Rev Fish Biol Fisheries
https://doi.org/10.1007/s11160-024-09895-7

ORIGINAL RESEARCH

Optimising the review of electronic monitoring information for management of commercial fisheries

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Received: 1 March 2024 / Accepted: 6 September 2024

Abstract Electronic monitoring (EM) systems incorporating cameras and other devices can collect a broad range of data to support fisheries management. We reviewed the data collection capabilities of EM and considered approaches to increasing efficiency, including cost effectiveness, of EM review. EM can provide information on catch, effort, catch handling, bycatch mitigation, fishing gear and operational data, which are relevant for fisheries management including by Regional Fisheries Management Organisations (RFMOs). Methods to increase efficiency and decrease costs of EM review apply from the programme design phase, through data collection and review. At review, costs may be reduced by sampling imagery optimally to meet monitoring objectives. Considering RFMOs as users of EM-collected information, we applied *EMoptim,* an open-source simulation model developed in R that estimates the amount of EM review necessary to meet one or more user-specified monitoring objectives. *EMoptim* uses stratification to increase review efficiency and incorporates a function to explore review costs against the monitoring objectives set. We evaluated the amount of EM review needed to estimate catch with specified precision, using fishery data available from the Western and Central Pacific Fisheries Commission. Model outputs show that EM review requirements increase as catch frequency decreases, dispersion of catch events increases, and when more precise catch estimates are required. Geographical stratification reduced the amount of review required for more commonly caught species and when catch events were focused in a limited area. Optimising review rates across multiple monitoring objectives was most effective for more commonly caught species. We highlight opportunities for future use and development of this prototype modelling package.

Keywords Electronic monitoring · Fisheries management · Fisheries monitoring · Optimisation · Review · Regional fisheries management organisation

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11160-024-09895-7.

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Published online: 23 September 2024

Introduction

Electronic monitoring (EM) incorporating cameras on fishing vessels has developed since the late 1990s (van Helmond et al. 2020). As well as cameras that record fishing activities, EM systems incorporate GPS tracking, satellite reporting of system status, a control unit that stores recorded information, and often, sensors that detect gear movement indicating fishing activity. EM has been implemented on a trial basis and as part of routine fishery monitoring in more than 100 fisheries (van Helmond et al. 2020; Moncrief-Cox et al. 2021; ICES 2023; Bolger 2024a, b; Razzaque et al. 2024). Strengths of EM include the capability to collect high quality, minimally biased, detailed and comprehensive information on fishing activities, through methods which are readily scalable and do not involve risks to human health and safety (Michelin et al. 2018; van Helmond et al. 2020; Dobson et al. 2023; Garcia 2024). Fishery information that can be effectively collected by EM may include catch landed and released, catch handling practices, gear used, compliance with management regimes, and fishing effort and location (Gilman and Zimring 2018; Pierre 2018; Román et al. 2020; van Helmond et al. 2020, 2021; van Helmond 2021).

A significant amount of the data needed to support fisheries management can only be captured onboard fishing vessels. Among fishery management entities, Regional Fisheries Management Organisations (RFMOs) are multilateral bodies that hold critical fishery management responsibilities across most of the world's oceans (Løbach et al. 2020). Their management roles are typically defined in relation to target species within a particular geographic area (summarised in Online Resource 1). To support their management of focal fisheries, RFMOs set requirements for information collection and monitoring, control and surveillance within their areas of competence (MRAG 2019; Ewell 2020). The emergence of EM as a fishery monitoring tool has led RFMOs and their members to evaluate opportunities for EM-based data collection. This has included considering data requirements that can be met using EM, and how EM may be formally incorporated into RFMO management regimes (FFA Member CCMs 2022; IATTC 2023; ICCAT 2023).

Identified barriers to EM adoption, including by RFMOs, may involve establishing operational, regulatory and management frameworks that accommodate EM, and managing costs (Michelin et al. 2018; Michelin and Zimring 2020; van Helmond et al. 2020). For example, regulations may specify that certain monitoring information must be collected by human observers (e.g. because regulations were written before EM was available), and management frameworks typically require updating to work with EM data. Operational culture change onboard vessels involves crew accepting that their workplace is a monitored environment (James et al. 2019). Perceptions of EM cost are influenced by the challenges of reconciling costs and benefits of EM. While costs are immediately calculable and apply from the outset of a programme, benefits (and timeframes to accrue them) tend to be more variable and are more difficult to specify (Sylvia et al. 2016; Michelin et al. 2018; Rogers et al. 2022). In addition, cost efficiencies provided by EM are not fully realised in trial or pilot programmes. Instead, cost efficiencies tend to increase when EM is scaled up to operational programmes (Lowman et al. 2013; Michelin et al. 2018). If the operational stage is not reached, the true cost–benefit profile remains unknown.

Costs of EM programmes include fixed and variable components. One of the variable costs characterising EM programmes is the cost of reviewing the imagery and associated information recorded by the EM system. Reported review costs vary from 2.5 to 39% of EM programme costs (Pierre et al. 2022). Review costs are affected by a range of factors, including the amount of imagery that is reviewed, on-vessel practices in place to facilitate review, and any efficiencies built into the review methodology such as automation (Sylvia et al. 2016; Michelin et al. 2018; Rogers et al. 2022). In practice, the amount of EM review undertaken may be more influenced by budget than a review design that is appropriate to meeting monitoring objectives (as for human observer programmes (Brooke 2014)).

For EM, human fishery observers and other monitoring methods, programme design critically affects whether monitoring objectives will be met. The design of human observer programmes has been actively investigated for decades (e.g. Bravington et al. 2003; Kennelly 2016; Cahalan and Faunce 2020; Wang et al. 2021). Sufficiency of information and managing and minimising systematic and random error are vital for ensuring information accuracy and the efficacy of monitoring programmes in supporting fisheries management (MRAG 2019; Pierre et al. 2022, 2023). Critical design questions include what level of coverage to implement, how to distribute coverage across vessels, space and time, and how to analyse the data collected (Haigh et al. 2002; Babcock et al. 2003; Miller et al. 2007; Amandè et al. 2012; Duarte and Cadrin 2024). Where census-level coverage is not in place, sampling approaches must be considered. These may be random, stratified, or another structure, with sampling design having implications for the data collected and the appropriateness of different analytical methods (Davies and Reynolds 2002; Scott-Denton et al. 2011; Faunce 2015; Fernandes et al. 2021). Human fishery observers and EM both rely on visual detection of fishing events of interest onboard vessels, and such design considerations are relevant to both monitoring methods (Moore et al. 2021; Pierre et al. 2023).

In this paper, we focus on optimising EM review to cost-effectively deliver information required for fisheries management. We review how EM can contribute data supporting the needs of management entities including Regional Fisheries Management Organisations, focusing on RFMOs that manage tuna and other highly migratory species. We also consider the progress of these organisations with EM adoption. Using examples from fisheries where EM has been implemented and considering fishery datasets collected at a regional scale, we then:

- Investigate methodological approaches to maximise the cost efficiency of EM review, and,
- Apply a prototype open-source customisable simulation model (*EMoptim)* to real-world fishery data, to:
  - Explore the amount of EM review required to estimate catch composition,
  - Investigate how stratifying review affects review rates and estimated costs of review; and,
  - Consider sampling efficiencies achieved by optimising review rates across multiple monitoring objectives.

Methods

EM to support the data needs of RFMOs

We reviewed the convention texts of six RFMOs. Five of these are focused on the management of tuna and other highly migratory species (Inter-American Tropical Tuna Commission, IATTC; International Commission for the Conservation of Atlantic Tunas, ICCAT; Indian Ocean Tuna Commission, IOTC; Western and Central Pacific Fisheries Commission, WCPFC, Commission for the Conservation of Southern Bluefin Tuna, CCSBT). The sixth RFMO reviewed focuses on a broader range of fish species, molluscs and other taxa (North Pacific Fisheries Commission, NPFC). We considered the objectives and purposes stated in RFMO convention texts (Online Resource 1) and categorised the stated principles, functions and actions (PFAs) into themes which link to specific information needs, in turn represented by data fields.

We then reviewed the literature to identify these RFMO information needs that have been or could be met using EM in its current state. Our literature search used keywords singly and combined with Boolean operators, in Google and Google Scholar. Keywords included generic terms (e.g. electronic monitoring, EM, REM) and more specific combinations including fishing methods or subject areas (e.g. electronic monitoring AND discard*, electronic monitoring AND longlin*, electronic monitoring AND mitigat*). We also searched online repositories of fishery and monitoring information (em4.fish and the Bycatch Management Information System) and our own reference libraries. For the most recent information, we reviewed conference proceedings, websites and Twitter feeds of EM practitioners, and personally contacted practitioners to follow up on particular areas of work. Sources encompassed research on whether data requirements traditionally met by observer data collection could also be met using EM.

