Assessing the potential costs and benefits of electronic monitoring for the longline fishery in the Eastern Pacific Ocean

Anthony Rogers, *Sea Change Economics, LLC*
Dr. Dale Squires, *National Oceanic and Atmospheric Administration*
and University of California, San Diego
Dr. Joshua Graff Zivin, *University of California, San Diego*

Table of Contents

Acknowledgements

This report is funded in part by The Pew Charitable Trusts with additional support from the Walmart Foundation. Pew and the Walmart Foundation do not necessarily endorse the opinions and conclusions herein, and any errors found in this document are solely the responsibility of the authors.

We would like to extend a special thanks to the staff of the Inter-American Tropical Tuna Commission (IATTC), whose collegial feedback was invaluable throughout the production of this report.

1. Introduction

Tuna fisheries are collectively among the most valuable fisheries in the world (McKinney et al., 2020). However, adequately monitoring the operations and catch of these fisheries with human observers has often been a challenge, due to a combination of cost, logistics, and difficult or unsafe working conditions. This lack of structured information gathering and oversight creates a significant challenge for both scientific data collection and verification or enforcement of regulations, which in turn create substantial barriers to achieving long-term conservation objectives and sustainable use of ocean resources. This situation is most severe in longline fisheries, which due to their relatively small vessel size, sheer number of vessels, and the extensive footprint of fishing gear used have created a scenario with a high potential for environmental impact combined with low (5% or less of all activity) oversight (Román-Verdesoto et al. 2020; Brown et al. 2021). Challenges associated with this low oversight of longline vessels include potentially high rates of bycatch (including protected species of concern, such as marine mammals or seabirds), the inability to ensure responsible fishing activity for market supply chains, and low collection of scientific data to enable robust stock assessments.

Many of the Regional Fisheries Management Organizations (RFMOs) that regulate and manage global tuna fisheries thus have a growing interest in electronic monitoring (EM) as a potential path forward towards solving this challenge for longline fisheries. EM captures video of fishing activity alongside associated sensor and positional information, allowing for a level of monitoring and data collection without the need for human observer presence. The potential benefits flowing from the implementation of EM – including the potential to scale observed fishing activity coverage while avoiding human-centric challenges, such as observer intimidation or bribery – have been qualitatively described in detail (e.g. Michelin et al. 2020); however, the potential economic benefits remain unquantified except in very specific cases, limiting the extent to which tradeoffs can be assessed and creating a persistent barrier to decisions to move forward with implementation.

This analysis quantifies the potential costs and benefits of the adoption of an EM program for the Eastern Pacific Ocean (EPO) longline fishery, making three important contributions in the process. First, the work is centered on the EPO, primarily within the confines of the Convention Area of the Inter-American Tropical Tuna Commission (IATTC), the RFMO responsible for the conservation and management of tuna and other marine resources in the EPO, a region with interest in EM but for which no specific quantified EM benefit estimates currently exist. Second, this analysis is explicitly focused on the longline fishery in the EPO; most cost-benefit analyses of EM to date have focused primarily on purse seiners and other large vessels (e.g., Banks et al. 2016). Finally, this work builds upon previous EM cost-benefit contributions by explicitly allowing for uncertainty (or variability) in the parameters informing the analysis, in an effort to account for the uncertainty in forecasting the costs and benefits of the effects of rapidly changing technology on a sparsely quantified fishery. Allowing for this variability will also support translation to other regions in the future. It is our hope this work may in the future also serve as a foundation for incorporating management goals and uncertainty into future EM estimates for other fisheries.

2. Study background

2.1 Longline tuna fishing in the EPO

This analysis is focused on the longline fishery operating within the EPO. Specifically, longline vessels 12m in length or greater (sometimes referred to as “large longliners”) are the vessel of interest for this study. There are approximately 1,800 of these vessels operating in the EPO, with sashimi-grade yellowfin and bigeye tuna as the primary target species (IATTC 2021d). Space may limit the practicality of fitting human observers aboard vessels below 20m in length, meaning in practice many operate without any observer coverage at all, further increasing the potential attractiveness of EM as an alternative option.

An issue of particular concern in the EPO longline fishery is that of inadequate observer coverage (IATTC 2021b; Griffiths & Wiley 2019). Observers allow for the collection of scientific data, such as catch composition and distribution, biological sampling, and interactions with non-target (bycatch) species, including protected species of concern such as marine mammals, seabirds, and turtles. Observer can also collect information related to compliance with fishing regulations and the identification (and measurement) of illegal, unreported, and unregulated (IUU) fishing, although in the IATTC convention area they are strictly employed for the collection of scientific data. Like all statistical sampling, the more fishing activity observed, the more accurate science-based fisheries management, including stock assessments and the fulfillment of ecosystem stewardship and conservation goals, can be.

Several studies suggest that 20% observer coverage of all fishing activity is a minimum level of coverage required for accurate scientific data collection that reflects the true distribution of fishing activities and information, including estimations of baseline information such as total catch and discards, with higher rates needed for species caught less frequently (Wang et al. 2021; Babcock et al. 2003). Expanding observer coverage to a minimum 20% has also been a recommendation of both IATTC scientific staff and the IATTC Scientific Advisory Committee for the last few years; under IATTC Resolution C-19-08, however, only 5% of coverage is stipulated for each CPC’s (Member and Cooperating Non-Contracting Parties) longline effort, considerably below the 20% minimum (IATTC 2011; IATTC 2021b). The cost of raising observer coverage to meet this shortfall is a significant impediment to changing this situation (Lowman et al. 2013; Michelin et al. 2020; Román-Verdesoto et al. 2020).

2.2 Overview of electronic monitoring programs

Electronic monitoring is often proposed as a potential solution to inherent challenges in increasing the level of observer coverage, as it can afford many of the same benefits as onboard observers at, potentially, a fraction of the speed and cost (Román-Verdesoto et al. 2020; Michelin et al. 2018).

On a technical level, EM includes a system of cameras and sensors onboard individual fishing vessels that capture video of fishing activity. The recorded video is subsequently reviewed by analysts onshore to record data of interest, including catch volume, non-target bycatch, discards, and fishing location (Michelin et al. 2018; Michelin et al. 2020).

There are some differences in the type of information EM is able to collect than from standard onboard fishing observers, most notably the collection of biological samples (Michelin et al. 2018). However, technological progress has steadily improved over time, and increasingly EM systems and video reviewers are able to either compliment or collect much of the same baseline data as onboard human observers, with future advances in artificial intelligence and machine learning expected to further close the gap (Román-Verdesoto et al. 2020). EM can therefore be thought to compliment, supplement, and in some cases even replace observer coverage, depending on the data collected.

Interest in the use of EM systems in tuna fisheries management is growing rapidly, though different policy objectives can affect the rationale for (and economic assessment of) adoption. While enforcement and verification is discussed to some degree in this analysis, IATTC has specified that the primary motivation of EM adoption in the EPO is the generation of scientific data to inform and assist in fisheries management and sustainability objectives (IATTC, per. comm.). Regardless of primary policy goal, however, EM-generated data affords a number of potential advantages compared to human observers, including lower susceptibility to bias from observers, non-random selection of trips chosen for observation, and avoiding any intimidation or corruption of observers (Michelin et al. 2018).

A note on terminology: “EM observers”, “EM reviewers”, and “EM observer coverage” may be used interchangeably in this report. Each of these terms are intended to refer to observation of vessel activities by an EM system, including post-trip review by video reviewing agents; where relevant, this can be thought of as equivalent to “effective observer coverage through the use of a complete EM system”.

2.3 Cost-benefit analyses of implementing electronic monitoring

Worldwide there have now been just over 100 pilot EM programs (Michelin and Zimring 2020), but only a small number of cost-benefit analyses have been conducted for EM in fisheries to date. Even rarer are those centered on tuna fisheries; rarer still are analyses that touch on longline-specific costs and benefits.

A more recent regional exploration of EM benefits and costs is a 2016 report by Richard Banks of Poseidon Aquatic Resources Ltd., titled “Analysis Of The Costs And Benefits Of Electronic Fisheries Information Systems Applied In FFA Countries And Identification Of The Legislative, Regulatory And Policy Supporting Requirements” (Banks et al., 2016). This analysis was an early study of the potential economic costs and benefits of EM in an international tuna fishery, and found a high level of economic benefits relative to costs. However, many of the costs and benefits in this analysis were highly specific to the WCPFC RFMO, limiting its utility in other RFMO regions. For example, the vessel day scheme (VDS), a system in which vessel owners can purchase and trade days fishing at sea, is a significant source of value in the Banks et al. 2016 analysis – but only for places subject to the Parties to the Nauru Agreement, and thus not appropriate for this EPO-focused analysis. Furthermore, the Banks et al. 2016 report was included a number of vessel types, with emphasis (and more data) on purse seine vessels, again somewhat limiting the relevancy to this analysis.

Many economic analyses of EM to date have relied upon point estimates, potentially making the analysis less robust to uncertainty, particularly for costs projected into the future that could change year-over-year. This analysis takes a novel approach in addressing this shortcoming through the use of uncertainty analysis and Monte Carlo simulation-driven estimates (see below) for many of the values used in the analysis.

3. Methods & Approach

The approach taken in this analysis is to quantify the relevant costs and benefits related to, or potentially affected by, an EM program that includes longline vessels, identify how these parameters change in different scenarios of interest (e.g. business as usual vs. adopting EM), and then comparing the total. This will include two levels of analysis: financial, which looks at the impact on individual operators (vessels, but also other operators along the supply chain to the extent possible), and economic, which looks at the net benefits to industry and nations (or collectives, e.g. RFMOs) as a whole. The initial focus here is on quantifiable market values, but some non-market benefits (such as marine mammal non-market values associated with a reduction in entanglement mortality; see section 3.3.2 below for more detail) were also incorporated in some specific instances, in order to fully characterize any potential societal benefits of EM adoption.

It should also be noted that this comparative economic analysis has foregone components of the longline tuna fishery that will be unaffected by the adoption of EM; in other words, the model used here removes those components (e.g. fixed input costs that are the same whether EM is installed or not) that are likely unaffected by EM, as they are irrelevant to the comparison this analysis is concerned with. Likewise, a comprehensive bioeconomic model could capture long-term stock growth effects based on changes in harvest due to EM effects; this is beyond the scope of this initial analysis, but likely results in a conservative underestimation of any potential benefits flowing from EM adoption.

As EM has not yet seen widespread adoption in global fisheries, there simply haven't been a large number of cost-benefit analyses conducted to date. Initial values for parameters were thus collected through past published EM cost-benefit studies in both the academic and grey literature. When possible, EPO-related numbers were prioritized, though EM-related values in particular were primarily found for other regions. These parameters were used to seed starting values and ranges for the Monte Carlo uncertainty analysis (see below). IATTC has graciously shared some initial quotes for EM equipment, as well as other relevant fisheries data; where possible, these values were used as the initial parameter estimates in order to make this analysis as specific to IATTC as possible.

3.1 Scenarios Explored

Three primary scenarios are explored in this analysis:

1. 5% "observer coverage", defined as 5% of all sets observed, either by an onboard observer or an EM equivalent (e.g. video footage reviewed);
2. 10% observer coverage, equally split between onboard and EM observers; and
3. 20% observer coverage, with 5% onboard observer coverage and 15% EM coverage.

Other scenarios – such as 100% EM coverage – are additionally calculated for illustrative purposes.

Scenarios 2 & 3 are reflective of an expressed policy preference by IATTC for maintaining the current level of onboard observer employment. This objective is thus treated as a "baseline" structural assumption in the model, with 5% onboard coverage held as a minimum in most analyses. Note also in this analysis it is assumed, given the limitations of information available, that the current level of observer coverage in the longline fishery is equivalent to 5%; all subsequent calculations, where relevant, thus treat 5% onboard observer coverage as the starting baseline (business as usual) scenario.

Finally, an overarching presumption of this analysis is that EM will be adopted across the entire fleet, with an "audit approach" (i.e. random sampling) taken to EM observer review coverage, resulting in a true random sample (Stanley et al, 2011). In other words, for any given specified observer coverage level, the sample is potentially drawn from the entire EPO longline fishery, with the specified level of coverage specifying what percentage of review is conducted. For example, if 20% observer coverage is desired, then it is assumed that a) 100% of all sets, from all vessels in the fleet, are recorded through EM, and b) 20% of those sets (and accompanying recordings) are randomly selected and reviewed.

3.1.1 Uncertainty & Monte Carlo Analysis

There are substantial challenges to quantitatively estimating costs and benefits for a rapidly evolving technology such as EM. Values reported from different sources in the existing EM literature can vary substantially for specific parameters. Furthermore, many relevant cost and benefit factors, such as price, fluctuate and are neither constant nor predictable. A reliance on point estimates and reporting ranges of values (e.g. maximum and minimum values) or averages may skew the likelihood of the true value, and even if not, may prove to be an inaccurate predictor as future costs change. Point estimates may also exaggerate likely outcomes, and ignore correlations across variables.

