How much is enough?
Review optimization methods to deliver best value from electronic monitoring of commercial fisheries

Pew Project: 2021-IF-02

Final report: 30 October 2022

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Glossary

ADP	Annual Deployment Plan (set out plans for fishery monitoring)
AFG	Alaska Fixed Gear fishery
AGAC	Association of Large Tuna Freezers (an industry body)
AI	Artificial Intelligence
AR	Activity recognition software
BFT	Atlantic bluefin tuna (*Thunnus thynnus*)
CCSBT	Commission for the Conservation of Southern Bluefin Tuna
CGP	Code of Good Practice
CV	Coefficient of Variation
dFAD	Drifting Fish Aggregating Device
DOS	Digital Observer Services (an EM review service provider)
EEZ	Exclusive Economic Zone
EFL	Electronic Fishing Log
EM	Electronic Monitoring
ERandEM-IWG	WCPFC Intersessional Working Group on Electronic Monitoring and Reporting
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HMS	Highly Migratory Species
IATTC	Inter-American Tropical Tuna Commission
IBQ	Individual Bluefin Quota Program
ICCAT	International Commission for the Conservation of Atlantic Tunas
IFOP	Fisheries Development Institute (Chile)
IOTC	Indian Ocean Tuna Commission
KPI	Key Performance Indicator
MCS	Monitoring, Control and Surveillance
MSY	Maximum Sustainable Yield
NOAA	National Oceanic and Atmospheric Administration (USA)
NPFC	North Pacific Fisheries Commission
OLE	Office of Law Enforcement (NOAA Fisheries)

OPAGAC	Organization of Associated Producers of Large Tuna Freezers (an industry body)
PFAs	Principles, functions and actions (specified in RFMO convention texts)
RFMO	Regional Fisheries Management Organization
SERNAPESCA	National Fisheries and Aquaculture Service (Chile)
SUBPESCA	Undersecretariat for Fisheries and Aquaculture (Chile)
TNC	The Nature Conservancy
UNCLOS	United Nations Convention on the Law of the Sea
VMP	Vessel Monitoring Plan
VMS	Vessel Monitoring System
WCPFC	Western and Central Pacific Fisheries Commission
WGEMS	IOTC Ad-hoc Working Group on the Development of Electronic Monitoring Programme Standards

Executive summary

Electronic monitoring (EM) using on-vessel cameras can effectively collect a broad range of data to support fisheries management. Key advantages of EM include its flexibility, scalability, verification capability, and the avoidance of health, safety and logistical challenges that human observer deployments can involve. EM can also offer cost efficiencies relative to other monitoring methods. In this report, we consider the use of EM to meet a range of fishery monitoring objectives, present case studies from EM programs in real-world fisheries, and evaluate the level of review needed to extract EM-collected information to support management objectives. Our goal is to show how the efficiency of EM review can be maximized to support management, within budgetary requirements. We focus on Regional Fisheries Management Organizations (RFMOs) managing tuna fisheries, and also set out the broader application of findings across other management entities and fishing methods.

RFMOs require extensive datasets to meet their management objectives. Supporting such data requirements, EM has the capacity to collect comprehensive data on fishery catch (retained and discarded), catch handling, fishing gear, and operational characteristics of fisheries (e.g. date, time and location of sets and hauls). Opportunistic or partial data collection supported by EM includes discarded gear and other marine pollution events. Most RFMOs have taken significant steps towards progressing EM, while adoption is at different stages.

Case studies spanning the Pacific, Indian, and Atlantic Oceans show the efficacy of EM in collecting fisheries data in the real world. Monitoring objectives to be met by EM and approaches to review of EM imagery and associated information vary among these and other EM programs. Using EM to capture 100% of fishing activity is recognized as best practice, while EM review may be undertaken as a census (all imagery reviewed) or with samples of imagery collected. Auditing EM-derived data against other sources, typically logbook information, offers additional options for review.

EM review efficiency, in terms of time and cost, can be increased by considering review requirements during the EM program design (e.g. development of EM-appropriate data definitions) and on-vessel data capture phases (e.g. lens cleaning to improve image clarity). Efficiency of the review phase itself can also be increased, for example by reviewing at speeds faster than real time and supporting review with computer vision tools.

EM review costs as a proportion of program costs vary from 2.5 – 60% (noting that what is incorporated in review process costs differs among programs). Review costs do not scale linearly with review rates, and service providers emphasize that collaboration among themselves, clients and vessel operators is important for maximizing review cost efficiencies.

Identifying the minimum level of review necessary to provide the data required for management is also recommended, to maximize cost efficiency. To investigate minimum EM review rates, we prototyped a simulation tool based in R, *EMoptim*, that uses stratified random sampling to address one or more fishery monitoring objectives. *EMoptim* also incorporates a cost function, developed based on pricing estimates for analysis of EM imagery and associated information. Using *EMoptim*, fishery-specific information can be used to fine-tune review rates, within specified limits including cost, and across a suite of fishery monitoring objectives.

We applied *EMoptim* using publicly available information from longline and purse seine fisheries operating in the western and central Pacific Ocean, and the scientific literature. Results confirmed that minimum effective review rates increase as catch frequency decreases, and as the required coefficient of variation decreases. Stratified sampling approaches were effective in reducing the level of review required for more commonly caught taxa. However, stratification

had little effect on review rates for rare capture events that were geographically widespread. As a result, significantly higher levels of EM review are required to estimate numbers of rare events effectively.

EM programs often include multiple monitoring objectives, and we used *EMoptim to* explore optimized rates of EM review required to estimate target and bycatch catch, to achieve specified coefficients of variation. Outputs highlight that optimizing review regimes for different monitoring objectives is most effective among more commonly caught species. The required EM review rate increases dramatically when rarely caught species are considered, such that "optimizing" at a lower review rate is not effective for monitoring these taxa. Outside strata with higher review rates set using *EMoptim*, we recommend that a minimum baseline level of random review should be maintained to enable detection of fishery changes.

EM has great potential to collect data cost-effectively at scale to support fisheries management. Information requirements that can be met by EM are broadly consistent across RFMOs and other management bodies. Furthermore, service providers operate across jurisdictional boundaries. Therefore, there is significant potential and opportunity to accelerate the development and adoption of methods to optimize EM review, both in the immediate future and longer term.

Contents

1. Introduction

Electronic monitoring to support fisheries management

Monitoring commercial fisheries is essential for their effective management. Human observers have been a mainstay of on-vessel fisheries monitoring, used alongside methods such as position monitoring through satellites, at-sea patrols and aerial surveillance[28,44]. While monitoring by human observers can work well, challenges such as occupational safety, representativeness of data collected, and cost, have catalyzed the development of complementary monitoring methods.

Electronic monitoring (EM) using on-vessel cameras is a fishery monitoring tool that has developed since the late 1990s. In that time, EM has been trialed in more than 100 fisheries and operationalized in some, to address a range of fishery monitoring objectives[17,71,89]. In addition to the cameras that record fishing activity, typical functions and components of EM systems include GPS tracking, a control unit that monitors the operation of the system and records data, satellite reporting of system status, and sensors that indicate fishing activity (Figure 1).

From a fishery management perspective, key benefits of EM compared to other monitoring tools include[17,25,49,84,89]:

- the capability to collect high quality, comprehensive and detailed information on fishing activities
- flexibility of the monitoring method which enables scaling across fleets and in accordance with risk and evolving management priorities,
- ability to support incentive-based management (including fishery access and market-based incentives),
- verification capability; and,
- relative cost efficiency.

Significant broader benefits include the avoidance of health, safety and logistical challenges that human observer deployments can involve[25,49,51].

While the benefits of EM are well-recognized, there are perceived barriers impeding its adoption. Barriers are largely human-focused rather than technological, e.g. culture change required to accept working in a monitored environment, and the need to encompass a new monitoring tool in existing regulatory and management frameworks (e.g. where regulations specify that human observers must be used to meet at-sea monitoring requirements)[49,89]. Another key barrier is cost[50]. The perception of cost impacts is heightened by costs being immediately calculable and incurred in the short-term (and on an ongoing basis). In contrast, benefits may be variable and accrue in a longer timeframe[49,51]. Further, EM programs generally cost more per unit of monitoring effort and information in their initial stages (pilot or trial programs), becoming cheaper when scaled up and implemented as operational programs[49,68]. If the operational stage is never reached, the cost to benefit ratio of EM cannot be optimized, recognized or realistically compared with other monitoring tools.

The costs of EM can be partitioned into fixed and variable components (Figure 2). Fixed costs include the EM system hardware, installation onboard vessels and some maintenance elements. Variable costs can include administration of the EM program, software, and review of the EM imagery and associated information. Data storage may be a fixed or variable cost. Fixed and variable costs and the ratio of these cost types vary with program, vessel and fishery-specific factors, e.g. monitoring objectives, fishery scale, geographic location, level of engagement and support from industry operators and management bodies, and program standards (which may include specifying imagery review rates)[84]. Beyond monetized costs, so-called "soft costs" are the on-vessel changes in operational practice that can support or improve the efficacy of EM (e.g. catch handling protocols)[65].

Information needs of Regional Fisheries Management Organizations

Among fishery management entities, Regional Fisheries Management Organizations (RFMOs) are multilateral bodies that hold critical fishery management responsibilities across most of the world's oceans. RFMOs comprise countries (represented by their governments) which may be termed members, parties and contracting parties. Countries that are not full RFMO members may hold other status, e.g. as cooperating non-members or cooperating bodies. The management roles of RFMOs are typically defined in relation to fished species within a particular geographic area. RFMOs are focused on sustainable management of focal species, which also involves managing the impacts of fishing activity on non-target species and the marine environment (Appendix 1).

To support fishery management, RFMOs set requirements for information collection and monitoring, control and surveillance (MCS) within their areas of competence. Human observers are a common component of on-vessel MCS and minimum levels of observer coverage are often specified (e.g. by fishing day, trips, vessels, or hooks). However, these minima do not necessarily reflect data requirements for robust fisheries management (e.g. to effectively characterize catch composition[4,7,42,90]). Furthermore, coverage achieved by some RFMO members falls below levels required on an ongoing basis[39,70,95].

EM for RFMOs and this report

The emergence of EM as a fishery monitoring tool has led some RFMOs, and their members, to evaluate the possibilities for EM-based data collection. This has included considering data requirements that may be met using EM, and standards for data collection. Members of RFMOs managing tuna fisheries have been particularly active in this regard[19,55,73,76,93]. Furthermore, opportunities for accelerating EM adoption have been identified[49,50,51]. However, foundations for structuring EM review have seldom been investigated analytically, including trade-offs of data quantity, quality and cost. This is despite review processes being highlighted repeatedly as a vital consideration for EM program design and cost management[17,65,84].

In this report, we focus on the review of EM imagery and associated data that can be used to support RFMO fishery management objectives. We:

- identify the RFMO fishery management objectives that can be supported by information collected using EM
- present case studies of EM implementation, to show how fishery management and monitoring objectives are being met using EM in the real world
- demonstrate a prototype simulation tool, *EMoptim*, to explore EM imagery review rates that provide information supporting fishery management, and associated costs; and,
- illustrate how monitoring costs incurred at the review stage of EM programs can be reduced, while optimizing the suite of data collected.

We focus on RFMOs managing tuna fisheries, while reflecting broader application of findings across other management entities and fishing methods.

We consider EM review as the process of extracting and processing data collected by EM systems into a form ready for consideration by end-users. We do not consider broader review-related elements of an EM program (e.g. training, data management, data storage).

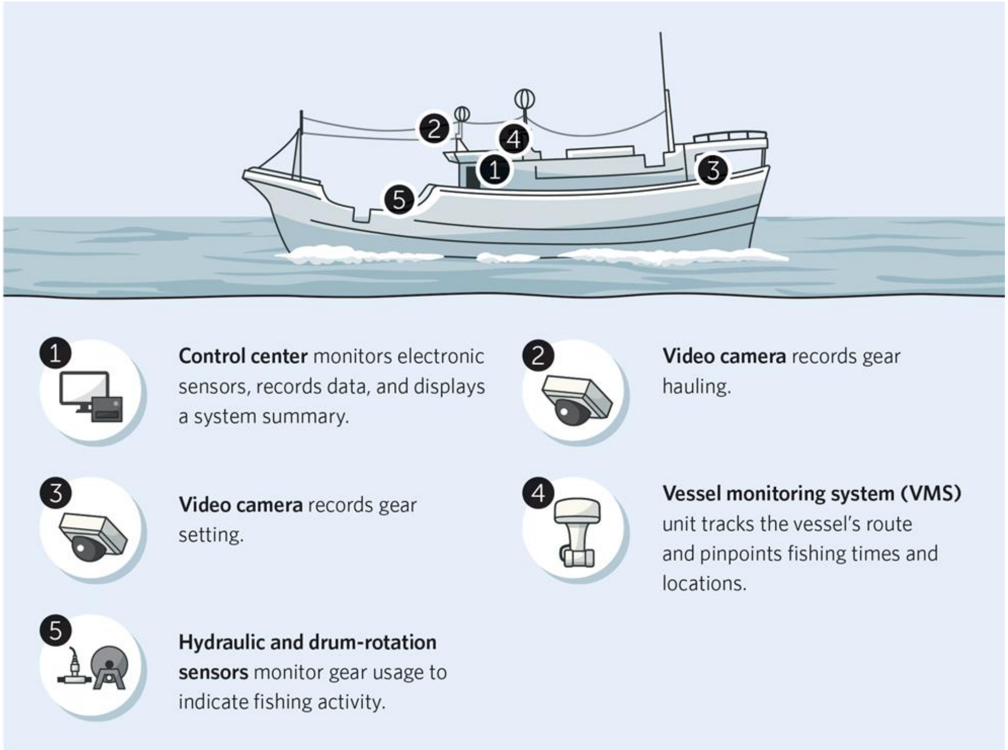

Figure 1. Generalized schematic showing electronic monitoring system components on a fishing vessel.

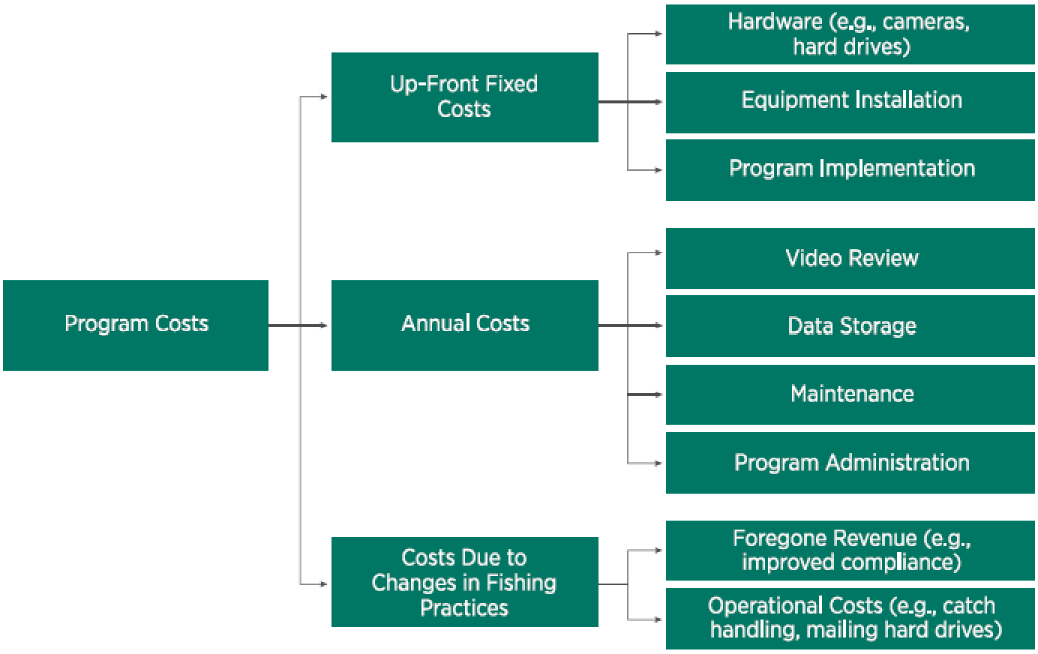

Figure 2. Overview of EM program costs. Source: Michelin et al. 2018.

2. RFMO fishery information requirements

RFMO information requirements are defined by the objectives or purposes of these management bodies. Key themes among RFMO objectives are sustainable use and conservation in the long-term. Both fished species and non-target species are in-scope for management. Among those considered in detail here, one RFMO explicitly includes ecosystem protection in its overarching objective (Appendix 1).

Principles, functions and actions (PFAs) specified in RFMO convention texts provide insights on how the objective or purpose of RFMOs is defined and may be addressed (i.e., what conservation or sustainable use means in practice). PFAs can be grouped into three categories: biological, environmental and operational (Figure 3). Key biological PFAs include 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. Taking account of biological uncertainties may also be highlighted (Appendix 1). 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. Some conventions also include a specific requirement for a precautionary approach (Appendix 1). While each invokes specific data needs, there is significant overlap such that some data support multiple PFAs.

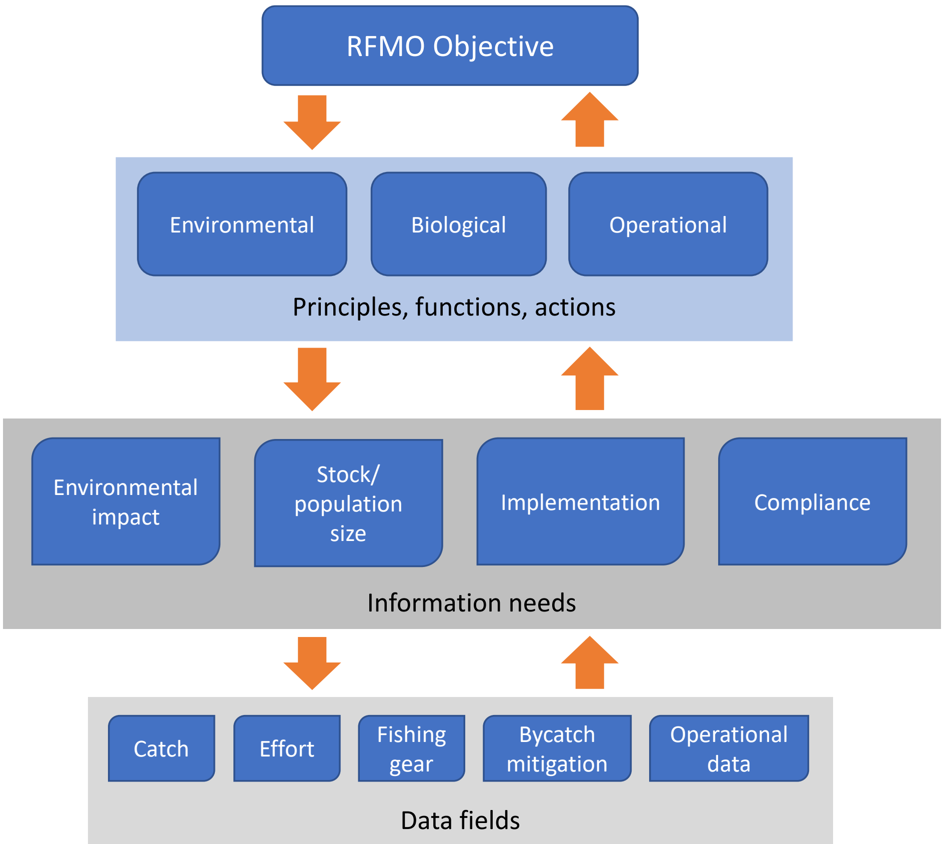

Figure 3. Schematic diagram of linkages between fishery management objectives, principles, functions and actions, and information and data needs. The two-way flow indicates that each layer informs the other on an ongoing basis.

A significant amount of the data needed to support RFMO management can, and must, be captured onboard fishing vessels during fishing operations. As an on-vessel monitoring tool, the data that EM can collect in support of fisheries management traverses all PFAs. For example, fishing catch and effort data are vital for assessing the fishery impacts on target stocks and non-target species, supporting the development of management measures, evaluating compliance with management measures, and assessing the impacts of fishing on the environment. In recent years, some RFMOs (and their members) have investigated whether their data requirements can be met using EM. Such evaluations have typically included a comparison of EM capabilities with data recorded by fisheries observers[55,93].

An overview of data requirements that can be effectively met using EM is set out below, for five fishing methods used in the RFMOs considered in Appendix 1. However, given ongoing technological and practical developments in EM systems and applications, considering how EM can meet management and monitoring objectives is recommended as any monitoring program is conceived. What has been achieved to date provides a baseline but does not limit future possibilities.

Catch and discard information

More than 75 EM projects or programs have been conducted worldwide with the objective of monitoring catch. Focal catch components have included target species, fish bycatch, and bycatch of endangered, threatened and protected (ETP) species and other megafauna. Data recorded have included retained and discarded catch species, size, and life status[17,71,89].

