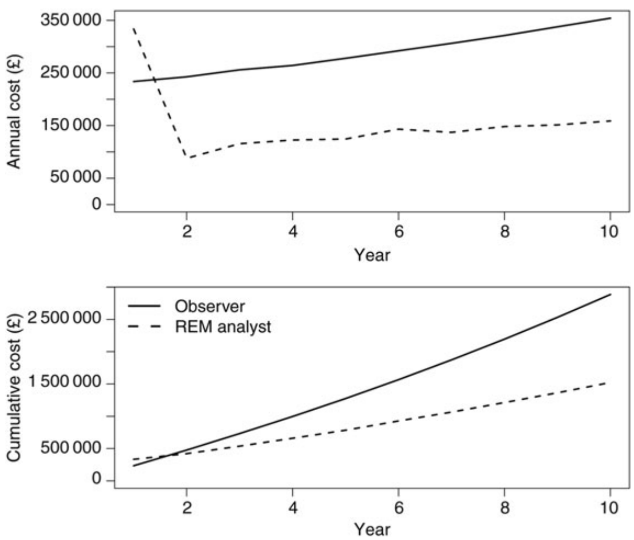

Figure 5. Summary of annual costs for simulation study of discard monitoring using at-sea observers or the CCTV component of an REM system. The scenario given here is intended to reflect the Scottish sampling programme for the demersal whitefish fleet as it was in 2012 (21 REM vessels, 4 observers, and 2 REM analysts).

coverage of observers is generally lower, which will increase variance, but length measurements are more precise, which will decrease it. CCTV monitoring can cover many vessels and use truly random sampling to reduce variance, but weights and ages need to be inferred, which increases variance. Work is underway on simulation studies to address this question, but we hypothesize that a holistic sampling programme including at-sea observers, CCTV monitoring, and market sampling is likely to be most beneficial in terms of accuracy and cost.

Morphometric length inference

The range of detailed biological information that can be obtained from REM video footage is rather limited: for example, the direct determination of such parameters as age, sex, weight, and maturity is clearly impossible. However, one key parameter that can be derived from such footage is the length of the fish, and hence the length distribution of the sampled population. Length is an important morphological parameter for many biological, ecological, and fisheries assessment studies. Many of the processes that affect fish are driven by length, including predation, retention in fishing gear, maturity and spawning, etc. (Marais, 1985; Reis and Pawson, 1999; Huse *et al*., 2000; Stergiou and Karpouzi, 2003; Pauly and Palomares, 2005). Length distributions enable us to define predator–prey relationships and the ecological position of fish within the foodwebs, and can also be used in length-based stock assessment models (thereby saving time and resources currently spent on ageing fish; Dalskov and Kindt-Larsen, 2009).

However, the use of REM video footage to provide length frequency data is not always straightforward, as it is not always possible to view the full body of each fish due to occlusion by other fish or waste materials, or by body distortions arising from trawling. This reduces accuracy when determining length and length distributions. During the summer of 2013, we undertook a study (Butler, 2013) that aimed to look at alternatives to total length when measuring fish size, and thereby to develop additional relationships that can serve as a proxy for total body length. The question was what is the relationship between fish morphology and total body length, for a number of commercially important European fish stocks?

We addressed this question through a combination of video analysis and ground-truthing through measuring fish landed at markets. The main focus of the study was on the application of morphometric measurements to fish observed on REM video; however, as these are all discards and therefore tend to be smaller, it was of interest also to determine whether the length range observable on REM footage could be extended using fish measured manually at Peterhead fish market. For each species and alternative measurement, we plotted the measurement (for example, eye diameter) against total length, and fitted two regression lines through the points (one for REM data, one for market data). If the regression lines fitted to the comparisons were not significantly different, then we concluded that the overall relationship could be based on both REM and market data, rather than just REM data alone. Similarly, we checked for differences in the fitted regression lines for data from different vessels.