To address these concerns, a Monte Carlo simulation is employed in this analysis. Monte Carlo simulations are commonly used in situations where there are a range of possible outcomes for multiple variables. The technique effectively mimics a random statistical sampling by selecting an objective (or subjective) probability distribution for each parameter, then assigning values within that distribution and re-calculating the results of the analysis over and over, thousand or tens of thousands of times. The resulting output from a Monte Carlo simulation in a cost-benefit analysis is a range of possible outcomes, and their probabilities, for any given decision; in this case, the choice of either adopting or not adopting EM. Decision-makers can use the results to directly compare the likely costs and benefits of two “projects”; for instance, adopting EM or not, or comparing between different observer coverage/review levels. Additionally, while the values used in this report are specific to the EPO, another advantage of coupling the underlying model and Monte Carlo approach is the potential ease of translation to other regions.

The Monte Carlo simulations conducted in this analysis used Oracle Crystal Ball software. In each simulation, 10,000 runs were conducted to ensure a sufficiently high number of simulated randomized samples. A triangular distribution assumption was used for each parameter, using the maximum, minimum, and mean value for each parameter; a sensitivity analysis using median values is included in Appendix B, and specific exceptions to this assumption are noted in the relevant subsection below. The full range of values used for each parameter in the Monte Carlo simulation can be found in Appendix A.

3.2 Costs

3.2.1. Onboard & EM observer costs

Perhaps the single EM benefit that receives the most attention in the literature is the potential for significantly expanding observer coverage on vessels at a lower cost than using human observers. Specifically, the claim is that human observers can only observe one vessel at a time, and only one vessel per day, whereas EM allows a handful of video reviewers to “observe” multiple vessels, with enough speed to cover multiple trips or sets in a single day. There are four categories of consideration to consider for this argument:

1) Basic costs (observer equipment and travel, compensation)
2) How comparable the accuracy and data generated by human vs. EM observers are
3) How efficiently reviews of EM footage can be conducted

4) Other cost considerations (training, indirect staff costs)

Basic costs are straightforward to calculate. Onboard observers require basic inputs that EM reviewers do not, such as supplies and travel costs, owing to requiring their physical presence on a vessel; estimates for these come directly from the Agreement on the International Dolphin Conservation Program (AIDCP) annual observer program budget (IATTC, 2020). Other general values (e.g., observer days at sea, days at sea per observer, etc.) also come directly from IATTC.

Likewise, onboard observer compensation is specified by IATTC directly, based on a calculation using experience at sea; the higher estimates come from rates for MRAG longline transshipment vessel observer salary (IATTC, per. comm.). These daily costs range from 48 to 380 USD per day, depending on observer experience and the complexity of the vessel activity (e.g. fishing vs. transshipment) being observed. There is considerably less data available for EM analyst compensation. IATTC advised, depending on the percentage of sets reviewed, EM analysts may potentially earn between 30 to 97 USD per day. It is important to note, however, that the place where the EM analysts are hired may also have a significant effect; EM analyst compensation based on an EM review center in Europe, for example, would likely compensate higher than an EM review center located in South America.

Onboard observers also require insurance, and are paid benefits, on top of their direct wages; these amounts, calculated as a per-observer cost, are again sourced directly from the IATTC annual observer program budget. EM observers likely require less insurance costs than onboard observers, but without empirical information and in order to keep this estimate conservative, the same per-observer benefits & insurance rate is applied to EM observers as well.

The annual AIDCP annual observer program budget also includes “indirect staff” which includes both support staff and scientific/technical staff line items. These values were divided by the number of observers to calculate per-observer estimates, to be applied in the model based on the number of observers needed. Despite likely differences in what the “indirect” needs may entail (e.g., travel coordination for onboard observers vs. IT support for EM analysts), the same per-observer rate is applied to EM and onboard observers.

The AIDCP annual observer program budget includes the cost of training for observers. These are again calculated as a per-observer value, to allow for scaling depending on the number of observers employed under each scenario. In addition to the specific training necessary to be an EM reviewer, it is assumed some onboard training will need to occur as well, in order to give EM reviewers context and familiarity with vessel operations (IATTC, per. comm.). As a starting assumption, and in order to keep these estimates conservative, EM reviewers therefore have an additional training cost applied equal to half of the onboard observer training costs, in addition to EM-specific training costs; in total, EM observers thus have training costs equal to 1.5 times the onboard observer training costs.

Accuracy is also an important component of observer costs. While EM and onboard observers are almost unanimously treated in the literature as complementary, rather than viewing one as a replacement for the other, the overlap in basic fisheries information each can collect is quite high, and growing. For the purposes of this analysis, therefore, “observer-generated data” are treated as equally valuable regardless of the source (i.e. EM or onboard observer). While there may be some concerns post-implementation about specific scientific data unable to be collected via EM, such as biological sampling, this is ameliorated somewhat by the fact (as noted above) that a stated policy goal, and thus main component of one of the scenarios explored in this analysis, is to not decrease the level of human observers even if EM is fully implemented. This analysis therefore makes the simplifying assumption that observation by an on-vessel human observer and by an EM reviewer have a similar level of accuracy and produce equivalent scientific data.

Review times will also have a significant impact on the cost analysis of an EM observer. Banks et al. 2016 used the assumption of 2 sets reviewed per day; subsequent studies have shown this may have in fact been an underestimate, with more recent experience and technological advances allowing for 4 or more sets reviewed per day (Cap Log Group 2015).

This raises an important calculation hurdle for this analysis, however: estimating effort. Estimates of total longline effort in the EPO does not appear to exist at present. However, estimating minimum observer coverage in this analysis requires using some measure of total effort to estimate potential costs and benefits of EM implementation (or not). IATTC recently adopted “number of hooks” as a standard fisheries effort metric (Griffiths & Wiley, 2019); however, reported EPO longline data is still mixed between metrics and does not allow for a 1:1 comparison (IATTC 2021b), and most EM studies report observer review times in terms of number of sets. IATTC has not specified a number of hooks-to-sets or days at sea conversion rate; a stand-in for sets per year by longline vessels in the EPO is therefore needed.

The approach taken in this analysis is the following:

1. Existing IATTC data reported by Members and Cooperating Non-Members on retained catch industrial longline vessels, and associated data, were used to obtain two metrics: the total number of hooks (an existing effort metric used by IATTC) and the total amount of reported catch.
2. Combined, these metrics were used to calculate the number of hooks per metric ton (mt).
3. This new “hooks/mt” metric was then applied to IATTC estimates for the total amount of longline catch in the EPO, resulting in an estimated 468,060,359 total hooks (average of this calculation for 2010-2019) for the EPO.
4. Dividing the total hooks per year by an average of 2,491 hooks per set (data provided by IATTC), which results in approximately 187,913 longline sets on average per year.

All of the values used in the above calculations can be found in Appendix A.

Finally, the time it takes an EM observer to review recorded footage can significantly affect the potential cost efficiency of an EM program. As far back as 2014, potential efficiencies were becoming apparent: “In a fishery with compliance as the primary objective of review, the software was able to reduce video review time to less than 25 percent of real time.” (NOAA, 2015). The Banks et al. 2016 analysis noted that the “AFMA ETBF system requires 3 hours per set (Andrew Fedoric, Archipelago AP, pers. comm., November, 2015).” Though technology continues to improve, 4-5 sets per day appears to still be the average estimate in more recent literature, with 8.75 being the highest estimate reported (Cap Log Group, LLC, 2019).

For human observers, the starting assumption is that they are able to review one set per day (that is, that a longline vessel is setting no more than once per day, and since a human observer must physically be on the vessel, they are limited to reviewing only what a longline vessel can set in a given day). For video reviewers, this analysis assumes they work approximately the same number of days per year as onboard observers (as they would, in theory, reviewing the same fishing activity over the course of a year). Because video feeds can be reviewed more quickly than live onboard observations, the range of sets EM observers are able to review is between 2 and 9 sets, with a mean (and/or most likely value) being 5 sets/day.

3.2.3. Vessel hardware costs

Point estimates for onboard vessel costs were collected for the following EM-related equipment:

- Cameras
- Camera central units/onboard computer
- Sensors
- Hard drives
- Software licenses, remote assistance, and EM data analysis

For all but hard drive costs, direct quotes received by IATTC from private vendors were used for the starting values used in this analysis. Hard drive costs were taken directly from published EM literature with no adjustment. Note that while software licenses, remote assistance, and EM data analysis are included as costs borne by the vessel, there are separate additional software and data analysis costs included at the management level (discussed below).

Installation of vessel hardware is another significant associated cost. There is considerable variability in estimates in the literature; however, once again direct quotes (point estimates) provided by IATTC were used in the baseline analysis. We acknowledge, however, that even these quotes are quite possibly more accurate for the installation of EM on purse seine vessels at located in the Eastern Pacific; there could very well be substantially different installation costs for EM equipment on longline vessels based in Asia, for example.

An assumption made in this analysis, based on some published estimates (e.g. Cap Log Group, LLC, 2019), is that this hardware has a shelf life of 5 years. Therefore, vessel hardware and installation costs are treated as recurring every 5 years, with 4 “in-between years” that only include annual software costs. Repair costs, also collected from published estimates, also only occur in each of these 4 “in-between years”.

Finally, data transmission costs must be accounted for – that is, the cost of actually getting the recorded data into the hands of EM reviewers. (In the literature, and thus in this analysis, this is treated as a cost borne by individual vessels.) Estimates vary widely, from less than $200 to over $1,200 per vessel per year (Sylvia et al., 2016). Direct transmission via satellite is an alternative innovation that could, in theory, reduce lag time as well as per-vessel costs in the future; at present, however, the capabilities of transmission from at-sea relative to the sheer volume of data needed to be transmitted make this technological fix difficult to predict when, and if, it will become a central component of EM operations (Banks et al. 2016). For now, data transmission in this analysis is treated as the costs of hard drive delivery.

3.2.4. Other management costs

Aside from the direct costs of the observer program (on board and/or EM equivalent), there are additional startup costs that fall to management (i.e. IATTC and/or individual National review programs) in order to get an EM program in place.

The first of these costs are “reviewing stations” i.e. computer equipment to allow for the review of EM data once acquired from vessels. These are again difficult to predict, owing to the uncertainty in the size of the potential EM program and the specifics of what equipment may be needed. This is further complicated by the fact that management entities likely have some applicable computer equipment already. As a stopgap solution, the total cost of the IATTC technology budget is used, and EM is calculated as an additional fraction of that total. The designated “likeliest value” is set at 25% of the realized 2020 IATTC technology cost, $58,653, with minimum and maximum values set at 10% and 100%, respectively (IATTC, 2021a). Because technical staff costs were already included in the EM observer cost estimates, no further staff costs are included in this section.

Even if there is existing computer hardware that can be repurposed to some extent, the sheer volume of data needed will incur significant data storage costs; ranges for these are drawn past empirical estimates (e.g. Piasente et al 2012, NOAA 2015).

Software licenses for the review and analysis of EM will also be needed for management authorities to make use of collected EM information. The costs in this analysis are direct cost estimate quotes received by IATTC from private vendors; however, these quotes are aggregated to include software and machine learning license fees, software and equipment training (separate from EM reviewer training). Rather than make assumptions in an attempt to further disaggregate, these costs remain combined in the model.

A final additional management cost for consideration is costs related to a location for the EM review center(s), operational support, etc. This cost has the potential for some variability, depending on whether the final form of the EM program adopted is a centralized management program (e.g. similar to IATTC's International Dolphin Conservation Program, IDCP), or whether each IATTC Member will maintain their own EM review program. For simplicity, this analysis treats this value as one cost, with the assumption that the aggregate cost value of either approach would not change the cost estimate by orders of magnitude.

While a centralized EM review center would likely be housed within existing facilities (e.g. IATTC headquarters), extra office space, operational supplies, etc. would still be needed for a new program of any significant size. We again look to the IATTC budget as a starting point, this time at the "Field office facilities and related supplies: includes rent, utilities, insurance, telephone and office supplies for the Commission's field offices," line item, at $100,000. It is doubtful this cost would need to double due to the formation of an EM management program, so we also look to the FAO study of the Fiji EM trial program, which included an annual cost of $28,000 for "Office and other costs" (Stobberup et al., 2020). The mean between these two values is $64,000; this value, which is likely still high (and thus, makes the estimate for EM conservative), is used as a starting value in the model.