We summarised findings in terms of whether EM can provide data required to support fishery management by the focal RFMOs in whole or in part. Specifically, we report work describing the use of EM to monitor fishing effort and gear, catch and discard information, bycatch mitigation and handling, and operational data.

Based on material posted on RFMO websites, including meeting documents and reports, and the texts of management measures, we also summarised progress with EM adoption among the focal RFMOs.

Cost efficiency of EM review

We considered opportunities for increasing the efficiency of EM review that could be supported from the EM programme design stage, through the on-vessel data collection and review stages. Programme design establishes the purpose of a programme including how monitoring systems and processes will deliver on that purpose (Pierre et al. 2023). Costs are focused on creating a robust foundation for the programme, including the review stage. On vessels, efficiencies in review costs are associated with capturing data to facilitate its extraction by EM analysts. At review, costs are focused on resource requirements to process EM imagery and associated information, to extract the fishery data sought. Our own experience with the design and implementation of EM programmes, and the search process described above, provided information supporting this evaluation. Specific to the design stage, we compared census and sample-based review (including the audit model) for providing the monitoring information needed to support fisheries management.

Simulation modelling to evaluate options for EM review

We used a prototype simulation modelling package, *EMoptim* (Dunn and Pierre 2022), to explore the amount of EM review required to estimate the catch of selected species and species groups, by tuna fisheries operating in the Western and Central Pacific Ocean in 2019. *EMoptim* was developed in the R programming language (R Core Team 2021). This package uses stratified random sampling to estimate the EM review rates required to meet user-defined monitoring objectives, and associated review costs. (We define EM review rate as the proportion of fishing effort sampled for review, from the EM record). *EMoptim* comprises three components:

(1) A spatially explicit operating model, which is customisable by the user for application to different regions, fisheries, fleets, etc.
(2) An evaluation model, which explores the probability of detecting event(s) of interest to the user given specified assumptions of the underlying statistical and spatial distribution, with associated uncertainty
(3) An optimisation framework, which allocates review rates across strata to improve review efficiency and provide the best possible dataset to address user requirements (e.g. precision, cost).

The *EMoptim* package was designed for when EM is used as a standalone monitoring tool, assuming that 100% of fishing activity has been captured by EM and that review involves sampling a proportion of activity from 0 – 100%, within that 100% record (Pierre et al. 2022). The underlying approach uses the *SamplingStrata* R package (Barcaroli 2014; Barcaroli et al. 2020) to evaluate and optimise the strata within which review occurs. Stratified random sampling enables higher review efficiency by focusing review effort where it is most needed (Latpate et al. 2021). Strata contain components with similar properties, with stratification providing greater sampling efficiency by reducing the number of samples needed to achieve a particular level of confidence in the population estimate generated. For each monitoring objective considered by *EMoptim*, the total population is divided into strata (which may be defined by the user or the model), with samples taken from each stratum that are then combined to provide a population-level estimate of the monitoring rate needed to meet each objective. Infinite sampling theory (Horvitz and Thompson 1952) provides the basis for *EMoptim*, to enable its application to fisheries with any, and potentially an unknown, amount of fishing effort.

The *EMoptim* prototype package used for this case study is available online at https://github.com/pewtrusts/EMOptim, with guidance and worked examples. Full input grids used for the case study presented here are also available in that repository.

We used *EMoptim* to explore the amount of EM review that would be needed to estimate longline and purse seine catches of a range of taxa with specified levels of precision (measured as a coefficient of variation (CV)). We considered two monitoring design scenarios. In the first scenario, we used *EMoptim* to estimate the extent of EM review needed to meet monitoring objectives for each focal species/species group, comparing the review rates required with and without a simple geographic stratification in place. We created a geographic stratification at a scale of 25° × 30° within the Convention Area of the Western and Central Pacific Fisheries Commission (WCPFC). Latitudinal and longitudinal differences in species distributions and catch patterns are well recognised in this region (Williams et al. 2009; Rice et al. 2015; Oceanic Fisheries Programme 2022; New Zealand 2024). The amount of EM review was estimated as a proportion of gear sets within each of the 25° × 30° strata, and overall, for each taxa. Focal species and species groups were:

- For longline fishing, yellowfin tuna (*Thunnus albacares*), porbeagle (*Lamna nasus*), oceanic whitetip shark (*Carcharhinus longimanus*), black-footed albatross (*Phoebastria nigripes*), seabirds, turtles and marine mammals
- For purse seine fishing, yellowfin tuna, silky shark (*C. falciformis*), whale shark (*Rhincodon typus*), turtles and marine mammals.

Catch patterns have been widely shown to be critically relevant to effective monitoring design (Babcock et al. 2003; Fernandes et al. 2021; Moore et al. 2021). Therefore, focal taxa were chosen to range from a very commonly caught species (yellowfin tuna) through less frequently (porbeagle) and very rarely caught species and species groups (whale sharks, turtles, seabirds, marine mammals). Captures of silky and oceanic whitetip sharks ranged from uncommon to very rare depending on fishing method.

In the second monitoring design scenario, we used *EMoptim* to investigate optimised sampling allocations that would be required to simultaneously meet two monitoring objectives. For this scenario, we did not pre-determine strata. We considered one commonly caught species (yellowfin tuna, both longline and purse seine fisheries), one less frequently caught species (porbeagle shark in the longline fishery) and one very rarely caught species (oceanic whitetip shark, purse seine fishery). We compared the level of review required to estimate catch, and CVs achieved when sampling was not stratified and also when *EMoptim* was used to assign an optimal stratification for EM review.

The input dataset used for this case study is publicly available on the WCFPC's website (https://www.wcpfc.int/scientificdatadissemination, downloaded 20 July 2022). Data sources differed for focal taxa. Logbook reporting provided data on the catch of yellowfin tuna, porbeagle, silky and oceanic whitetip sharks. Onboard fishery observers collected catch data for whale sharks, turtles, seabirds and marine mammals. Accuracy and coverage constraints associated with each data source are discussed elsewhere (e.g. Brown et al. 2021; Peatman and Nicol 2023), with our focus here being on the application of *EMoptim* for developing monitoring regimes.

EMoptim was designed to take data from an external file that defines the fishery, distributions of events of interest, encounter rates expected (with associated statistical distributions), and definitions of monitoring objectives (Dunn and Pierre 2022). These inputs are read into R as an object, called *EMobject,* which is created by the R command *input.config.file()*. The *EMoptim* input configuration file is a plain text file comprising several commands (each with subcommands) which specify various options for each of the components. The use of a plain text external configuration file allows the assumptions and data definitions to be recorded in a simple human-readable format. Commands always begin with the @ character, with several commands also requiring a label. Subcommands follow the command, with each subcommand having some number of arguments that must be specified. Arguments can be strings, numbers, or vectors of strings or numbers. The type of argument is always specific to the subcommand. The order of subcommands or commands in a file does not matter, except that the subcommands for each command must always follow the associated command and occur before the next command.

To define the model structure in *EMoptim*, we used the command @model to specify the size of the map grid (number of rows and columns) within which the fishing effort and sampling for review occurred, and the names of the strata (when specified), fleets, and definitions of the events of interest for monitoring. The Convention Area of WCPFC is defined within the Western and Central Pacific Ocean (https://www.wcpfc.int/doc/convention-area-map). We represented this Convention Area as a matrix of cells of 5° × 5°, because longline fishery data available from WCPFC are aggregated at that scale. We defined the areas in which fishing occurred using *EMoptim*'s @base_map command, with '0' and '1' denoting cells in which fishing did not and did occur (and therefore, sampling for EM review should not and should be allocated), respectively.

We used the @fleet command to define the two fleets of interest in the case study (longline and purse seine). Fishing effort for each of the two fleets was entered in each 5°×5° cell mapped. For the purse seine fleet, effort was described by set in the source dataset. Longline data are made publicly available by WCPFC in numbers of hooks, while electronic monitoring review could be structured by sets or hooks (as two examples). We assumed that each set represented 3,500 hooks, broadly characteristic of a larger-scale pelagic longline fishery (e.g. Akroyd and McLoughlin 2020) and hence approximated the longline effort in sets for each cell as the number of hooks reported in that cell and divided by 3,500.