Information capture using EM is most straightforward when catch items come aboard serially (e.g. piece by piece on a longline) or in smaller clusters (e.g. gillnets), compared to when catch is landed on deck or into storage holds in bulk (e.g. purse seine and trawl methods). For all gears, catch handling protocols may facilitate enumeration, identification, size and life status assessments of catch items. For bulk fishing gears, catch handling protocols are essential to support quantitative data capture from larger catches using EM[46].

Discarded catch items may be landed on deck (for enumeration and identification with the rest of the catch prior to discarding) or removed from gear without being brought aboard. For catch discarded after being brought aboard, EM and landed catch reconciliations (e.g. conducted by dockside monitors) may be viable monitoring methods[46]. When catch items are removed, released in the water or dropped from gear before being brought aboard, EM-supported enumeration is achievable (with appropriate camera placement) though the view may not enable identification to the same level of granularity as when catch items are brought aboard (e.g. to family or genus level, rather than species). Similarly, determining life status and size is less achievable when catch items are removed, released or dropped directly into the water, and not brought aboard vessels[31].

Catch and discard data inform RFMO information needs relating to stock/population status of species caught, implementation of fishing operations, and compliance with management requirements (Figure 3).

Fishing effort

Among more than 100 trial and operational EM programs worldwide, monitoring fishing effort has been the most common objective. The efficacy of monitoring fishing effort is demonstrated across the longline, purse seine, trawl, gillnet and pot/trap methods[17,89]. 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 unassociated schools.

Fishing effort data are relevant across the four categories of RFMO information needs (Figure 3).

Fishing gear

EM can be effective in capturing imagery of some fishing gear characteristics, e.g., presence of floats and weights on longlines, presence of shark lines, and characteristics of floating objects used in purse seine fishing[19,29].

The presence of some bycatch mitigation devices is also discernible from EM imagery[20,71]. For example, sorting grids used to reduce ETP bycatch in trawl fisheries can be detected as gear is deployed. Wire traces (associated with increased shark bycatch, and prohibited in some fisheries), and tori lines (also known as streamer lines) used to reduce seabird captures in longline and trawl fisheries are detectable in EM imagery (though tori line dimensions are not currently well captured). Pingers deployed on gillnets to reduce cetacean impacts are detectable. Seal exclusion devices and some operational practices (e.g. backdowns to release marine mammals from purse seines) to reduce ETP captures are also expected to be detectable[1,73].

Fishing gear characterization is relevant to RFMO information needs including catch per unit effort, stock/population status of species caught, implementation of fishing operations, and compliance with management requirements (Figure 3). Broader environmental impacts of fishing gear may include accounting for lost gear (e.g. reconciling gear hauled against gear set).

Bycatch handling

Handling practices used to remove bycatch from the gear and release it into the water affect post-release survival[96]. Some fisheries management entities including RFMOs have adopted mandatory provisions for carrying release equipment (e.g. dehookers and line-cutters[16]) and best practice handling guidelines to promote post-release survival of live-captured animals (e.g. supplements to the Western and Central Pacific Fisheries Commission's (WCPFC) Conservation and Management Measure (CMM) 2018-03 for the safe handling and release of seabirds, and CMM 2019-04 for some sharks, mantas and mobulids. EM can be used to collect information on bycatch handling, as well as to identify opportunities to improve handling (e.g. developing guidance materials and training[17]). This information is relevant to RFMO fishery impacts on populations of species caught, implementation of fishing operations, and compliance with management requirements (Figure 3).

Operational data

A range of general operational data characterizing 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[73,89,93].

Operational fishery data is critical for addressing all categories of RFMO information needs (Figure 3). While not in-scope for this report, the potential for EM to contribute to monitoring of labor and human rights onboard fishing vessels has also been identified[25,49].

Table 1. Data required for fisheries management, that can be obtained in whole (✓) or in part (*) using electronic monitoring systems in commercial fisheries. Catch fate includes whether catch is released alive or dead, and injury status. In general, less detailed information is expected to be obtained for discarded catch items because at least some animals are released before being landed on the vessel. For example, animals may be identified to genus level rather than species level, if released while still in the water and not subject to detailed examination. Life status may also be difficult to estimate effectively for catch released without being brought aboard. The presence of line weights can be detected by EM, while the weight of weights may not be. FAD = Fish Aggregating Device, used in purse seine fisheries.

RFMO principles, functions or actions		**Catch and discard information**					**Gear and operational information**				
		Catch species / stock	**Landed catch size**	**Discarded catch species / stock**	**Discarded catch size**	**Discarded catch life status**	**Hooks set, hauled**	**Floats**	**Set / haul time / location**	**FAD use, type**	**Gear not retrieved; discarded**
Biological	**Target species**	✓	✓	*	*	*	✓	✓	✓	✓	*
	Non-target species	✓	✓	*	*	*	✓	✓	✓	✓	*
Environmental	**Environmental impacts**									✓	*
Operational	**Implementation and compliance**	✓	✓	*	*	*	✓	✓	✓	✓	*
Objectives		**Bycatch mitigation usage information**									**General**
		Tori lines	**Line weights**	**Hook-shielding devices**	**Dyed bait**	**Bird curtain**	**Fish waste discharge**	**Wire traces**	**Dehooker / linecutter use**	**Bycatch / unwanted catch handling**	**Marine pollution**
Biological	**Target species**		*							✓	*
	Non-target species	✓	*	✓	✓	✓	✓	✓	✓	✓	*
Environmental	**Environmental impacts**								*		*
Operational	**Implementation and compliance**	✓	*	✓	✓	✓	✓	✓	✓	✓	*

3. EM adoption by RFMOs

RFMOs are at different stages in the progression of EM. For example, the Inter-American Tropical Tuna Commission (IATTC) held its first workshop on the implementation of electronic monitoring in 2021. This followed the 2019 Commission resolution (C-19-08) that the IATTC Scientific Staff would prepare a draft proposal for the development of minimum standards for EM implementation on longline vessels for consideration by the Scientific Advisory Committee in 2020. Subsequent work undertaken has included the development of agreed definitions for EM-related terminology, a proposed framework for EM implementation for longline and purse seine vessels (including draft minimum standards, data collection and reporting requirements, institutional structure supporting an EM program, and data management, among other content)[35], and a workplan for the introduction of EM[34]. The workplan identified 1 January 2025 as the date at which the Electronic Monitoring System should be operative on longline and purse seine tuna fishing vessels, subject to Commission agreement.

The International Commission for the Conservation of Atlantic Tunas (ICCAT) recommended the adoption of minimum standards for purse seine vessels on which EM was voluntarily implemented in 2016 and 2017[80]. In 2021, the ICCAT Subgroup on Electronic Monitoring Systems was established to consider EM, with a focus on billfish and longline fishing, noting that other methods would require attention in due course (e.g. gillnet). Group recommendations included that focal species should be expanded, to include sharks, albacore tuna, and other species. The first meeting of the ICCAT Working Group on Electronic Monitoring Systems (WG-EMS) took place in early 2022[94].

The Indian Ocean Tuna Commission (IOTC) adopted preliminary minimum standards in 2017 for purse seiners voluntarily using EM to augment observer coverage. The development of minimum standards for all IOTC fisheries was recommended in 2018 by the Scientific Committee. In 2020, EM data capture capabilities were documented for purse seine, longline, gillnet and pole and line vessels greater than 24 m in overall length, and vessels under that length using the same or other methods when operating in the high seas [55]. Areas of consideration for EM program and data standards were also summarized and minimum requirements and the definitions of key terms stated. The IOTC Ad-hoc Working Group on the Development of Electronic Monitoring Programme Standards (WGEMS) held its first meeting in late 2021[38]. The group adopted a workplan which identified the facilitation of pilot EM projects and development of minimum data standards as the highest priority work areas for 2022/23.

WCPFC has held five meetings of its intersessional working group on electronic reporting and monitoring to date (ERandEM-IWG). Proceedings of the 2020 meeting included consideration of draft minimum standards for that RFMO's electronic monitoring program[22]. These draft standards include program standards (e.g. the independence and impartiality of EM programs), 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) and data analysis standards (e.g. analyst training, data entry checks, sub-sampling considerations for audit-based review). WCPFC has also drafted a consultative proposal for a future CMM for a regional EM program[23]. At its 2022 meeting, the ERandEM-IWG updated its workplan including the consideration of integrating EM with other elements of the management framework (e.g. its regional observer program) and progressing the drafting of the EM CMM[24].

Members of the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) have contributed papers on EM to meetings of this RFMO and its subsidiary bodies over time, and the 2021 meeting of the Compliance Committee discussed the monitoring method. That meeting recommended that EM systems be the main item of discussion for the Technical Compliance Working Group in 2022[12]. Information sharing on electronic monitoring is also a workplan (and agenda) item for CCSBT's Ecologically Related Species Working Group.

The North Pacific Fisheries Commission (NPFC) is in the preliminary stages of considering the potential for EM as a monitoring tool in the fisheries in its area of competence[77]. At its 2021 meeting, the NPFC Scientific Committee tasked subsidiary bodies with reporting to its next meeting on the potential use of EM (and other data collection methods) to address data needs and gaps for NPFC priority species and non-target species[78].

4. Case studies

The following five case studies exemplify the diverse application of EM in real-world fisheries to date. Case studies demonstrate EM adoption by fishing industry and government bodies operating within Exclusive Economic Zones, in areas beyond national jurisdictions, and within RFMO areas of competence. Monitoring objectives include assessing conformance with good practice measures, monitoring catch limits of quota-managed species and broader characterization of catch composition, and detecting incidental bycatch and discarding. Case studies were compiled using published sources and additional information provided by program participants listed below.

4.1. EM adoption by industry to demonstrate responsible fishing practices: Association of Large Tuna Freezers (AGAC) – Pacific, Atlantic and Indian Oceans

Information contributors and reference sources: M.A. Herrera, J. Morón, I. Moniz, J. López (OPAGAC-AGAC), G. Legorburu (Digital Observer Services (DOS)), I. Canive (Datafish Technology Solutions), J. Ruiz (AZTI); 43, 52, 53, 72, 74, 75, 76

Purpose of EM

AGAC is an industry body that represents the interests of vessels registered in nine countries (Spain, Belize, Curacao, Ecuador, El Salvador, Guatemala, Panama, Tanzania and the Seychelles). The AGAC fleet comprises 48 purse seiners and 10 support vessels.

AGAC adopted a Code of Good Practice (CGP) in 2012. The main objective of the CGP[68] is to reduce the environmental impact of the AGAC fleet's fishing activities. Vessel crew are responsible for implementing the Code. EM is one of the methods used to monitor conformance with the Code, primarily:

- safe release of sensitive bycatch species (e.g. sharks, turtles and marine mammals); and,
- the use of non-entangling FADs.

EM is also used in some cases to monitor retained non-target catch and collect other scientific monitoring information.

Context for EM implementation

The AGAC fleet operates in the Pacific, Atlantic and Indian Oceans, in the high seas and various EEZs. The fleet targets tropical tunas, mostly in association with drifting Fish Aggregating Devices (dFADs). Full documentation of AGAC purse seine vessel activities has been compulsory since 2015. This was extended to support vessels from 2017, and is achieved through a combination of human observers and/or EM. At present, EM systems are installed on 28 purse seiners and all support vessels.

The EM program

The first EM pilot program was conducted in the AGAC fleet in 2011 – 2012. The pilot program involved comparing data collection from EM and by human observers on three purse seine vessels to investigate the efficacy of EM. Additional trials followed using EM systems from a range of EM service providers. This work underpinned the development of the minimum EM standards for tropical tuna purse seine fisheries, published by the International Seafood Sustainability Foundation in 2014.

EM-based verification of AGAC's CGP was first investigated on support vessels in 2015. Two years later and coincident with the adoption of preliminary EM standards by ICCAT and IOTC, science provider AZTI incorporated data obtained through EM in its verification of the AGAC fleet's conformance with the CGP.

The AGAC program is designed to capture 100% of fishing trips. Therefore, EM systems record every day for 24 h/day. Recording frame rates can be configured based on sensor and/or GPS data. Support vessels carry 2 – 3 cameras each, to document FAD-related activity. Purse seiners are fitted with 4 – 8 cameras per vessel, to enable monitoring of all fishing-related activities. Crew routinely clean camera covers, but otherwise have no need to engage with the EM system at sea. Hard drives are used to capture EM imagery and associated information. Vessel captains are responsible for shipping drives to the EM review service provider.

AGAC has adopted EM as a core component of its monitoring approach for several reasons:

- Economic: monitoring costs were generally lower for EM than other methods, and EM has also proven more time efficient.
- Logistical: EM circumvents the logistical difficulties associated with boarding observers, which would otherwise be necessary to meet flag state and some coastal state requirements.
- Comprehensive data collection: EM can be used to monitor all activities on the vessel, including when these occur concurrently in different locations (e.g., brailing on the upper deck and loading of catch on the lower deck), and in areas unsafe for people. Such activities would not be possible for a human observer, therefore EM data are more complete for some tasks.
- Information validation: EM enables the objective validation of divergent reports of vessel activities, e.g., when observer and skipper reports have differed, EM information has been used for conflict resolution.

Other benefits of EM adoption recognized by AGAC include high acceptance overall among vessel owners and most crew (noting that some vessel owners retain a preference for human observers, due to crew preference for not being monitored by cameras), independence of monitoring, tamper resistance of systems, the ability to review imagery multiple times as required, and that high levels of monitoring can still be achieved when the health and safety of human observers may be compromised (including where there are piracy threats and during the COVID-19 pandemic). Space available onboard vessels is also not a limitation for EM, whereas this is an important constraint for human observer deployments on support vessels.

Challenges for EM operation were technological and operational, including equipment failure and maintenance needs in remote locations, inability to collect biological samples, difficulties with some species identifications, and the current time delay between the collection and extraction of EM information (e.g. due to hard drives being shipped on return to port after lengthy trips). In the broader operational environment, AGAC considers that the adoption of EM minimum standards by management bodies (e.g. RFMOs) will foster acceptance and implementation of EM among flag and coastal states.

A census approach is taken to EM review for monitoring conformance with CGP bycatch handling and FAD-related requirements. Algorithms in the analytical software are used to identify different vessel activities based on characteristics such as vessel speed and course, and georeferencing is in place with position, date and time.

Data routinely captured during EM review include:

- For sensitive bycatch species: species identification (and sex, where possible), size, origin (encircled, entangled by purse seine net/on FAD), location of release (net, brailed to upper deck/lower deck), handling (including the tools used, e.g. hopper, stretcher, etc.), time spent from capture to release, and condition at release (to estimate fate).
- For FADs: identification of the device (using the tracking buoy); materials used on the surface and for the underwater structure of FADs, both for new deployments and visits/encounters of dFADs already in the water; any modifications made to FAD structure.

EM review service providers have put standards in place to reduce bias and improve consistency among EM analysts (termed dry observers).

Key Performance Indicators (KPIs) used to monitor the time it takes to extract EM data collected include:

- Time between the end of the last trip recorded and receipt of the hard drive by the review company (generally less than 2 months, but a broad range of 15 days to 15 months depending on landing location)
- Time spent between receipt of the hard drive and completion of data extraction from EM onto data forms (35 days on average, ranging from 7 – 75 days)
- Observer working hours, calculated as an Analysis Ratio of Sea Days/Office Days. Office days are considered as the sum of hours dedicated to one fishing trip divided by the office day of eight hours. (Ratios show that it takes 4 – 8 times more working hours for a human observer at sea to complete purse seine trip records compared to EM analysis by a dry observer. For support vessels, this figure is 10 – 15 times).

Program development

The performance of the EM program is reviewed annually by AZTI and the EM service providers. This review includes an assessment of any changes that may be needed to improve monitoring or to address new requirements. For example, the CGP is updated regularly to incorporate new provisions or amend the existing ones based on the results of research activities. In addition, UNE 195007 was adopted in Spain in 2021, requiring some updates for AGAC vessels. (UNE 195007:2021 is the first European standard developed to harmonize requirements for the use of on-board cameras among industry and data users[88]). The development of AI and machine learning is expected to support improvement in EM analysis KPIs in future.

Overall, AGAC reports that for monitoring fleet compliance with the CGP, data collected using EM are as good or better than data collected by human observers.

4.2. EM to verify fisher reported catch and discarding of a quota-limited species: USA

Information contributors and reference sources: B. McHale, I. Miller (Office of Sustainable Fisheries, NOAA), M. Wealti (Saltwater Inc.); 57

Purpose of EM

In the Atlantic Highly Migratory Species (HMS) fishery, catches of Atlantic bluefin tuna (*Thunnus thynnus*) are quota-managed. It is required that both landings and dead discards are accounted for within the US national quota (established through binding recommendations of ICCAT). This operational EM program was initially designed as a tool to audit logbook information on bluefin tuna being retained and discarded in the pelagic longline fishery. More recently, the program has been broadened to include monitoring catch, retention and discarding of shortfin mako sharks (*Isurus oxyrinchus*).

EM is intended to provide an incentive for accurate logbook reporting; it gives the National Marine Fisheries Service the ability to verify vessel owner/operator catch and discard records for these two species, and their life status at the haul.

Context for EM implementation

In 2006, conservation and management measures for the Atlantic bluefin tuna (BFT) were updated, through Amendment 7 of the 2006 Consolidated Highly Migratory Species Fishery Management Plan. This included the development of new management measures for the pelagic longline fishery. Targeting of Atlantic bluefin tuna (BFT) by pelagic longline fishers is not permitted, though the species is caught in the course of fishing for swordfish (*Xiphias gladius*), yellowfin tuna (*Thunnus albacares*), and bigeye tuna (*Thunnus obesus*). As part of Amendment 7, the Individual Bluefin Quota Program (IBQ) was developed. For several years prior to the development of this program, catches (landings plus dead discards) of BFT by pelagic longline vessels had regularly exceeded the longline quota. The IBQ was developed to incentivize pelagic longline fishers to minimize interactions with this species, and to support individual accountability for BFT catch. While landing limits had been in place previously, management changes included new discard limits. EM was introduced to provide an independent verification measure for logbook reporting of landings and discards.

Amendment 11 to the 2006 Consolidated HMS Fishery Management Plan addresses Atlantic shortfin mako sharks[64]. The North Atlantic shortfin mako shark stock is overfished, and subject to overfishing. ICCAT Recommendation 17-08 sets out the multilateral management requirements for this species, which Amendment 11 is designed to respond to. The measures in Recommendation 17-08 are expected, by ICCAT, to prevent further deterioration in the status of the shortfin mako stock, stop overfishing and enable the stock to start to rebuild. Up to July 2022 in the commercial pelagic longline sector of the Atlantic HMS fishery, all live shortfin mako sharks were required to be released alive with a minimum of harm (with due consideration of crew safety). Only shortfin makos that were already dead on haulback could legally be retained. Reported disposition of shortfin makos at the haul was verified using EM. Since 5 July 2022, release of all shortfin makos has been required, regardless of life status[67].

EM was selected for implementation in the pelagic longline component of the Atlantic HMS fishery because pilot programs elsewhere had proven the capabilities of the monitoring method. Implementation could also be supported by the budget available for fishery management. The audit design envisaged by managers would be difficult to achieve with human observers; EM system presence on all vessels and 100% capture of fishing activities enables monitoring bias to be eliminated.

The EM program

The EM program was initiated on 1 June 2015. Around 112 vessels have EM systems installed, and 80 of these vessels are currently fishing. Most vessels carry two cameras. Cameras must be installed to (i) record close-up images of the deck near the hauling bay or processing area, where gear is retrieved and catch is removed from the hook (this view is intended to collect information on species identification and length estimation), and (ii) record fish that are caught and discarded without being brought aboard, as well as whether those fish are alive or dead when released. Some vessels require a third camera if these views are obstructed (e.g. by structures on the vessel). Overall, camera views must capture fish from when they appear at the surface, through to being brought aboard and ultimately discarded, or processed and stored.

Two sensors are fitted as part of the EM setup: a hydraulic pressure sensor and a rotation sensor on the longline reel. These show when the fishing gear is engaged and trigger the cameras to record only when the sensors indicate the gear is being hauled back. This haul-only recording was in direct response to a request made by the fishing industry when Amendment 7 was first announced.

NMFS selects specific sets for review at the end of each quarter. The sample design is stratified based on historical data on where and when BFT have been caught. Hauls are sampled for review within this stratification, aiming to capture trips with BFT interactions. The goal is to review 10% of hauls and at least one longline haul from each active vessel each year. The extent of review is subject to budget allocations.

The focus of review is compliance with the landing and discard requirements for BFT and shortfin mako sharks. Date, time, location and disposition of the two focal species are the key data fields recorded from EM imagery and associated information. A key challenge with the audit model has been alignment of data fields from EM and VMS-reported data from vessels (e.g. local time versus UTC time stamps). Also, hauls selected for review based on the stratification approach and vessel reporting information have not always been available for EM review, e.g. due to hard drive loss.