3.2.5. Technological development

It is notoriously difficult to project into the future how technology - in terms of both capabilities and costs - will develop over time. It is generally a safe assumption that the same technology - i.e. with the same capabilities - grows cheaper over time. For instance, the same camera technology on a vessel, with the same general components, capable of the same resolution, reliability, etc., will almost certainly grow cheaper to produce over time.

However, there are two additional considerations to this characterization. The first is that alongside being able to produce the same technology more cheaply, the capabilities of technology also increase - such as improved camera resolution, hard drives that are able to store more data, etc. The second, closely related to the first, is that just because a level of technology grows cheaper to produce over time does not guarantee it will still be available in the market. Look no further than the trajectory of the smartphone market, in which improved versions of phones replace older models over time - rather than coexist alongside them on the store shelf. There is considerable potential for the same story to play out with EM components over time, with costs of those components potentially leveling off but improving in quality and capability in future years.

There is little evidence that costs could significantly increase over time; this very rarely happens with technology, and generally not as a continuing trend but as discreet inflection points (a short-term response to supply shortages, for example). In addition, the rapid development of machine learning and AI-assisted review promises to only make review of EM footage even more efficient over time (Michelin et al. 2020). Better case scenarios could include such improvements in technology that additional benefits accrue elsewhere (e.g. significantly enhanced capability to identify bycatch species), or that costs do indeed fall over time.

Personal communications with Dr. Roger Bohn, Professor Emeritus, UC San Diego, confirm this challenge. Dr. Bohn notes (for example) that mainstream smartphone prices fall at a rate of 0% to 20% per year, due to sellers competing on performance more than price. While in theory a device with today's capabilities would generally fall to 10-20% of its price today, the more likely outcome is that a considerably improved technology is instead available, at approximately half of today's cost.

This analysis will thus conservatively follow this recommendation, and show a moderate 25% reduction in technology costs 5 years after the initial purchase of EM-related technology (cameras, sensors, central onboard EM computer, hard drives).

3.3 Benefits

3.3.1 Observer coverage & scientific data improvement

One of the primary motivations for the exploration of EM by the IATTC is the potential to provide significantly more, and perhaps improved, scientific data at minimal cost. Achieving additional levels of observer coverage, particularly 20% or more as described above, could have significant positive benefits flowing from potential fisheries management decisions based on accurate catch information. However, as stated previously, a full bioeconomic modeling exercise is outside of the scope of this analysis, especially given the high range of potential actions and outcomes resulting from this newly acquired information. However, as a stated primary management goal of potential EM adoption by the IATTC, we felt it was critical for this cost-benefit analysis to reflect the value of this gained scientific information somehow.

The approach taken in this analysis is therefore as follows. In 2019, $2,699,664 (USD) was spent on the observer program (IATTC 2020). We make the assumption this is an indication the level of data currently collected by all observers is thus worth that amount, at minimum. Dividing this number by the 285 employed observers (Appendix A) results in an estimate of $9,472.51 per observer deployed. Multiplying this amount by the number of observers it takes to achieve 5% coverage (approximately 60.62; recall that 5% is the assumed current baseline observer coverage) and then dividing by 5 results in $114,839 as an estimate for the value generated per 1% of observer coverage.

We acknowledge there are several assumptions in this calculation, including assuming value equivalency between data generated by observers in the purse seine fishery (i.e. the bulk of the 285 observers) and data theoretically generated in the longline fishery. We also implicitly treat marginal benefits as constant here, when in reality they likely fall as observer coverage grows. (Whether that point is below or above the 20% target point is, at present, unable to be answered empirically.) However, in the absence of other approaches, and given the final analysis introduced uncertainty into the parameters that produce these calculations, we assume for now that this is a valid minimum estimate for the value of scientific data generated by additional observer coverage.

Finally, note that this benefit of $114,839 generated per 1% increase in observer coverage occurs whether the coverage is produced through EM or onboard observers. In other words, the benefit generated in this category by an increase to 20% observer coverage would be the same whether it was done through EM or onboard observers. (The costs will in all likelihood be different.)

3.3.2 Bycatch

Recent studies have shown there may be significant differences in detection rates between EM and non-observed reported catch, including interactions with non-target species such as turtles, marine mammals, or seabirds (Brown et al. 2021). There are known significant interactions with the EPO longline fishery and non-target species (IATTC, 2021b); quantifying a value to any changes in mortality driven by the presence of EM is thus of critical importance to capture the full potential benefits to society generated by an EM program.

The key assumption in this benefit category is that increased detection of bycaught species results in decreased mortality (e.g. safe release) of the species in question. The presence of observers (onboard or EM) has been shown to alter fishermen behavior, colloquially known as the “observer effect” (Emery et al. 2019). There are several plausible explanations for this effect: perhaps onboard operators are more diligent or compliant in their observations and actions knowing they’re being observed, or perhaps the presence of an impartial evaluator increases the incentive to be more consistent and comprehensive in reporting. It is therefore plausible, with some empirical evidence, that the presence of an observer may translate to decreases in species mortality.

We therefore combine these two observations and assume that if there are any additional rates of detection resulting from EM, these in turn translate into additional conservation benefits in the form of decreased species mortality. Because this analysis assumes that 100% of the vessels would have EM installed, this change in behavior is assumed to occur on all vessels (i.e. not just the percentage of those that are actually reviewed). There is evidence that the presence of any observer – onboard or EM – may produce some increase in bycatch detection (Emery et al. 2019, Brown et al. 2021); because this baseline detection would be present under both options, however, this analysis is only concerned with the additional benefit produced by any possible additional detection from EM systems.

To quantify this benefit, an economic value per additional individual released alive is multiplied by the change in rate of detection (and survival). A benefits transfer approach is employed to import previously published non-market values for each species of interest, converted into a $/set (in 2021 $USD) common metric, as seen in Table 1 below, and multiplied by the number of sets per year in the EPO (estimated previously). Differences in detection between EM and human observers, if any, are then multiplied by these non-market values to calculate any additional benefit potentially produced by the presence of EM.

Because the use of non-market values can be controversial amongst some stakeholders – despite broad societal agreement there are some benefits to species conservation – the baseline analysis in this report includes values for only a sample of representative species that capture benefits afforded to major groups of vulnerable species (i.e. marine mammals, sharks and rays, sea turtles, and seabirds). Results of a Monte Carlo simulation using a (somewhat) expanded list of vulnerable species values can be found in Appendix B. There are 18 species considered highly vulnerable and 37 considered moderately vulnerable to becoming unsustainable under the current longline fishing regime in the EPO (Griffiths et al. 2017); unfortunately, for many of these species, estimates of non-market value simply do not exist.

Seabirds, for example, are known to have high bycatch rates with longline vessels in the EPO (e.g., Anderson 2009), but have very little representation in the non-market value literature; we therefore use a generic “seabird” value adapted from Börger et al. 2020 to ensure seabird bycatch benefits have some level of quantified representation in this analysis.

Table 1. Values (USD) Used As a Baseline Bycatch Economic Benchmark

		Low	**High**	**Mean**	**Source**
Marine Mammals					
	Spinner dolphin	$9.34	$65.63	$37.48	Wiener et al. 2020
Sharks & Rays					
	Silky shark	$8.00	$9.44	$8.80	Booth et al. 2021b
	Mobula rays	-$13.44	$12.00	-$0.64	Booth et al. 2021b
	Thresher shark	$1.92	$8.96	$5.44	Booth et al. 2021b
Sea Turtles					
	Leatherback turtle	$34.01	$43.78	$38.81	Booth et al. 2021a
Seabirds					
	Seabirds (generic)	$5.22	$13.49	$9.35	Börger et al. 2020

While converted to a value per hook metric and granted additional confidence through the Monte Carlo simulation analysis, because these values originated from many different case study sites, including some not within IATTC jurisdiction, and because there may be different approaches and values bundled together in some of these estimates – e.g. the value of changes in conservation status vs. pure existence – the benefits transfer method employed here may mean the actual values of EPO stakeholders are higher or lower than these specific starting values. Nevertheless, it should be emphasized again that this is likely a significantly conservative estimate, meant to serve as an indication that there is significant societal value attached to the conservation benefits likely flowing from an EM program.

3.3.3 Price Premiums

There are several pieces of evidence that suggest there could conceivably be a price premium associated with EM adoption in the future. Anecdotally, some seafood ecolabels, such as Marine Stewardship Council (MSC), may in the future be looking towards EM (or, at minimum, observer coverage that is significantly higher than the current 5% level) as a prerequisite for certification. There is also a related argument that EM as a tool for verification of quality, and compliance with handling standards and best practices, could be used to prove or showcase product worthy of higher prices.

To explore this potential benefit, the average prices for the last decade were collected for both yellowfin and bigeye tuna, the two primary target and high-volume species caught by the longline fishery (Ruaia et al. 2020). These two species, sold primarily for sashimi, seem the likeliest candidates for realizing any price premiums. The model allows input of – and later, the Monte Carlo simulation will alter – the percentage price premium for each of these species. (Price premium pessimists may enter 0% to remove this benefit from consideration, for example.) This price premium is then calculated by the respective average annual landings in the EPO, producing an estimate for the total EPO-wide annual benefit resulting from the currently set price premium.

It should also be noted that swordfish and albacore tuna are two additional species caught in significant amounts by longline vessels in the EPO. Some yellowfin and bigeye are additionally destined for canneries, instead of higher-priced sashimi. However, even less is known about what price premium, if any, swordfish or albacore species might fetch, and most canned tuna do not attract the same price premiums sashimi-grade tuna does. For now, none of these values are included in the base model, which serves as an additional measure to ensure the estimate is conservative.

The Monte Carlo simulation introduces an additional challenge to this component of the model: that of correlations across variables. It is highly likely that prices (and price premiums) for yellowfin and bigeye sashimi are likely to move in the same direction at the same time. For example, if changes in consumer preferences suddenly result in a higher premium for one, then there is likely a similar change for the other. Because a Monte Carlo simulation varies each variable randomly in each run, this correlation between related variables is potentially lost. In order to account for this and protect the correlated relationship, a new variable that is simply the combined yellowfin and bigeye sashimi prices was created, with the model then assigning a calculated percentage (46.22% and 53.78%, respectively, and 50% each for the price premium) of the total to each product.

Finally, as noted previously, a comprehensive bioeconomic model would capture long-term stock growth effects based on changes in harvest due to EM effects; this is beyond the scope of this initial analysis. It is unlikely there are significant changes in harvest amounts flowing purely from the adoption of EM in the 10-year period this analysis is concerned with - outside of any resulting management changes, which are difficult to predict and, again, outside the scope of this analysis. A more likely scenario is that the *observed* harvest rates of longline vessels could theoretically change, and more accurately reflect current harvest trends. In either case, the change in total tuna on the market is unlikely to have a significant effect itself on the market price of longline-caught bigeye and yellowfin tuna (sashimi). The simplistic approach taken in the initial analysis here of holding price and quantity constant - and thus presuming only minor changes in either over time - has the benefit of likely producing a conservative underestimation of the potential price premium benefits flowing from EM adoption. This conservative approach is further reinforced by the fact that the average and maximum values for annual bigeye catch used in the model (27,229 and 41,524 metric tons, respectively) are both well under conservation limits (63,131 metric tons) from IATTC itself (IATTC 2021c).

3.3.4 Compliance / IUU

The EM literature (and the policy goals of other RFMO regions, most notably WCPFC) strongly suggest there is a likely compliance benefit associated with EM, specifically in regards to potential IUU reduction resulting from enhanced monitoring capability. (“IUU” refers to illegal, unreported, and unregulated fishing activity; acknowledging that the fishery in question in this study is regulated by the IATTC and its members, we nevertheless use the full IUU term to align with common nomenclature.) Because at least some of these benefits are likely to accrue to the region regardless of policy objective chosen, owing to the “observer effect” (Emery et al. 2019), we nevertheless include this benefit category in this analysis.

The most basic analysis of IUU reduction benefits here requires two things: (1) an estimate of the value of IUU catch taking place within the EPO; and (2) an estimate of how much EM adoption would reduce the level of IUU occurring.

Potential values to use for (1) are not easy to obtain; intuitively, illegal fishing operations have a vested interest in remaining unquantified. Instead, we look to previously published global estimates. While more recent IUU estimates exist (e.g. MRAG 2021), few are specifically focused on the EPO. We therefore update data from Agnew et al. 2009, which estimates the value of IUU-caught fish in the Eastern Central Pacific to range between \$117-\$251 million (in 2003 dollars; \$172-\$370 million converted to 2021 dollars); IUU catch in the region is estimated to be between 9.44% and 20.26% of total catch in the region, with an average of 15%. We use these ranges as starting values in this analysis.