To estimate the costs of EM review, *EMoptim*'s cost function includes a fixed cost per unit of effort to characterise the sampling frame for review, and a separate cost per unit of effort to conduct the review (Dunn and Pierre 2022). As defined, the cost function assumes the monitoring objectives and therefore review required are the same for all samples. This is a simple approach and review costs and scaling may be programme-specific for many reasons (Pierre et al. 2022). We used indicative cost figures based on real-world monitoring programmes for the longline and purse seine fishing methods (G. Legorburu, pers. comm.). The fixed daily cost for characterisation of the sampling frame was set with the @fleet information, as €5 per day for longline fishing (corresponding to one set, based on an assumption of approximately one set being conducted per day) and €15 per day of purse seine fishing. The daily review cost for determining catch composition was specified with the species catch distribution information (*EMoptim*'s @species command, below). For longline fishing, an additional €90 per day was costed for review where catch composition is relatively simple (while including target and non-target species catch events). For purse seine fishing, an additional €30 per day included analysis of target and bycatch events.

We specified capture rates using the @species command, drawing from the source dataset to set out the expected spatial distribution of captures for each of the focal taxa across the cells of the base map and for each of the two fishing methods. Assumed statistical characteristics of capture events were specified for focal taxa under the @encounter command, with these based on published literature when not estimable from the case study dataset. (Source references are listed in Online Resource 2). The assumed distributions implemented were lognormal for yellowfin tuna (parameterised by μ and *CV*), and zero-inflated (zif) Poisson for all other species/species groups (parameterised by λ and *pzero*, the probability of zero catch).

Review to meet a single monitoring objective with geographic stratification

For the first monitoring scenario, we defined the geographic strata of 25°×30° across the base map using the command @strata. We specified the monitoring objectives for the focal taxa using the @objective command, requiring EM review to support catch estimation of each of these taxa with CVs of 0.1 and 0.3. Using the @simulation command, we ran 1,000 and 10,000 simulations to evaluate the monitoring objectives set. We conducted these two sets of simulations to compare the potential benefit of additional simulations for convergence and refining review sampling allocations to meet the precision requirements set. Specifying simulations in *EMoptim* requires the user to set a range of sampling rates that are to be evaluated and the number of steps between the minimum and maximum sampling rate within that range. Balancing the accuracy of sampling rate evaluations with the computation time required, we set 26 steps between the minimum and maximum sampling rates of 0.01 and 0.99.

EMoptim uses Neyman allocation (Olayiwola 2021) to assign samples to strata. Allocations were evaluated using the function EMiterate(), which takes arguments of the *EMobject* along with an objective label and estimates a sampling rate and total number of samples required together with an expected CV for comparison against each objective set (that is, captures of focal taxa detected with specified precision). Then, the optimal sampling coverage to achieve the target CVs for each of the focal taxa is estimated using the EMoptimise() function. This function applies a linear approximation to the output of EMiterate() (interpolating between sampling steps, each of which has an associated sampling rate, to find an optimum sampling rate), and re-runs the simulator with this value to evaluate the sampling CV for the approximated sample size.

We present results output using the EMsummary() and plotEMsummary() functions.

Review to meet multiple monitoring objectives with optimised stratification

We explored an optimised stratification to support estimation of catch of yellowfin tuna (to CV = 0.1) and the focal shark species (to CV = 0.3) for each fishing method. (Strata are not user-defined in this scenario). *EMoptim* evaluates multiple monitoring objectives using genetic algorithms from the *SamplingStrata* R package (Barcaroli 2014; Barcaroli et al. 2020). Genetic algorithms simulate an evolutionary process, using a random search supported by data to move to an improved outcome within a specified framework. These algorithms are recognised as highly applicable to optimisation problems (Lucasius and Kateman 1993; Alam et al. 2020). *SamplingStrata* uses a modified version of the functions in the *genalg* package (Willighagen and Ballings 2022) to implement the genetic algorithm. We used the *EMoptim* defaults for the genetic algorithm iterations (300) and populations (50). Each specification of strata across the base map of $5^{o} \times 5^{o}$ cells is considered as an individual in a population with the fitness of all individuals evaluated by applying the Bethel-Chromy algorithm. This algorithm calculates the sampling size that meets the precision requirements of the target estimates (Willighagen and Ballings 2022).

To hold the resulting optimal estimated stratifications output from the model for each fishing method, we created a new strata label using EMoptimiseStrata(). We then evaluated the new optimised stratifications using EMiterate() and EMoptimise() as for the single objective scenario, to explore the level of review necessary to meet the target CVs, and the achieved CVs realised by implementing the optimal stratifications.

We present tabulated outputs from the EMsummary() function, summarising overall review rates and review rates per optimised stratum.

Results

EM to support the data needs of RFMOs

Key themes among the objectives of the six RFMOs considered are sustainable use and conservation in the long-term (Online Resource 1). Both fished species and non-target species are in-scope for management. One RFMO explicitly includes ecosystem protection in its overarching objective (NPFC). PFAs in RFMO convention texts formed three categories: biological, environmental and operational (Fig. 1). Key biological PFAs include supporting maximum sustainable yield (MSY) for focal or target species that are fished, and ensuring non-target species affected by fishing activities are maintained above levels at which reproduction may be threatened. Broader environmental PFAs include addressing pollution originating from vessels, lost gear, and ecosystem impacts. Operational PFAs cover implementation and compliance, e.g., determination of total catch and fishing effort, adopting evidence-based management measures, and ensuring compliance with binding measures (Online Resource 1). Supporting these RFMO PFAs, information needs that can be effectively met by data derived from EM are set out below, for five fishing methods

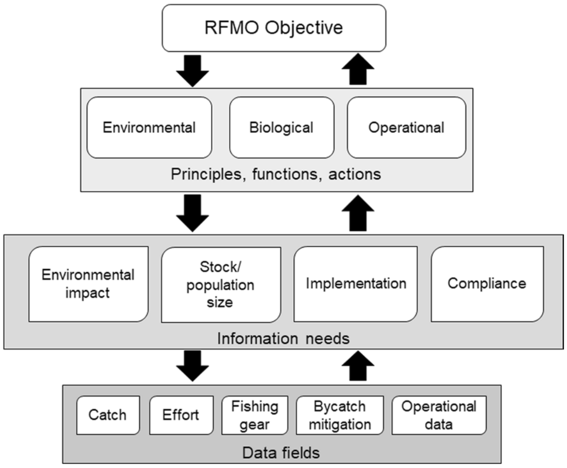

Fig. 1 Schematic diagram of linkages between Regional Fisheries Management Organisations' objectives, principles, functions and actions, and information and data needs. The two-way flow indicates that each layer informs the other on an ongoing basis, enabling ongoing evaluation of management performance against the RFMO objective

among those used in the six RFMOs (longline, purse seine, trawl, gillnet and pot/trap).

Fishing effort

Using EM to monitor fishing effort is reported from more than 100 trial and operational programmes worldwide. This is the most commonly reported monitoring objective, with efficacy demonstrated across the longline, purse seine, trawl, gillnet and pot/trap methods (Course et al. 2020; van Helmond et al. 2020). The duration of fishing activity may also be used to define and quantify fishing effort (i.e. hours fished), and for purse seine fishing, effort characteristics include searching and setting time and whether sets are made on fish schools associated with floating objects or animals (e.g. fish aggregating devices, whales), or unassociated schools.

For RFMO management of fisheries, fishing effort data are relevant to all four categories of information needs (Fig. 1).

Catch and discard information

Monitoring catch is reported as the objective of more than 75 EM projects or programmes conducted worldwide (van Helmond et al. 2020). Monitored catch components have included target species and non-target bycatch, such as endangered, threatened and protected (ETP) species and other megafauna. Data derived from EM have included retained and discarded catch species, size, and whether catch is alive, dead or injured (Pierre et al. 2018; Course et al. 2020; Glemarec et al. 2020; van Helmond et al. 2020; Briand et al. 2023a; Stahl et al. 2023). EM has also been used to collect information on cetacean depredation of target catch (Monaghan et al. 2024).

Capture of catch information by EM is most straightforward for serial fishing methods, e.g. when catch comes aboard piece by piece on a longline, or in smaller clusters in a gillnet. By contrast, when catch is landed on deck or into storage holds in bulk (e.g. purse seine and trawl methods), determining composition from EM imagery is more difficult (Lowman et al. 2013; Michelin et al. 2018; Briand et al. 2023b). Catch handling protocols have been implemented, or recommended, to facilitate quantification and catch species identification, as well as size and assessment of life status (e.g. Gilman et al. 2019; van Helmond 2021). Catch handling protocols are considered essential to support EM data capture for bulk fishing gears landing large catches (Lowman et al 2013).