The clearly defined scope of review has contributed to the success of the program. Currently, the data collected are used for compliance purposes, with the EM program acting as an incentive for accurate reporting by those on vessels. The level of review makes the detection of underreporting trends difficult. However, the IBQ limits are not being met or exceeded currently, diminishing the imperative to increase review rates.

Beyond providing assurance of the quality of vessel reporting, EM has delivered other advantages. These include the ability to review imagery and associated information more than once. EM also provides a basis for the continued evolution of management. A third unforeseen advantage of EM has been vessels utilizing EM-collected information for legal reasons.

Program development

Activity recognition (AR) software has been in development to improve the efficiency of review. AR is intended to facilitate reviewer detection of fish on the line, by recognizing human activities associated with fish captures (e.g., increased movement of crew, presence of fish shapes). Critical to the success of AR will be testing to demonstrate that the accuracy of review is maintained (or increased). Initial testing showed comparable results between human and AR-facilitated review for retained and total catch. However, discard detection was unacceptably low (less than 70% of discards were detected). Development of the software continues.

A new rule has been proposed to require the installation of booms to improve camera views over vessel rails, and a measuring grid to enable recording of lengths of retained catch and smaller catch items. Future developments could include real time transmission, while this is not feasible within the program budget currently.

4.3. EM to support management of fishery discards and incidental bycatch: Chile

Information contributors and reference sources: L. Cocas (SUBPESCA), R. Toro (SERNAPESCA); 14, 15, 37

Purpose of EM

EM is being implemented in Chilean fisheries to improve fisheries sustainability and facilitate high-end market access. EM implementation to date has focused on monitoring compliance with regulations applying to discarded catch and incidental bycatch (seabirds, marine mammals, turtles, sharks and rays), as well as fishery regulations on fishing locations and gear.

Context for EM implementation

Two government agencies hold responsibility for fisheries management in Chile - the Undersecretariat for Fisheries and Aquaculture (SUBPESCA) sets fisheries and aquaculture policies, regulations and management measures. The National Fisheries and Aquaculture Service (SERNAPESCA) conducts monitoring, compliance and enforcement (e.g. conducting EM review and applying sanctions). Additionally, the private Fisheries Development Institute (IFOP) is in charge of research in fisheries and scientific observation programs. IFOP provides the information used to make management decisions.

In 2001, a broad prohibition on discarding was introduced in Chilean fisheries. Sanctions were introduced for violating the prohibition, without at-sea monitoring in place. The substantial penalties in place impeded the acquisition of information about discarding, and the extent of discarding remained unknown.

In 2012, the Chilean government reviewed fisheries legislation such that the main objective became the conservation and sustainable use of marine resources, incorporating ecosystem and precautionary approaches. The revised legislation identified discards and incidental catch (including seabirds, marine mammals and sea turtles), and specified control mechanisms for these. Additionally, the legislation provided for vessel-specific exemptions to the discard prohibition, conditional on at least two years of fishery-based research or monitoring. The purpose of the two-year exemption period was to enable an unbiased quantification of discarding and incidental bycatch, to understand these events, and to develop (with the sector) proposals for how to address both issues. Proposals were later translated into mandatory plans for each fishery, which contain management measures and technological means to reduce both discards and bycatch, handling protocols, codes of good fishing practice, a continuous scientific monitoring and compliance program, training and dissemination programs, etc. At-sea observers and fisher logbooks were key sources of information throughout this process. New management categories were implemented: species for which (i) discarding is prohibited (all species with quota and species for human consumption), (ii) discarding is authorized (damaged specimens, species with no current commercial value) and (iii) return to the sea is mandatory (all bycatch, chondrichthyans, prohibited species and species not subject to exploitation). Discards have been considered in total allowable catches since 2018. Now, procedures are in development for the explicit incorporation of discards in fishing permits and licenses.

The difficulty of controlling discarding at sea led to the incorporation of EM in the revision of the fisheries and aquaculture law in 2012 (Law No. 20.625, 2012). This enabled the use of EM to support the management of discards and incidental bycatch, by detecting and recording any discarding actions occurring (thereby enabling the monitoring of compliance with the reduction plans). To implement this law, Supreme Decree No. 76 (2015) sets out the requirements for EM systems on both industrial and smaller-scale vessels. Regulatory provisions include, for example, EM system design and technical specifications, number and location of cameras by fishery, details on image collection, processing and confidentiality, obligations of vessel owners, and the role of SERNAPESCA. There is also a complementary Resolution that sets out the technical standard for an EM system.

By 2022, 11 discard and incidental bycatch reduction plans were established, covering 17 fisheries (both artisanal and industrial), and other plans are still in the research phase. Additionally, the list of species subject to such plans for each fishery, and the associated management classification (i.e. prohibited discard, authorized discard, mandatory return) is updated annually by Resolution. This Resolution also set out requirements for incidental bycatch, including the use of mitigation devices and handling practices. All the industrial fisheries subject to reduction plans are being monitored by EM.

The EM program

The use of EM by Chile's industrial fleet (> 18 m in length) has been mandated since January 2020. The fleet comprises vessels using demersal and midwater trawl, purse seine and longline fishing methods. EM roll-out in this fleet was preceded by extensive research, hundreds of meetings with industry participants, and other preparatory work. The EM program was immediately implemented as an operational one (no pilots occurred). In 2020 and 2021, 109 and 92 vessels, respectively, were operating in the fleet and all were covered by EM. (Vessel numbers vary year to year, e.g., due to vessels being sold, repaired, or moving into a different sector of industry). SUBPESCA and SERNAPESCA collaborated extensively throughout the development and implementation of regulations relating to bycatch and discarding, to ensure that the required measures could be efficiently monitored using EM. Collaboration is ongoing to address issues arising, e.g., requiring additional cameras in some fisheries.

EM captures fishing trips from when vessels depart through to when they return to port. (The regulatory framework also enables the use of sensor-based systems). Vessels carry 2 – 8 cameras each, depending on the vessel size, fishery and fishing operation, and extent of catch processing that is undertaken onboard. In general, hard drive storage capacity determines the schedule of collection and a range of days is specified by law. However, operators can be compelled to provide hard drives at any time on demand from various authorities, and for administrative or compliance purposes.

Vessel owners are legally responsible for the costs of EM equipment, installation and maintenance. These costs are set by the chosen EM supplier.

The law enables the collection and processing of EM imagery to be carried out by SERNAPESCA or outsourced. SERNAPESCA currently conducts the review of EM imagery and associated information, recognizing that the experience gained will inform any future competitive outsourcing process undertaken. Review costs could also be on-charged to vessel owners in future.

After collection of hard drives, EM imagery and associated information is checked for integrity and completeness. The number of trips and hauls is identified. Selection of the review sample follows a stratified random process. Review is prioritized where there is considered to be a higher probability of discarding or bycatch occurring. On each hard drive, a sample of 10% of the hauls is randomly selected (without replacement). Review is more time consuming on factory vessels conducting onboard processing and vessels with catch storage tanks/pounds, because the catch is followed throughout processing in multiple areas of the vessel. When instances of regulatory non-compliance are detected, additional samples are reviewed.

The Electronic Fishing Log (EFL) maintained by the captain of the vessel, and mandatory for industrial fleets since 2020, provides the basis for comparison with the data extracted from EM. In EFLs, captains must record all fishing events, and for each set, required records include estimated catches by species or species group, geographical position, date and time of each set/haul, quantities and species discarded, and the bycatch of seabirds, marine mammals, sea turtles and chondrichthyans. At the end of a fishing trip, EFLs are submitted via cellular network or Wi-Fi, to SERNAPESCA. When inconsistencies between the data extracted from EM and the EFL are identified, the vessel owner is notified and sanctions may be applied. At this point, the vessel owners, vessels and captains most likely to use fishing practices associated with unacceptable discarding have been identified in each fishery across the industrial fleet.

Currently there are three full-time EM analysts conducting review, each working 44 hours per week. Analysts conduct review in accordance with a documented standard. Analysts review EM imagery, prepare reports and communicate findings to management. They also validate findings as required to support sanctioning processes.

Program development

Implementing the EM program during the COVID-19 pandemic was challenging. Nonetheless, the program has catalyzed change in the industrial fishery. EM information has contributed to the management agencies' understanding of behavior patterns and entities and individuals associated with non-compliance, and supported a significant improvement in undesirable practices at sea in a way that was not previously possible. Remaining challenges include species identification in some fishery operating conditions, and catch (and discard) identification and quantification using EM. In the cases when discards cannot be fully quantified using EM, other information sources may be considered (e.g. average catches per trip).

Building on the knowledge acquired during the first two years of the program in the industrial fleet, new approaches to sampling imagery for review are being explored, such as the development of fleet-specific criteria. The program will continue to cover 100% of vessels and fishing activity. New review technologies (using machine learning and artificial intelligence) will be trialed in two pilots starting in 2022 in the artisanal fleet, supported by The Nature Conservancy and Future of Fish.

Work underway also includes integrating various electronic monitoring and reporting tools to provide more streamlined and efficient systems (such as EFLs, EM cameras, VMS, catch certification, and weighing systems). Future steps include transitioning from hard drive storage to wireless transmission over 5G networks and cloud storage, implementing pre-review within the EM system onboard vessels, and improving image quality to support a broader range of monitoring objectives. Exploration of the use of EM for scientific purposes and complementarity with other observation systems is also underway.

The rapidly changing characteristics of the fishery and its environment are driving the need for fishery data with higher spatial and temporal resolution, to account for growing uncertainty and enable adaptive management. The implementation of EFLs and EM has enabled the modernization and updating of fisheries data systems, and significant expansion of the collection and analysis of information for both management and research. This has created an opportunity to coordinate and enhance the work of SUBPESCA, SERNAPESCA and IFOP. The collection of high-resolution data, as well as faster data processing, analysis and preparation of more detailed reports enables management responses in times closer to real time.

The roll-out of EM across Chilean fisheries is ongoing, and implementation on artisanal vessels 15-18 m in length is regulated from January 2024 (Law No. 21.259, 2020).

4.4. EM to provide catch composition information for fishery management

Alaska Fixed Gear fishery: USA

Information contributors and reference sources: C. Paiva (Pacific States Marine Fisheries Commission), J. Keaton (Alaska Regional Office, NOAA), J. Ferdinand, J. Calahan, G. Campbell (Alaska Fisheries Science Center, NOAA), N. Munro, A. Snedeker (Saltwater Inc.), E. Torgerson (Chordata LLC); 5, 6, 22, 53, 54, 56

Purpose of EM

EM is used to collect catch composition information, including characterizing retained and discarded catch in the Alaska Fixed Gear (AFG) fishery. The AFG includes hook and line, and pot/trap fishing gear.

EM-derived data are used in stock assessments, bycatch species risk assessments, to better understand marine mammal depredation of catch, and for compliance purposes.

Context for EM implementation

EM had been of interest among Alaskan fixed gear fisheries for some years when an observer program review conducted in 2013 triggered the progression of pre-implementation EM. The review and associated restructure resulted in increases to the daily cost of observers, and the addition of smaller vessels (<60 ft) to the North Pacific Observer Program's partial coverage category[66]. (In the partial coverage category, a sample of trips is monitored. By contrast, in a full coverage program, all trips would be monitored). Fishery managers sought more data and more randomized sampling from the AFG fleet targeting Pacific halibut (*Hippoglossus stenolepis*), which included these smaller vessels. EM was seen by industry and the North Pacific Fishery Management Council as a potential alternative to human observers to meet the increased demand for fishery monitoring.

A pilot program was undertaken on volunteer vessels from 2014 – 2017. Review protocols for the AFG program were initially sourced from the US West Coast Region fixed gear EM program and updated as required for the AFG fishery. Learnings from the pilot program were used to develop AFG program standards and specifications. For example, information from the pilot led to the focus on collecting catch and fate data from EM, rather than hook counts for longline fishing.

The EM program

The operational EM program has been implemented through regulation in the AFG fishery since 2018. The approach to delivering the program is set out in annual deployment plans (ADPs). ADPs also describe requirements for monitoring by human observers. The EM selection pool has comprised around 170 approved vessels from 2020 – 2022.

Vessels operate under Vessel Monitoring Plans (VMPs) that include requirements for monitoring EM system functions, camera maintenance, and catch handling. Submission and approval of a VMP are pre-requisites for participating in the AFG EM program on an annual basis once accepted into the EM pool. Failure to comply with the VMP may result in exclusion from the EM pool the following year. On average, 3 – 4 cameras are in place on vessels while there is no regulated number and the focus is on what is necessary to achieve monitoring goals on each vessel. The EM system is able to trigger camera recordings conditionally through the use of various sensors, such as those installed on the vessel's gear to monitor fishing activity, or detect movement using GNSS/GPS. Sensor information facilitates review.

EM is used as a standalone data source for reviewed trips (i.e. audit of logbook information is not conducted). In 2017, 50% of hauls were reviewed. This has since been reduced to one third of hauls due to review time and cost considerations. All hauls from a selected trip are reviewed if only two or one have occurred during that trip. Trips are randomly pre-selected for EM review through the Observer Declare and Deploy System. This baseline approach to review may change subject to a prioritization request from the Observer Program or the Office of Law Enforcement (OLE). Observer Program prioritization requests may result from stock assessment matters or other areas of concern. OLE requests may arise from unusual VMS information and/or previous behaviors. Once selected for review, the full review process is conducted as documented in the review protocol (i.e. there is no subsequent prioritization among monitoring objectives or tasks).

In 2020, review ratios (that is, the ratio of EM review time to real time) ranged from 0.4 (1 hour of catch handling took less than half an hour to review) to 2.2 (1 hour of catch handling took more than 2 hours to review) (Table 2). For cod, the relatively higher review ratios were due to the diversity of catch species and stern hauling (resulting in poor lighting at night and a side view rather than a clearer top-down view). Industry buy-in is vital for optimizing catch handling to support review, and providing prompt feedback when issues are detected has been appreciated by vessel operators. This also supports prompt improvements in data quality.

Data collected from the AFG EM program have been used for management since 2018. Beyond data provision for stock assessments, risk assessments, etc., EM also provides OLE with evidence of illegal and egregious at-sea practices such as illegal discarding and shooting seabirds. This can be used in support of legal proceedings.

Program development

The EM program is subject to ongoing development and improvement. This includes considering ways to improve data quality, such as alternative sampling methods that would alleviate catch handling requirements, the direct incorporation of effort/logbook data with review, and a baseline level of review to achieve specified data quality objectives (e.g. for discarded catch and species of interest).

AI tools to facilitate review are in development for this program. In the future, it is anticipated that these tools will increase review speeds (enabling an increase in the amount of review that can be completed). For example, if AI is effective in quantifying and identifying retained catch to species level, reviewers would be able to focus their time on characterizing the discarded catch.

*Table 2. Average ratio of review time to catch handling time, for the Alaska Fixed Gear electronic monitoring program in 2020. Review includes the characterization of both retained and discarded catch. Target species are Pacific halibut (*Hippoglossus stenolepis*), Pacific cod (*Gadus macrocephalus*) and sablefish (*Anoplopoma fimbria*). (Source: Alaska Fisheries Science Center and Alaska Regional Office 2021).*

Gear	Target species	Review time: Real time
Fixed hook longline	Pacific halibut	0.66
	Sablefish	0.68
Snap longline	Pacific halibut	0.61
	Sablefish	0.42
	Pacific cod	2.22
Single pot	Pacific cod	1.01
String pot	Sablefish	0.66

4.5. Regional EM initiatives: Pacific Ocean tuna fisheries

EM development in the region

Numerous EM programs have been undertaken in fisheries targeting tunas and billfish in the Pacific Ocean (Table 3[89]). To date, two have become operational, in Australia's Eastern Tuna and Billfish (longline) Fishery and the AGAC purse seine fishery program (described in detail in Case Study 4.1). The objectives of Pacific-based programs have ranged from compliance to catch accounting. There has been a focus on the comparability of data derived from EM and data collected by human observers deployed on fishing vessels, and also logbook reporting in some cases (Table 3). EM implementation is increasing in the region. For example, Thai Union and The Nature Conservancy (TNC) have recently partnered to deploy EM and/or human observers on all vessels in Thai Union's tuna supply chain by 2025[85,86]. Among government-led initiatives, EM is scheduled for implementation on New Zealand's pelagic longline fishing fleet from November 2023[27].

Below, we consider two EM programs conducted in Pacific pelagic longline fisheries in more detail. These are the Hawai'i longline fishery (Pacific Islands Region) and the TNC-Pacific Islands Cooperative Longline EM Project[10].

EM as a monitoring tool for the Hawaii longline fishery (Pacific Islands Region)

Information contributors and reference sources: K. Bigelow, J. Stahl, J. Tucker (Pacific Islands Fisheries Science Center, NOAA); 11, 30, 48, 62, 79

EM has been explored as a monitoring tool for the Hawaii longline fishery since 2009, when an initial trial was conducted. The objective of the pre-implementation program that commenced in 2017 is to evaluate the efficacy of EM as a monitoring tool. Monitoring using EM is focused on the detection of all catch events, including fish (marketable and nonmarketable species) and protected species (sea turtles, seabirds, marine mammals, and sharks). For protected species, monitoring objectives include the collection of mortality and serious injury information. Currently, sea turtles and marine mammals are the focal taxa for assessing injury and mortality using EM imagery. Other areas of current research include a catch-handling study to determine whether detection of shark bycatch can be improved with fishers bringing sharks in closer to the vessel, and whether catch items brought on deck and released in the water (including fish and bycatch species) can be detected using machine learning. Routine analysis of EM imagery in this fishery covers the longline haul, however EM has previously been used to address specific research objectives, e.g., the efficacy of tori lines during longline setting.

A key motivator for the pre-implementation program was the relatively high cost of human observers and opportunities to realize cost savings with EM. The work program is designed to identify how EM and human observer coverage can be used together to best deliver the required fishery monitoring information. There is currently no target coverage for EM deployments. EM and human observers monitor 20% of fishing effort in the deep-set pelagic longline fishery and 100% in the shallow-set fishery. Coverage levels are under evaluation (bearing in mind human observer costs).

EM systems are carried voluntarily by 20 vessels. Sensors initiate camera recording and facilitate the detection of catch events by EM analysts. Two cameras are fitted, to provide a rail view and a deck view. These views record catch items in the water before hauling or release, as well as catch items that come aboard. A Vessel Monitoring Plan is in place on each vessel, setting out equipment maintenance protocols. Fishers keep cameras clean. There are catch handling protocols in place for protected species, which may facilitate their detection at review. Some fishers value the ability that EM provides, of viewing catch coming aboard without them having to leave the wheelhouse.

The efficacy of various reviews speeds has been analyzed during this program (see section 5.2). Other learnings include the importance of daily limits on review time to ensure EM analysts retain their focus, and the need to avoid interpreting an event without watching all imagery of that event (e.g. what initially appears to be a gear tangle may actually be a protected species capture event).

Overall, EM has proven very effective at monitoring catch brought aboard vessels. Detecting fish bycatch released in the water has been the most difficult at review. However, for commonly caught species (e.g. longnose lancetfish (*Alepisaurus ferox*) or snake mackerel (*Gempylus serpens*)), total catch across the fleet can be extrapolated from information collected by human observers. Regulatory changes that require fishers to use monofilament leaders and bring protected oceanic whitetip sharks into the camera view are expected to result in improved EM-based detections of sharks.

It is expected that the overall coverage levels of 20% and 100% for deep- and shallow-set fisheries will remain in place in the future, and that EM will continue to be used to supplement human observer coverage. The integration of EM and human observer monitoring is an active area of research. To facilitate the use of data collected from EM and by human observers, a data integration group is being formed to pull data from both sources into one database. A regulatory framework for the program is in development. Depending on the outcomes of current research, AI could be used to detect catch events in future, while human review focuses on species identification and assessment of mortality and serious injury.

EM-based catch characterization across multiple Pacific jurisdictions

Reference source: 10

The western and central Pacific is well suited to a multi-jurisdictional approach to EM deployment for several reasons. The regional and subregional bodies in place (e.g. WCPFC, Pacific Islands Forum Fisheries Agency, Parties to the Nauru Agreement) comprise a management framework that is implemented across national jurisdictions, noting that individual countries also develop their own legislative requirements. Other monitoring tools (e.g. VMS) are established at the regional level[92]. There are many vessels active in tuna fisheries in the western and central Pacific Ocean (WCPO) that fish across multiple EEZs, and both inside EEZs and on the high seas.