We focused on commercial species that would be both common in discard footage and large enough for detailed measurements, and developed linear allometric models relating total length (which is the baseline that would be measured if possible) with alternatives such as fork length, operculum to tail, tail length, pre-operculum length, pre-pectoral length, mouth length, eye diameter, mid-orbital height, least caudal peduncle height, and pectoral orbital height (Figure 6). Linear models were chosen following an extensive literature review (Butler, 2013) from which it was clear that this approach is widely used for allometric analyses of this kind. Additionally, preliminary comparisons indicated that linear models would be appropriate for our data. Note that the standard and fork lengths (StL and FkL in Figure 6) were the best indicators of total length, but are not considered further here because total length was measurable in all cases where standard or fork lengths were measurable. Specifically, we fitted the following model to our data:

$$\begin{aligned} ToL_i = \alpha + \beta_1 Source_i + \beta_2 X : Source_i + \beta_3 Vessel_i \\ + \beta_4 X : Vessel_i + \varepsilon_i \end{aligned}$$

where i indices the observation; ToL is the total length measurement; Source is a categorical variable that distinguishes between REM and market data; Vessel is a second categorical variable to identify the originating vessel; X represents the alternative measurement of interest; α, β_1, β_2, β_3, and β_4 are parameters to be estimated; and ε_i is the error term. Alternative measurements were then ranked using a combination of goodness-of-fit statistics from the fitted model, and the final conclusion was a ranked list of how well each measurement predicted the total length (Butler, 2013). The species of interest were saithe, cod, haddock, hake, and whiting.

Figure 7 gives an example of the relationship between total measured length (ToL) and an alternative (in this case, pre-operculum length or POL) for cod. Values are plotted both for fish measured on REM video, and for fish measured at the fish market, and the regression R^2 and slope p-value has been given for straight lines fitted to both. Fish measured using REM tend to be smaller than fish measured on the market (as the former are discards while the latter are landings), and the ToL–POL relationship estimated from REM is slightly noisier than that estimated for market fish (R^2 values of 81.79 and 98.23%, respectively).

Table 4 summarizes the results for each species, indicating the data used for analysis in each case and the three best morphometric

Figure 6. Body measurements taken to determine allometric relationships with total body length (ToL). The morphological variables were as follows: standard length (StL), fork length (FkL), operculum to tail (OpT), tail length (TL), pre-operculum length (POL), pre-pectoral length (PPecL), mouth length (ML), eye diameter (ED), mid-orbital height (MO), least caudal peduncle height (CP), and pectoral orbital height (PecO). Image source: Marine Scotland.

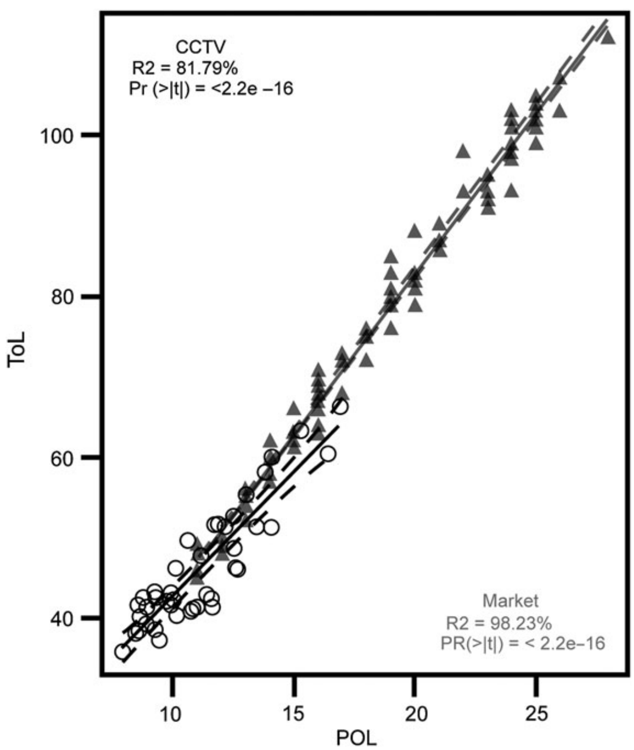

Figure 7. Relationship between total length (ToL, cm) and pre-operculum length (POL, cm) for cod discards measured through an REM CCTV system (black open circles), and for cod landed to fish markets (grey-filled triangles). Solid lines give linear model fits to each dataset, dashed lines give $\pm$95% confidence intervals, and the goodness-of-fit statistics of each model are given in the legends.

variables to use to predict total length. The validity of using market data alongside REM data varied from species to species and variable to variable, and there were vessel effects noted for some measurements for cod and hake. Overall, the best indicator of total length is the operculum to tail length (OpT), followed by the pectoral orbital height (PecO). Measurements such as the eye diameter and the mouth length fared poorly. The broad conclusion is that more accuracy is achieved by being able to observe more of a fish. While this is unsurprising, the analysis has merit in showing that total length can be approximated with a reasonable level of accuracy, and that it should therefore be possible to infer unobservable total lengths in a full discard estimation programme.

Space restrictions mean that we cannot report this analysis more fully here, but we intend to do so in a companion paper soon. Fruitful further work would include testing the proposed models by applying them to video footage from a research-vessel survey in which the true lengths of each fish were known.