EM, together with landed catch reconciliation (e.g. dockside monitoring), can effectively characterise catch discarded after being brought aboard (Lowman et al. 2013). For catch items not landed on deck, EM-supported enumeration is optimised when catch is handled within camera views (e.g. sea turtles, sharks (Pierre et al. 2022; Briand et al. 2023b; Stahl et al. 2024)), and with appropriate review methods (e.g. review speed to enable detection of releases (Stahl and Carnes 2020)). However, when catch items drop from gear or are removed in the water, EM may not enable identification to the same level as when catch items are brought aboard (e.g. identification may be limited to family or genus level, not species). As for any visual identification method, similar taxa may be difficult to distinguish by non-experts even if they are brought aboard (Pierre et al. 2023), noting that for EM this issue is conflated with handling practices onboard (e.g. for some seabirds, McKenzie 2021). Determining life status and size is also less achievable when catch items are removed, released or dropped directly into the water, compared to onboard vessels (Gilman et al. 2019; Course et al. 2020; Stahl and Carnes 2020).

Catch and discard data are critical for RFMO management, relating to stock/population status of species caught, fishery impacts on target and non-target species, implementation of fishing operations, and compliance with management measures (Fig. 1).

Fishing gear

Some fishing gear characteristics can be effectively captured in EM imagery, e.g., presence of floats, weights, and shark lines on longline gear, and characteristics of floating objects used in purse seine fishing (Emery and Nicol 2017; Gilman and Zimring 2018; Legorburu et al. 2018). Some bycatch mitigation devices are also detectable in EM imagery. For example, sorting grids used to reduce ETP bycatch in trawl fisheries can be seen as gear is deployed. The presence of wire traces (associated with increased shark bycatch, and prohibited in some fisheries), tori lines (also known as bird-scaring or streamer lines, used to reduce seabird captures in longline and trawl fisheries), and pingers (deployed on gillnets with the aim of reducing cetacean bycatch) are all detectable (Emery et al. 2018; Pierre 2018; Acharya et al. 2024). Backdown operations to release marine mammals from purse seines are also expected to be detectable (Román et al. 2020).

Gear characteristics that are difficult to derive from EM imagery currently include dimensions of gear elements, e.g. hook size, and tori line, longline mainline and branchline lengths (Emery et al. 2018; Pierre 2018).

Fishing gear characterisation is relevant to RFMO information needs including catch per unit effort of target and non-target species, stock/population status of species caught, implementation of fishing operations, environmental impacts, and compliance with management measures (Fig. 1). By reconciling gear hauled against gear set, EM could also be used to account for lost gear that contributes to the broader environmental impacts of fishing.

Bycatch handling

EM can be used to record bycatch handling practices to evaluate the implementation of mandatory and non-mandatory measures (e.g. RFMO handling guidelines (WCPFC 2017, 2018), industry codes of practice (Morón and Herrera 2020; Pierre et al. 2022)), as well as identifying opportunities to improve handling practices (Course et el. 2020). This information is relevant to RFMO fishery impacts on populations of species caught, fishing operations, and compliance/conformance (Fig. 1).

Operational data

A range of general operational data characterising fishing activities is readily collectible using EM, e.g., the date, time and location of various fishing activities including (but not limited to) the start and end of sets and hauls (Román et al. 2020; van Helmond et al. 2020; WCPFC Secretariat 2020).

Operational fishery data is critical for addressing all categories of RFMO information needs (Fig. 1).

EM adoption by RFMOs

The six RFMOs examined are at different stages of the adoption of EM (Table 1). In most cases, an EM-dedicated workstream has been defined to support progression of this monitoring method (Table 1). Four of the six RFMOs considered have accepted EM formally as a data provision method, and the remaining two have discussed the possibility of EM data collection. Data collection using EM may be recognised as an alternative to human observation at sea, or as a method to augment or complement human observer coverage requirements.

The development of standards is a critical precursor to EM adoption (Murua et al. 2020; Gilman 2023). Standards enable a common understanding of a minimum baseline requirement, and are also intended to support comparability between datasets, such as when information is collected through otherwise separate programmes. For EM, standards also serve to eliminate approaches that will not meet monitoring objectives. Depending on the implementation approach taken, standards drafted by RFMOs may cover programme standards (e.g. the independence and impartiality of EM programmes), technical standards (e.g. requirements for camera capabilities, tamper-evident systems, malfunction alerts), logistical standards (e.g. operational procedures to ensure the secure collection and distribution of data storage devices), data analysis standards (e.g. analyst training, data entry checks, sub-sampling considerations for audit-based review) and detailed data definitions. Integration with other components of the RFMO structure and operations may also be required, as when any new requirement, or information collection method or source is introduced (Table 1).

Two RFMOs have adopted EM-specific standards (ICCAT and IOTC; Table 1), with this preceded by endorsing voluntary standards in both cases (SCRS 2018, 2021; Murua et al. 2020). The scope of data collection reflected in these standards broadly covers EM's recognised capabilities (with the exception of gear discarding and marine pollution. Such events may be detectable using EM but camera coverage designed specifically to record them may be required). Among other RFMOs, WCPFC has tasked its Intersessional Working Group on Electronic Monitoring and Reporting (ERandEM IWG) with developing a set of interim EM standards for adoption at the Commission's 2024 meeting (WCPFC 2023). This follows the development of draft standards formally circulated in 2020 (ERandEMWG Chair 2020a). Most recently in February 2024, the South Pacific Regional Fisheries

Table 1 Summary of steps taken by six Regional Fisheries Management Organisations towards the adoption of electronic monitoring for fishery data collection

	Regional Fisheries Management Organisation					
Steps taken	IATTC	ICCAT	IOTC	WCPFC	CCSBT	NPFC
Definitions of key terms adopted	✓	✓	✓	Draft	✓	✕
EM-focused subgroup or workstream created	✓	✓	✓	✓	Underway	✕
Data fields for EM collection defined	Discussed	✓	✓	Draft	As per human observers; not specific to EM	✕
Institutional requirements for EM	Discussed	✓	✓	Discussed	✓	✕
Formal acceptance as an alternative data collection method	Acknowledged and endorsed as a "promising tool"	✓	✓	✓	✓	✕ Discussed as one possible method for data collection
Standards developed	Discussed	✓	✓	Draft	As per human observers; applied to EM, not EM-specific to date	✕
Standards adopted	✕	✓	✓	✕		✕
Sources	IATTC 2019; 2021a, b; 2022a, b, c; 2023; Román et al. 2023	Ruiz et al. 2017; SCRS 2018; ICCAT 2021, 2023	Murua et al. 2020; IOTC WGEMS Chair and IOTC Secretariat 2021; IOTC 2023	WCPFC 2015 ERandEMWG Chair 2018, 2020a, b, 2022; FFA Member CCMs 2022	CCSBT 2022a, b, 2023	NPFC 2023

IATTC Inter-American Tropical Tuna Commission, *ICCAT* International Commission for the Conservation of Atlantic Tunas, *IOTC* Indian Ocean Tuna Commission, *WCPFC* Western and Central Pacific Fisheries Commission, *CCSBT* Commission for the Conservation of Southern Bluefin Tuna, *NPFC* North Pacific Fisheries Commission

Management Organisation discussed the Terms of Reference for its new ad hoc Working Group on EM, and the goal of adopting EM standards in 2025 (https://www.sprfmo.int/meetings/comm/comm12/). Taking a different approach, CCSBT has amended its programme standards applicable to human observers to broadly encompass EM, while the Commission hasn't detailed EM-specific standards to date (Table 1).

Cost efficiency of EM review

Cost efficiency of EM can be increased during the design, on-vessel data capture and review components of EM programmes (Table 2). Approaches including the following provide alternatives to reducing cost beyond simply reducing the amount of EM review undertaken.