The Nature Conservancy's Pacific Islands Cooperative Longline EM Project is an example of a multi-jurisdictional EM initiative. For this project, EM systems were installed on 15 longline fishing vessels operating in the EEZs of the Republic of the Marshall Islands, Federated States of Micronesia, and the Republic of Palau (and adjacent high seas). These included vessels chartered into the EEZs of Pacific nations while flagged to Japan and Taiwan. While some jurisdictional differences were detected, project findings demonstrate an overall pressing need to improve the quality of logbook reporting of target, retained and discarded species from these longline vessels. For example, catches of significantly more yellowfin and albacore tuna were documented from EM-derived data compared to logbook reporting. Discards of tunas, billfish and marine turtles detected by EM and human observers were almost never reported in logbooks. Logbook reports included fewer species and species groups than EM-derived data (typically five species in logbook records compared to an average of 8 – 10 for EM). Inaccurate and under-reporting has clear implications for species and fishery management. EM was identified as a key solution to the low level of monitoring in place in western and central Pacific Ocean tuna longline fisheries.

Some vessels participating in the project were included in Units of Certification of Marine Stewardship Council-certified fisheries. This was considered to provide a potential incentive for better quality logbook reporting. From an EM review perspective, logbook reporting would need to improve significantly before an audit model could be used to effectively document catch composition.

Table 3. Results of selected electronic monitoring (EM) programs undertaken in Pacific Ocean longline and purse seine fisheries targeting tunas, 2014 - 2022.

Region/nation	Scope	Scale/Stage	Main objectives	Sources
Australia	Eastern Tuna and Billfish (longline) Fishery All vessels conducting 30 or more longline sets per season	Operational	Seabird captures at hauling Tori line deployment at setting Composition of fish catch (logbook audit)	1, 17, 19, 20, 21
Hawaii (USA)	Hawaii EEZ and high seas pelagic longline fishery 18 vessels (20 vessels in 2022)	Pilot	EM efficacy as a monitoring tool Catch accounting comparing human observer and EM-derived data	11, 79 Case Study 4.5
Fiji	EEZ pelagic longline fishery 51 vessels	Pilot	Compliance monitoring, fishery information to support market access (e.g. Marine Stewardship Council certifications), and to improve onboard operations (e.g. safety)	83
Solomon Islands	EEZ pelagic longline fishery 2 vessels	Pilot	Comparing human observer and EM data collection capabilities	32
Federated States of Micronesia, Republic of the Marshall Islands, Palau	EEZ pelagic longline fisheries and adjacent high seas 15 vessels	Pilot	Comparison of catch rates between human observer, EM-derived and logbook data	10
Pacific Ocean	Purse seine fishery 2 vessels	Pilot	Comparing fishery data collected by human observers and EM	56
Pacific Ocean	Purse seine fishery 28 purse seiners 12 support vessels	Operational	Conformance with Code of Good Practice	Case Study 4.1

5. Optimizing EM review

5.1. Approaches to EM review

Fishery management objectives and EM program objectives should underpin the approach to review used in an EM program. Ensuring appropriate levels of review are conducted to efficiently meet management and monitoring objectives has been identified as possibly the "*number one near-term cost-reduction opportunity for EM programs*"[49]. Census and sample-based methods can be used to review EM imagery and associated information.

Census review

Census review involves the review of all imagery and associated information collected by EM systems. This approach provides the most comprehensive dataset and it is often used in pilot or trial programs, as well as to meet ETP monitoring objectives in operational programs[17,51]. In pilot programs, census review has value beyond the data collected as it also provides a basis for developing review processes and standards for scaling up to operational EM programs[49,51].

Sample-based review

A sample-based approach to EM review enables the scaling of review to fit budget (and other) constraints. Data derived from sampling can be used as a standalone information source. An alternative approach is to use sampled data derived from EM to audit fisher logbook reporting.

Audit-based review with logbook data

Taking an audit approach, data collected from reviewing a sample of EM imagery are compared to fisher reports and the deviations between the two datasets are scrutinized. 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 therefore are not scaled up, and logbook reporting becomes the fleet-level record. Ideally samples used for an audit approach would be randomly selected.

Where differences between EM and logbook datasets are significant at audit, further investigation is required (e.g., additional EM review and evaluation of logbook data to identify issues for improvement). Recovering additional review costs directly from individuals filing low quality records is one approach to encouraging improvements in logbook data quality[17,82]. Where logbook data are of low quality across a fleet, the audit approach will not work well and use of EM data as a standalone data source (sample or census) is appropriate until logbook data quality improves.

Sample data as a standalone source

EM review rates required to support different fishery monitoring objectives have not been widely explored empirically, though the value of identifying these rates is well recognized[84]. In one example, simulation modelling undertaken for the US Northeast Multispecies (groundfish) Fishery found that bias in logbook reporting of 12 species of discards could be corrected with EM review rates below 50%. (In this fishery, strong covariance was evident between logbook reporting and EM-derived discard data). In an example year, 35% was the lowest EM review rate that achieved a coefficient of variation of 30% for all species considered[45]. In a second case in British Columbia, Canada, simulation modelling was not undertaken but 10% EM review proved effective in meeting the requirements of the fishery, when used to audit logbook reporting and in conjunction with other monitoring tools (such as dockside monitoring)[81].

Clear objectives are essential to determine appropriate EM review rates and a higher level of accuracy necessitates higher review rates. For example, when monitoring catch of a quota limited species for compliance purposes is the objective, higher review rates will be needed than when EM-based catch characterization is used for stock assessment purposes. The characteristics of the event of interest will also affect EM review rates required to provide information for management. For example, estimating catch levels of a commonly caught species will require lower review levels than for a rarely caught species.

Such concepts are also evident in literature on human observer monitoring rates[7,8,18,36,42]. However, a critical difference between human observer monitoring and EM is the ability to sample and resample EM imagery and associated information after it is collected. Provided EM captures all fishing activity, the review rate and sample selection process can both be set in advance and adjusted retrospectively, in accordance with management priorities, risk, resourcing, and any other relevant factors. This allows a much more agile and adaptive approach to monitoring than is achievable with on-vessel human observer deployments.

Within a sampled unit of fishing effort, subsampling may be sufficient to meet data needs (while also reducing time required for review). For example, subsampling catch from a portion of the hooks from each longline haul may enable more hauls to be reviewed than if entire longline hauls were sampled. Depending on the nature of the fishery, the subsampling approach may result in more representative catch characterization (e.g. if a fishery operates across a large geographic area with considerable variation in catch species distributions).

Combining census, sample and subsampling approaches in one EM program to meet a set of monitoring objectives may also be appropriate (e.g. a census approach reviewing 100% of hauls to identify ETP bycatch, 20% of hauls sampled to record fish bycatch, and hook counts conducted on 5 baskets from each haul sampled for fish bycatch). Typically, the addition of monitoring objectives adds complexity and therefore time, to review processes. Where resources are finite, prioritizing monitoring objectives is another effective approach to managing review time and cost.

Regardless of the review approach used, 100% capture of fishing operations (i.e. all vessels, with all fishing activity recorded) is recognized as best practice, enabling avoidance of the "observer effect" (when fishing operators change practice because they are being monitored, resulting in data collected from observed trips not being representative of normal fishing operations)[17,49].

5.2. Increasing EM review efficiency

Practical steps to maximize the efficiency of EM review can be taken at the design, on-vessel data capture and review stages (Table 4).

Suitability of data fields for EM

In many cases, EM programs are being developed and implemented in fisheries in which human observers have operated. It is essential to consider, especially when transitioning from an at sea observer program to an EM program, that not all data fields and definitions can be identically transferred. Each data collection method differs, and EM analysts do not handle the organisms they see. For example, Alaska's at-sea observer and EM programs collect data on Pacific halibut viability, injury, and gear release methods. This information is provided to the International Pacific Halibut Commission and informs halibut mortality rates. The current condition codes are defined based on at-sea observer fish-in-hand assessment. EM condition definitions have not been adapted and remain the same as the observer definitions. This is problematic for EM analysts, as they are often unable to view (and therefore assess condition of) both sides of the halibut. Adjustments to data definitions that can be met using EM have been recommended[13].

Considering alternative methods for collecting data from EM can also improve efficiency of review. For example, hook counts are a typical measure of fishing effort. Depending on factors such as camera views, image quality, and gear configuration, hook counts can be challenging and time consuming for analysts. Alternative approaches explored to collect this data element include census counts, computer vision (the use of artificial intelligence that enables computers to derive meaningful information from visual inputs), and subsampling. Census counts were found to be costly, computer vision was not complimentary to all programs, but subsampling was considered to warrant further exploration.

Hook subsampling methods have included using time as a proxy, using gear segments/sections, and a combination of time and gear segments. Determining which hook subsampling approach would best complement a program depends on the type of gear used, the identifiable presence of gear markers, and/or the reliability of gear documentation (logbooks) if available. Hook count subsampling was found to be most representative for fixed longline gear with easy to identify segment markers that were positioned at semi-regular intervals and an expected number of hooks per segment. The amount of time to collect this information depends on the proportion of gear subsampled across the trip and the total amount of gear. Preliminary results showed a small percentage of added time (less than 10%) to complete subsampling, which is less cost prohibitive than conventional hook enumeration approaches[13]. Having the ability to efficiently collect hook count information could support options for sampling including audit approaches.

Operational changes to facilitate data capture

Fishers can influence review costs by operating in ways that facilitate effective image capture. When developing and operating in EM programs, a key question is how fishers can alter their operations to support successful collection of data for management. For example, if the goal of the program is catch accounting, the catch needs to be handled in a manner that allows reviewers to identify and count catch to meet the minimum data need.

When establishing catch handling requirements for EM programs, it may not be necessary for fishers to significantly alter their regular operations or not to the extent that some programs currently require. Important considerations for the development of handling requirements include gear configuration, hauling operations, and catch composition and volume. In parallel, an awareness is required of the potential for handling requirements to lead to compliance issues, slowed fish production, negatively impacted data, and/or increased review time due to fishers' difficulties in meeting these expectations. A collaborative approach that involves the EM review service provider, fishers and the agency identifying data needs is recommended to optimize the specification of any handling requirements. Prompt feedback to vessel crew is also important for addressing on-vessel issues affecting image capture as quickly as possible. Where review costs are on-charged to vessel operators, there is the opportunity to incentivize facilitative operational changes such as catch handling practices through the commensurate reduction in review time (and therefore cost).

Within the Alaska Fixed Gear (AFG) program, EM service provider Saltwater Inc.'s review team actively researched current data needs and uses, reached out to fishers to gain a better understanding of their operations, and assessed program protocols to look at other review approaches and ways to reduce impacts on fishing operations. The AFG program currently requires vessels using single pots to clear all catch from each pot prior to hauling and processing the following pot. This is to ensure reviewers are able to identify and count all catch items associated with that pot, the defined sampling unit. However, when catch volume and species diversity are higher, the ability to sort, process, and clear the table prior to the next pot arriving can become challenging if not impossible. This can lead to catch being mixed from multiple pots and/or discarding species by the armfuls preventing reviewers from obtaining catch composition information, and making the pots unsampleable.

The review team tested an altered sampling unit, defined as a string or cluster of pots, with an allowance for clearing catch by the end of the string or cluster. Promisingly, results found that increased flexibility in catch handling requirements paired with alternative sampling units led to improved catch monitoring throughout fishing events. Furthermore, the amount of data per dollar increased due to a decrease in unsampleable data caused by catch handling issues[13].

Varying playback speed

EM imagery can be replayed at normal speeds (i.e., speeds equivalent to real time), sped up, or slowed down. The appropriate playback speed will depend on monitoring objectives and data to be extracted, as well as human constraints such as limits of analyst concentration and fatigue. For example, for large and highly visible cetaceans, imagery review at 10 – 12x normal speed has been effective[41]. In the Hawaii longline fishery, reviewer accuracy in detecting catch events was tested at three playback speeds faster than real time (4x, 8x and 16x normal speed). EM reviewers detected retained catch with similar accuracy at all three playback speeds. For discarded catch, on average, detection accuracy was highest at a playback speed of 8x. At 4x normal speed, reviewers did not detect some protected species, possibly due to waning focus as the haul review progressed. At 16x normal speed, reviewers detected all protected species caught except one albatross. The potential to miss protected species events at such rapid playback speeds was noted, e.g., drop-offs or cut-offs would take place in an instant on-screen. Above 16x normal speed, the EM video skipped and catch events may not have appeared on screen at all[79].

Ergonomic tools

Ergonomic efficiency can also save analysts' time at review. EM analysts work by transitioning back and forth between their keyboard and mouse to conduct review. While each movement is short, cumulatively these transitions can account for a significant amount of time. Hotkeys (project customizable key-bindings) assist reviewers in minimizing transitional movements, navigating efficiently across the keyboard during review, and reducing the steps involved in creating annotations at review. Hotkeys can be programmed to easily allow reviewers to interact with playback speed, advance or reverse video, and create fishing and species annotations within the data. This leads to an overall decrease in review time, and a potential increase in data quality as the hotkeys reduce the number of fields and/or forms a reviewer needs to complete. To maximize the benefit of hotkeys, collaborating with review teams is recommended to establish hotkey utility and which key bindings would be best to implement. The reviewers who directly interact with the data on a regular basis are best placed to identify limitations and workable improvements for staff who are setting up these tools.

Computer vision and artificial intelligence

Computer vision tools can perform or augment the process of marking fishing events, establishing sampling frames, monitoring for compliance, detecting catch and identifying catch[17,87]. Compared to manual review and marking of events, the application of computer vision/machine learning reduces review times and cost, and increases data confidence (as long as algorithms are trained appropriately). One use case example involves detecting humans interacting with gear or present on deck to direct EM reviewers to areas of interest - with an accuracy of 95%. This dramatically reduced the amount of non-useful video that needed to be scanned by the review team (Saltwater Inc. unpubl.).

Another computer vision tool utilized the automatic detection and event marking of fishing gear, which can be a time-intensive component of analysis. This tool can achieve close to 100% accuracy, reducing the amount of analyst time needed for this task considerably (e.g. reductions of hours in the time needed for marking a high effort pot fishing trip). The detector finds and pre-identifies selected pots for sampling in a fishery where gear deployment may be upwards of a thousand pots per trip. Sampling rates can be set for gear detection tools to meet project requirements. Other computer vision applications include discard compliance monitoring, species identification, and low-level analysis of EM system performance[13].

Many factors affect which computer vision tools will be effective in a monitoring program including camera views, image quality, catch handling, general fishing operations, and management objectives. Having a strong understanding of both the management objectives and the EM data will help determine which computer vision tools could be beneficial. It is also important to consider the start-up costs associated with computer vision tool development and implementation. Additional time and resources are needed to create, train, assess functionality and success, and incorporate the tool into the overall review workflow. Labelling and saving data and metadata during EM review may provide longer term value that is unquantifiable in the short term, by facilitating development of review processes that incorporate machine learning when computer vision tools are developed.

5.3. Costs of EM review

EM review costs range from 2.5% to more than 60% of the total costs of EM programs (Table 5; noting that the approach to defining the review component of EM programs affects the comparability of cost information between programs). Review cost profiles for pilot and operational programs are expected to differ significantly, because review methods and standards will be developing in the former case while in place at scale for the latter. Also, for operational programs, equipment may already be aboard vessels if a pilot program has been conducted. This will affect the perception of review costs as a proportion of operational program costs. Where review occurs may also affect costs, assuming EM analyst remuneration reflects local labor costs.

How costs scale with review rates is not linear[54,81]. Regardless of the review rate, initial screening of the EM imagery and associated information and determination of the sampling frame (e.g. number of trips, sets/hauls) are required. This comprises a baseline minimum cost. From there, irrespective of review rate, costs increase with some relationship to the complexity of review tasks. The process of EM review enables significantly more granular analyses and management of cost-per-datum compared to human observers. (For human deployments, the length of a trip does not change with respect to the number of tasks undertaken during that trip, and moving between vessels at sea has significant logistical implications). Generalized figures from one EM review service provider illustrate the scale of variation in review costs across different fisheries and monitoring objectives (Table 6). Service providers emphasize that determining the best approach to review involves collaboration among providers, clients and vessel operators, to ensure monitoring objectives are met with maximum cost efficiency (DOS and Saltwater Inc., pers. comm.). Growth in the scope of an EM program can make costs more difficult to predict, and also makes EM cost less comparable to pre-existing monitoring programs with the same initial objectives as the evolving EM program.

Table 4. How EM review efficiency can be increased for the census and sample review methods.

When applicable	Approach	Review method	
		Census	**Sample**
Program design phase	Focused monitoring objectives	✓	✓
	Information collection priorities set	✓	✓
	Sample selection specified (random, stratified, risk-based)		✓
	Subsampling units identified		✓
	EM-appropriate data definitions developed	✓	✓
	Use of the audit approach		✓
On-vessel data capture	Catch handling protocols in place	✓	✓
	Lens cleaning undertaken	✓	✓
	High quality logbook reporting		Only for audit method
	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 program design, objectives, data needs	✓	✓
	EM-appropriate data collection units identified	✓	✓
	Review speeds faster than real time	✓	✓
	Hotkeys used by analysts	✓	✓
	Review supported with Computer Vision, Artificial Intelligence	✓	✓

*Table 5. Summary of published information on the cost of electronic monitoring review. (*excludes project management and some staff-related and training costs; ⁺Conditions of the Marine Stewardship Council certification of the fishery related to management of target stocks and some non-target species[2]. $Costs are estimates, predicted prior to the implementation of an operational program. ⁺EM review plus a 10% audit of review for quality assurance. @Calculation of this estimate excludes investments already made in the pilot trial for 50 vessels, therefore, the percentage of total costs allocated to review will be less than 7.8%. ^Data review, processing analysis costs (2020). Avg. = average, EFP = Exempted Fishing Permit).*

Monitoring objective / data collected	Fishery	Target	Location	Program type	Review approach	Review cost as % of program cost	Source
Verify reported catch of Atlantic bluefin tuna	Pelagic longline	Highly migratory species	East Coast USA, Caribbean and international waters	Operational (67 active vessels; 110 carrying EM)	10% baseline	16%	60
Monitor compliance, document fishing practices, monitor setting and hauling including safety conditions, address MSC conditions+	Pelagic longline	Tuna	Fiji	Pilot (50 vessels)	Objective of census review. Review of 44% of trips achieved.	4.5%	83
Operational monitoring of longline fishing	Pelagic longline	Tuna	Fiji	Operational (50 vessels)	Sample (~20% of fishing days)	7.4%$	33
Operational monitoring of longline fishing	Pelagic longline	Tuna	Fiji	Operational (90 vessels)	Risk-based (Low risk: sample of 5%; High risk: census of 100% review; Avg. 22% review overall)	<7.8%$@	33
Operational monitoring of longline fishing	Pelagic longline	Tuna	USA (Hawaii)	Operational (160 vessels)	Sample (25% of sets)	31%$ +3%+	62
Operational monitoring of fixed gear fishery: • catch composition (retained and discarded, by species) • discarded halibut condition • presence of streamer lines and discarded halibut release method with longline gear	Hook and line, pots/traps	Sablefish (*Anoplopoma fimbria*) Pacific cod (*Gadus macrocephalus*) Pacific halibut (*Hippoglossus stenolepis*)	USA (Alaska)	Operational (169 vessels approved for EM)	Sample (From vessels with EM, 100% of string pot gear hauls; 33% of hauls with other gear)	17.5%^	5

Collect data on fishing operations • Catch by species • Discards • Fishing effort (including FAD activity) Monitor compliance with national and regional management measures	Purse seine		Ghana	Pilot	Census	2.5%*	83
Discard accounting	Trawl	Groundfish	USA (Pacific Coast)	EFP (84 vessels) transitioning to regulatory program	Census	Review, reporting, storage 39% (Avg. 2015 – 21) 18% (2022)	63
Cetacean bycatch	Inshore gillnet		Europe	Operational	Census	36%$	17
Complete sensor record of trip Verify logbooks and audit catch records (retained and discarded catch) Confirm fishing locations	Hook and line		British Columbia, Canada	Operational (~200 active vessels)	Audit (10%)	34%	81

Table 6. Relative costs per sea day for analysis of electronic monitoring imagery and associated information, for the purse seine, longline and trawl fishing methods. (Source: G. Legorburu, DOS, pers. comm.). Figures are not necessarily applicable to any specific fishery and are provided as indicative. Fishing effort screening analysis includes trip and set start/end date, time and locations; number of sets, detection and description of encounters with other vessels/vehicles. Detection and description of Fishing Aggregation Devices is also included for purse seine. For longline, bait, hook and baskets are also characterized, and seabird mitigation measures checked. Species of special interest include sharks, rays and turtles, and this analysis includes detection, handling, condition and fate analyses. Standard catch characterization for purse seine includes data collection for species of special interest, estimating total catch per set, per brail and per well, species composition estimation, detection and estimation of tuna discards, detection and identification of fish bycatch and associated condition, fate and release information. In addition to these data, full characterization for the purse seine method includes digital counting and sizing of catch per set and total catch. Longline catch characterization includes catch composition by species, condition and fate, size and sex determination, hooks per basket, interactions with species of special interest; discard characterization includes date, time and location of discard events, discard species composition and size, estimated reason for discarding. Trawl catch and discard characterization includes estimated total catch per haul discard estimation, estimation of species composition, counting and sizing of samples of retained and discarded catch and estimates of their condition and fate.