The benefit of the model used in this analysis, and in particular the Monte Carlo approach applied to the parameters, is that it affords an opportunity to explore possible effects for highly uncertain parameters such as (2) with different assumptions. Here, we use the estimates of value of IUU in the EPO in total, and explore an assumption of what additional % reduction in IUU EM might motivate. By dividing the estimates from (1) above by different percentages of potential IUU rates (starting with the 15% average from Agnew et al. 2009), we can calculate an approximate “per % of IUU” value. If EM reduces the level of IUU fishing at all, the benefit realized will be that per % IUU value multiplied by the percentage reduction in IUU EM caused. Because the “observer effect” is an established phenomenon even on fully compliant vessels, there’s reason to believe installing cameras on vessels previously engaging in illegal fishing will motivate at least some reduction in IUU activities.

This approach makes several simplifying assumptions. It implicitly assumes each % of IUU reduced is worth the same flat amount; in reality, the value of IUU catch will be heavily dependent on multiple factors, including species and quality. The point of this exercise, however, is not to definitively state the exact value of IUU reduction resulting from EM, but to illustrate that value by calculating a semi-realistic estimate. There are complicated alternatives – for example, estimating long-term stock benefits resulting from lowered IUU mortality over time

– but those carry their own assumptions about the future that make such estimates equally uncertain.

Finally, it is reasonable to expect reductions in potential IUU activity during fishing activity that is observed through any means, whether via onboard human observers or EM systems. At the same time, many of the same heinous barriers to putting human observers on board longline vessels in the first place – such as coercion, threats, and violence – likely also diminish the effectiveness of human observers in reducing illegal fishing activity. Regardless, as this analysis is focused on any *additional* costs or benefits stemming from the adoption of EM, the "observer effect" resulting from the assumption that EM equipment will be required aboard each vessel is the only IUU-related benefit included in this model. An understanding of the effect on IUU activity scales with additional onboard observers, or for that matter with review rates for EM, is needed to further quantify any additional benefit beyond the known "observer effect" generated by putting EM systems in place. Any IUU reduction effects resulting from the presence of onboard observers are, for now, considered a baseline, particularly in light of the operating assumption that there is to be no reduction from the current level of onboard observers, even if an EM program were to be put in place in the future.

3.4. Unquantified Benefits

3.4.1 Health & Safety

There are two potential health & safety benefits potentially resulting from EM. The first stems from a version of the “observer effect” discussed above, in which some of the extreme barriers to putting human observers on some longline vessels – i.e. coercion, threats, injuries, and death – are avoided entirely by instead requiring an impassive EM system (Michelin et al. 2018). Because these sorts of safety issues are not tracked, however, and at any rate because the very increase in observer coverage via EM may already capture some portion of this benefit, this is not quantified in this analysis.

EM footage could conceivably protect vessel owners from lawsuits related to staged or exaggerated accidents by crew or observers, as well as the any resulting changes to insurance premiums. On a more positive note, EM may also in the future allow private companies to verify health & safety standards, as well as the avoidance of labor rights abuses, on board the vessels they source seafood product from. As crew welfare becomes increasingly important within and outside the seafood industry, there is potential for verification of onboard activities to become an important component of market requirements. However, due to the multitude of paths this benefit could take in the future, the fact that IATTC does not track onboard accident statistics, and even the lack of clarity on whether this would already be captured within the price premium benefit quantified above, prevents a quantification at this time.

3.4.2 Efficient targeting of bycatch measures

A widespread EM system could also allow for efficiencies in the deployment of bycatch mitigation measures. For example, (Michelin et al., 2018) note that managers in some tuna longline fisheries used to close “five-degree latitude bands for the entire fishery if the seabird mortality rate exceeded a threshold of 0.05 birds per 1 thousand hooks.” By using EM, managers could in theory employ an incentive-based approach that specifically targets just those vessels with a high rate of seabird bycatch, requiring them to use additional mitigation methods without restricting or obligating additional economic costs across the entire fleet. Unfortunately, no data exists that could be adapted to plausibly estimate such a scenario for the EPO longline fleets, but the potential is there.

3.4.3 Transshipment detection

Outside the fishing vessel-level of operation, EM may also have some potential benefit in regards to transshipment. For example, EM sensors are able to detect and log when transshipment events occur; at minimum, this suggests the presence of EM would likely to reduce the number of unauthorized or unregulated transshipment events. How this results in quantifiable economic benefits, however, will require more detailed information than is currently available, including both an estimate of value and the size of the effect EM presence would have. For example, if transshipments are levied in some way, then a quantified increase in non-reported transshipment detection could be translated into a quantifiable benefit. Data on transshipments could also potentially help better target the deployment of MCS (monitoring, control and surveillance) assets; however, as there is no data currently available and enforcement is expressly not the main policy goal of IATTC in pursuing EM adoption, this benefit is unquantified for now.

There could also be efficiencies (in both enforcement terms and base catch data terms) in incorporating EM as a tool to monitor transshipment events. As the ability of EM technology to differentiate species improves, so, too, does the potential for EM to augment and increase overall observer coverage of transshipment events. The specific economic costs and benefits of that potential benefit, however, rely upon the specific operational details of transshipment vessels and activities, and thus lay outside the scope of this fishing vessel-focused analysis.

3.4.4 Efficiency in onboard operations

A final potential benefit of EM implementation is that of enhanced efficiency in onboard operations. As vessels learn to utilize the information having cameras on board affords them – for example, vessel captains benefitting from a “bird’s eye view” from cameras without having to leave the cabin to remain situationally aware – there are perhaps efficiencies in operations that could translate into economic benefits. For example, quality control (i.e. the ability to detect and mitigate catch handling problems) is often cited in vessel operator communications as a potential on board benefit of EM. It is unclear, however, through what mechanism (e.g. price, lowered costs, etc.) this possible efficiency might actually translate into tangible economic benefits, without more detailed information on how vessel operations might change. Personal communications surrounding Australian EM trials indicated no such benefit was ultimately observed, despite the a priori expectation it would be realized; however, vessel operators elsewhere in the world have indicated seeing promise in such efficiencies, suggesting there may yet be an uncovered benefit along these lines. Some of these operational changes may also require that the vessel crew and/or fishing company are able to view the EM data in real time (e.g. by having a monitor for viewing), which may not always be possible or practical. Until more empirical evidence is collected specifically on these efficiencies, however, they remain unquantified in this analysis.

4. Results

4.1 Base Case & Pre-Uncertainty Analysis

Before examining the results of the uncertainty analysis, the results of the static “base case” (i.e. the net present value, computed using the static mean values used for each parameter) are themselves informative to review.

Table 2 provides an overview of each scenario explored in this analysis, with the model outputs for each discussed in the subsections below. The full list of parameters used, as well as each mean values used to compute the outputs in this section, can be found in Appendix A.

Table 2 Scenarios & Starting Assumptions

Scenario	**Description**
1. Base case: 5% observer coverage, onboard observers (OBO) only	Starting “base case” of the current (business as usual) state of the world: 5% observer coverage, only from human onboard observers (i.e. no EM)
2. 5% coverage, EM only	Similar to Scenario 1, but with the 5% observer coverage coming from EM instead of OBO
3. 10% coverage, 5% OBO + 5% EM	Observer coverage raised to 10%, with 5% each coming from OBO and EM
4. 20% coverage, 5% OBO + 15% EM	Observer coverage raised to 20%, with 5% from OBO and the remaining 15% from EM
5. 20% coverage, OBO only	Observer coverage raised to 20%, entirely from OBO
6. 100% EM + 5% OBO	EM review of 100% of all sets, with an additional 5% OBO coverage
Model assumptions	
Time length of analysis	10 years
Discount rate	3% - 7%

5% observer coverage level

Beginning at the 5% observer coverage level using just onboard observers – AKA “business as usual” – the model outputs in Table 3 reveal exactly the expected result: $0 in all EM-related cost parameters, and $0 in all benefits - again, because the benefits categories here are specifically *additional* benefits resulting from EM.

Table 3: Model outputs for 5% total observer coverage, onboard observers only

category	**costs**			**benefits**			**net benefits**
		% of total			% of total		
observers - on board	$14,842,174	100.00%		$0	0.00%		-$14,842,174
observers - EM	$0	0.00%		$0	0.00%		$0
vessel hardware	$0	0.00%		$0	0.00%		$0
other management costs	$0	0.00%		$0	0.00%		$0
price premium - EM	$0	0.00%		$0	0.00%		$0
scientific data value	$0	0.00%		$0	0.00%		$0
bycatch reduction	$0	0.00%		$0	0.00%		$0
IUU reduction	$0	0.00%		$0	0.00%		$0
Total	$14,842,174			$0			**-$14,842,174**

The total, $14.8 million in costs, is the 10-year discounted total resulting from an annual expense of approximately $1.8 million. These are the costs resulting from the model's estimate that 61 onboard observers would be needed to be employed per year to cover 5% of all sets by the longline vessels operating in the EPO. As a reminder, this is not to imply that *zero* benefits are generated by the current observers; instead, this analysis is setup to explore any *additional* benefits above this 5% baseline.

Table 4 displays the base model outputs again for 5% total observer coverage, but this time in a scenario where only EM, rather than onboard observers, is used.

Table 4: Model outputs for 5% total observer coverage, EM observers only

category	**costs**			**benefits**			**net benefits**
		% of total			% of total		
observers - on board	$0	0.00%		$0	0.00%		$0
observers - EM	$1,593,698	2.70%		$0	0.00%		-$1,593,698
vessel hardware	$56,257,168	95.27%		$0	0.00%		-$56,257,168
other management costs	$1,199,532	2.03%		$0	0.00%		-$1,199,532
price premium - EM	$0	0.00%		$43,339,332	17.34%		$43,339,332
scientific data value	$0	0.00%		$0	0.00%		$0
bycatch reduction	$0	0.00%		$93,433,716	37.39%		$93,433,716
IUU reduction	$0	0.00%		$113,135,759	45.27%		$113,135,759
Total	$59,050,397			$249,908,806			**$190,858,408**

While the labor costs have declined – owing to the efficiencies in video review, only 12 EM reviewers are needed instead of the equivalent 61 onboard observers, and thus labor costs are now only slightly more than 10% of the onboard observer scenario above – total discounted costs for the entire 10-year period are higher, at $59.1 million. This is due to the fact that the use of EM obligates the upfront purchase of all related vessel and management equipment.

Most notable of these new costs are the vessel hardware costs, which are over 95% of all costs and total $56.3 million across the EPO; using the average number of large longline vessels in the EPO across the last five years, 1,183, results in an estimate of $3,443 per vessel per year, with $14,862 in startup costs in Year 1. The range in the EM literature for vessel startup costs is approximately $10,000 - $14,000, with most on the lower end of that range (e.g. Cap Log Group

2019; Stobberup et al. 2020; Sylvia et al. 2016); therefore this major cost is conservative while remaining in line with other estimates.

Overall, however, the net benefits are high in this first EM scenario, due to the potential benefits of an EM price premium, additional bycatch mitigation effects, and a slight decline in IUU fishing all occurring, as discussed in the Methods section above. The price premium benefit, which is the monetary benefit in this model accruing solely to fisheries operators, is lower than the total vessel hardware costs. However, the value reported in Table 4 is the aggregated total for the entire fishery across the full 10 year timeframe; setting aside the upfront investment in hardware, annual additional operating costs per vessel are more than compensated for by the projected price premium ($3,443 vs. $4,387, respectively). This benefit, slightly more than 17% of total benefits, is however dwarfed by the bycatch and IUU reduction benefits, which collectively comprise over 82% of the total benefits in this starting scenario. Given that the additional bycatch and IUU reduction rates are conservatively set at 3% and 5%, respectively, there is an implication that there are significant societal benefits to be gained for the costs incurred.

10% observer coverage scenario

Table 5 displays the results of a 10% observer coverage scenario that includes 5% of coverage coming from both EM and onboard observers. As discussed above, this is an expression of a policy goal of IATTC in potentially adopting an EM program, in which the number of onboard observers is not reduced from the present amount, and thus EM provides any additional coverage.

Table 5: Model outputs for 10% total observer coverage, EM & OBO each 5% of coverage

category	**costs**			**benefits**			**net benefits**
		% of total			% of total		
observers - on board	$14,842,174	20.09%		$0	0.00%		-$14,842,174
observers - EM	$1,593,698	2.16%		$0	0.00%		-$1,593,698
vessel hardware	$56,257,168	76.13%		$0	0.00%		-$56,257,168
other management costs	$1,199,532	1.62%		$0	0.00%		-$1,199,532
price premium - EM	$0	0.00%		$43,339,332	17.02%		$43,339,332
scientific data value	$0	0.00%		$4,794,781	1.88%		$4,794,781
bycatch reduction	$0	0.00%		$93,433,716	36.68%		$93,433,716
IUU reduction	$0	0.00%		$113,135,759	44.42%		$113,135,759
Total	$73,892,571			$254,703,587			**$180,811,016**

Note that many of the upfront EM costs are the same as the previous scenario in Table 5, as vessel costs and management costs for implementing EM are treated here as “all or nothing” – i.e. either the equipment is purchased in full because EM is implemented, or there’s no EM at all. The total costs are those of Tables 3 and 4 added together – in other words, the cost of 5% onboard observer coverage added to the costs of 5% EM observer coverage. For this reason, the total net benefits are actually slightly lower than the 5% EM-only scenario in Table 4. Given that the present real-world state is the 5% onboard observer scenario, however, there are significant net benefits that can be achieved by adding EM (i.e. moving from the results in Table 3 to Table 5).