Table 2 Approaches to increasing EM review efficiency during the programme design, data capture and review phases. ✓ identifies approaches applicable to both census and sample review models. S and A identify methods that apply only to sample- and audit-based review, respectively

When applicable	Approach	Review method
Programme design phase	Clearly defined monitoring objectives	✓
	Information collection priorities set	✓
	Sample selection specified (random, stratified, risk-based)	S
	Subsampling units identified	S
	EM-appropriate data definitions developed	✓
	EM-appropriate data collection units identified	✓
	Use of the audit approach	S
On-vessel data capture	Catch handling protocols in place	✓
	Lens cleaning undertaken	✓
	High quality logbook reporting	A
	Incentives for operational practices that facilitate review	✓
	Feedback provided to crew rapidly to enable prompt on-vessel changes	✓
At review	Review instructions that accurately reflect programme design, objectives, data needs	✓
	Review speeds faster than real time	✓
	Hotkeys used by analysts	✓
	Review supported with Computer Vision, Artificial Intelligence	✓

Suitability of data definitions for EM

For decades, human observers have been collecting information onboard fishing vessels. In many cases, EM is implemented in fisheries where human observers have operated. Some data collection approaches translate effectively and efficiently between the two methods, while others do not. One example of where data collection methods are transferable is observer instructions for conducting hook counts in larger scale longline fishing operations (e.g. WCPFC 2016). Observers count the number of hooks in a subsample of longline baskets (a basket being the longline between two buoys). They record the total number of hooks as the number in the subsample multiplied up by the number of baskets on the longline. This method also works for EM analysts, with efficiency affected by the identifiable presence of gear markers, and regularity of marker spacing (Chordata and Saltwater Inc., unpublished report).

By contrast, at-sea observer and EM programmes in Alaska, USA, are required to collect data on Pacific halibut (*Hippoglossus stenolepis*) viability, injury, and release methods. This information is provided to the International Pacific Halibut Commission and informs the determination of halibut mortality rates. The condition codes currently used by both human observers and EM analysts were defined based on at-sea observer fish-in-hand assessment. This is problematic for EM analysts, as they are often unable to view both sides of the halibut or assess details such as operculum pressure, as observers would. Amended data definitions that would be effective for EM have been recommended, including reducing the number of halibut injury groupings used in the assessment (Chordata and Saltwater Inc., unpublished report).

The Alaska fixed gear programme provides an example of where changes to the sampling unit have been explored to facilitate data capture by EM analysts. In this case, the sampling unit was defined differently for EM compared to observers. A single pot is the defined sampling unit for EM. However, when catch volume and species diversity are higher, it is not always possible to sort, process, and clear the table prior to the next pot arriving. As a consequence, catch from multiple pots becomes mixed. The practice of discarding unwanted catch by armfuls prevents EM analysts from obtaining catch composition information and the pot catch record is lost (decreasing data usability for the programme). Defining the sampling unit as a string or cluster of pots, with an allowance for clearing catch by the end of the string or cluster, provided increased flexibility in catch handling requirements and improved EM analysts' ability to collect catch information throughout fishing events. Furthermore, cost efficiency (data per dollar) increased due to a decrease in unsampleable data caused by catch handling issues (Chordata and Saltwater Inc., unpublished report). Currently, the single pot unit remains in place for EM, until the definition of a haul can be addressed for individual (unconnected) pots. By contrast, the definition of a string or cluster of pots has been resolved for the longline pot method and observer instructions allow observer judgement on how the pot units in a haul are defined (e.g. as a single pot, or all pots hauled within a 24 h period (AFSC 2024)).

Review model

Monitoring objectives determine the review model which is most effective for obtaining fishery information. The most comprehensive dataset is derived from census review of all imagery and associated information collected by EM systems. This approach is often evident in pilot programmes, and it is also deployed in some operational programmes (Course et al. 2020; Pierre et al. 2022). In pilot programmes, census review has value beyond the data collected, as it also informs the process of scaling up to operational EM programmes, e.g. the development of standards and review requirements (Michelin and Zimring 2020; Michelin et al. 2020).

Sample-based EM review can meet some monitoring objectives, either when used as a standalone information source, or to audit other reporting such as fisher logbook records. For example, EM-derived data from a sample of monitored hauls have been used as a standalone source of catch composition information in the Alaska fixed gear fishery since 2018. In this example, trips are randomly pre-selected for EM, with this pre-selection modifiable based specific prioritisation requests (e.g. relating to compliance monitoring). A subset of the fleet is involved in the EM programme and sampled data are not used for audit (Pierre et al. 2022; Oberg et al. 2023).

Also well established, the audit approach to EM review involves comparing data collected from reviewing a sample of EM information with fisher reports (e.g. Stanley et al. 2011; Emery et al. 2019; Pierre et al. 2022). The deviations between the two datasets are then scrutinised. If audited fisher-reported data meet pre-defined accuracy thresholds, logbook data are accepted as the source of fishery data at the fleet scale, and additional EM review is not pursued. Sampled data are not scaled up, and logbook reporting becomes the fleet-level record (Emery et al. 2023a, b). From a statistical perspective, samples reviewed and used for an audit approach would ideally be randomly selected. However, in some circumstances targeted (or stratified) sampling may be appropriate, such as when monitoring objectives are developed based on risk. Where logbook data are of low quality across a fleet, the audit approach will not work well (Brown et al. 2021).

Whether a census or sample-based approach to review used, 100% capture of fishing operations (i.e. all vessels in a fleet, with all fishing activity recorded) enables avoidance of the "observer effect". This well-known behaviour involves operators changing their practices because they are being monitored, resulting in data collected from monitored trips not being representative of normal fishing operations (Benoît and Allard 2009; Course et al. 2020; Moore et al. 2021).

Operational changes to facilitate data capture

Review efficiency can be increased by fishers operating in ways that facilitate effective image capture for review (van Helmond et al. 2017; Gilman et al. 2020). Identifying catch handling methods that will facilitate data extraction from EM involves considering gear configuration, hauling operations, catch composition and volume, and integration with crew operations. The potential for handling requirements to lead to compliance issues, slowed fish production, and any negative data impacts also requires consideration (van Helmond et al. 2017; NOAA 2020; Tide and Eich 2022).

A collaborative approach among the EM review service provider, fishers and the entity identifying data needs is recommended to optimise the specification of any handling requirements. Appropriate training, availability of educational resources and prompt feedback to vessel crew are also important for addressing on-vessel issues affecting imagery capture to minimise data loss. Where review costs are on-charged to vessel operators, there is the opportunity to incentivise facilitative operational changes such as catch handling practices through the commensurate reduction in review time (and therefore cost).

Varying playback speed

At EM review, optimal imagery playback speed is affected by monitoring objectives, gear and catch characteristics, and data to be extracted, as well as human factors. In the Hawaii longline fishery, 90% of hooks have no catch at the haul (K. Bigelow, J. Stahl and J. Tucker, unpublished). Reviewer accuracy in detecting catch events was tested at three playback speeds faster than real time (4×, 8 × and 16 × normal speed) (Stahl and Carnes 2020).

EM reviewers detected retained catch with similar accuracy at all three playback speeds. At 4 × normal speed, reviewers did not detect some protected species, possibly due to waning focus as the haul review progressed. For discarded catch, on average, detection accuracy was highest at a playback speed of 8x. At 16 × normal speed, reviewers detected all protected species caught except one albatross. However, the potential to miss unwanted species catch events was reported at this speed. This was because protected species and discards could drop off or be cut off the gear in an instant on-screen. At 16 × speed, crew behaviours associated with discarding animals in the water could be missed by analysts. Above 16 × normal speed, the EM video skipped and catch events may not have appeared on screen at all (Stahl and Carnes 2020).

As another example, imagery review at 10 – 12 × normal speed has been effective for monitoring large and highly visible cetaceans in a gillnet fishery (Kindt-Larsen et al. 2012).

These studies show that varying playback speed can increase the efficiency of EM review. However, programme- and objective-specific consideration of playback speed is needed to ensure that time (and commensurate cost) savings do not result in unacceptable losses of data quality.

Ergonomic tools

EM analysts work by transitioning back and forth between their keyboard and mouse to conduct review. Therefore, ergonomic tools can increase review efficiency. While each hand movement is short, cumulatively these transitions can account for a significant amount of time. Hotkeys (project customisable keybindings) assist reviewers in minimising transitional movements, navigating efficiently across the keyboard during review, and reducing the steps involved in creating annotations at review. Hotkeys can be programmed to allow reviewers to interact with playback speed, advance or reverse video, and create fishing and species annotations within the data. This supports an overall decrease in review time and may increase data quality.