Discard-rate estimation

One of the key elements of the Scottish cod quota proposal that encouraged many skippers to apply to join was the potential use of REM data "to improve science", and in particular, to estimate reliable discard rates. The rates that are currently used in the ICES stock assessment and advice process are fully derived from observer programmes organized by government laboratories or associated University departments (ICES, 2013). As at-sea observation is an expensive process that is resource-hungry (in terms of both staff and finance), and since carrying observers is not mandatory in European fisheries, observer programmes are necessarily limited in scope. Consequently, there has always been a concern that the discarding that occurs on the trips when an observer is

Table 4. Summary of data used and the best explanatory variables for predicting total length for five species.

	Data used for measurement comparisons				Three best explanatory variables		
Species	REM only	REM and market	All vessels combined	Vessel specific			
Saithe	All variables	None	OpT, TL, ML, ED, CP, PecO	POL, PPecL, MO	OpT	PecO	PPecL
Cod	All variables	None	All variables	None	OpT	PecO	POL
Haddock	All variables	None	All variables	None	OpT	PecO	CP
Hake	OpT, POL, PPecL, ML, ED, MO, CP, PecO	TL	OpT, TL, ED, MO, PecO	POL, PPecL, ML, CP	OpT	PecO	MO
Whiting	OpT, TL, PPecL, ED, MO, CP, PecO	POL, ML	All variables	None	OpT	PPecL	POL

Standard and fork lengths (StL and FkL) have been omitted from this analysis as total length was always measurable when they were. The morphological variables were as follows: operculum to tail (OpT), tail length (TL), pre-operculum length (POL), pre-pectoral length (PPecL), mouth length (ML), eye diameter (ED), mid-orbital height (MO), least caudal peduncle height (CP), and pectoral orbital height (PecO). Source: Butler (2013).

present may not reflect the true discard pattern of that vessel for most trips, or the other vessels in the fleet that are assumed to discard in the same way (see, for example, Benoît and Allard, 2009). Cameras offer the opportunity to cover the whole fleet for the whole year, and could result in discard-rate estimates that are more representative.

The approach currently used to estimate REM-based discard rates from one trip of one vessel (in the first instance) is as follows. Using the sampling scheme outlined in the Sampling schemes for REM data section, fish from the six key species that were observed to go through the discard chute are counted, and the counts C_h^s for species s and haul h are recorded. Total length measurements are taken where possible (see Morphometric length inference; note that this analysis did not use inference), and the number of fish measured to be length l is denoted by $n_{h,l}^s$. The total number of fish for which length measurements were taken is also noted as $N_h^s = \sum_l n_{h,l}^s$. The measured number of fish at length l is then raised to an estimate of the discarded number of fish at length l using the simple ratio estimator

$$L_h^s = n_{h,l}^s \times \frac{C_h^s}{N_h^s}$$

which assumes that the discarded fish for which length can be measured is an unbiased sample of the discarded population (this could be tested using on-board observers, or data from research-vessel surveys in which the actual length distribution is measured at sea). If H_t is the number of hauls on the trip and H_s is the number of hauls sampled, then the number of fish discarded at length l during the trip is then estimated using

$$L^s = \frac{H_t}{H_s} \times \sum_{\text{Sampled } h} L_h^s$$

which also assumes that the discards from the hauls analysed represent an unbiased sample of the discarding practice during the full trip. In the results given here, the proportion of hauls during a trip that were sampled was around 30% (so that $H_t/H_s \sim 0.3$). This value was chosen following earlier unpublished work in which all discards from a trip were measured in 10-min blocks: these blocks were then subsampled, and it was found that the average full-trip discard rate across a number of species could be estimated to 95% precision using 30% of the 10-min blocks (Dinsdale, 2011). Figure 8 gives estimated length distributions L^s from Trip 1 of Vessel A in the available dataset, on which discards of haddock and whiting were of smaller fish near to the minimum landing size (30 cm for haddock, 27 cm for whiting), and on which there were no discards of monkfish. On the other hand, there were considerable discards of large cod, saithe, and hake, caused by lack of quota for these species for this vessel at the time of the trip. It would have been illegal for this vessel to discard cod caught in the North Sea, but the fishing location map in Figure 9 shows that more than half the trip was in ICES Division VIa (West Coast of Scotland) in which there was no directed cod quota at the time of the trip. Discarding of all cod caught in Division VIa would therefore have been mandatory (save for a limited bycatch allowance), and that is where the cod discards for that trip occurred.