Most of the benefits are the same as the 5% EM-only scenario explored above (Table 4), as the IUU reduction, bycatch mitigation, and price premium benefits are all treated as a binary effect – that is, the benefit in this model is either completely gained if present, or not received at all. (It is doubtful there would be a continually scaling price premium for every percentage of EM coverage, for example; rather, the price premium would likely be the result of something like sustainability certification, where having an EM program checks a box, regardless of the level of observer coverage above some minimum.) The additional benefit in this scenario is that of scientific data value, as any scenario above the 5% current level of observer coverage – regardless of whether it comes from EM or on board – begins to generate additional benefits above today's current baseline information collected.

20% observer coverage scenario

Table 6 displays the base model outputs for setting observer coverage to 20%, the minimum observer coverage recommended for scientific data collection purposes, as discussed above. Once again, looking to the IATTC policy recommendation as a guideline, onboard observer coverage is held constant at 5%, with EM coverage contributing the remainder.

Table 6: Outputs for 20% total observer coverage, EM 15% & OBO 5% of coverage

category	**costs**			**benefits**			**net benefits**
		% of total			% of total		
observers - on board	$14,842,174	19.26%		$0	0.00%		-$14,842,174
observers - EM	$4,781,093	6.20%		$0	0.00%		-$4,781,093
vessel hardware	$56,257,168	72.99%		$0	0.00%		-$56,257,168
other management costs	$1,199,532	1.56%		$0	0.00%		-$1,199,532
price premium - EM	$0	0.00%		$43,339,332	16.40%		$43,339,332
scientific data value	$0	0.00%		$14,384,343	5.44%		$14,384,343
bycatch reduction	$0	0.00%		$93,433,716	35.35%		$93,433,716
IUU reduction	$0	0.00%		$113,135,759	42.81%		$113,135,759
Total	$77,079,966			$264,293,149			**$187,213,182**

Interestingly, both the costs and benefits (and, therefore, net benefits) are barely changed in this scenario. Costs only rise by $3.2 million total over the 10-year period, entirely as a result of increased EM observer costs. Though benefits only rise by approximately 4% ($9.6 million, which more than compensates for the increase in costs), that is a small increase relative to doubling the level of observer coverage from the previous scenario.

It is also important to note that once observer coverage reaches 20%, there are many additional benefits likely to accrue in the long-run due to the potential for accurate stock assessments and resulting fisheries management benefits; however, such benefits require additional assumptions and require a much more detailed bioeconomic modeling exercise, which is outside the scope of this analysis.

Table 7: Outputs for 20% total observer coverage, OBO providing all 20% of coverage

category	**costs**			**benefits**			**net benefits**
		% of total			% of total		
observers - on board	$59,368,695	100.00%		$0	0.00%		-$59,368,695
observers - EM	$0	0.00%		$0	0.00%		$0
vessel hardware	$0	0.00%		$0	0.00%		$0
other management costs	$0	0.00%		$0	0.00%		$0
price premium - EM	$0	0.00%		$0	0.00%		$0
scientific data value	$0	0.00%		$14,384,343	100.00%		$14,384,343
bycatch reduction	$0	0.00%		$0	0.00%		$0
IUU reduction	$0	0.00%		$0	0.00%		$0
Total	$59,368,695			$14,384,343			**-$44,984,352**

As a comparative exercise, Table 7 displays the results of a scenario run with the base model in which 20% observer coverage is reached using onboard observers alone. Unsurprisingly, the cost entirely comes from hiring a significant number of onboard observers. While the benefits of gaining additional scientific data are still present, all other potential additional EM-generated benefits are absent in this scenario, as expected. Note also that costs in this scenario also accrue entirely to management (e.g. IATTC, or potentially also shared with National programs depending on how the program is set up), as opposed to less than half that ($20.8 million) in the previous (5% onboard, 15% EM) scenario in Table 6.

100% EM coverage

Finally, Table 8 displays the results of setting the base model to 100% EM observer coverage, while additionally retaining the 5% onboard observer coverage. This would be equivalent to moving from an “audit approach” to “census approach” for the EM observer coverage (Stanley et al, 2011). Surprisingly, costs are only 35% higher than the 20% scenario in Table 6, as the only cost that continues to scale with percentage of EM coverage is the EM observer costs.

Table 8: Outputs for 100% EM observer coverage, plus 5% OBO coverage

category	**costs**			**benefits**			**net benefits**
		% of total			% of total		
observers - on board	$14,842,174	14.25%		$0	0.00%		-$14,842,174
observers - EM	$31,873,953	30.60%		$0	0.00%		-$31,873,953
vessel hardware	$56,257,168	54.00%		$0	0.00%		-$56,257,168
other management costs	$1,199,532	1.15%		$0	0.00%		-$1,199,532
price premium - EM	$0	0.00%		$43,339,332	12.53%		$43,339,332
scientific data value	$0	0.00%		$95,895,620	27.73%		$95,895,620
bycatch reduction	$0	0.00%		$93,433,716	27.02%		$93,433,716
IUU reduction	$0	0.00%		$113,135,759	32.72%		$113,135,759
Total	$104,172,827			$345,804,426			**$241,631,599**

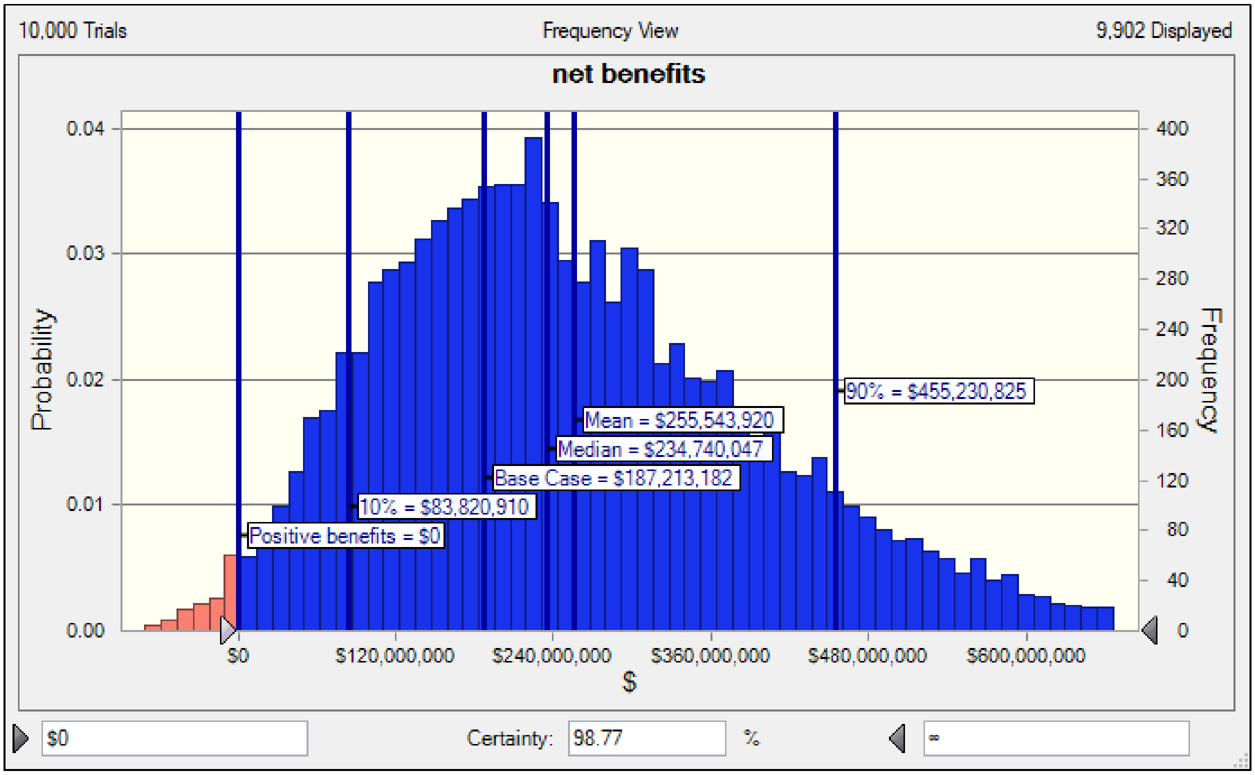
Likewise, as previously discussed, the benefit categories are mostly static, and thus the same as in the other EM scenarios previously analyzed. The sole exception in this scenario are the continually scaling scientific data value, which has climbed to over 27% of all benefits in the 100% coverage scenario; however, while other additional benefits might be expected (e.g. further declines in IUU fishing, and more generally compliance with all IATTC resolutions), this is likely an unrealistic estimate of the value of scientific data, given the benefit is treated as a flat increase instead of the likely decline in marginal value as scientific data collection approaches an upper limit.

4.2 Uncertainty Analysis & Monte Carlo Simulation Results

A significant contribution of this report to past EM cost-benefit analyses is the additional of a Monte Carlo simulation, to account for the inherent uncertainty in projecting future costs for each parameter in the base model. The full range of values used for each parameter in the Monte Carlo simulation can be found in Appendix A.

The results of this Monte Carlo analysis can be seen in Figure 1 below.

Figure 1: Results of the Monte Carlo simulation, 20% observer coverage



Through simulating 10,000 trials – that is, model runs with different combinations of values ranging between the minimum and maximum input values for each parameter in the model – the mean net benefit value of all simulations was $255.5 million. Most assuring is the fact that 98.8% of all trials resulted in positive net benefits. In other words, implementing EM to achieve 20% observer coverage has a very high probability of resulting in more benefits than costs – in approximately 99% of all cases. (In Figure 1, the red bars on the far left represent the 1% of cases with a net negative value.) Table 9 includes the minimum, maximum, and percentile cutoff points for the results. (In other words, only 10% of the random simulations produced net benefits of $83,820,910 or less, 50% produced net benefits of $234,737,933 or more, etc.)

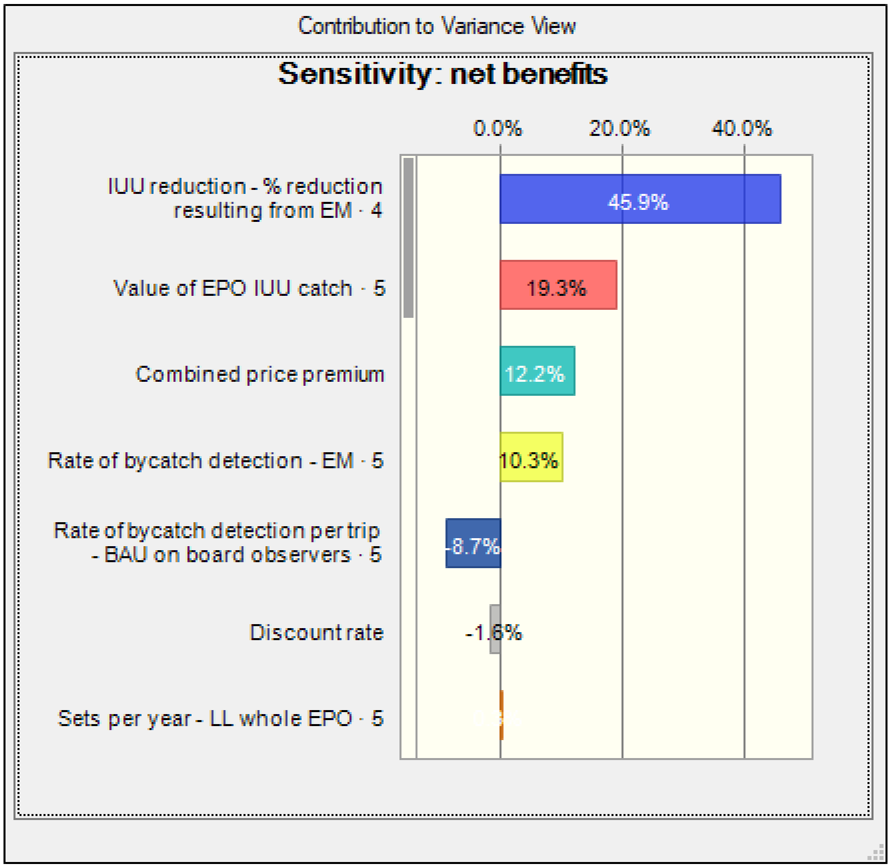
Table 9: Percentiles of Simulation Runs

Forecast: net benefits	
Percentile	Forecast values
0%	-$70,161,990
10%	$83,820,910
20%	$129,294,427
30%	$166,798,429
40%	$201,094,987
50%	$234,737,933
60%	$273,273,459
70%	$315,927,812
80%	$372,834,035
90%	$455,230,825

100%	$850,065,876

Finally, another advantage of a Monte Carlo simulation is that by modifying the parameter values over and over again, it can also calculate how sensitive the model's overall output is to particular parameters. The result of this sensitivity analysis can be seen in Figure 2.