Automation in EM review

The potential for increasing the efficiency of EM review by incorporating automation based on computer vision and artificial intelligence is well recognised (van Helmond et al. 2020). Algorithms for automation have been focused on object identification and activity recognition (Woodward et al. 2020), and such tools can perform or augment the process of marking fishing events, establishing sampling frames, monitoring implementation of bycatch mitigation (tori lines) and compliance with discard measures, measuring features such as length, and detecting and identifying catch (Barbedo 2022; Acharya et al. 2024AI. Fish, unpublished; Chordata and Saltwater Inc., unpublished). However, participants at a 2023 fisheries AI Summit reported that 85% of algorithm projects are abandoned pre-production, due to cost, time, or complexity (The Pew Charitable Trusts 2023).

Two examples from Alaskan fisheries demonstrate increases in EM review efficiency that have been supported by automation. In the Alaska fixed gear fishery, AI-assisted review designed to select imagery that included fish was tested in 2023. Six trips were examined, with a mean duration of five days. These occurred in 2018 (one trip), 2020 (two trips) and 2021 (three trips). A random sample of 36 hauls was selected for processing using the AI tool. The sampled hauls comprised approximately 12 h of imagery. Human analysts then reviewed the segments selected using AI. Results were compared against standard

EM reviews conducted entirely by human reviewers without AI-assisted selection of relevant imagery. When enumerating total catch for five of the six trips using a standardised protocol, catch counts differed by 2.7% for AI-assisted compared to human review. Catch counts conducted by two EM analysts differed by 1.3%. For the sixth trip, inadequate camera placement was considered to reduce the efficacy of the AI tool significantly because views of fish were occluded. Overall, AI-assisted review resulted in a 48% reduction in review time compared to standard (unassisted) review by focusing reviewer time on segments in which fish were detected. Time savings were estimated to correlate with a 46% reduction in review cost (https://em4.fish/projects-in-the-field-operationalizing-machine-learning-in-the-alaska-fixed-gear-electronic-monitoring-program/; M. Johnston, pers. comm.).

In a second example, a computer vision tool was tested for pot detection and marking in the Alaska cod (*Gadus macrocephalus*) fishery. Testing of imagery recorded in 2023 from nine trips (> 3,600 pots with an average of 401 pots set per trip) showed this tool saved an average of 85.3% of the time spent by a human reviewer identifying and marking gear. In this fishery, more than 1,000 pots may be deployed per trip. Time savings resulting from the use of automation equated to 174.9 ± 96.2 min per trip. The accuracy of automated detection was almost 100%. In addition, sampling rates can be set for gear detection tools to meet project requirements and allow the tool to highlight the pots that need to be sampled during review (Chordata and Saltwater Inc., unpublished report).

Estimation of EM review rates for longline and purse seine fisheries

Simulations conducted in *EMoptim* show that EM review requirements increased as catch frequency decreased, and when monitoring objectives required more precise catch estimates. Simulations also demonstrated that the geographic stratification applied increased the sampling efficiency most for commonly caught species. For example, to estimate (with CV of 0.1) the number of yellowfin tuna caught in WCPFC longline fisheries, 26% review was required across the WCPFC Convention Area, without stratification (Table 3). When regional stratification at the 25° × 30° level was introduced, the required EM review rate decreased to 4.4% of sets within the strata selected for review (Table 3; Fig. 2). Review effort was allocated across strata as shown in Table 4. When a CV of 0.3 was required, the review rates became 7.8% and ~ 1% of longline sets without and with stratification, respectively (Table 3), again, with this review effort allocated proportionally among strata as shown in Table 4.

In the case of porbeagle sharks, when captures occurred on 20% of longline sets, EM review of 86% of sets was required to estimate catch numbers with CV of 0.1 in the absence of stratification. With stratification at the 25° × 30° level, the required review rate decreased to 28% of sets (Table 3). For silky sharks caught in purse seine fisheries, a census review was required when geographic stratification was not in place because the target CV was not reached (Fig. 2). However, with stratification in place and a required CV of 0.3, the estimated review rate required decreased to 18.7% (Table 3). Cost estimates commensurate with review levels are also illustrated (Fig. 2).

For geographically widespread and rare ETP capture events, the geographic stratification implemented had little effect on review rates. Without geographic stratification, EM review of > 90% of sets was required to estimate catch of rarely caught species such as black-footed albatross and whale shark with CVs of 0.3 and 0.1 (Table 3). This is reflected in the number of sets required for review, e.g. for black-footed albatross catch in the longline fishery (Table 4). Estimating bycatch of the seabird, turtle, and marine mammal species groups with a CV of 0.1 also required very high levels of review (close to a census review). Stratifying sampling and also reducing precision requirements by specifying a CV of 0.3 reduced required review rates (Table 3). This was particularly evident for turtles, when the probability of catch occurring in a set also increased from 5 to 10% (Table 3).

Optimising sampling regimes to meet more than one monitoring objective was most effective for more commonly caught species. Introducing very rarely caught species into this optimisation process led to the required EM review rate increasing significantly (Table 5).

Runs of 10,000 simulations provided review level estimates within 10% of those obtained from 1,000

Table 3 EM review rates (% sets) calculated using *EMoptim* for a range of tuna fishery catch elements. Publicly available fishery data from the Western and Central Pacific Fisheries Commission (WCPFC) were used in *EMoptim* to derive review rates.

Catch element	Example species/group	Statistical characteristics of capture events	Target CV	Longline fishery review %		Purse seine fishery review %	
				No stratification	25° × 30° stratification	No stratification	25° × 30° stratification
Target species	Yellowfin tuna *Thunnus albacares*	Lognormal p0 = 0	0.3	7.8	~ 1.0	3.8	1.0
			0.1	25.8	4.4	10.8	2.1
Other retained species	Porbeagle *Lamna nasus*	Zif Poisson p0 = 0.40–0.80	0.3	9.5–11.7	3.2–4.2		
			0.1	37.9–86.1	10.2–27.5		
ETP species	Oceanic whitetip shark *Carcharhinus longimanus*	Zif Poisson p0 = 0.75–0.90	0.3	11.2–47.4	3.9–18.3		
			0.1	45.5–68.0	18.1–43.9		
		Zif Poisson p0 = 0.99	0.3			~ 99.0	~ 99.0
			0.1				
	Silky shark *C. falciformis*	Zif Poisson p0 = 0.99	0.3			~ 99.0	18.7
			0.1			~ 99.0	~ 99.0
	Black-footed albatross *Phoebastria nigripes*	Zif Poisson p0 = 0.99	0.3	~ 99.0	~ 99.0		
			0.1	~ 99.0	~ 99.0		
	Whale shark *Rhincodon typus*	Zif Poisson p0 = 0.99	0.3			~ 99.0	95.1
			0.1			~ 99.0	~ 99.0
ETP species groups	Seabirds	Zif Poisson p0 = 0.95	0.3	~ 99.0	18.6		
			0.1	~ 99.0	~ 99.0		
	Turtles	Zif Poisson p0 = 0.90 – 0.95	0.3	71.6–99.0	9.3–95.1	95.1– ~ 99.0	8.5–87.2
			0.1	95.1–99.0	83.2–95.1	~ 99.0	85.9–99
	Marine mammals	Zif Poisson p0 = 0.99	0.3	92.1	87.2	87.2	51.3
			0.1	~ 99.0	~ 99.0	~ 99.0	~ 99.0

Note that stratification focuses review effort in strata within which catch of the monitored taxa occurs, whereas unstratified monitoring spans the WCPFC Convention Area (that is, that Area is treated as one stratum). Review effort in accordance with the optimum rates displayed is proportionally allocated across strata (Table 4)

p0 The proportion of zero-catch sets, derived from published sources (Online Resource 2) when not estimable from the dataset; *ETP* Endangered, threatened and protected species.

simulations, with exceptions for two taxa. These were in the level of review required to estimate turtle catch (longline fisheries with regional stratification, CV = 0.3, difference of 13%) and marine mammal catch (longline fisheries with regional stratification, CV = 0.3, difference of 12%; purse seine fisheries with and without regional stratification, difference of 12% and 19% respectively).