Once length distributions of discarded fish of each species have been estimated for the trip, these are converted to an estimate of the weight of discarded fish by application of weight–length relationships such as those given by Coull *et al.* (1989). Given stock-specific parameters α_s and β_s, the weight of an individual of length l is given by

$$w_{l,s} = \alpha_s l^{\beta_s}$$

which gives a total discard weight of species s for the trip of

$$W_s^D = \sum_l w_{l,s}.$$

Finally, the discard rate for the trip is obtained by comparing the estimated weight of discarded fish with the reported weight W_s^L of landed fish:

$$D_s = \frac{W_s^D}{W_s^D + W_s^L}$$

A trip was classified as taking place in the North Sea or the West Coast of Scotland by determining on which side of the 4°W line the majority of REM fishing locations occurred (see the example in Figure 9).

All data in the available dataset, which currently covers the fourth-quarter of 2012 and the first three-quarters of 2013, were analysed in this way, with the further restriction that 30% of all trips undertaken by REM vessels were included in the estimation. The results are summarized in Figure 10. Discards of cod in the North Sea are almost zero, as would be expected given the stipulations of the cod quota scheme, while those in the West Coast of Scotland are considerably higher. Discards of haddock and monkfish are low in both areas, while those of whiting are slightly higher. Discard rates for saithe and hake are both high and extremely variable: these are species for which the Scottish share of the total quota is both relatively low and possibly unrepresentative of local abundance, and this can lead to high over-quota discards (although not always).