	Fishing effort screening analysis	**Catch analysis**		
Fishing methods	**Trip and set description**	**Species of special interest only**	**Standard catch characterization**	**Full catch and discard characterization**
Purse seine	$3x$	$4x$	$10x$	$15x$
Longline	x			$19x – 24x$
Trawl	$3x$			$20x$

6. *EMoptim*: a prototype tool to evaluate EM review rates

6.1. Exploring EM review rates

EMoptim, a simulation tool

To investigate minimum EM review rates, we developed a prototype simulation tool based in R, *EMoptim*, that uses stratified random sampling to address one or more monitoring objectives. We used this tool to evaluate EM review rates when EM is implemented as a standalone monitoring method (noting that other data collection tools that may complement EM will often be in use and these should be considered when developing fishery-specific monitoring programs, e.g. logbook data collection). A worked example showing implementation of *EMoptim* using publicly available fishery data from WCPFC is provided at Appendix 2.

Our approach involves setting monitoring objectives to be met by EM (single or multiple objectives can be set in *EMoptim*), and identifying accuracy/confidence requirements (e.g. coefficient of variation, which can differ between objectives), cost limits, or other constraints. We assume that 100% of fishing activity is captured on all vessels in the focal fishery. Existing fishery knowledge is used to identify strata within which sampling effort is allocated for review. Strata may be defined using statistical reporting areas, gear type, fisheries sector, time periods, risks, species characteristics (e.g. distributions of age/size cohorts) or any other factor. Information sources such as risk assessments can be used to estimate the distribution of taxa of interest and interaction rates (e.g. if fishery-dependent information is inadequate).

Simulation modelling is conducted to identify the required review rate within the limits set. In general, review to meet compliance monitoring objectives would require much greater certainty (smaller coefficient of variation) than the collection of target catch information for stock management purposes, for example, and such differences are accommodated when limits are set.

Evolution of any EM program is expected based on lessons learned within the program and new knowledge from external sources. That can be accommodated in *EMoptim* through changing to monitoring objectives (including confidence limits), iterative updates to strata and repeating review rate calculations. Outside of strata with higher review rates identified using *EMoptim*, we recommend that a minimum baseline of 5% random review is maintained to enable detection of significant changes in the fishery and previously unknown fishery issues (e.g. changes in fishing location, bycatch hotspots, etc.) (Figure 4).

Bias is addressed by several facets of this approach. First, all fishing activity is monitored (there is no observer effect) and is therefore available to be sampled. Second, a minimum of 5% of EM imagery is randomly sampled for review in the fishery of interest, over and above any more intensive sampling within strata (noting that small sample size considerations are relevant here[7]). More broadly, bias introduced at the review stage by analysts can be addressed through quality assurance processes implemented at review (e.g. a second independent reviewer auditing 10% of EM imagery, after which the data extracted from the two reviews is compared to assess accuracy)[71].

Using *EMoptim*, we evaluated EM review rates appropriate to monitor target and non-target catch to achieve specified coefficients of variation (Table 7). We emphasize the following caveats on these review rates:

i. Review rates are estimated using aggregated data (WCPFC data at 5° x 5° resolution). Set-level data were not available for use, and therefore we sourced estimates of the number zero-catch sets for each fishing method and taxa from the literature (see Appendix 2).

ii. At the aggregate level, set by set variation is no longer apparent. Therefore, for fishery-specific determinations of review rates, the use of set-level data is strongly recommended, as these data provide significantly more information about the statistical characteristics of events of interest.

iii. In the absence of set-level data, we have based assumptions about the statistical characteristics of events of interest assumed on published literature. These assumptions strongly influence the estimation of review rates. For example, rare bycatch events are characterized by zero-inflation and overdispersion and may be modelled using different distributions depending on dataset characteristics[8,9].

iv. We present *EMoptim* outputs generated from 1,000 simulations. The nature of the approach using genetic algorithms means that consecutive iterations at the same number of runs are likely to have slightly different outputs (i.e. review rates), but these will be in proximity. Simulations should be increased in number until emergent outputs show an acceptable level of stability in review rates. (We also used 10,000 runs of *EMoptim* to generate review rates in Table 7 and explore optimized review rates in Table 8. Many values were the same in the outputs from both sets of runs. With 10,000 runs, only seven values differed by 5% or more, and all except one of these differences was for very rarely caught ETP species characterized by highly overdispersed and zero-inflated capture rate distributions).

EM review rates to monitor catch

Simulations using *EMoptim* demonstrate that stratification can increase the efficiency with which monitoring objectives are met for common catch species (e.g. the target species of yellowfin tuna in this example). For example, to estimate (with CV = 0.1) the number of yellowfin tuna caught in WCPFC longline fisheries, 26% review is required without stratification. When stratified sampling at the 25^{o} x 30^{o} level is introduced, the required EM review rate decreases to 4.4%. If a CV of 0.3 is required, the review rates become 7.8% and ~1% without and with stratification, respectively (Table 7).

Whether or not sampling is stratified, the amount of review required increases as catch frequency decreases. For example, where porbeagle sharks (*Lamna* nasus) are captured on 20% of longline sets, 90% EM review would be required to estimate catch numbers with CV = 0.1 in the absence of stratification. With stratification at the 25^{o} x 30^{o} level, the required review rate decreases to 27% (Table 7).

Endangered, threatened and protected species bycatch events are generally characterized as rare with zero-inflated distributions. As a result, significantly higher levels of EM review are required to estimate numbers of these events effectively. Without stratification, estimating seabird, turtle, and marine mammal bycatch events with a CV of 0.1 would require very high levels of review (effectively a census review in most cases). Considering ETP species groups, stratifying sampling, and requiring a CV of 0.3 can reduce required review rates (Table 7). However, stratification should be expected to have little effect on review rates when rare events are widespread geographically. In such cases, very high review rates will still be required. Ensuring a baseline level of monitoring and considering fishery-independent data across the fishery of interest are critical in this regard to ensure that areas in which bycatch occurs are not overlooked (Figure 4).

Table 7. EM review rates calculated using EMoptim *for a range of tuna fishery catch elements. Publicly available fishery data from the Western and Central Pacific Fisheries Commission were used in* EMoptim *to derive review rates. p0 = the proportion of zero-catch sets, derived from published sources (for sources and a description of* EMoptim*, see Appendix 2). ETP = Endangered, threatened and protected species.*

Catch element	**Example species/group**	**Statistical characteristics of capture events**	**Target CV**	**Longline fishery review %**		**Purse seine fishery review %**	
				No stratification	**25^{o}x30^{o} stratification**	**No stratification**	**25^{o}x30^{o} 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	9.4 - 11.7	3.2 - 4.2		
			0.1	37.9 - 90.1	10.8 - 26.9		
ETP species	Oceanic whitetip shark *Carcharhinus longimanus*	Zif Poisson p0 = 0.75 – 0.90	0.3	11.1 – 47.4	3.8 – 18.3		
		Zif Poisson p0 = 0.75 – 0.90	0.1	12.3 – 73.0	4.8 – 44.6		
		Zif Poisson p0 = 0.99	0.3 0.1			~99.0	~99.0
	Silky shark *C. falciformis*	Zif Poisson p0 = 0.99	0.3			34.2	18.7
			0.1			95.1	32.4
	Black-footed albatross *Phoebastria nigripes*	Zif Poisson p0 = 0.99	0.3	~99.0	91.2		
			0.1	~99.0	95.1		
	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	18.4		
			0.1	~99.0	~99.0		

	Turtles	Zif Poisson p0 = 0.90 – 0.95	0.3	76.4 - ~99.0	9.3 - 95.1	95.1 - ~99.0	8.4 - 87.2
			0.1	95.1 - ~99.0	84.1 - ~99.0	~99.0	80.4 - 91.2
	Marine mammals	Zif Poisson p0 = 0.99	0.3	92.1	87.2	87.2	51.3
			0.1	~99.0	91.2	~99.0	~99.0

Table 8. Examples of optimized 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. Optimization was conducted using publicly available catch information from the Western and Central Pacific Fisheries Commission. CV = Coefficient of variation. p0 = the proportion of zero-catch sets, derived from published sources (for sources and a description of* EMoptim, *see Appendix 2).*

Species	Target CV	No stratification	Optimized stratification		No stratification	Optimized stratification
		% review	**% review**	**Achieved CV**	**% review**	**% review**
Longline						
Yellowfin p0 = 0 Porbeagle p0 = 0.4	0.1 0.3	25.8 9.5	~1.0 ~2.0	0.05 0.22	25.8	~2.0
Purse seine						
Yellowfin p0 = 0 Oceanic whitetip shark p0 = 0.99	0.1 0.3	9.7 ~99	~1.1 ~99	0.09 1.07	~99.0	~99.0

Table 9. EM review rates calculated using EMoptim *with 10,000 runs, showing differences of >5% (italicized) among in outputs among example species/groups compared to 1,000 runs {as shown in Table 7}.*

Catch element	**Example species/group**	**Statistical characteristics of capture events**	**No. runs conducted in *EMoptim***	**Target CV**	**Longline fishery review %**		**Purse seine fishery review %**	
					No stratification	**25ºx30º stratification**	**No stratification**	**25ºx30º stratification**
Other retained species	Porbeagle *Lamna nasus*	Zif Poisson p0 = 0.40 – 0.80	1,000	0.1	37.9 - 90.1	10.8 - 26.9		
			10,000		37.1 – *84.7*	10.5 – 26.5		
ETP species groups	Turtles	Zif Poisson p0 = 0.90 – 0.95	1,000	0.3	76.4 - ~99.0	9.3 - 95.1	95.1 - ~99.0	8.4 - 87.2
			10,000		73.9 - ~99.0	8.7 – *82.1*	95.1 - ~99.0	9.0 – 87.2
			1,000	0.1	95.1 - ~99.0	84.1 - ~99.0	~99.0	80.4 - 91.2
			10,000		~99.0	82.1 - ~99.0	~99.0	83.8 - *~99.0*
	Marine mammals	Zif Poisson p0 = 0.99	1,000	0.3	92.1	87.2	87.2	51.3
			10,000		*~99.0*	*~99.0*	*~99.0*	*30.4*

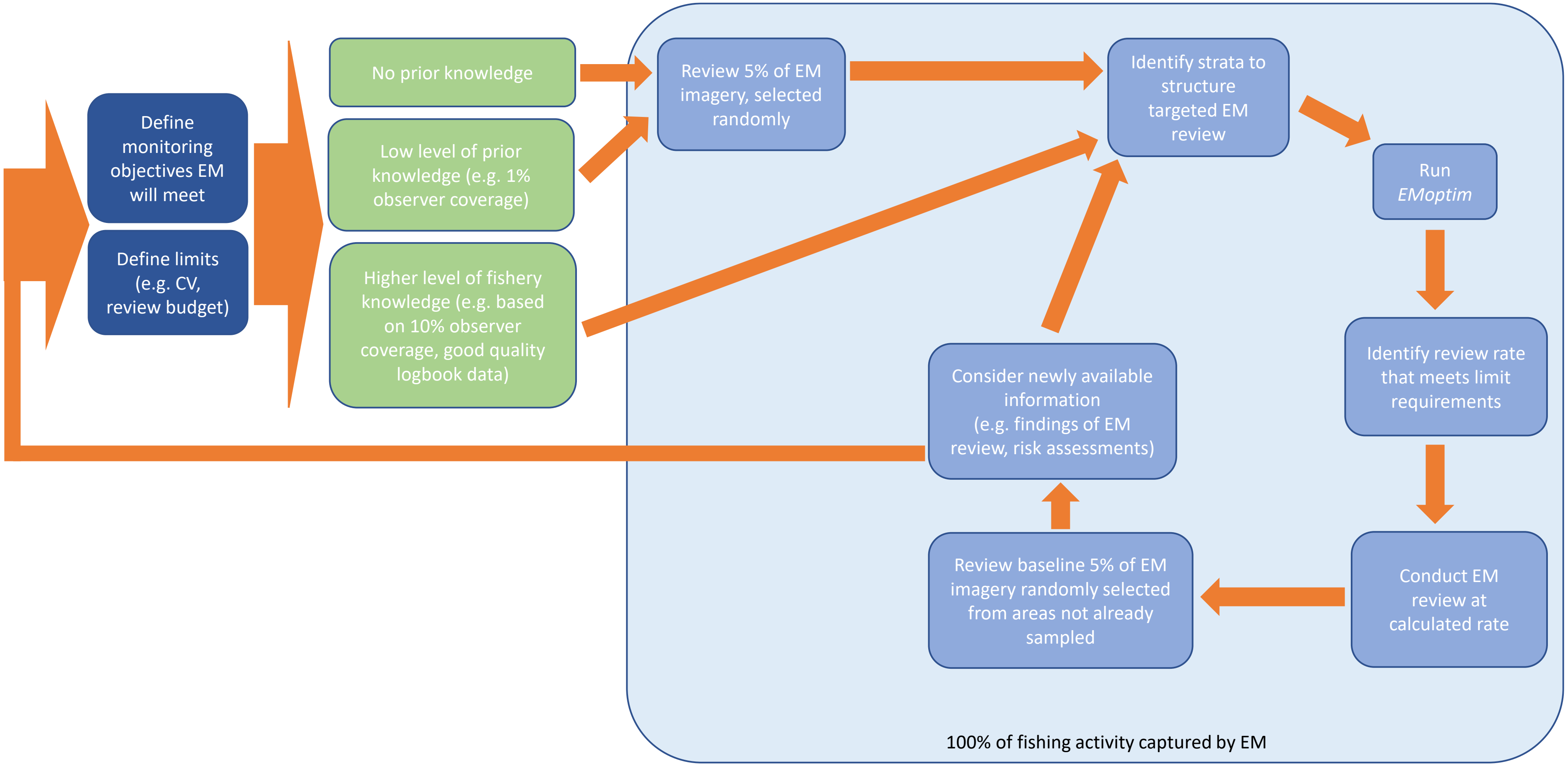

Figure 4. Approach to setting review rates for fishery information collected through electronic monitoring. See Appendix 2 for a description of EMoptim, *a prototype simulation tool based in R that was developed to identify review rates required to meet monitoring objectives within identified limits.*

6.2. Optimizing EM review rates

EM programs often have multiple objectives. Broadly, two approaches can be taken to optimizing EM review rates among management and monitoring objectives. These are (i) to identify the highest priority objective and design review to address that objective. Data relevant to other objectives are then collected to the extent possible within the regime designed for the priority objective. Associated uncertainties can be determined analytically and considered alongside review findings. Alternatively, approach (ii) is when review is designed to meet multiple monitoring objectives, such that more review may be required than the minimum level needed for any single objective. This could result from differences in the spatial distribution and statistical characteristics of events of interest (e.g. common, ubiquitous events compared to rare, clustered events).

Using *EMoptim*, we explored optimized rates of EM review needed to estimate target and bycatch catch, to achieve specified coefficients of variation. Review rates necessary to optimize any combination of objectives could be examined using this simulation tool. Outputs highlighted that practically, optimizing sampling regimes for different monitoring objectives is most effective among more commonly caught species. As soon as rarely caught species are introduced to the optimization process, the required EM review rate increases dramatically (Table 8). For optimization scenarios, increasing the number of simulations conducted by *EMoptim* from 1,000 to 10,000 had little impact on required review rates in most cases (Table 9).

The cost of review is usually a critical factor affecting EM review rate selection, and the key trade-off becomes data needs versus available resources (budgetary and/or human, in the form of analyst hours). To enable exploration of costs against monitoring objectives, *EMoptim* incorporates a cost function, developed based on pricing estimates for analysis of EM imagery and associated information (Table 6). Costs are estimated as a baseline for characterizing the sampling frame, with an additional amount commensurate with the monitoring objectives. Cost estimates would be refined over time for monitored fisheries, e.g., as fishery-specific information becomes available from EM programs, analyst efficiency increases with experience, etc., and this information could then be incorporated in *EMoptim* to refine review strategies.

7. Best-value approaches to EM review: present and future

Robust EM program design is critical for supporting efficient and cost-effective EM review, and fishery-specific information is an essential input to program design. Indicative baseline rates can be identified for appropriate EM review (Table 10), while fishery-specific review rates should be determined using set by set data. Stratifying samples of EM imagery reviewed can significantly increase review cost efficiency, notably for taxa that are commonly caught and/or have restricted distributions. Nonetheless, a baseline cost is required to identify the sampling frame for EM review, beyond which costs increase with review complexity.

Opportunities for increasing cost efficiency of EM review, both now and into the future, vary among monitoring objectives and data types. Such opportunities include improving the quality of logbook data to support audit-based EM review and investigating subsampling approaches for data elements not expected to change dramatically within a fishing trip. Contributing to the continued development and implementation of automated review tools supported by computer vision and artificial intelligence is also strongly encouraged, e.g. through contributing imagery to open access datasets used for computer vision work (Table 10).

EM has great potential to collect data at scale to meet the needs of commercial fisheries management. Information requirements that can be met by EM are shared across RFMOs and among other fishery management bodies. EM service providers operate across geographic and jurisdictional boundaries. Existing knowledge provides a strong foundation for progress without reinvention. Evidence requirements of seafood sustainability schemes[47] and consumer-driven demands for supply chain transparency[90] provide additional stimuli for knowledge-sharing, optimizing EM implementation including at review, and improving EM cost efficiencies. As a result, there is a nascent and significant opportunity to accelerate EM adoption and accrual of its benefits, to realize best value from this monitoring method in the immediate future and for the longer term.

*Table 10. EM review rate guidelines for the collection of selected EM-derived data elements to support longline and purse seine fishery management. Figures are indicative not definitive, do not consider stratified review sampling options, and will vary with respect to management and monitoring objectives and fishery characteristics. Partial documentation by EM implies detection in the absence of a dedicated set-up that would not routinely be part of an EM system (e.g. to monitor fish waste discharge, camera coverage of all points of waste exit from the vessel would be required). Options to optimize the use of EM could be supported and implemented by a range of actors, including EM practitioners, fishery scientists and management bodies. (*EM is expected to more accurate than logbook information, and in use in the absence of human observers).*

Data types	Data elements	Review rate (no stratification)	Considerations	Options to optimize the use of EM
Operational	Trip and set start and end date, time, location	100%	Baseline review element required to determine sampling frame.	Mainstream automated detection of fishing events in EM review software.
	Marine pollution events	Opportunistic	Partial documentation by EM.	Collect data from EM review as objectives require and resources allow.
	Abandoned/lost gear	Opportunistic	Partial documentation by EM.	
Fishing gear, effort	Floats (longline)	100%	Indicates number of baskets; proxy for number of hooks per set.	Normalize float counts as a proxy for extensive hook counts at EM review (see below).
	Hooks set/hauled (longline)	Subsample	Float counts and hooks per basket provide a proxy for total hooks; subsampling approach assumes consistent number of hooks/basket.	Investigate variation in hook numbers per basket in focal fisheries, to determine optimal subsampling rates in lieu of extensive hook counts.
	FAD use, type (purse seine)	100%	Relevant to fishery characterization and compliance.	
	Search time (purse seine)	100%	Relevant to fishery characterization and compliance.	
Catch characterization	Target catch species (assuming catch on all sets)	~5 – 10% (CV = 0.3)	Most likely catch component to be recorded accurately in logbooks. Verification of retained catch also possible at landing.	Use set by set data from at least 5% monitoring coverage (Figure 4) to stratify sampling for review, estimate fishery-specific EM review rates to meet monitoring objectives. EM imagery also provides a source of length information (sampling process determined by monitoring objectives; sampling can also be stratified using *EMoptim*). Improve quality of logbook data to support an audit approach to review.
	Commonly caught retained species (e.g. caught on 20 - 40% of sets)	~10 – 15% (CV = 0.3)	May be relatively accurately recorded in logbooks. Verification also possible at landing.	

				Contribute imagery to open access datasets that support the development of computer vision tools for catch identification[40].
	Bycaught/discarded species (e.g. caught on 10 - 25% of sets)	~10 – 50% (CV = 0.3)	EM likely to be the most accurate data source*.	Use set by set data from at least 5% monitoring coverage (Figure 4) to stratify sampling for review; estimate fishery-specific EM review rates to meet monitoring objectives. Contribute imagery to open access datasets that support the development of computer vision tools for catch identification[40].
	Rarely bycaught species groups (caught in low numbers on 1 - 10% of sets)	~75 – 100% (CV = 0.3)		Explore review speeds faster than normal time, to identify optimal speeds for detection accuracy and efficiency. Contribute imagery to open access datasets that support the development of computer vision tools for catch identification[40].
	Rarely bycaught species (caught in low numbers on ~1% of sets)	~100% (CV = 0.3)		
Bycatch mitigation	Tori line deployment	Recommended minimum: all sets/hauls for which catch sampling is undertaken. Sampling level up to 100%.	Can quickly be assessed at the start of each longline set/haul. Relevant to fishery characterization (seabird bycatch risk) and compliance.	
	Bird curtain			
	Dehooker and line-cutter use	Sampling rate same as for focal taxa; up to 100%.	Relevant to fishery characterization (impacts of bycatch on non-target species) and compliance.	
	Bycatch handling			
	Wire traces	Subsample	Combine with hook subsampling. Relevant to fishery characterization (bycatch risk) and compliance.	Investigate consistency in usage per basket and attrition/maintenance through trips, to determine optimal subsampling rates in lieu of requiring comprehensive counts.
	Line weights	Subsample		
	Hook-shielding devices	Subsample		
	Dyed bait	Subsample		
	Fish waste discharge	Opportunistic	Partial documentation by EM. Relevant to fishery characterization (bycatch risk).	Collect data from EM review as objectives require and resources allow.