Discussion

Findings of our review emphasise that EM can provide a substantial amount of the critical fishery information that the focal RFMOs require to meet their management obligations. Technical capabilities of the monitoring method are well established, having been investigated in multiple studies and across jurisdictions, among a range of gear types. Management information needs that can be met in whole or in part by EM span target and non-target stock and environmental impacts, implementation of management measures, and conformance and compliance

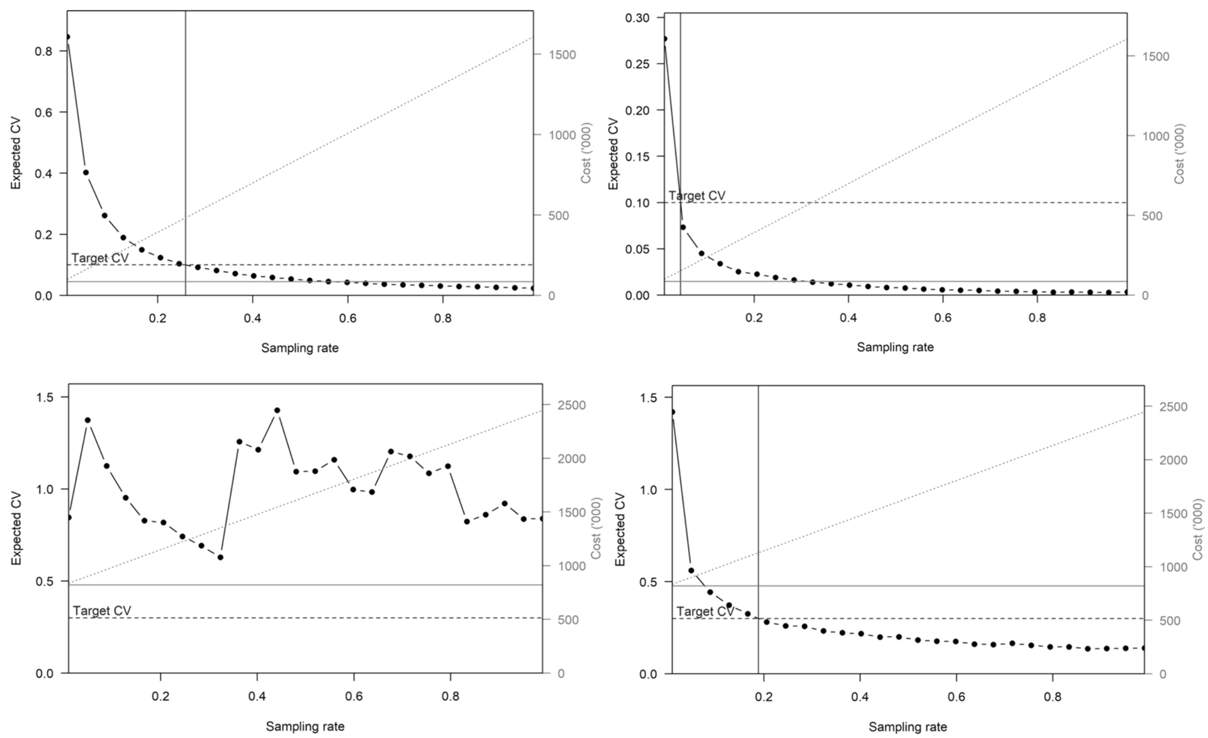

Fig. 2 Electronic monitoring review ("sampling") rates, by set, required to estimate catch composition in the Western and Central Pacific Ocean tuna fishery, with target and expected coefficients of variation (CV) without stratification (left) and with regional stratification applied (25°×30°; right). The upper and lower figures show review rates for yellowfin tuna (*Thunnus albacares*) in the longline fishery (CV = 0.1) and silky sharks (*Carcharhinus falciformis*) in the purse seine fishery (CV = 0.3), respectively. The solid vertical lines show the sampling rate at which the target CV is estimated to be met. The dashed horizontal lines show target CVs, the grey horizontal lines are the baseline cost (€) to assess the EM sampling frame, and the sloping dotted lines indicate increased review cost above the baseline, as the set sampling rate increases. Review effort in accordance with the optimum rates displayed is allocated proportionally across strata, e.g., as set out for yellowfin tuna in Table 4

with RFMO guidelines and requirements. Our review focused on five fishing methods used within six RFMOs. There are many similarities across fisheries and management bodies in the data required for management. Nonetheless, considering specific characteristics of any fishery and gear type is essential for monitoring programme design, and this remains appropriate when EM is considered as a fishery monitoring method in any new context.

EM can be implemented as a standalone monitoring and data collection method, or in combination with other methods (Gilman 2019, 2020; Ewell et al. 2020; Pierre et al. 2023). For example, augmenting EM data collection using portside sampling can address a range of biological data needs (e.g. collection of otoliths, or sex determination of retained catch). Even without complementary data collection methods in place, key deficiencies in the information base supporting fishery management by RFMOs can be addressed by EM implementation at scale. For example, as a standalone tool, EM-based data collection could significantly improve information on discarded and non-target catch, which is often incompletely and inaccurately recorded in logbooks (Brown et al. 2021; Peatman and Nicol 2023). Considering the most appropriate suite of tools for the collection of fishery information remains important for obtaining best value, both in terms of data acquired and economic outlay. As with any monitoring programme, robust design is also critical to ensure the quality of EM-derived data (Pierre et al. 2023). Further, as EM system capabilities continue to develop, the range of applications should be expected to increase.

Table 4 Examples of the allocation of longline EM review effort across geographic strata (25°×30°), derived using *EMoptim*. Monitoring allocation is the proportion of monitoring effort required per stratum (%), which would contribute to the overall proportion of sets sampled for review (as set out in Table 3).

Species/group	Strata																CV	n
	2	3	4	6	7	8	9	10	12	13	14	15	17	18	19	20		
Yellowfin tuna *Thunnus albacares* p0 = 0	0.009	0.03	0.05	0.44	5.70	7.08	3.77	0.61	10.8	44.6	19.3	5.73	0.72	0.74	0.42	0.12	0.3	170
																	0.1	752
Porbeagle *Lamna nasus* p0 = 0.80	12.6	0.53			0.25	13.4			0.25	28.2	7.62			37.2			0.3	718
																	0.1	4,700
Black-footed albatross *Phoebastria nigripes* p0 = 0.99							1.53	0.25	5.74	12.5	8.90	11.3	29.1	26.1	3.38	1.10	0.3	16,922
																	0.1	16,922

p0 The proportion of zero-catch sets, derived from published sources (Online Resource 2) when not estimable from the dataset. The number of sets that require review to meet target CVs for catch composition (n) is also shown for selected species. Fishing effort was reported in 15 of the 25 geographic strata created; *CV* Coefficient of variation

Investigation and adoption of EM has progressed at different rates among the focal RFMOs. EM-specific standards have been adopted by two of six RFMOs considered for this review (ICCAT 2023; IOTC 2023). Adoption by a third is anticipated in 2024 (WCPFC 2023). Commonalities in objectives, principles, functions and activities of RFMOs, fishing methods used across RFMOs considered here, analogous data requirements, and the extent to which different RFMOs involve the same operators (both in their member nations, and among large-scale fishery operators), should facilitate progression on EM standards.

Increasing the efficiency of EM review provides opportunities to decrease costs, and these require consideration from programme design through implementation and review. While the incorporation of automated elements into EM review has commenced, EM imagery and associated information is generally still subject to substantial manual review. Nonetheless, significant gains in review efficiency are still achievable by implementing automation to focus human reviewers' time on relevant sections of imagery, among the stream recorded. Labelling and saving data and metadata during EM review can provide longer term value by facilitating development of review processes that incorporate machine learning (Pierre 2018; NOAA 2020). Open access training data libraries are a developing resource for progressing automated EM review, noting that large amounts of training imagery are necessary for algorithm development (Kokher et al. 2022; https://www.fishnet.ai/). Automation remains a prolific field of research and development, with significant potential to support data extraction from EM information (Wing and Woodward 2024).

Analytic determination of the amount of EM review needed to provide fishery data meeting management and monitoring requirements provides another approach to managing monitoring costs. The simulation model we used enables fishery practitioners to estimate EM review rates needed to meet fishery monitoring objectives, using empirical or other information. The model, *EMoptim*, offers three unique features not previously explored by published models used to estimate monitoring coverage requirements (e.g. Babcock et al. 2003; Curtis and Carretta 2020). First, incorporating stratification in the model structure enables more efficient allocation of review

Table 5 Examples of optimised EM review rates estimated by the *EMoptim* simulation tool, as required to monitor the number of yellowfin tuna (*Thunnus albacares*) and two shark species (porbeagle, *Lamna nasus*, and oceanic whitetip shark, *Carcharhinus longimanus*) caught in longline and purse seine fisheries.