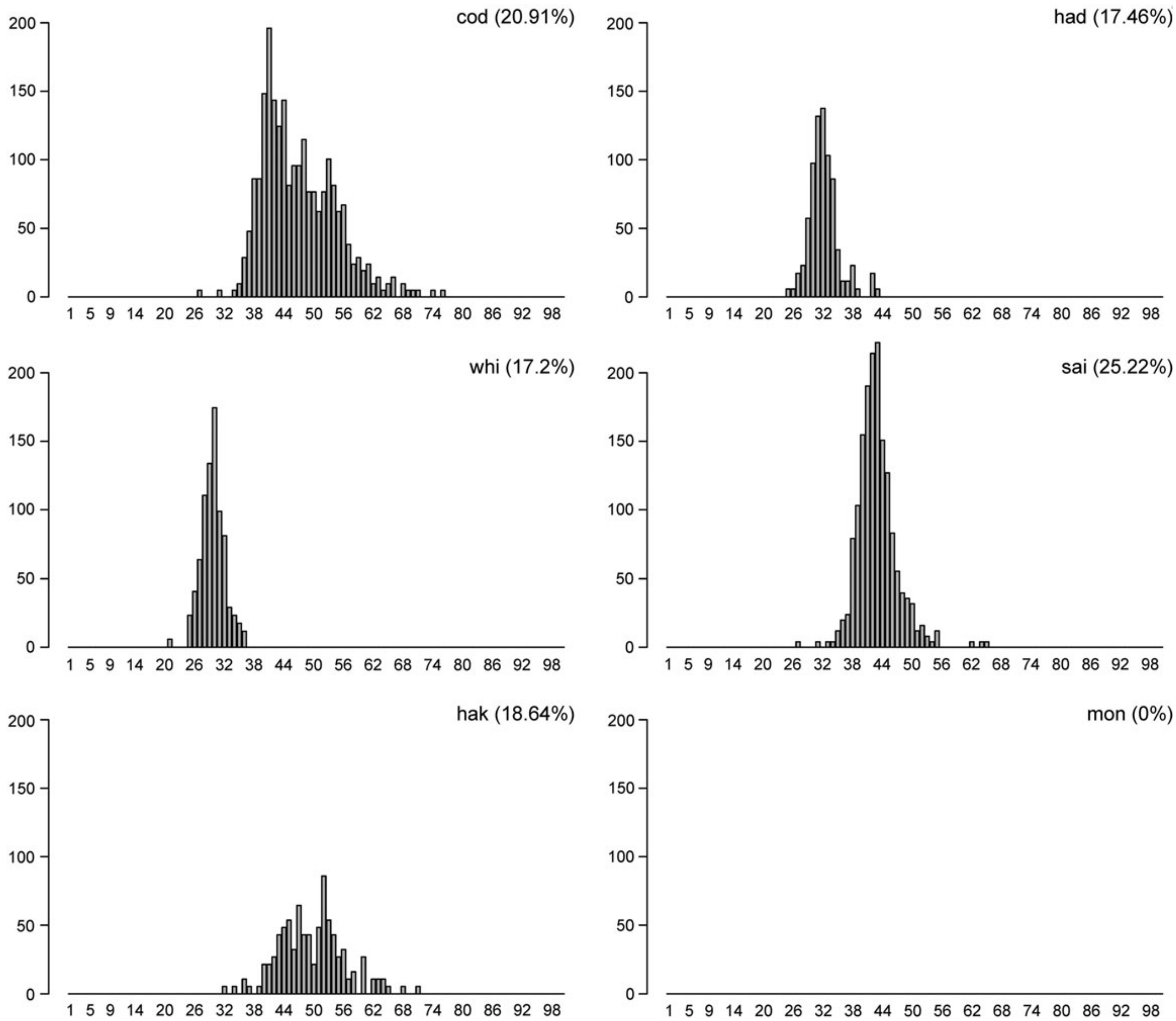

Figure 8. Estimated length distributions L^s for discards of the six analysed species (cod, haddock, whiting, saithe, hake, and monkfish) for Trip 1 of Vessel A in the available Scottish REM dataset. Legends give the percentage of fish in the plotted length distribution, which were measured, given by $(C_h^s/N_h^s) \times (H_t/H_s)$.

Table 5 compares the mean discard-rate estimates obtained from REM monitoring with those from two Scottish observer schemes. The first is the long-running programme operated by Marine Scotland Science at the Marine Laboratory in Aberdeen (denoted here as MSS), which has been conducted since 1978 on Scottish demersal whitefish trawlers (Fernandes *et al.*, 2011). On average, it covers 60 trips in the North Sea and 30 trips in the West Coast of Scotland each year, using around 10 observers. The second is the more recent industry-run observer scheme implemented by the Scottish Fishermen's Federation (denoted here as SFF; Coull and Birnie, 2013), which covers around 100 trips using 6 observers. Both programmes run through the year. These estimates are simplistic, in that they are straight averages of the observed trip-based discard rates rather than being raised to fleet-wide values using the same methodology as used for the estimates used in the ICES assessments (ICES, 2013). We also note that the estimates from the SFF and REM observer schemes are not yet used in the ICES analysis processes: the current assessments for the stocks considered here are all age-based (except for monkfish), and there is an ongoing debate about the extent to which exclusively length-based discard estimates can be used in data collation for age-based assessments (ICES, 2014). However, the estimates still provide a valid comparison as they are all derived using the same simple basis, and indeed the SFF estimates will be used in the ICES assessments from 2015 onwards. Given this, we see that discard rates for all species (except for monkfish for which discards are negligible for all vessels) are lower on North Sea vessels carrying cameras than on vessels sampled for the MSS and SFF programmes. The low North Sea discard rates for cod are to be expected given the regulatory restriction on cod discarding in the North Sea for REM vessels, but there are no additional limitations for camera vessels on discarding for the remaining species. It may be that the presence of cameras encourages reduced discarding, or the lower rates could be an artefact of smaller sample size, or they could be the result of the selection criteria used to admit vessels to the camera scheme (such vessels may have generated lower discards of these species in any case, even