Figure 2: Sensitivity of New Benefit Parameters



Perhaps unsurprisingly, the parameter that most affected the value of the model's final output (i.e. net benefits) had to do with the largest positive benefit values: IUU catch reduction. To a lesser extent, the other major benefits – the price premium, and bycatch reduction – also affected results the most.

Further sensitivity test

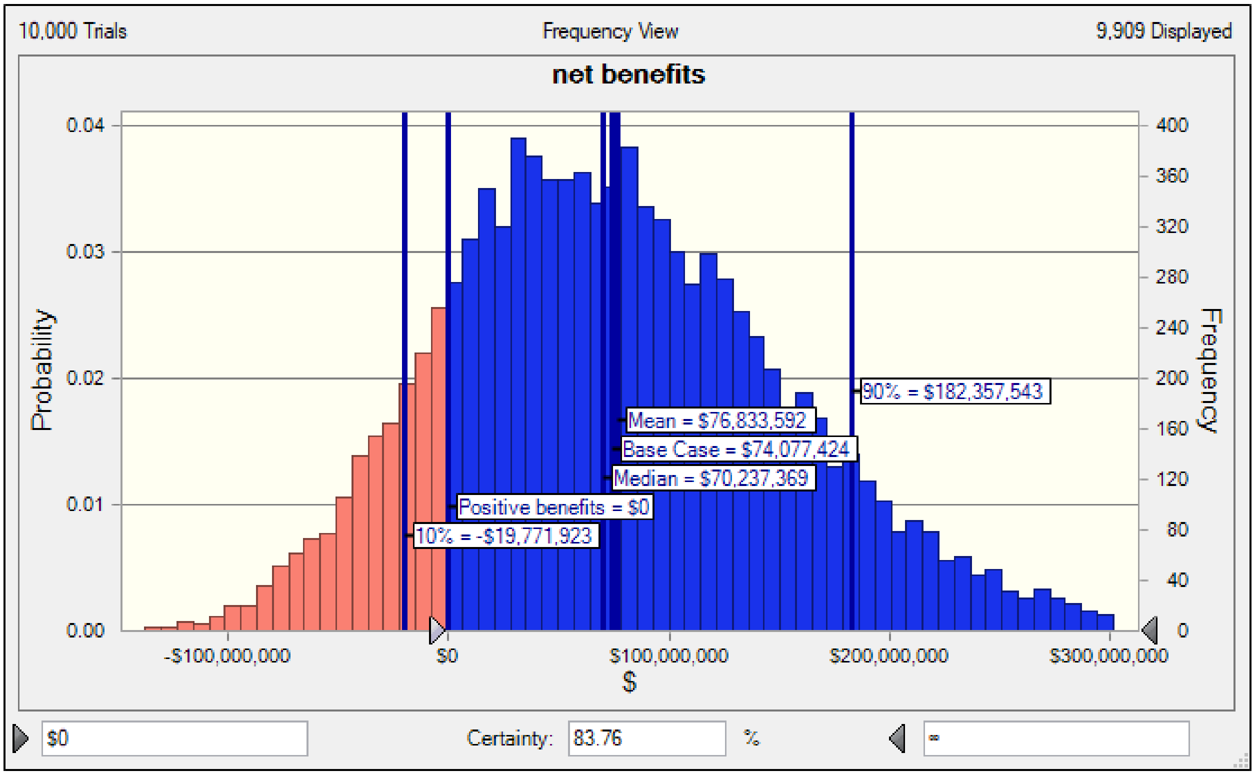
While the range of values used in this analysis are justifiable, such strong sensitivity to just a few parameters (or, debatably, one, as both the value of IUU catch and the rate of IUU reduction contribute to the same benefit) could theoretically raise concerns, especially as they're tied to one the most “uncertain” of the model's potential benefits.

To explore this sensitivity further, an experiment was run where both of these parameters were held at $0 in the model – effectively removing their influence on the results. Table 10 below summarizes the result in the static base model with 20% observer coverage, while Figure 3 displays the new Monte Carlo result and Figure 4 showing the related sensitivity analysis:

Table 10: Base Model Output for 20% Observer Coverage with IUU Reduction Held at $0

category	costs			benefits			net benefits
		% of total			% of total		
observers - on board	$14,842,174	19.26%		$0	0.00%		-$14,842,174
observers - EM	$4,781,093	6.20%		$0	0.00%		-$4,781,093
vessel hardware	$56,257,168	72.99%		$0	0.00%		-$56,257,168
other management costs	$1,199,532	1.56%		$0	0.00%		-$1,199,532
price premium - EM	$0	0.00%		$43,339,332	28.67%		$43,339,332
scientific data value	$0	0.00%		$14,384,343	9.52%		$14,384,343
bycatch reduction	$0	0.00%		$93,433,716	61.81%		$93,433,716
IUU reduction	$0	0.00%		$0	0.00%		$0
Total	$77,079,966			$151,157,390			$74,077,424

Figure 3: Monte Carlo Simulation with IUU Reduction Benefit Held at $0

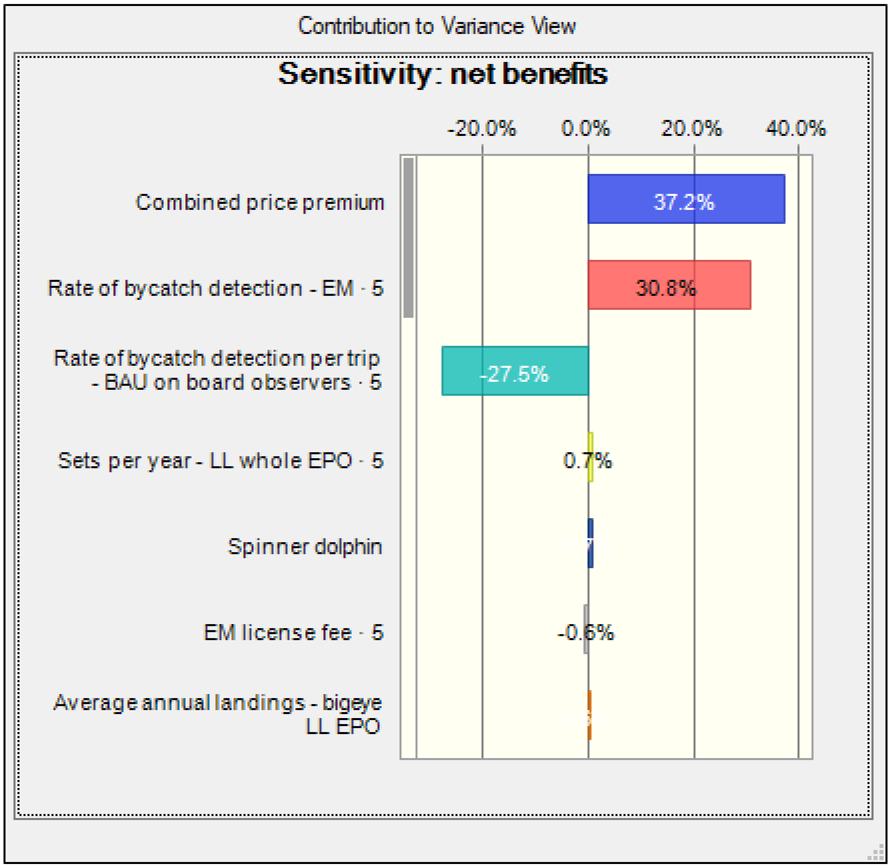


$0

Certainty: 83.76 %

∞

Figure 4: Sensitivity Analysis with IUU Reduction & Bycatch Held at $0



In the static results of the base model (Table 10), net benefits remain positive with benefits $74.1 million higher than costs. The results of the Monte Carlo simulation (Figure 3) indicate that 83.8% of simulation runs still result in positive net benefits. While approximately 16% resulting in $0 or less net benefits is higher than the previous 1%, the results indicate the base model's $74.1 million output (Table 10) is slightly lower than the mean result of $76.8 million.

Finally, the new sensitivity analysis in Figure 4 now indicates the combined sashimi price premium is the leading parameter most likely to (positively) affect the results, with the two rates of bycatch reduction (first EM, with a positive effect, followed by OBO with a negative effect) close behind.

Taken together, these results suggest that even without the single biggest sources of benefits in the model estimations, and even taking into account the uncertainty in all of the components of the model, the adoption of EM is highly likely to result in significant overall economic benefits.

5. Key Takeaways and Discussion

This report presents a cost-benefit analysis for the adoption of an electronic monitoring program specific to the longline tuna fishery of the Eastern Pacific Ocean. It is also, to our knowledge, the first-ever use of Monte Carlo simulation to address the significant uncertainty in parameters and estimates necessary to project future costs and benefits related to EM.

While the specific outputs and interpretation of the results of this cost-benefit analysis can be found above, we conclude with a few high-level takeaways this report has uncovered and discuss below:

1. **EM adoption is highly likely to produce a net positive economic benefit.** On average, the model employed here projects more than $187 million in net benefits upon reaching 20% observer coverage through the combined use of EM and onboard observers. Many of these benefits (e.g. increased scientific data, bycatch mitigation) are broadly beneficial to society, but even vessel owners and operators, who bear the brunt of the upfront costs of installing EM equipment, are likely to see many positive benefits as well (e.g. reduction in IUU fishing, potential sustainability-related market premiums).
2. **The results of this analysis are robust to the inherent uncertainty in projecting future EM costs and benefits, suggesting EM adoption is a sound investment.** The use of Monte Carlo simulation in this analysis, in particular, affords an additional level of confidence beyond simply using point estimates, which can quickly become out of date as technology and familiarity with EM systems continues to evolve. This also further reinforces key takeaway #1, as almost all possible iterations of the model used here returned a positive economic result.
3. **EM has significant potential to scale up once the initial investment has been made.** The outputs of this analysis suggest moving from 20% observer review of EM data to 100% review will be only 35% higher in cost than the initial investment to reach that first 20%. In other words, once the startup costs necessary to establish an EM program has been made, few significant costs remain to increasing review coverage further. Because 20% observer coverage is a *minimum* recommended level, there are likely considerable additional benefits once an EM program is in place.
4. **EM has the potential to bring much-needed insight into the Eastern Pacific Ocean's longline fishery.** Perhaps the biggest challenge of this analysis was the paucity of longline-specific data applicable to the EPO. Despite the exemplary reports and data made available by IATTC, there simply isn't as enough detailed information on the longline fishery in the EPO to conduct a more thorough cost-benefit analysis. In particular, information related to both catch data and vulnerable species interactions could see immense improvement from the installation of an EM program.

Overall, the findings of the analyses conducted in this report suggest that there are very likely positive economic benefits to implementing an electronic monitoring program for the longline tuna fishery in the Eastern Pacific Ocean.

These results are significantly bolstered by the novel use of Monte Carlo simulations in an analysis of EM. The power of this approach lies in the ability to see outcomes across a wide spread of values for each of the different factors that go into the cost-benefit model, providing a much higher level of confidence that results are robust to changes and uncertainty, and are not based upon very specific input value selections. This is particularly important given the rapidly developing nature of EM technology, as both costs and capabilities are changing over time.

The economic impacts of EM adoption, both positive and negative, will affect different users to different degrees. Vessel hardware costs, the highest cost category, likely fall to fishing operators. (See Table 11, Appendix A for specific items included in this category.) Many of these costs are upfront hardware investment costs, with annual operating costs much lower. However, private fishing entities could also be the main benefactors of any price premium associated with EM adoption (depending on how these benefits flow through the supply chain), which could offset these costs. Private operators will also likely see market benefits as well resulting from some of the other benefit categories in this analysis, most notably a potential reduction in IUU. We also acknowledge that some of the other benefits in this analysis ascribed to other decision-making entities may conflate some benefits that in reality flow to private industry as well – most notably the scientific data and bycatch benefits, which protect ecosystem integrity and afford a positive effect to the resource and, therefore, the resource users.