8. Acknowledgements

The authors thank the many case study contributors, as well as C. Heberer, G. Hurry, G. Legorburu, M. Michelin, and JT Mudge, for sharing their knowledge, experience and insights. (See individual case studies for a full list of contributors). Thanks also to Pew's International Fisheries and Conservation Science teams and peer reviewers H. Walton and A. Barney for their contributions, which enhanced the products of this project.

This work was completed with the support of 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.

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Appendix 1. Data requirements that support fisheries management by selected Regional Fisheries Management Organizations.

*Regional Fisheries Management Organizations (RFMOs) are 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. Material relating to ICCAT is derived from the Protocol to amend the International Convention for the Conservation of Atlantic Tunas, as adopted by the Contracting Parties to ICCAT on 18 November 2019. The Protocol has not entered into force as yet, while Contracting Parties deposit their instruments of approval, ratification, or acceptance. 'Functions / actions' are the obligations or actions of the Commissions that are relevant to the information that can be collected by electronic monitoring. Those in bold have specific quantitative or analytical meanings. 'Focal fish stocks' are those in-scope for the Convention, that are not associated or dependent species, or otherwise identified as non-target species. MSY = Maximum Sustainable Yield. FAO = Food and Agriculture Organization of the United Nations. *1982 Convention = the United Nations Convention on the Law of the Sea of 10 December 1982; Agreement = Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks. Italic table text indicates verbatim wording.*

	IATTC **https://www.iattc.org/**	**ICCAT** **https://www.iccat.int/en/**	**IOTC** **https://www.iotc.org/**
RFMO Objectives	*to ensure the long-term conservation and sustainable use of the fish stocks covered by this Convention, in accordance with the relevant rules of international law*	*to cooperate in maintaining the populations of tuna and tuna-like fishes and elasmobranchs that are oceanic, pelagic, highly migratory and found in the Atlantic Ocean, at levels that will permit their long-term conservation and sustainable use for food and other purposes*	*promote cooperation among Members with a view to ensuring, through appropriate management, the conservation and optimum utilization of stocks covered by this Agreement and encouraging sustainable development of fisheries based on such stocks*
Focal fish stocks	*stocks of tunas and tuna-like species and other species of fish taken by vessels fishing for tunas and tuna-like species in the Convention Area*	*populations of tuna and tuna-like fishes and elasmobranchs that are oceanic, pelagic, and highly migratory found in the Atlantic Ocean*	populations of 16 tuna and tuna-like species occurring in the Convention Area or migrating into or out of that Area
Precautionary approach explicit	Yes	Yes	No
Principles / Functions / Actions	research on the abundance, biology and biometry of focal fish stocks, and associated or dependent species as necessary	protect biodiversity in the marine environment	to gather scientific information, catch and effort statistics and other data relevant to the conservation and management of the stocks and to fisheries based on the stocks
	adopt evidence-based measures such that harvested stock status supports MSY	study of the populations of tuna and tuna-like fishes and elasmobranchs that are oceanic, pelagic, and highly migratory species, species belonging to the same ecosystem, and associated and dependent species	to adopt evidence-based conservation and management measures to ensure the conservation and optimum utilization of the focal stocks

	assess focal stock status, with specific reference to whether stocks are fully fished or overfished	collecting and analyzing statistical information relating to the current conditions and trends of focal species	ensure implementation and enforcement of binding conservation and management measures [Members]
	adopt measures to ensure associated and dependent species populations are above levels at which reproduction may be seriously threatened	**studying and appraising information relevant to ensuring focal species populations are at or above levels commensurate with MSY, and exploitation is consistent with MSY**	
	adopt appropriate measures to address waste, discards, non-target catch, catch by lost or discarded gear, and impacts on associated and dependent species	**make evidence-based recommendations designed to ensure focal species are at or above status commensurate with MSY**	
	ensure fishing effort does not exceed a level commensurate with sustainable use of focal species	**promote the conservation of associated and dependent species such that populations are above levels at which reproduction may become seriously threatened**	
	ensure implementation of, and compliance with, adopted conservation and management measures [Parties]	take all actions necessary to enforce the Convention [Members]	

	WCPFC **https://www.wcpfc.int/**	**CCSBT** **https://www.ccsbt.org/**	**NPFC** **https://www.npfc.int/**
RFMO Objective	*to ensure, through effective management, the long-term conservation and sustainable use of highly migratory fish stocks in the western and central Pacific Ocean in accordance with the 1982 Convention and the Agreement**	*to ensure, through appropriate management, the conservation and optimum utilisation of southern bluefin tuna*	*to ensure the long-term conservation and sustainable use of the fisheries resources in the Convention Area while protecting the marine ecosystems of the North Pacific Ocean in which these resources occur*
Focal fish stocks	all fish stocks listed in Annex 1 of the 1982 Convention that occur in the Convention Area (except sauries), and other fish species as determined by the Commission	Southern bluefin tuna	Fish, mollusks, and other marine species caught by fishing vessels, with specific exclusions (sedentary species, indicator species of Vulnerable Marine Ecosystems, catadromous species, marine mammals, reptiles and birds, other species covered by pre-existing management instruments)
Precautionary approach explicit	Yes	No	Yes

Principles / Functions / Actions	**determine the total allowable catch or total level of fishing effort and adopt measures to ensure long-term sustainability of highly migratory fish stocks**	consider regulatory measures for conservation, management and optimum utilization of southern bluefin tuna including catch limits, and any other measures	promote the optimum utilization and ensure the long-term sustainability of fisheries resources
	adopt evidence-based measures such that stock status supports MSY	assess and analyze the status and trends of the population of southern bluefin tuna [Scientific Committee]	**adopt evidence-based measures such that stock status supports MSY and long-term sustainability of fisheries resources is ensured**
	assess the impacts of fishing on target stocks, non-target species, and species belonging to the same ecosystem or dependent upon or associated with the target stocks	report views on the stock status of southern bluefin tuna and, as appropriate, ecologically related species [Scientific Committee]	adopt measures in accordance with the precautionary approach and an ecosystem approach to fisheries
	adopt measures to ensure non-target, associated and dependent species populations are above levels at which reproduction may be seriously threatened	provide scientific information, fishing catch and effort statistics and other data relevant to the conservation of southern bluefin tuna and, as appropriate, ecologically related species [Parties, to the Commission]	assess impacts of fishing on associated and dependent species and those belonging to the same ecosystem as target stocks
	adopt appropriate measures to address waste, discards, non-target catch, catch by lost or discarded gear, and impacts on associated and dependent species	ensure enforcement of the Convention and compliance with binding measures [Parties]	**adopt measures to ensure non-target, associated and dependent species populations are above levels at which reproduction may be seriously threatened**
	collect complete and accurate data concerning fishing activities, including vessel position, catch of target and non-target species and fishing effort		protect marine biodiversity including by preventing significant adverse impacts on Vulnerable Marine Ecosystems
	implement and enforce conservation and management measures through effective monitoring, control and surveillance		ensure that complete and accurate data concerning fishing activities are collected, including target and non-target species
	take into account, among other things, uncertainties relating to the size and productivity of the stocks, reference points, stock condition in relation to such reference points, levels and distributions of fishing mortality and the impact of		minimize pollution and waste originating from fishing vessels, discards, catch by lost or abandoned gear, and impacts on other species and marine ecosystems

	fishing activities on non-target and associated or dependent species		
	develop data collection and research programs to assess the impact of fishing on non-target and associated or dependent species and their environment		ensure compliance with conservation and management measures
	subject stocks and species of concern to enhanced monitoring to review their status and the efficacy of conservation and management measures (and update measures in light of new information)		

Appendix 2. EM review rate evaluation and optimization by *EMoptim*

Introduction

EMoptim is a prototype simulation tool based in R[4], that optimizes a sampling stratification with stratified random sampling (SRS) for multiple objectives assuming distributions and sampling based on electronic monitoring of fisheries activity. SRS is a random sampling technique in which the total population is divided into strata, with samples taken from each stratum and combined to give a population estimate. When groups with similar properties are combined into a stratum, greater efficiency can be obtained which reduces the total number of samples required to achieve a given level of uncertainty in the resulting population estimate.

The *EMoptim* R software provides a simple interface into functions that (i) provide an expected sampling coefficient of variation (CV) for a given stratification, based on assumed or actual data from a fishery; and (ii) provide an estimate of optimal strata definitions and sampling allocation that can meet multiple objectives with different underlying statistical and spatial distributions to improve the overall sampling efficiency.

We assume that electronic recording of all fishing events is available, and that the expected rates of capture are available for a fishery and are ordered in some spatially aggregated manner. The simulation tool (*EMoptim*) takes data from an external file that defines the fishery, species distributions, encounter rates expected (with the assumed statistical distributions), and definitions of sampling objectives. This is read into R as (and object called) *EMobject*. Statistical distributions for the encounter rates that are implemented are the binomial distribution (parameterized by a proportion p), the Lognormal distribution (parameterized by μ and CV), the negative binomial distribution parameterized by μ and θ), the normal distribution (parameterized by μ and σ), the Poisson distribution (parameterized by λ), and the zero-inflated Poisson (parameterized by λ and *pzero*, the probability of zero).

Here we use the Western and Central Pacific Fisheries Commission's (WCPFC) publicly available data for the longline fishery. Using these data, we provide an example of how the package can work and be used to identify optimal strata and resulting coverage rates to meet different objectives across different species of interest and different assumed statistical distributions.

In the example below based on the WCPFC longline data, the assumed data is held in *EMobject* which can be created from a simple text file with a specific command and subcommand structure.

Specification of the input configuration file

Defining the *EMoptim* fleets, species, encounter rates, and objectives

The *EMoptim* input configuration file is a plain text file and is made up of a number of commands (each with subcommands) which specify various options for each of these components. Commands always begin with an **@** character, with several commands also requiring a label.

Subcommands follow the command, with each subcommand having an argument. Subcommands have a 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.

For example, to specify the model structure in *EMoptim*, use the command **@model** to specify the size of the grid (rows and columns), and the names of the strata, fleet, and species definitions. For example, the Convention Area of WCPFC covers a region 60° S to 55° N and 100° E to 141° W in the Pacific Ocean (Figure 1). This can be represented as a matrix of 29×25 cells of 5°×5° aggregated data.

The fisheries that operated in the region can be classified into 'fleets', however for this example we will assume that there were two fleets, longline and purse seine as these two fleets are the fisheries that were specified in the publicly available data. In practice, fleets could be defined using vessel, nation, or other operating characteristics to identify and improve estimates of incidence rates that may be more appropriate for management advice.

Species of interest will depend on the management requirements. In this example, we use the publicly available data to identify a subset of species/species groups for the purposes of this example: yellowfin tuna catch, shark catch, seabird captures, and marine mammal captures.

The WCPFC CMM 2018-03 (Conservation and Management Measure to mitigate the impact of fishing for highly migratory fish stocks on seabirds) defines seabird management areas for mitigation requirements: south of 30° S, at least two of the three defined mitigation measures; 25° S to 30° S at least one of the three defined mitigation measures; 25° S to 23° N, no mitigation measures required; and north of 23° N, to use at least two of the mitigation measures in Table 1 of CMM 2018-03.

Hence, we can specify a model using a map size of 29×25 cells with the pre-defined strata for the seabird mitigation management (labelled *ManagementUnits* in this example); the longline (LL) and purse seine (PS) fleets; longline capture rates for yellowfin tuna (LL_yellowfin), sharks (LL_shark), seabirds (LL_bird), and marine mammals (LL_mammal); purse seine capture rates for yellowfin (PS_yellowfin), marine mammals (PS_mammal), and sharks (PS_shark).

This model structure is defined in the *EMoptim* input configuration file as:

```
@model
map_rows 29
map_cols 25
strata_definitions ManagementUnits
fleet_definitions LL PS
species_definitions LL_yellowfin LL_porbeagle LL_bird LL_shark LL_mammal PS_yellowfin PS_mammal PS_shark
```

Historically available public data from the WCPFC has data at 5°×5° aggregated cells for the longline fishery. We can identify those cells where no sampling should be undertaken (i.e., as no effort is recorded there, a cell that is on land, or to select subregions of the area of interest, etc.) with the definition of a base map. This defines those cells that are available for *EMoptim* to use in simulations or as valid cells for optimization of strata. Cells with a base map value of zero are ignored. The base map used for the WCPFC example is given as Figure 2.

The definition of the base map in the input configuration file uses the *table* and *end_table* subcommands to define the map of areas available, i.e.,

```
@base_map
table data
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0
... [more rows]
end_table
```

Similarly, any pre-defined strata have a similar format but use the command **@strata [label]**, where **[label]** represents the label for that stratification. Multiple strata can be input using a separate **@strata** command for each with unique labels for each one.

```
@strata ManagementUnits
table data
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
...[more rows]
5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5
end_table
```

We use the 2019 data from the WCPFC in this example (the most recent year for which all data were available and a year prior to any potential effect of COVID-19 on fishing patterns), but we note that data could be averaged across several years or different years' data could be trialed to assess the effect of temporal variation in fishing patterns on the *EMoptim* model outputs. Temporally specific fleet maps and the sampling could also be specified in the optimization to consider fleet and event distributions for different seasons or temporal periods.

The **@fleet** definition command and subcommands are similar to **@strata**, but with the value in each cell of the matrix indicating the amount of "effort". The values in the 'fleet' represent the available sampling units.

In this case the publicly available longline data are available in numbers of hooks, but the sampling unit for any electronic monitoring sampling is most likely to be sets. We assume that each set represents 3,500 hooks, broadly characteristic of a large-scale pelagic longline fishery[3], and hence assume the effort in each cell is the number of hooks reported in that cell and divided by 3,500. For the purse seine data, the effort is given in days, and we assume that each day represents one purse seine haul[5]. We note that these are approximations, and that set by set data would ideally be used (while such data are generally publicly unavailable due to confidentiality requirements).

Associated with each unit of effort is a cost. Here, we assume that identifying each unit of effort has a fixed cost and is directly proportional to the amount of effort recorded in each fishery (i.e., fleet). In this case, we assume that the cost of identifying each unit of effort and characterizing this using electronic review is: €5 for each day of longline fishing (corresponding to a set, with approximately one set per day) with an additional €90 per day for analysis where catch composition is relatively simpler (including identifying bycatch events); and €15 for each day of purse seine fishing (corresponding to a set, with approximately one set per day) with an additional €30 per day for standard analysis (including identifying bycatch events) but excluding length sampling (G. Legorburu, DOS, pers. comm.).

In the case of the WCPFC, the longline fishery (Figure 3) is represented in the input definition file as,

```
@fleet LL
table data
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
...[more rows]
0 0 0 0 0 0 0 0 0 25 29 6 0 0 4 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 13 14 33 17 0 0 25 0 0 0 19 11 0 0 0 0 0
...[more rows]
end_table
cost 5
```

For the species used in the WCPFC example, logbook (yellowfin, porbeagle, and oceanic whitetip) and observer (seabirds and marine mammals) capture rates were available. Capture rates are given in two @commands. **@species[label]** gives the expected spatial distribution of capture rates (scaled to have a maximum of one). The scaling multiplier to scale the distributions to reported capture rates is given in **@encounter**, along with the assumed statistical distribution associated with the capture rate (i.e., Poisson, negative binomial, lognormal, etc).

```
@species LL_yellowfin
table data
0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 ...[more columns]
0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 ...[more columns]
0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 ...[more columns]
0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 ...[more columns]
0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0006 0.0015 0.0022 0.0000 0.0000 ...[more columns]
...[more rows]
end_table
cost 90
```

With encounters of yellowfin in the longline fleet described by an assumed lognormal distribution with μ = 684.5 and CV = 0.3 (i.e., the maximum capture number of yellowfin per 3,500 hooks in 2019 in the WCPFC 5°×5° aggregated data (Figure 4)),

```
@encounter LL_yellowfin
fleet  LL
species LL_yellowfin
type lognormal
mu 684.4986
cv 0.3
```

Similar distribution maps and encounter assumptions are required for each species or species group (e.g., seabirds, see Figure 5) and fleet combination that will be evaluated using *EMoptim*. Note that in this example we have used the observed capture rates estimated from observer coverage and available from the WCPFC public aggregated logbook data. Alternatively, species distribution maps could be used or some other estimates of species' distributions or capture rates as the basis for this process.

Sampling objectives are defined using the command **@objective[label]**. For example, to define an objective for the longline fleet for sampling of yellowfin, the **@objective** command specifies the *encounter* (LL_yellowfin) along with the target CV. Given that yellowfin abundance is an important quality to verify, we assume that the target coefficient of variation in the abundance estimate for yellowfin was CV=0.10.

```
@objective LL_yellowfin
encounter LL_yellowfin
cv 0.1
```

Multiple objectives can be supplied (e.g., sampling for sharks, seabirds, marine mammals, etc), and for each objective there must be 'fleet' and 'species' maps that correspond to the objective subcommands fleet and species respectively. (Note that *EMoptim* will only optimize across multiple objectives if multiple objectives are defined. See later for optimizing over multiple objectives).

Simulation ranges and values are defined with the **@simulation** command. This specifies the number of simulations (in this example, n = 1000) to use when evaluating an objective; the default *sampling_rate* (for evaluating current sampling rates for example and set to 3.8%, based on the level of coverage achieved by observers in the WCPFC in 2019), and the range of sampling rates to value (*min_sampling_rate* to *max_sampling_rate* with the number of steps equal to *steps*) to determine the sampling rates required for achieving sampling targets.

```
@simulations
N_simulations 1000
sampling_rate 0.038
max_sampling_rate 0.99
min_sampling_rate 0.01
steps 26
```

Note that more simulations improve accuracy but may take some time to undertake. Similarly, a greater number of steps also may take some to evaluate and complete the simulations. The speed of *EMoptim* will also strongly depend on the specifications of the computer used to undertake the simulations.

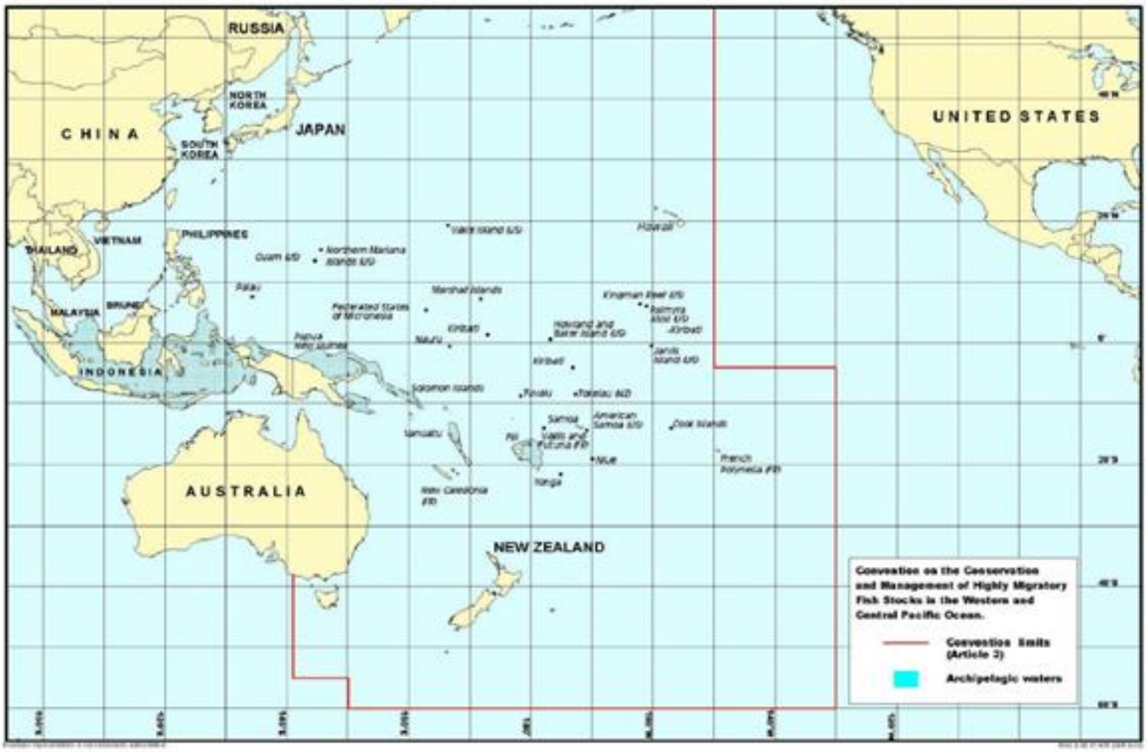

Figure 1. The Convention Area of the Western and Central Pacific Fisheries Commission (Source: https://www.wcpfc.int/ [Accessed 15 May 2022]).