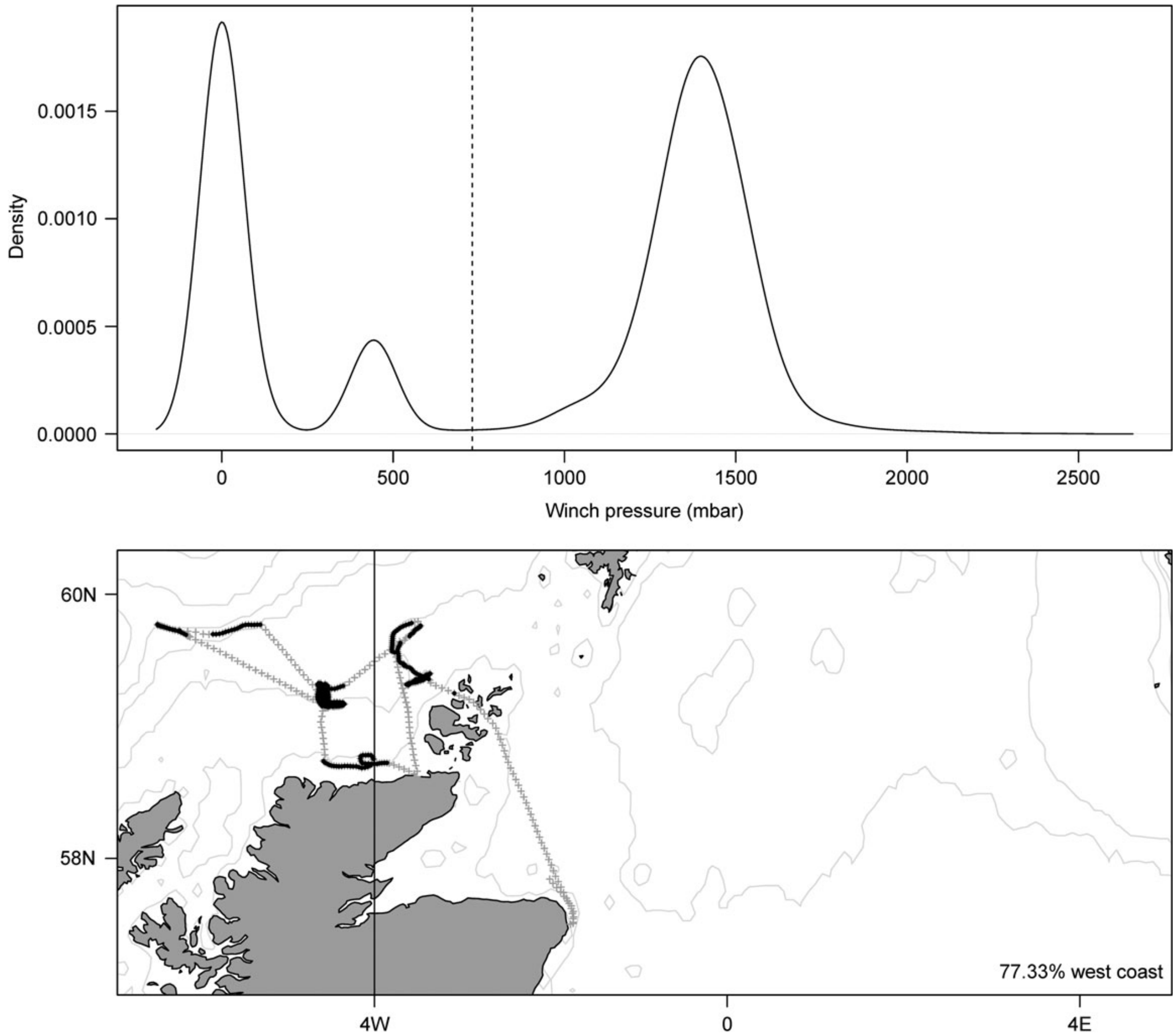

Figure 9. Summary of sensor-record data for Trip 1 of Vessel A in the available Scottish REM dataset. Upper plot: frequency density summary of winch pressure data, which is used to determine whether a particular point in the trip track represents fishing or not fishing. The dotted vertical line indicates the threshold between not fishing (left) and fishing (right), determined by the minimum of the frequency density between the two maxima (Needle, 2012). Lower plot: GPS vessel location data, with non-fishing and fishing locations indicated by grey crosses and black circles, respectively. The vertical line shows the 4°W line of longitude, and the legend indicates the proportion of fishing locations to the west of this line. For clarity, every 100th location datum is shown.

before the installation of cameras). It is also clear that discarding of cod, hake, saithe, and whiting in the West Coast of Scotland (ICES Division VIa) is higher than in the North Sea (Figure 10).

Discussion and conclusions

Historically, one of the principal obstacles in the way of effective and responsive fisheries science has been the lack of fisheries data. Research-vessel survey data lie within the remit of scientists, but involve relatively few vessels for a relatively short time each year and can only ever provide a snapshot of population distribution and abundance. Data from commercial fishing vessels have been compromised to a certain extent in the past by issues such as misreporting of catches and fishing locations, unaccounted discards, and simple hyper-aggregation on the remaining areas offering decent catch rates. The information available to scientists on fishing location used to be derived entirely from landings notes and submitted logbooks, which could be inaccurate for a number of reasons. The availability of VMS data started to change this, but it is really with the advent of detailed and unambiguous REM data that scientists can begin to understand truly what fishers are doing and why, and thereby provide advice to facilitate the most sustainable and productive fisheries possible. In this paper, we have summarized the scientific analyses that we have conducted in Scotland using REM data, which we believe to be among the first science applications of such data in Europe (along with the excellent work being carried out in Denmark and England: see Catchpole *et al.*, 2011; Kindt-Larsen *et al.*, 2011).