Species	Target CV	No stratification	Optimised stratification	
		% review	% review	Achieved CV
Longline				
Yellowfin p0 = 0	0.1	25.8	~1.0	0.05
Porbeagle p0 = 0.4	0.3	9.5	~2.0	0.22
% review required to meet target CVs		25.6	~2.0	
Purse seine				
Yellowfin p0 = 0	0.1	10.8	~1.1	0.09
Oceanic whitetip shark p0 = 0.99	0.3	~99	~99	1.07
% review required to meet target CVs		~99.0	~99.0	

Optimisation was conducted using publicly available catch information for 2019, made available by the Western and Central Pacific Fisheries Commission.

CV Coefficient of variation; *p0* The proportion of zero-catch sets, derived from published sources (see Online Resource 2) when not estimable from the dataset

effort. *EMoptim* allows for strata to either be defined by the user (e.g. vessel size, type, flag state, region), or defined optimally as an output from the model. The impacts of different strata on review required can also be explored. Second, *EMoptim* enables practitioners to explore options to optimise review requirements simultaneously for two or more monitoring objectives. These points of difference may increase review efficiency, thereby supporting reduced review costs. Third, the model incorporates a cost function, enabling users to tailor review levels for each monitoring objective to provide the best possible dataset for the budget available. *EMoptim*'s cost function is currently simplistic and could usefully be developed further. Nonetheless, its utility is shown in the case study conducted.

While EM was the focus of our work, *EMoptim* could also be used to structure other monitoring programmes (including those deploying human observers), with strata, fishery and cost information input the same way. Exploring coverage required in a hybrid monitoring programme (with human observers and EM) would also be feasible. Inputs to *EMoptim* can be based on real fisheries data, as in our case study. However, if this is unavailable or only available for a subset of a fleet or fishery of interest, expert opinion, risk assessments or any other information can be used as inputs. We note that user guidance recommends review rates estimated using *EMoptim* should be taken as indicative and considered pragmatically. For example, where required rates are estimated at around 1–2%, Pierre et al. (2022) recommended initiating review at closer to 5–10% subject to refinement over time as any assumptions can be tested and review efficacy verified. The veracity of outputs should also be considered in the context of the inputs used.

Review rates required to estimate catch of selected species in the WCPFC longline and purse seine were broadly aligned with findings of other practitioners working on different fisheries (Pierre et al. 2023). Required review rates increased as catch rates decreased, and higher levels of review were necessary to provide more precise catch estimates. ETP captures which are typically defined by zero-inflation and overdispersion required the highest review rates, akin to census-level review. For turtles however, geographic stratification enabled detection of an optimum, providing for consequently lower levels of review at higher CVs. Such results are common to fisheries monitoring studies because they reflect the fundamentals of sampling theory (Babcock et al. 2003; Haddon 2011). When the stratification is a poor fit with the occurrence of the event of interest, there is reduced potential for increasing sampling efficiency. However, different review rates, stratifications and precision requirements could be implemented for different taxa as part of an EM programme, potentially together with the use of different review speeds to optimise time efficiency and event detection by analysts.

Optimisation across multiple monitoring objectives provided the best options for targeting review rates among more commonly caught species. Rarely caught species invoked high review rates that limited optimisation options; review adequate to meet monitoring objectives for target species was ineffective in estimating ETP catch, while review levels required to estimate ETP catch would result in oversampling target species catch (exceeding specified precision requirements). Optimisation will be facilitated when species of interest share similar catch patterns and distributions, or when events of interest are correlated.

When using *EMoptim*, we compared figures depicting simulation decay curves and output tables for consistency. When a table output identifies an optimum level of sampling, the associated figure should also show the decay curve intercepting the target CV and remaining at or below that CV through subsequent runs as review levels continue to increase. If the figure does not, the table output has captured a false optimum. Increasing the number of model runs to assess convergence provides another check on the review sampling solution reached. In this study, increasing the number of simulations from 1,000 to 10,000 had little impact on required review rates in most cases. The exceptions of turtles and marine mammals were both rarely caught taxa with an indication of some subregional structure in catch data. Lastly, we note that *EMoptim* is based on infinite sampling theory (Pierre et al. 2022) and infinite and finite sampling can be expected to lead to divergent outputs at levels close to 100% (Horvitz and Thompson 1952). Other consequences of applying infinite sampling theory include overestimation of standard error for high per stratum-samples (Cochran 1977). In such cases, sampling may have limited value as an approach to review and census coverage may be warranted (e.g. as evident with the achieved CV reported for oceanic whitetip shark in Table 5). Review at the 100% level is recommended where sampling optima are found at or above ~ 75–80% (Pierre et al 2022). Exploring the effects of finite sampling theory as an alternative basis for this simulation model would be informative.

Our case study analysis was conducted on aggregated data by necessity. However, use of set-level data is preferable when possible, as this avoids the potential for aggregation bias (recognised in fisheries and other fields, e.g. Frawley et al. (2022)). That is, set-by-set data provide significantly more information about the statistical characteristics of individual catch events, or other events of interest e.g. monitoring implementation of management measures. When assumptions are required about the statistical characteristics of events of interest, sensitivity testing to investigate different assumptions by comparing outputs generated using different input distributions appears worthwhile. *EMoptim* can accommodate the binomial, negative binomial, normal and Poisson distributions (Pierre et al. 2022) and sensitivity testing could be automated in future development of the model. Analogously, modelling practitioners often consider alternative distributions when fitting models of rare-event bycatch (Brodziak and Walsh 2013; Good et al. 2022).

EM review enables more agile scaling of review and finer-scale management of cost-per-datum than other onboard fishery monitoring methods. For example, entire sets or parts of sets may be reviewed, among some or all vessels (as the logistical constraints of moving human observers between vessels do not apply). Further, sampling for review can be managed adaptively once EM imagery and associated information is in-hand if review budgets change after information is collected at sea. The initial screening of EM imagery and associated information to determine the sampling frame (e.g. number of trips, sets/hauls) comprises a baseline minimum cost. From there, costs increase in relation to the complexity of review tasks. In this paper, we have used the linear cost function as specified in *EMoptim*. However, how review costs scale is expected to vary among programmes (Pierre et al. 2022) and this function could usefully be developed further.

Evolution of any monitoring programme is expected based on lessons learned and the acquisition of knowledge over time (e.g. Briand et al. 2023b). Analogous to any power analysis approach, the inputs to *EMoptim* determine the outputs, and users may wish to vary information inputs to understand where sensitivities lie. Our case study considered only one year of fishery information. Considering additional years individually, or an average of several years, will provide additional insights into the optimal deployment of future monitoring effort. Iterative application of *EMoptim* is appropriate to refine review rates implemented as fishery knowledge grows and review budgets change. Iterations could include changing monitoring objectives including precision requirements, and updating strata, species distribution and cost information in the model. Outside the strata with higher review rates identified using *EMoptim*, we consider that maintaining a baseline of random review (e.g. 5–10% of fishing effort) is prudent to enable detection of significant changes in the fishery and previously unidentified fishery issues. For example, operational changes could arise due to new vessels and captains with different fishing approaches entering a fishery (Squires et al. 2021; Roberson and Wilcox 2022), catch patterns may be affected by environmental changes over time (Bell et al. 2021), and bycatch issues may be undetected (Williams et al. 2021).

Data limitations are a well-known and multidimensional constraint on effective fishery management (Cope et al. 2023). EM has significant potential to collect fishery data at scale to meet management needs for information. Information requirements that can be met by EM are shared widely among fishery management bodies including RFMOs. Furthermore, EM service providers operate internationally, across geographic and jurisdictional boundaries. The scalability and adaptability of EM, ability to structure review to maximise data yield within resources available, likelihood of decreasing review costs with increasing automation, and adoption underway in RFMOs, signal the usefulness and practicality of this monitoring method for providing the data required for fisheries management.

Acknowledgements Support for this research was provided by The Pew Charitable Trusts. The views expressed herein are those of the authors and contributors, and do not necessarily reflect the views of The Pew Charitable Trusts. The authors wish to thank J. Freese and M. Johnston (AI.Fish) for providing details of their work on computer vision and machine learning, and G. Legorburu (Digital Observer Services, DOS) for sharing review cost information. The authors also thank the reviewers of the draft manuscript, for their constructive and helpful feedback.

Funding This work was funded by The Pew Charitable Trusts. A. Snedeker, M. Wealti, A. Cozza and K. Carovano are, or have been, employees of Saltwater Inc., a provider of fisheries monitoring services including electronic monitoring. The authors have no other competing interests to declare.

Data availability The input data and model that support the findings of the original research presented in this paper are available at https://github.com/pewtrusts/EMOptim as Version 0.1, dated 2022-06-03.

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