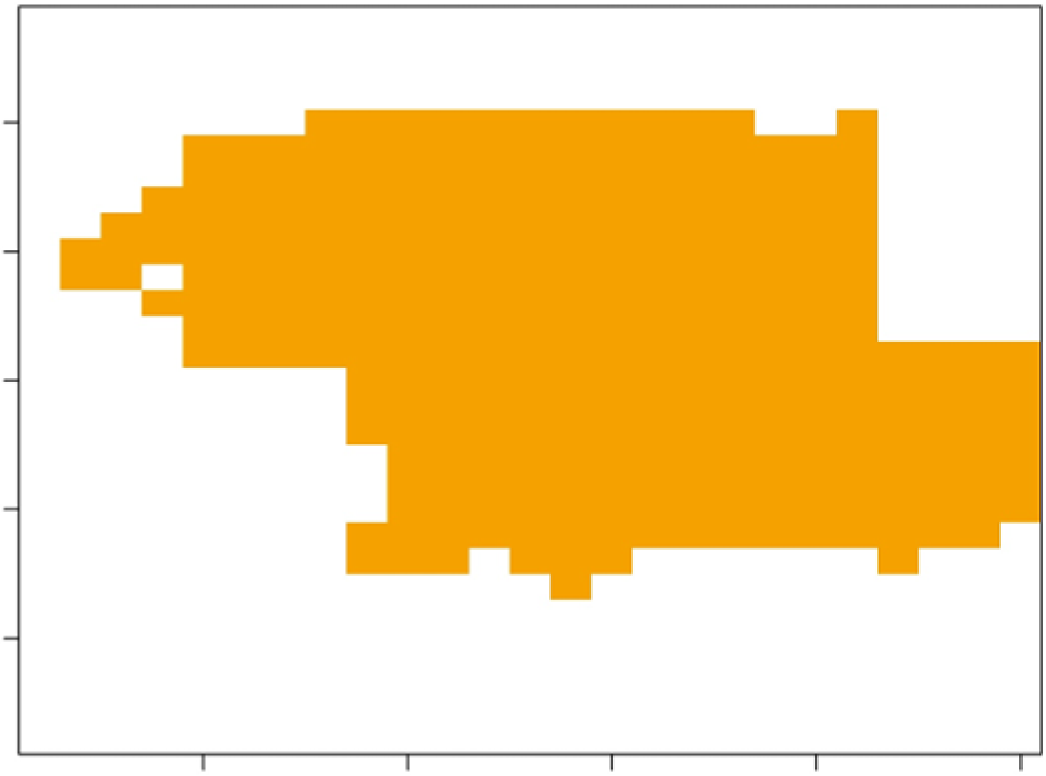

Figure 2. 5°×5° cells (orange shading) that have been historically fished with longlines in the Convention Area of the Western and Central Pacific Fisheries Commission between the years 1950 and 2019. Axes show latitude (y axis) and longitude (x axis) in 25° increments.

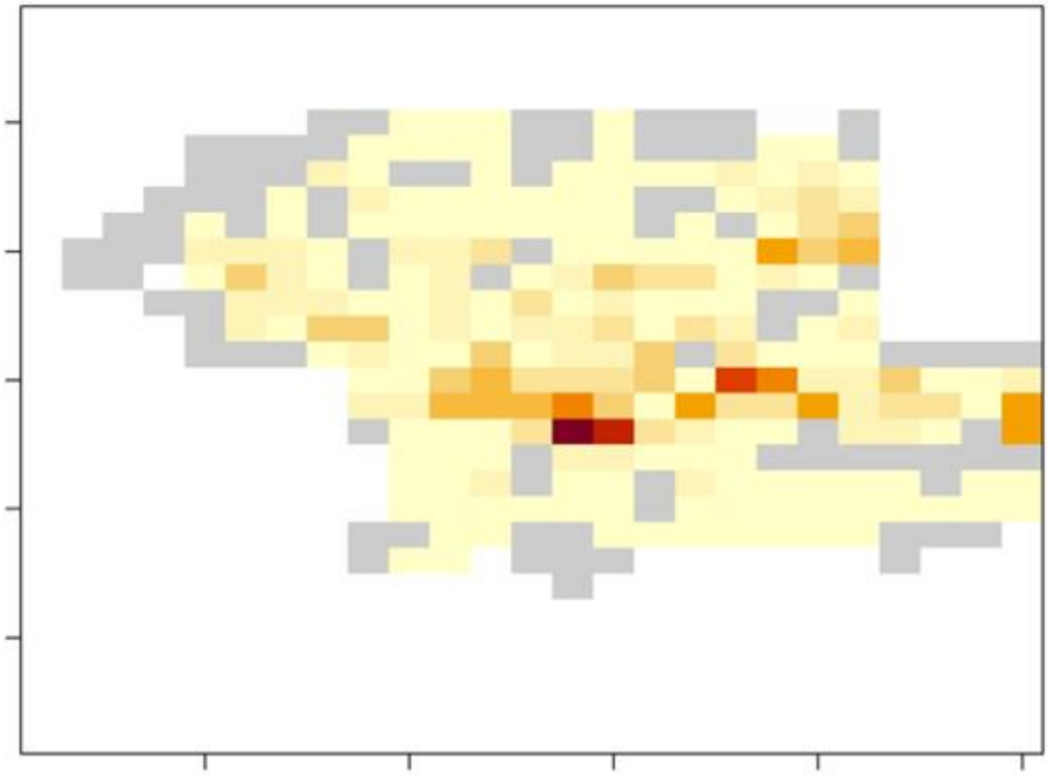

Figure 3. Density of the longline fleet by 5°×5° cells in the Convention Area of the Western and Central Pacific Fisheries Commission in the year 2019 (yellow to red indicates increasing density and grey cells indicate zero density). Axes show latitude (y axis) and longitude (x axis) in 25° increments.

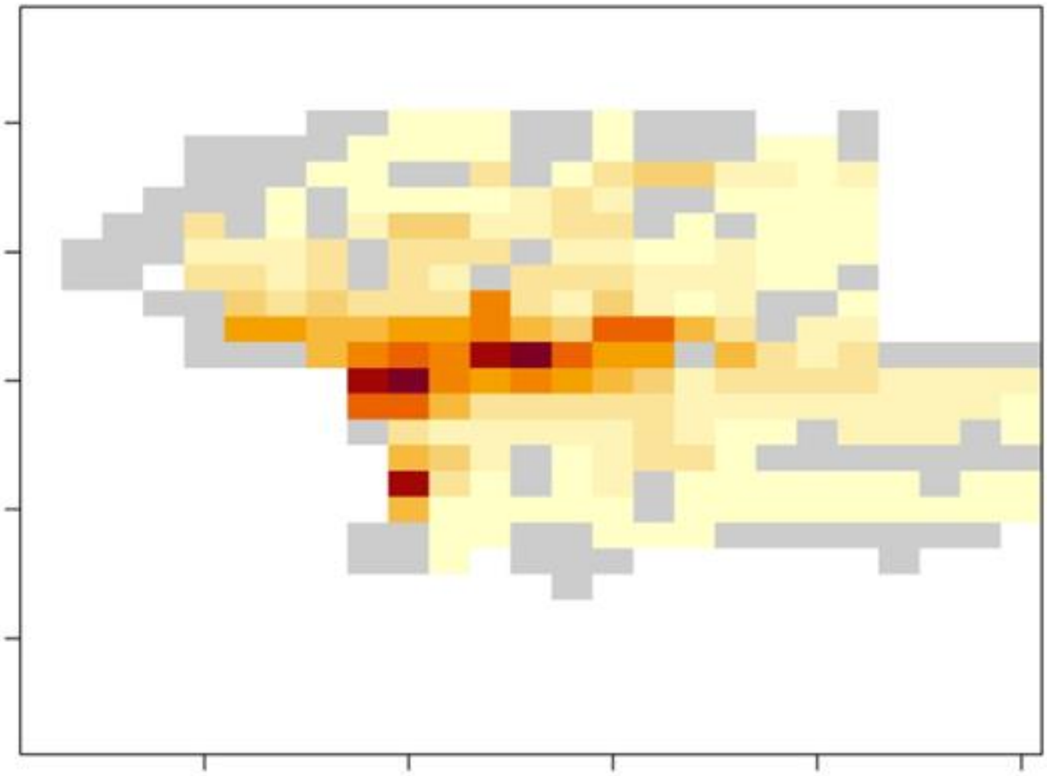

Figure 4. Density of logbook yellowfin tuna capture rates in the longline fleet by 5°×5° cells in the Convention Area of the Western and Central Pacific Fisheries Commission in the year 2019 (yellow to red indicates increasing density and grey cells indicate zero density). Axes show latitude (y axis) and longitude (x axis) in 25º increments.

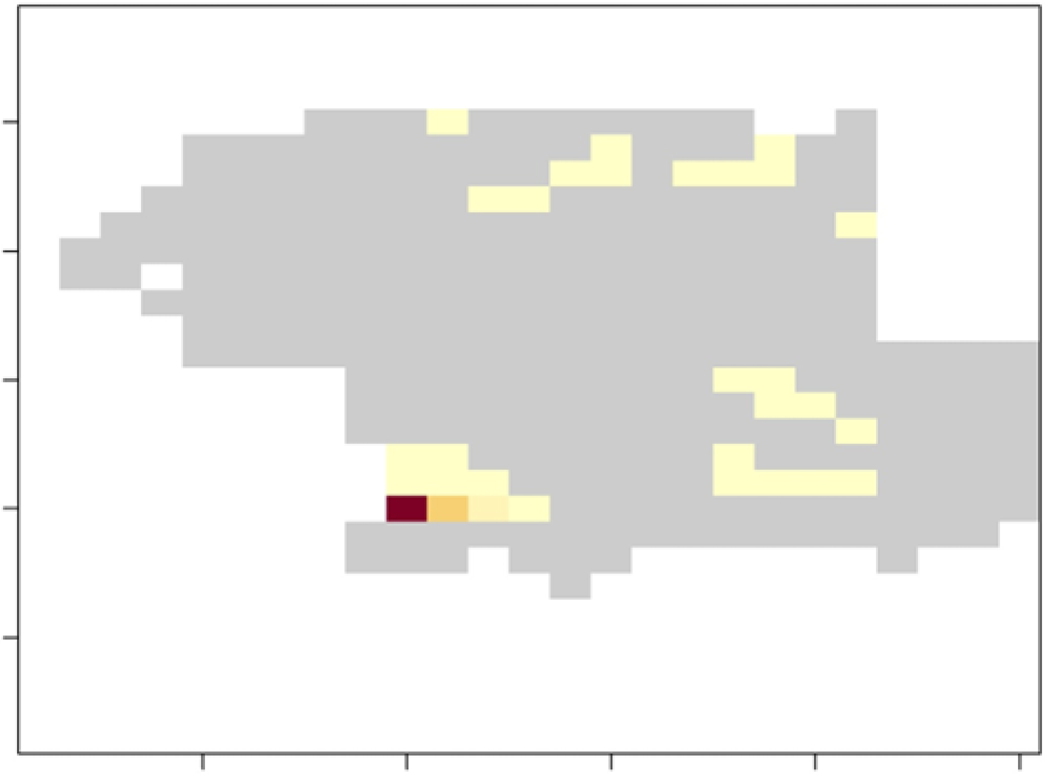

Figure 5. Density of seabird capture rates reported by observers in the longline fleet by 5×5° cells in the Convention Area of the Western and Central Pacific Fisheries Commission in the year 2019 (yellow to red indicates increasing density and grey cells indicate zero density). Axes show latitude (y axis) and longitude (x axis) in 25° increments.

Running *EMoptim*

EMoptim is run in **R** (R Core Team 2021), and is available as an R package. The R command **input.config.file()** is used to read an *EMoptim* configuration file into R. This creates an *EMobject* that is used by the rest of the *EMoptim* functions.

```
> library(EMoptim)
# Input config file
> EM <- input.config.file("WCPFC.def")
```

Simple lists of the objects available in the input file can be made with the utility function **getObject()**. This function takes an *EMobject*, and character string of the object names (i.e., fleet, species, encounter, or objective) and its label (or a list of labels if the label is not supplied).

```
> getObject(EM, "encounter", "LL_shark")
$encounter
[1] "LL_shark"
$cv
[1] 0.3
$min_value
[1] 0
```

Plotting of the supplied maps of data can be undertaken with the **plotEMmap()** function, i.e.,

```
plotEMmap(EM, type="base", xlab="Longitude (5 degree cells)", ylab="Latitude (5 degree
          cells)")
plotEMmap(EM, type="fleet", label="LL", xlab="Longitude (5 degree cells)", ylab="Latitude (5
          degree cells)")
```

Evaluating a pre-defined stratification

A single objective with a sampling stratification and a chosen sampling rate can be evaluated using **EMsample()**. For example, to estimate the sampling fractions for the *ManagementUnits* stratification defined above and using the default sampling rate,

```
> ans1 <- EMsample(EM, objective.label = "LL_bird", strata.label = "ManagementUnits")
```

This returns an object with the number of samples allocated using Neyman allocation to each of the stratum in the defined stratification, the expected CV in each stratum, and the overall expected CV for the sample design.

In this example, the overall expected number of samples would be *n* = 650, corresponding to a sampling rate of 3.8% (the supplied default and equal to the achieved overall rate of observer sampling in the WCPFC longline fishery in 2019), and giving an expected CV = 0.99 for the mean seabird captures.

The overall CV is given in the cv element, total number of samples for a rate of 3.8% in the N element, and the parameters for the sampling are given in the parameters element of the object returned by **EMsample()**, i.e.,

```
> set.seed(0)
> ans1 <- EMsample(EM, objective.label = "LL_bird", strata.label = "ManagementUnits")
> ans1$cv
[1] 0.9869387
> ans1$N
[1] 649.572
> ans1$parameters
  strata N.population   fraction          mu          sd   N
1      1         1342 0.01191153 0.017713459 0.002441512   8
2      2        14770 0.09872754 0.003777525 0.001838661  64
3      3          505 0.03285953 0.158897684 0.017898385  21
4      4          477 0.85650140 0.145950313 0.493916485 556
5      5            0 0.00000000 0.000000000 0.000000000   0
```

We can then use this stratification to evaluate its how efficient the sampling stratification and sampling fractions for each stratum would be with, for example, mammals. We can supply the stratification and sampling fractions in each strata to **EMsample()**.

```
> set.seed(0)
> ans2 <- EMsample(EM, objective.label = "LL_mammal", strata.label = "ManagementUnits",
          sampling.fractions = ans1$parameters$fraction)
> ans2$N
[1] 649.572
> ans2$cv
[1] 3.147359
> ans2$parameters
  strata N.population   fraction           mu           sd   N
1      1         1342 0.01191153 0.0005685337 2.321188e-05   8
2      2        14770 0.09872754 0.0004237071 1.953779e-05  64
3      3          505 0.03285953 0.0000000000 0.000000e+00  21
4      4          477 0.85650140 0.0018315841 2.432610e-04 556
5      5            0 0.00000000 0.0000000000 0.000000e+00   0
```

Here, the overall expected CV with the same sample size (*n* = 650) allocated to the *ManagementUnits* strata in the same proportions for marine mammals was CV = 3.15.

Iterating over a range of sampling rates can be used to evaluate a given stratification for its performance against an objective. To evaluate the expected CV for a given number of samples (or sampling rates) with a given strata use the function **EMiterate()**. This takes arguments of the *EMobject* along with an objective label.

For example, optimizing the sampling rate for seabirds in the longline fishery (and with 26 cores using parallel processing to reduce the time for the iterations to be undertaken), then summarizing the results (i.e., obtaining the expected CV for each sampling rate)

```
> LL_bird <- EMiterate(EM, objective.label = "LL_bird", strata.label = "ManagementUnits",
          parallel=TRUE, cores = 16)
Optimisation using parallel = TRUE. Using 26 cores
> ans3 <- EMsummary(EM, EMiterations = LL_bird)
$objective
[1] "LL_bird"
$species
[1] "LL_bird"
$fleet
[1] "LL"
$encounter
[1] "LL_bird"
$target.cv
[1] 0.1
$data
            strata sampling.rate       N cost.total cost.fleet cost.species        cv
1  ManagementUnits    0.01000000   170.9400   100854.6      85470     15384.60 1.3229521
2  ManagementUnits    0.01908163   326.1814   114826.3      85470     29356.33 1.1922891
3  ManagementUnits    0.02816327   481.4229   128798.1      85470     43328.06 1.0800177
4  ManagementUnits    0.03724490   636.6643   142769.8      85470     57299.79 0.9323695
5  ManagementUnits    0.04632653   791.9057   156741.5      85470     71271.51 0.9003333
6  ManagementUnits    0.05540816   947.1471   170713.2      85470     85243.24 0.8390496
7  ManagementUnits    0.06448980  1102.3886   184685.0      85470     99214.97 0.8216530
8  ManagementUnits    0.07357143  1257.6300   198656.7      85470    113186.70 0.7832370
9  ManagementUnits    0.08265306  1412.8714   212628.4      85470    127158.43 0.7273614
10 ManagementUnits    0.09173469  1568.1129   226600.2      85470    141130.16 0.7186518
11 ManagementUnits    0.10081633  1723.3543   240571.9      85470    155101.89 0.6642151
12 ManagementUnits    0.10989796  1878.5957   254543.6      85470    169073.61 0.6642138
13 ManagementUnits    0.11897959  2033.8371   268515.3      85470    183045.34 0.6098161
14 ManagementUnits    0.12806122  2189.0786   282487.1      85470    197017.07 0.6056442
15 ManagementUnits    0.13714286  2344.3200   296458.8      85470    210988.80 0.5928917
16 ManagementUnits    0.14622449  2499.5614   310430.5      85470    224960.53 0.5701600
17 ManagementUnits    0.15530612  2654.8029   324402.3      85470    238932.26 0.5669137
18 ManagementUnits    0.16438776  2810.0443   338374.0      85470    252903.99 0.5671152
19 ManagementUnits    0.17346939  2965.2857   352345.7      85470    266875.71 0.5347539
20 ManagementUnits    0.18255102  3120.5271   366317.4      85470    280847.44 0.5229706
…etc…
```

The resulting data table can be plotted with **plotEMsummary()**, and is given in Figure 6.

The optimal sampling coverage for the target CV can be approximated using **EMoptimise()**. **EMoptimise()** applies a linear approximation to the output of **EMiterate()**, and then re-runs the simulator with this value to evaluate the sampling CV for the approximated sample size. In this case a sampling rate of about 90% will achieve the target CV of 0.10, with the number of samples in each stratum given below.

```
> opt1 <- EMoptimise(EM, EMiterations = LL_bird)
$N
[1] 15229.36
> opt1$sampling.rate
[1] 0.8909184
> opt1$parameters
  strata N.population   fraction          mu         sd    N
1      1         1342 0.01191153 0.017713459 0.002441512   181
2      2        14770 0.09872754 0.003777525 0.001838661  1504
3      3          505 0.03285953 0.158897684 0.017898385   500
4      4          477 0.85650140 0.145950313 0.493916485 13044
5      5            0 0.00000000 0.000000000 0.000000000     0
```

The consequences of using this sampling design on other objectives can also be evaluated. For example, we can investigate how the *ManagementUnits* stratification and sample size allocation for seabirds (`opt1`) would perform on another species, such as marine mammals (`ans2`) or yellowfin tuna (`ans3`).

```
> set.seed(0)
> ans2 <- EMsample(EM, objective.label = "LL_mammal", strata.label = "ManagementUnits",
          sampling.fractions = opt1$parameters$fraction, sampling.rate = opt1$sampling.rate)
> ans2$N
[1] 15229.36
> ans2$cv
[1] 0.8685586
> ans2$parameters
  strata N.population   fraction           mu           sd     N
1      1         1342 0.01191153 0.0005685337 2.321188e-05   181
2      2        14770 0.09872754 0.0004237071 1.953779e-05  1504
3      3          505 0.03285953 0.0000000000 0.000000e+00   500
4      4          477 0.85650140 0.0018315841 2.432610e-04 13044
5      5            0 0.00000000 0.0000000000 0.000000e+00     0
> set.seed(0)
> ans3 <- EMsample(EM, objective.label = "LL_yellowfin", strata.label = "ManagementUnits",
          sampling.fractions = opt1$parameters$fraction, sampling.rate = opt1$sampling.rate)
> ans3$N
[1] 15229.36
> ans3$cv
[1] 0.006737339
> ans3$parameters
  strata N.population   fraction         mu        sd     N
1      1         1342 0.01191153  44.564837 19.732969   181
2      2        14770 0.09872754 153.507436 58.517783  1504
3      3          505 0.03285953  60.328047 34.340631   500
4      4          477 0.85650140   7.559763  7.129218 13044
5      5            0 0.00000000   0.000000  0.000000     0
```

In this example, the sampling stratification with a sampling rate optimized for seabirds (89%) performed poorly for marine mammals (resulting in an expected CV = 0.86) and significantly oversampled yellowfin tuna (expected CV = 0.007).