The training programme outlined in the Analyst training and evaluation section is necessarily quite long and detailed, but a rota of trained samplers is certainly required: even if functional

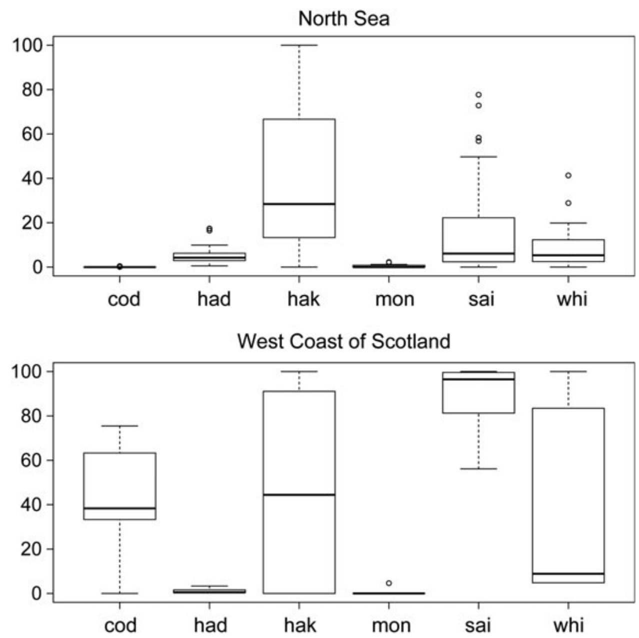

Figure 10. Summary of REM-based discard rate estimates (%) for the Scottish REM fleet in Q4 2012 and Q1-3 2013. Estimates are given for cod, haddock, hake, monkfish, saithe, and whiting, split further into North Sea (upper) and West Coast of Scotland (lower). For each stock and area, the thick line gives the distribution median, the box delimits the quartiles (25% and 75%), the whiskers extend to the most extreme data point, which is no more than 1.5 times the length of the box away from the box, and the open circles indicate outliers beyond these ranges.

Table 5. Estimated % discard rates (mean, standard deviation) by weight for Scottish vessels during Q4 of 2012 and Q1 – 3 of 2013, as derived from three observation programmes: Marine Scotland Science at the Marine Laboratory, Aberdeen (MSS); the Scottish Fishermen's Federation (SFF); and the camera-based estimates described in this paper (REM). Estimates are given separately for the North Sea (NS) and West Coast of Scotland (WC). Discard estimates from REM cameras are only available for demersal whitefish trawlers and seiners to date, so MSS and SFF estimates are for these vessels only.

	NS	WC
Cod		
MSS	32.23 (37.86)	73.54 (31.44)
SFF	22.2 (32.36)	43.92 (29.39)
REM	0.04 (0.09)	42.09 (29.27)
Haddock		
MSS	17.75 (29.24)	13.89 (24.6)
SFF	10.11 (10.92)	14.01 (12.23)
REM	5.45 (4.45)	1.20 (1.31)
Whiting		
MSS	25.79 (34.5)	48.11 (38.03)
SFF	26.8 (24.84)	31.39 (35.81)
REM	8.68 (9.08)	40.39 (47.25)
Saithe		
MSS	40.58 (32.38)	29.33 (31.3)
SFF	48.48 (36.45)	39.74 (27.88)
REM	17.52 (22.39)	86.71 (18.72)
Hake		
MSS	63.83 (34.73)	76.38 (29.8)
SFF	68.75 (37.95)	68.29 (26.66)
REM	42.41 (35.47)	78.5 (29.84)
Monkfish		
MSS	1.18 (5.32)	0.00 (0.00)
SFF	0.00 (0.00)	0.00 (0.00)
REM	0.48 (0.72)	1.16 (2.32)

automated image analysis methods can be developed, video analysts will still be required for checking and calibration, and for evaluation of uncommon species and benthos. In Aberdeen, we now have a trained rota of around 10 analysts, who can each analyse video footage for perhaps 2 h per week on average. The time available to carry out this task will be different for each analyst, and will depend on their other responsibilities (as all the members of our sampling rota have many other duties to fulfil). Too much time spent analysing CCTV video will lead to staff disaffection and mistakes. However, it is also important to ensure that sufficient time is allocated to sampling work, both to ensure an appropriate sampling coverage, and also to militate against skill loss through underuse.