Some management costs are likewise variable in their difficulty to delineate, as they depend on future management choices; for example, decisions around where and how EM data will be monitored and used. One of the most important findings of this analysis, however, is that even with the upfront investment required to bring an EM program online, EM will be a significantly cheaper approach to reaching the minimum level of observer coverage necessary for managers to collection sufficient data for the management of the EPO longline fishery (i.e. at least 20% coverage). In pure economic cost-benefit terms this appears to be a worthwhile endeavor, as many benefits accruing broadly to general society – such as the reduction of mortality for iconic bycatch species, or the generation of scientific data – are among the highest found in this analysis. Furthermore, this analysis finds that extending observer coverage to *all* vessels – i.e. 100% observer coverage – appears to be a goal within reach once 20% EM coverage has been achieved, as further extending coverage that high will only cost 1/3 more than what would have already been invested.

An ongoing challenge in cost-benefits analyses of EM, however, will be the necessity of including these benefits that are both tangible (such as price premiums) and intangible (such as non-market bycatch reduction value). Just as costs are typically more straightforward to quantify than benefits, benefits accruing through market mechanisms are easier to quantify than those that are more nebulously enjoyed by broader society. We have explored additional sensitivity analyses related to some of these benefits in Appendix B, which further suggest that even more heavily favoring the more readily quantifiable market-driven benefits will still result in net positive benefits. Despite challenges to their quantification, however, it should again be emphasized again that it would be inappropriate to ignore the more intangible benefits flowing from EM adoption in any cost-benefit analysis on an EPO-wide scale, as actions there will have significant society-scale benefits.

Finally, a motivating factor of this analysis was the lack of any cost-benefit analysis to date for EM in the EPO, coupled with the general sentiment that EM is the likely path to achieving more observer coverage in the longline fishery specifically. This analysis confirms this sentiment, but the approach taken here should not be thought of as applying exclusively to this regional context. Many of the EPO longline-specific inputs, as shown in the full model parameters in Table 11 of Appendix A, could be swapped out for values specific to other fisheries in other management regimes, while many of the EM-specific inputs are likely to be similar regardless of context, such as properly quantifying tradeoffs in cost and efficiency between EM review and onboard observers. The use of a Monte Carlo simulation is again a valuable tool for any such analysis, as the results would be robust to uncertainty in both future costs and transferability between factors populating this analysis. To illustrate this point, we present recommendations for necessary actions to extend this analysis to both the purse seine *and* longline fisheries in Appendix C.

This analysis finds that adoption of an electronic monitoring program will indeed generate significant positive economic benefits. The suggestion that EM could be a low-cost approach to significantly ramping up the level of observer coverage in EPO longline vessels is likewise shown to be true throughout this analysis. Furthermore, the novel approach taken here provides significant confidence in the results, and ensures robustness to future uncertainty. While further detail in both the cost and benefit data used in these estimates could provide more detailed estimates to inform different approaches to an EM program, there is now little doubt that the benefits of an electronic monitoring program for longline vessels in the EPO will greatly outweigh the costs.

6. References

Agnew, David J., John Pearce, Ganapathiraju Pramod, Tom Peatman, Reg Watson, John R. Beddington, and Tony J. Pitcher. “Estimating the Worldwide Extent of Illegal Fishing.” Edited by Stuart A. Sandin. *PLoS ONE* 4, no. 2 (February 25, 2009): e4570. https://doi.org/10.1371/journal.pone.0004570.

Anderson, Orea. “Estimating Seabird Bycatch Rates in IATTC Industrial Longline Fisheries,” 15. Del Mar, CA, USA, 2009.

Babcock, Elizabeth A, Ellen K Pikitch, and Charlotte Hudson. “How Much Observer Coverage Is Enough to Adequately Estimate Bycatch? Report of the Pew Institute for Ocean Science.” Rosentiel School of Marine and Atmospheric Science, University of Miami, 2003.

Banks, Richard, G Muldoon, and V Fernandes. “Analysis of the Costs and Benefits of Electronic Fisheries Information Systems Applied in FFA Countries and Identification of the Legislative, Regulatory and Policy Supporting Requirements.” World Wildlife Fund, 2016.

Booth, Hollie, William N. S. Arlidge, Dale Squires, and E. J. Milner-Gulland. “Bycatch Levies Could Reconcile Trade-Offs between Blue Growth and Biodiversity Conservation.” *Nature Ecology & Evolution* 5, no. 6 (June 2021): 715–25. https://doi.org/10.1038/s41559-021-01444-w.

Booth, Hollie, Dale Squires, Irfan Yulianto, Benaya Simeon, Muhsin, Luky Adrianto, and Eleanor Jane Milner-Gulland. “Estimating Economic Losses to Small-scale Fishers from Shark Conservation: A Hedonic Price Analysis.” *Conservation Science and Practice* 3, no. 9 (September 2021). https://doi.org/10.1111/csp2.494.

Börger, Tobias, Tara L. Hooper, Melanie C. Austen, Oceane Marcone, and Olivia Rendón. “Using Stated Preference Valuation in the Offshore Environment to Support Marine Planning.” *Journal of Environmental Management* 265 (July 2020): 110520. https://doi.org/10.1016/j.jenvman.2020.110520.

Brown, Christopher J., Amelia Desbiens, Max D. Campbell, Edward T. Game, Eric Gilman, Richard J. Hamilton, Craig Heberer, David Itano, and Kydd Pollock. “Electronic Monitoring for Improved Accountability in Western Pacific Tuna Longline Fisheries.” *Marine Policy* 132 (October 2021): 104664. https://doi.org/10.1016/j.marpol.2021.104664.

Cap Log Group, LLC. “Projected Costs of Providing Electronic Monitoring to 100 Vessels in New England’s Groundfish Fishery.” The Nature Conservancy, March 2019.

Emery, Timothy J., Rocio Noriega, Ashley J. Williams, and James Larcombe. “Changes in Logbook Reporting by Commercial Fishers Following the Implementation of Electronic Monitoring in Australian Commonwealth Fisheries.” *Marine Policy* 104 (June 2019): 135–45. https://doi.org/10.1016/j.marpol.2019.01.018.

Griffiths, Shane, Leanne Duffy, and Alexandre Aires-da-Silva. “A Preliminary Ecological Risk Assessment of the Large-Scale Tuna Longline Fishery in the Eastern Pacific Ocean Using Productivity-Susceptibility Analysis,” 22. La Jolla, California, USA, 2017.

Griffiths, Shane, and Brad Wiley. “Standardization of Reporting Formats and Effort Reporting for Longline Fisheries (Resolution C-11-08),” 5. IATTC, 2019. Last Accessed: February 28, 2022. https://www.bmis-bycatch.org/system/files/zotero_attachments/library_1/UP6KS7FW%20-%20Griffiths%20and%20Wiley%20-%20Standardization%20of%20reporting%20formats%20and%20effort%20re.pdf.

IATTC. “Resolution C-11-08: Resolution on Scientific Observers for Longline Vessels.” La Jolla, California, USA, 2011. https://www.iattc.org/PDFFiles/Resolutions/IATTC/_English/C-11-08-Active_Observers%20on%20longline%20vessels.pdf.

IATTC. “Document AIDCP-41-01: AIDCP Budget,” 2020. Last accessed November 3 2021. https://www.iattc.org/Meetings/Meetings2020/IATTC-95/AIDCP-41/_English/AIDCP-41-01_AIDCP%20budget.pdf.

IATTC. “Document CAF-08-02: Fiscal Year 2020 Results and Budgets for Fiscal Years 2022 and 2023,” 2021a. Last accessed October 15 2021. https://iattc.org/Meetings/Meetings2021/IATTC-98a/Docs/_English/CAF-08-02_Review%20of%20proposed%20budgets%20for%202022%20and%202023.pdf.

IATTC. “Document SAC-12-04: Synopsis of Longline Observer Data Reported Pursuant to Resolution C-19-08,” 2021b. Last accessed October 15 2021. https://www.iattc.org/Meetings/Meetings2021/SAC-12/Docs/_English/SAC-12-04_Longline%20observer%20program%20reports.pdf.

IATTC. “Resolution C-21-04: Conservation Measures for Tropical Tunas In The Eastern Pacific Ocean During 2022-2024,” 2021c. Last accessed February 15 2022. https://www.iattc.org/PDFFiles/Resolutions/IATTC/_English/C-21-04-Active_Tuna%20conservation%20in%20the%20EPO%202022-2024.pdf.

IATTC. Active Vessel Register, 2021d. Last accessed November 15 2021. https://www.iattc.org/VesselRegister/VesselList.aspx?List=AcPS&Lang=ENG.

Lowman, Dorothy, Randy Fisher, Mark Holliday, Sarah McTee, and Shawn Stebbins. “Fishery Monitoring Roadmap.” Environmental Defense Fund, 2013.

McKinney, Raiana, James Gibbon, Esther Wozniak, and Grantly Galland. “Netting Billions 2020: A Global Valuation of Tuna.” Washington, D.C.: The Pew Charitable Trusts, October 2020. https://www.pewtrusts.org/en/research-and-analysis/reports/2020/10/netting-billions-2020-a-global-tuna-valuation.

Michelin, Mark, Matthew Elliott, Max Bucher, Mark Zimring, and Mike Sweeney. “Catalyzing the Growth of Electronic Monitoring in Fisheries: Building Greater Transparency and Accountability at Sea.” San Francisco, CA, USA: California Environmental Associates and The Nature Conservancy, 2018.

Michelin, Mark, Nicole M Sarto, and Robert Gillett. “Roadmap for Electronic Monitoring in RFMOs.” San Francisco, CA, USA: California Environmental Associates, 2020.

Michelin, Mark, and Mark Zimring. “Catalyzing the Growth of Electronic Monitoring in Fisheries: Progress Update August 2020.” San Francisco, CA, USA: California Environmental Associates and The Nature Conservancy, September 2020.

MRAG Asia Pacific. “The Quantification of Illegal, Unreported and Unregulated (IUU) Fishing in the Pacific Islands Region – a 2020 Update,” 2021. https://sustainpacfish.ffa.int/wp-content/uploads/2021/12/ZN2869-FFA-IUU-2020-Update-final.pdf.

NOAA Fisheries Greater Atlantic Regional Fisheries Office and Northeast Fisheries Science Center. “A Preliminary Cost Comparison of At Sea Monitoring and Electronic Monitoring for a Hypothetical Groundfish Sector,” June 10, 2015. https://media.fisheries.noaa.gov/dam-migration/em_cos_assessment_for_gar_multispecies_20150610.pdf.

Piasente, Matthew, Australian Fisheries Management Authority, and Fisheries Research & Development Corporation (Australia). *Electronic Onboard Monitoring Pilot Project for the Eastern Tuna and Billfish Fishery*. Barton, A.C.T.: Australian Fisheries Management Authority, 2012.

Román-Verdesoto, Marlon H., Jon Lopez, Cleridy E. Lennert-Cody, Enrique Urena, and Alexandre Aires-Da-Silva. “An Electronic Monitoring System for the Tuna Fisheries in the Eastern Pacific Ocean: Objectives and Standards,” 2020. https://doi.org/10.13140/RG.2.2.20863.43686.

Ruaia, Thomas, Steve Gu’urau, and Chris Reid. “Economic and Development Indicators and Statistics: Tuna Fisheries of the Western and Central Pacific Ocean 2020.” Honiara, Solomon Islands: Forum Fisheries Agency, 2020.

Stanley, Richard D., Howard McElderry, Tameezan Mawani, and John Koolman. “The Advantages of an Audit over a Census Approach to the Review of Video Imagery in Fishery Monitoring.” *ICES Journal of Marine Science* 68, no. 8 (September 1, 2011): 1621–27. https://doi.org/10.1093/icesjms/fsr058.

Stobberup, Kim, Alejandro Anganuzzi, Netani Tavaga, Eparama Loganimoce, Malo Hosken, Michael Arthur-Dadzie, Godfrey Baidoo-Tsibu, et al. *Electronic Monitoring in Tuna Fisheries:*

Strengthening Monitoring and Compliance in the Context of Two Developing States. FAO, 2021. https://doi.org/10.4060/cb2862en.

Sylvia, Gil, Michael Harte, and Chris Cusack. “Challenges, Opportunities, and Costs of Electronic Fisheries Monitoring.” San Francisco, CA, USA: Environmental Defense Fund, 2016.

Wallmo, Kristy, and Daniel K. Lew. “A Comparison of Regional and National Values for Recovering Threatened and Endangered Marine Species in the United States.” *Journal of Environmental Management* 179 (September 2016): 38–46. https://doi.org/10.1016/j.jenvman.2016.04.053.

Wallmo, Kristy, and Daniel K. Lew. “Public Willingness to Pay for Recovering and Downlisting Threatened and Endangered Marine Species: Valuing Species Recovery.” *Conservation Biology* 26, no. 5 (October 2012): 830–39. https://doi.org/10.1111/j.1523-1739.2012.01899.x.