If we required the sampling rate, using the *ManagementUnits* stratification, that were required for yellowfin, we could repeat the above optimization with the yellowfin objective, i.e.,

```
> set.seed(0)
> LL_yellowfin <- EMiterate(EM, objective.label = "LL_yellowfin", strata.label =
          "ManagementUnits", parallel = TRUE, cores = 26)
Optimisation using parallel = TRUE. Using 16 cores
> opt2 <- EMoptimise(EM, EMiterations = LL_yellowfin)
> opt2$sampling.rate
[1] 0.07990016
> opt2$parameters
  strata N.population    fraction         mu        sd    N
1      1         1342 0.029051801  44.564837 19.732969   40
2      2        14770 0.948192381 153.507436 58.517783 1295
3      3          505 0.019025135  60.328047 34.340631   26
4      4          477 0.003730683   7.559763  7.129218    5
5      5            0 0.000000000   0.000000  0.000000    0
```

This shows that, instead of requiring a sampling rate of allocating 86% of the samples to the *ManagementUnits* stratum 4 as was required for the optimization for seabirds, 95% of samples are allocated to stratum 2. The change of allocation resulted in a different optimum; there was a considerable reduction in the sample size required for yellowfin tuna, with the number of samples required dropping from 15,229 to 1,365 (i.e., the coverage rate decreased from 89% to 8%) and the expected CV increased from 0.007 to ~0.08.

To compare the level of improvement in sampling efficiency that was from the stratified allocation, we can use the same approach, but with the definition of a single stratum to the region. Here, we update the *EM* definition file to include a new strata definition (labelled *None*) with the stratum label equal to 1 in every cell. Then re-run the optimization, i.e.,

```
> set.seed(0)
> LL_yellowfin2 <- EMiterate(EM, objective.label = "LL_yellowfin", strata.label = "None",
          parallel = TRUE, cores = 26)
> ans5 <- EMsummary(EM, EMiterations = LL_yellowfin2)
> opt3 <- EMoptimise(EM, EMiterations = LL_yellowfin2)
> opt3$sampling.rate
[1] 0.2568284
```

This suggests that, without any stratification, the required sampling rate for yellowfin tuna for the same expected CV was much higher, at 26%.

Similarly, the effect on other sampling objectives can be found by applying the stratification and sampling fractions to each objective respectively.

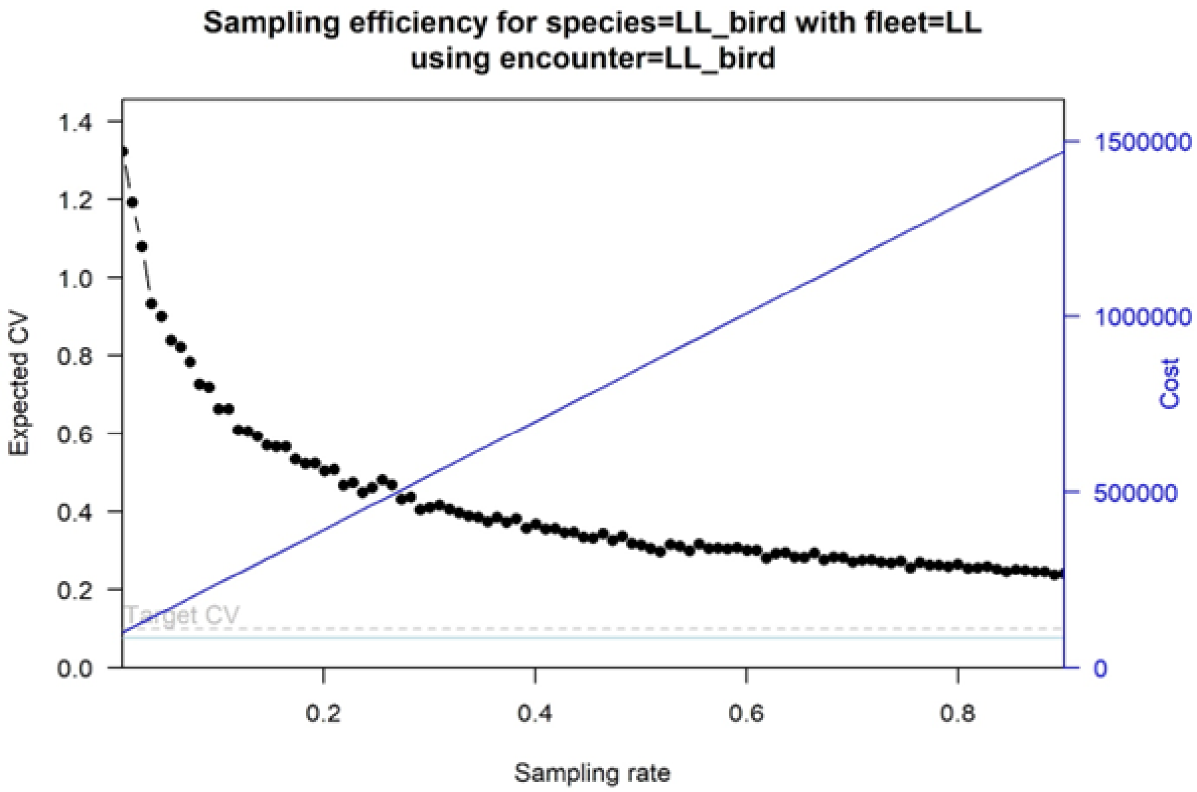

Figure 6: Expected CV with sampling rate, assuming the ManagementUnits stratification for seabirds in the western and central Pacific Ocean longline fishery. The target CV (shown by the horizontal dashed line) is 0.2. The baseline cost to assess the EM sampling frame is the light blue line. The dark blue line indicates increased review cost, above the baseline, as the sampling rate increases.

Evaluating a stratification for multiple objectives

Multiple objectives can be evaluated using genetic algorithms, from the 'SamplingStrata' **R** package[1,2]. For example, the list of objectives defined in the WCPFC example can be listed with `getObject(EM,"objective")`, and the longline objectives passed to **EMoptimiseStrata()**. At least two objectives must be used, but note as the number of objectives increases, the stratification will tend to be optimized with an increasing number of strata.

Each solution (i.e., a particular specification of strata across the map of spatial cells) is considered as an individual in a population with the fitness of all individuals evaluated by applying the Bethel-Chromy algorithm to calculate the sampling size to attempt to meet the precision requirements of the target estimates. 'SamplingStrata' uses a modified version of the functions in the 'genalg' package[6] to implement the genetic algorithm.

With **EMoptimiseStrata()**, an additional strata label needs to be defined to hold the resulting optimal estimated stratification. Optimizing for the longline shark, seabird, and mammal objectives, and assigning the resulting stratification to the additional strata with label *new*,

```
> getObject(EM, "objective")
[1] "LL_yellowfin" "LL_porbeagle" "LL_bird"      "LL_shark"     "LL_mammal"    "PS_yellowfin"
          "PS_shark"     "PS_mammal"

> set seed(0)
> EM <- EMoptimiseStrata(EM, objective.labels = c("LL_shark", "LL_bird", ″LL_mammal″),
          new.strata = "new")
```

This example resulted in 5 strata, numbered 0:4. An "empty" stratum (stratum 0) is indicated where no sampling would take place as there was no effort reported in those cells. A representative image of the stratification is shown in Figure 7. The strata map can be printed to see what cells were allocated to what stratum for the application of the actual electronic monitoring review. Note that there is no requirement that stratum be contiguous or a neighbor to be included within a stratum. Also note that the genetic algorithm may require more iterations (default value *iter* = 300) or populations (default value *pops* = 50) to successfully converge, and different random number seeds can also produce slightly varying results. For a specific application, these values may need to be increased. Evaluation of suitable convergence can be achieved by retesting with different random number seeds and/or by testing with larger values of *iter* and *pops*.

Once the stratification and associated sampling fractions are extracted, these can then be evaluated against any other or all objectives, using the approach in 'Evaluating a pre-defined stratification' above, i.e.,

```
> new <- EM$strata[["new"]]
> plotEMmap(EM, type="strata", label="new", xlab="Longitude (5 degree cells)", ylab="Latitude
          (5 degree cells)", as.image = TRUE)
> new$fraction$fraction
 [1] 0.0000000 0.4835681 0.3145540 0.0657277 0.1361502
> LL_yellowfin <- EMiterate(EM, objective.label = "LL_yellowfin", strata.label = "new", quiet
          = FALSE, sampling.fractions = new$fraction$fraction)
Optimisation using parallel = TRUE. Using 26 cores
> LL_bird <- EMiterate(EM, objective.label = "LL_bird", strata.label = "new", quiet = FALSE,
          sampling.fractions = new$fraction$fraction)
Optimisation using parallel = TRUE. Using 26 cores
> LL_shark <- EMiterate(EM, objective.label = "LL_shark", strata.label = "new", quiet = FALSE,
          sampling.fractions = new$fraction$fraction)
Optimisation using parallel = TRUE. Using 26 cores
> LL_mammal <- EMiterate(EM, objective.label = "LL_mammal", strata.label = "new", quiet =
          FALSE, sampling.fractions = new$fraction$fraction)
Optimisation using parallel = TRUE. Using 26 cores
```

And then summarized using **EMsummary()** and plotted using **plotEMsummary().**

Figure 8 gives the expected CV for different levels of sampling for yellowfin tuna with the *new* stratification. This shows, that with the stratification optimized over the shark, seabird, and mammal objectives the target CV for yellowfin tuna (CV = 0.10) is met with a low level of targeted sampling (i.e., an overall sampling rate of about 2%).

The optimal coverage for each species with the resulting stratification and sampling fractions can be obtained, as earlier, using **EMoptimise()**.

```
> opt1 <- EMoptimise(EM, EMiterations = LL_yellowfin)
> opt2 <- EMoptimise(EM, EMiterations = LL_bird)
> opt3 <- EMoptimise(EM, EMiterations = LL_shark)
> opt4 <- EMoptimise(EM, EMiterations = LL_mammal)
> opt1$sampling.rate
[1] 0.01908163
> opt2$sampling.rate
[1] 0.8909184
> opt3$sampling.rate
[1] 0.1968998
> opt4$sampling.rate
[1] 0.8727551
```

This gives the sampling rates required, using the stratification and sampling fractions determined above with the *new* stratification, as about 2% to obtain an estimate for yellowfin tuna with a target CV of 0.10; with 90% coverage required for an estimate of seabirds with a target CV of 0.10. Less coverage (20%) was required for sharks with a target CV of 0.30; and about 90% coverage for marine mammals with a target CV of 0.10 (Figure 9).

In this case, a user may wish to reduce the target CV for some species or increase it for others and rerun to determine the optimal stratification. Or alternatively, sampling at the highest rate could be implemented to ensure that all objectives are met.

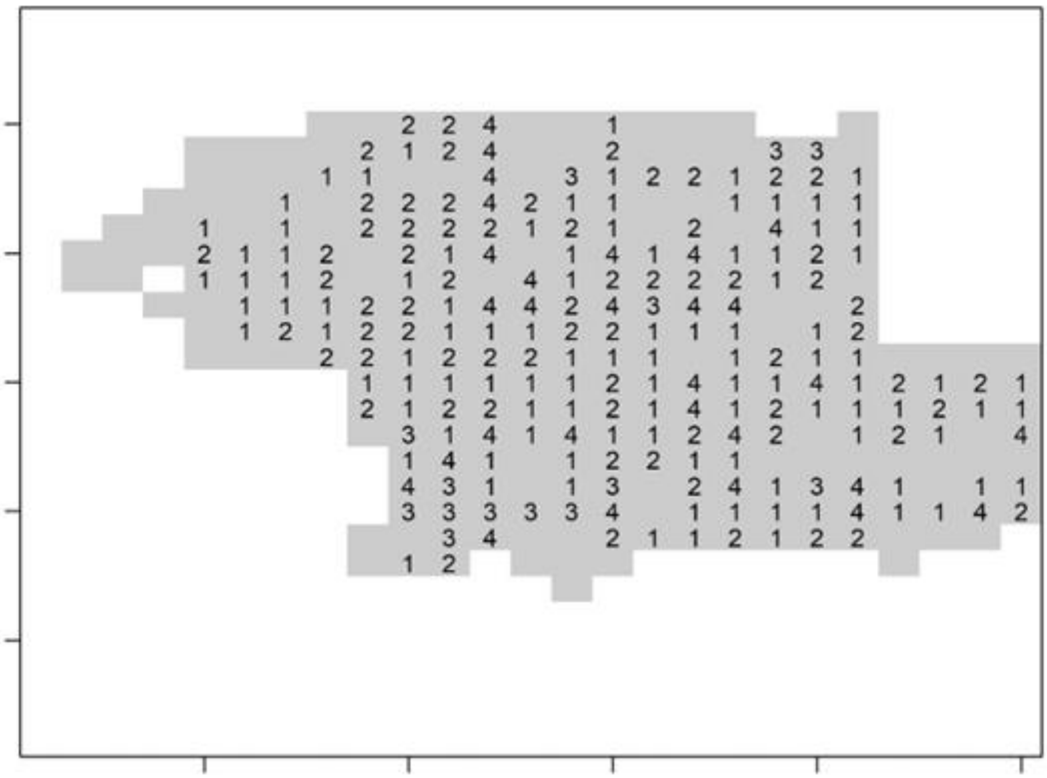

Figure 7. Locations of stratum in the new optimized strata for yellowfin and seabird objectives using longline fleet in the WCPFC. Axes show latitude (y axis) and longitude (x axis) in 25º increments.

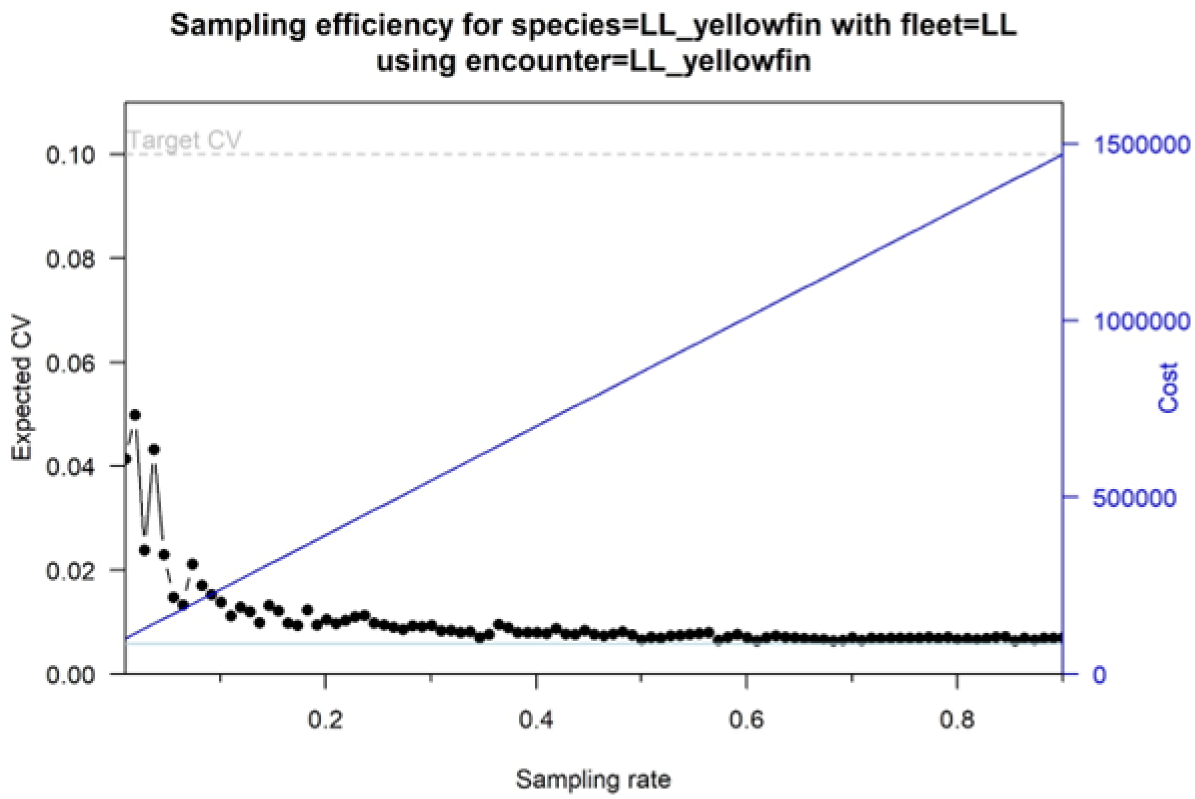

Figure 8. Expected CV with sampling rate, assuming the new stratification optimized for the combined bird, shark, and mammal objectives for yellowfin tuna in the western and central Pacific Ocean longline fishery. The dashed grey line shows the target CV. The baseline cost to assess the EM sampling frame is the light blue line. The dark blue line indicates increased review cost, above the baseline, as the sampling rate increases.

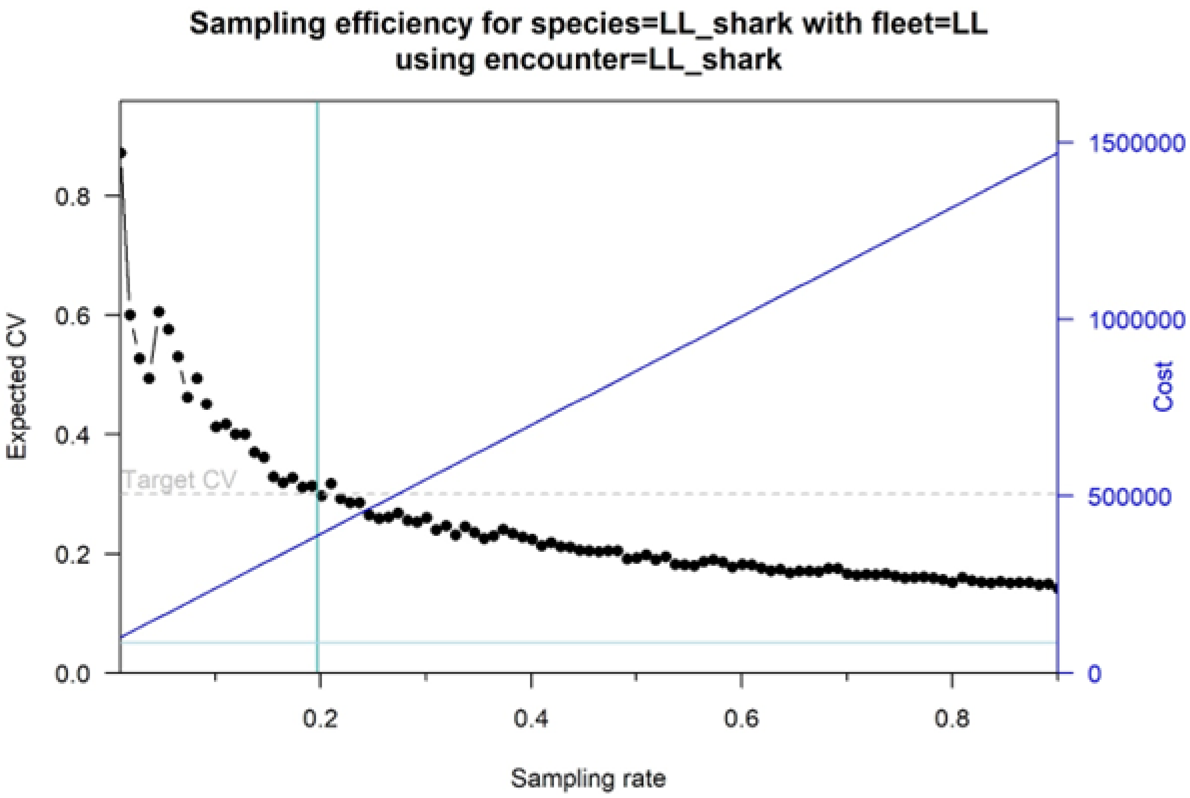

Figure 9. Expected CV with sampling rate, assuming the new stratification optimized for the combined seabird, shark, and mammal objectives for sharks in the western and central Pacific Ocean longline fishery. The dashed grey line shows the target CV. The baseline cost to assess the EM sampling frame is the light blue line. The dark blue line indicates increased review cost, above the baseline, as the sampling rate increases.

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EMoptim

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