Much like otolith reading, we envisage that regular analyst calibration workshops will be required to ensure continued accuracy. The installation of improved digital camera systems, running at a much higher frame rate and resolution, is planned in Scotland during 2014 and into 2015, and this will facilitate improved analyst accuracy. Morphometric analysis (see the Discard-rate estimation section) is still at a rather early stage of development. It will also improve with better cameras, but such an approach has the potential to slow down video analysis significantly and we are undertaking further evaluations to determine whether the approach is worthwhile. We need to understand whether it is better to infer the lengths of unmeasured fish from the full-length distribution of measured fish from a haul, or to attempt morphometric length inference for every visible fish—the latter will be slower and may not actually affect the final length distribution significantly, and this can only be determined with further ground-truthing experimentation. A third aspect that will improve considerably with better cameras is benthic species identification (see below), which is a potentially valuable application of REM systems following the implementation of a discard ban. With further uptake of REM systems and implementation of REM-based management, the work load could quite quickly outstrip the available resources of human analysts, and for this reason, we are currently working with partners to develop automated image analysis algorithms for application to CCTV video footage of discards. This work is at too early a stage of development to report as yet.

We have suggested a method by which discard estimation can be carried out based on fish count and length data from CCTV video (see Discard-rate estimation section). Thus far, this is quite an unsophisticated procedure. We generally cannot measure the lengths of all discarded fish, and so must apply inference from allometric analysis or by raising the measured length distribution to the level of the discarded population. We then raise further from sampled hauls to all hauls, and from sampled trips to all trips, and each of those raising stages can introduce error. As we cannot measure weight on CCTV video, we must apply externally estimated length–weight relationships, which may not be truly representative of the fish being measured. There also remain methodological problems with the use of length-based discard estimates in the collation of data to use in age-based ICES assessments that are still to be addressed (ICES, 2013). One possibility would be to continue development of length-based assessment methods, which would not require age data to the same extent as currently, and this is being explored.

The cost analysis summarized in the Relative costs of on-board and REM observation section takes real cost data for at-sea observers and the REM observation programme, and applies a simulation approach to estimate the likely overall costs of each observation system. Here we present an example only, intended to reflect the vessel coverage as it was in 2012, although Dinsdale *et al*. (2013) covered a wider range of coverage options. The overall conclusion was that REM observation was considerably cheaper, after the initial set-up phase which was more expensive due to the requirement to purchase and install systems. However, it is also clear that the data available from REM are different from other observers, and future work must include the estimation of comparative costs when generating discard estimates of the same variance (and under different levels of discarding).

The requirement to use REM video footage to estimate the discard rate of key commercial species may partially diminish in future as the EU land-all policy comes into force in 2015 for pelagic vessels and 2016 for demersal vessels (EU, 2013), although issues such as *de minimis* allowances, species that can survive discarding, and other potential derogations mean that the utility of such estimates is unlikely to reduce greatly. Even if this did happen, another key use of REM data will be to determine benthic diversity indirectly through an evaluation of what a vessel is catching and discarding of non-commercial species such as starfish, sponges, and urchins. This could be particularly pertinent to assessments of the status of benthic community biodiversity, seabed integrity, and foodweb dynamics required under the European Union's Marine Strategy Framework Directive (MSFD: European Commission, 2008, 2010). A brief study was undertaken in 2013 by one of the co-authors (Drewery) to attempt to determine what of this type had been caught and discarded by a vessel fishing at Rockall. While not a comprehensive survey (only three hauls were analysed), it did demonstrate that REM can be a valid source of information on benthic diversity. It should also be noted that a great deal of expert knowledge on species identification is required: it is important to know what is *likely* to be found in a given area at a particular time of year, and what benthic species might look like after trawling.

The Scottish REM schemes implemented to date have been voluntary, and interest has been maintained by the provision of sufficiently profitable incentives to encourage membership. Incentives such as additional quota have only been possible because the number of vessels involved has been limited, and it is hard to envisage an incentive structure that would be applicable were REM monitoring to become mandatory to all vessels participating in the fishery. In any case, we consider that discussion of fishery incentives, and the risks involved in a mandatory monitoring scheme, would currently be highly speculative and outwith the remit of this paper (which was principally to consider scientific applications of REM data).

The potential benefits of REM systems for scientific analysis of fisheries and fish populations are clear. REM sensors record vessel location and activity in unparalleled detail, while CCTV cameras are always on and do not need to conform to restrictive working time directives. REM systems are cheaper than at-sea observers after an initial start-up phase and can generate much of the same type of information, although observers will still be required to sample biological parameters such as age, sex, weight, and maturity that cannot be determined through video (no matter how high quality). REM monitoring has the potential to provide much wider coverage of the fleet, and enables truly random sampling of participating vessels in a way that observers cannot achieve. With regular feedback to the fishing fleets of sampling results, REM systems also have the potential to become a valuable information stream for fishers as well. There are clearly many issues to be addressed and much development work to be done, but the prospects for important scientific analyses based on REM data are increasingly good.

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