Wang, Jiaqi, Xiaodi Gao, Jessica Chen, Xiaojie Dai, Siquan Tian, and Yong Chen. “An Evaluation of Observer Monitoring Program Designs for Chinese Tuna Longline Fisheries in the Pacific Ocean Using Computer Simulations.” *Environmental Science and Pollution Research* 28, no. 10 (March 2021): 12628–39. https://doi.org/10.1007/s11356-020-11266-1.

Wiener, Carlie, Lars Bejder, David Johnston, Leesa Fawcett, and Paul Wilkinson. “Cashing in on Spinners: Revenue Estimates of Wild Dolphin-Swim Tourism in the Hawaiian Islands.” *Frontiers in Marine Science* 7 (August 13, 2020): 660. https://doi.org/10.3389/fmars.2020.00660.

Appendix A. Input Values Used in Base Model

The table below displays the input values used in the Monte Carlo simulation analysis. Due to the limited data available for each parameter, a triangular distribution was used for each, with the mean value used as the “most likely value” input. (Appendix B below conducts an additional sensitivity test, with the median values used in place of the mean values, where possible.)

Table 11. Parameter Values Used in the Base Economic Model.

Component	**Value (low)**	**Value (high)**	**Value (median)**	**Value (mean)**	**unit**
EPO					
Total EPO annual catch	780,561	856,404	836,817	825,154.80	mt
Longline (LL) catch - total EPO	104,466	159,660	144,379	139,318	mt
Longline vessels in fleet	1,113	1,253		1,183	#
Sets per year - LL whole EPO	111,827.92	254,795.43	186,928.49	187,913.16	sets/year
Total observers in EPO per year	272	302	282	285	#
Cost of IATTC observer program	2,642,531	2,743,292	2,705,041	2,699,664	$/year
Observer Costs					
Video reviewer wages	30	97	64	64	$/day
Video reviewer - sets per day	2	9	5	5	days/year
Video reviewers - # employed	-	-	-	36	days/year
Video reviewer - # of days worked per year	95	197	160	155	days/year
Onboard observer wages	48	380	65	148	$/day
Onboard observer - sets per day	1	2	1	1	#/day
Onboard observer - average days at sea per year	95	197	160	155	days/year
Onboard observers - # employed	-	-	-	61	#
Onboard training	29	127	97	83	$/observer
Onboard observer - supplies & equipment	56	109	79	82	$/observer
Onboard observer - travel	357	497	449	434	$/observer
Onboard observer - insurance & benefits	707	1,301	1004	1,004	$/observer
Administrative staff - per on board observer	1,034	1,325	1,056	1,109	$/observer
Administrative staff - per EM observer	1,034	1,325	1,056	1,109	$/EM observer
Technical staff	3,610	3,736	3,675	3,670	$/observer
EM software training	7.13	143.75	75.44	75.44	$/EM observer

Other Management Costs					
Computer costs	29,326.5	117,306		58,653	$/year
% total IATTC computer costs attributable to EM	0.10	1.00		0.25	%
EM review software license	6,600	10,714	9,750	9,021	$/year
Data review center costs	28,000	100,000	64,000	64,000	$/year
Data storage	45,356	65,652	56,884	55,964	$/year
Vessel hardware					
Cameras	1,880	2,613	2,289	2,272	$/vessel
Sensors	1,820	2,700		2,260	$/vessel
Camera central units/computer	3500	5000		4,250	$/vessel
Hard drive	200	963		581	$/year
Installation of hardware	1,500	8,298	2,344	4,027	$/vessel
Maintenance/repair of hardware	1620	2454	1,904	1,971	$/vessel/year
Data transmission	199	1,216.30	291.00	569	$/vessel
EM Equipment remote assistance	1,860	3,348	2,604	2,604	$/vessel/year
Data analysis	42	47	45	45	$/day
EM license fee	0	2,944	1,472	1,472	$/vessel
Compliance & Bycatch					
IUU reduction - % reduction resulting from EM	0.00	0.25		0.05	%
Amount of IUU in the EPO	9.44%	20.26%		15%	% of total catch
Value of EPO IUU catch	0	369,638,651.27	270,970,167	270,970,167	$/year
Value of bycatch reduction per set	$45.05	$153.30	$99.18	$99.24	$/set
Expanded value of bycatch reduction per set	$62.48	$104.49	$83.49	$83.64	$/year
Rate of bycatch detection per trip - BAU on board observers	0.03	0.08		0.05	%
Rate of bycatch detection - EM	0.03	0.10		0.08	%
Markets					
Average ex-vessel price - yellowfin sashimi	$10,114	$10,518	10,316	$10,316	$/mt
Average ex-vessel price - bigeye sashimi	$11,704	$12,299	12,002	$12,002	$/mt
Combined ex-vessel price - yellowfin & bigeye sashimi	$21,818	$22,817	22,317	$22,317	$/mt
Price premium for EM - yellowfin	0	0.05		0.01	% of price
Price premium for EM - bigeye	0	0.05		0.01	% of price
Combined price premium	0	0.1		0.02	% of price

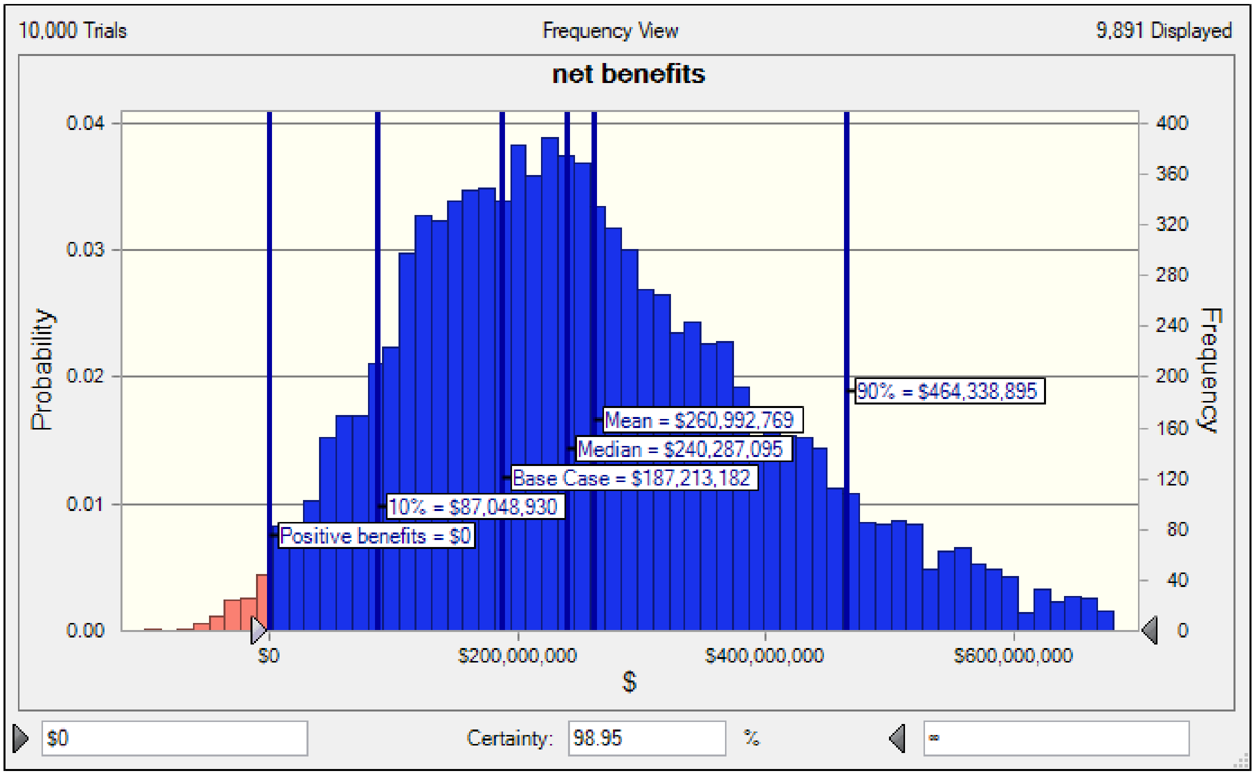
Average annual landings - yellowfin LL EPO	9,808	12,467	10,636	11,052	mt
Average annual landings - bigeye LL EPO	27,229	41,524	35,360	33,744	mt
Other					
Discount rate	0.00	0.07		0.035	%
Non-Market Values					
Marine Mammals					
Spinner dolphin	$9.34	$65.63		$37.48	$/set
Sharks & Rays					
Dusky shark	$21.12	$29.12		$25.12	$/set
Silvertip shark	$8.96	$19.52		$14.24	$/set
Silky shark	$8.00	$9.44		$8.80	$/set
Mobula rays	-$13.44	$12.00		-$0.64	$/set
Thresher shark	$1.92	$8.96		$5.44	$/set
Hammerhead sharks	$0.16	$4.16		$2.24	$/set
Tiger shark	$6.72	$10.40		$8.64	$/set
Mako sharks	$2.72	$15.84		$9.28	$/set
Sea Turtles					
Leatherback turtle	$34.01	$43.78		$38.81	$/set
Loggerhead turtle	$7.93	$8.95		$8.44	$/set
Hawksbill turtle	$14.87	$16.50		$15.68	$/set
Seabirds					
Seabirds (generic)	$5.22	$13.49		$9.35	$/set

Appendix B. Additional Sensitivity Analyses

B.1 Use of Median Values in Place of Mean Values

As an additional robustness check of the Monte Carlo simulation results, the simulation was run again, this time using the median instead of mean value for every parameter. Where no median value exists (i.e., blank in Table 11 in Appendix A), the mean value is still used.

Figure 5: Results of the Monte Carlo Simulation Using Median Values, 20% Observer Coverage

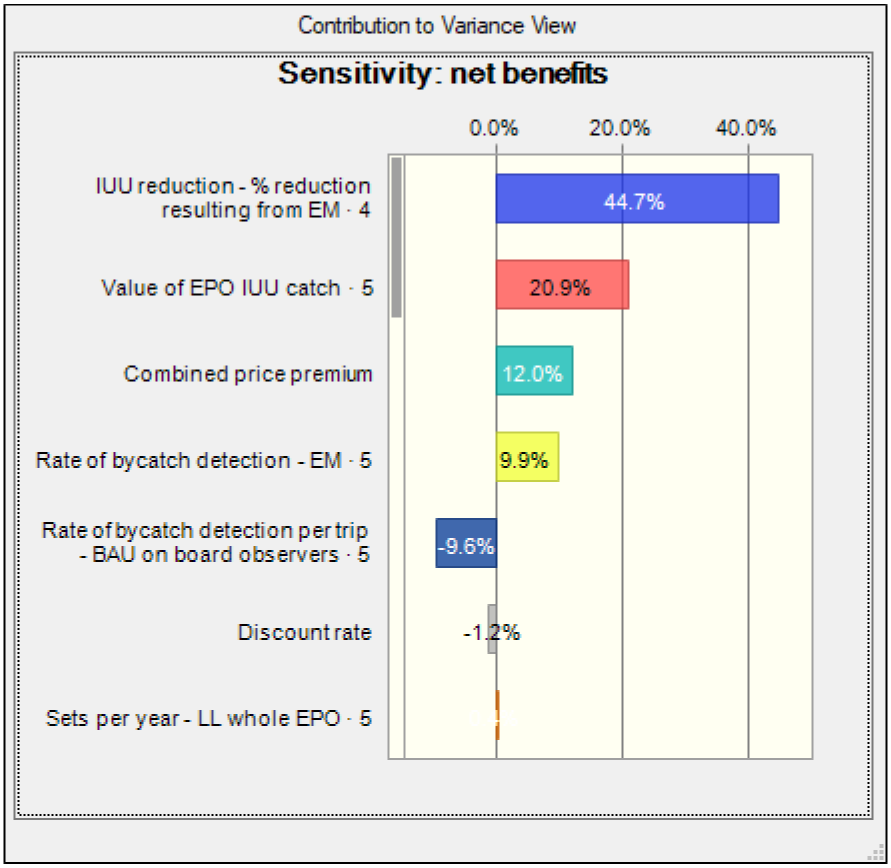


$0

Certainty: 98.95 %

∞

Figure 6. Sensitivity Analysis of the Median-value Monte Carlo Simulation.



The results of this new simulation can be seen in Figure 5 and Figure 6. Figure 5 is nearly identical to Figure 1, with 99% of runs in both simulations producing positive economic values. Similarly, Figure 6 highlights the highest level of sensitivity resulting from the same model components as in Figure 2. Together, this additional simulation suggests a high level of confidence in the base model results.

B.2 Inclusion of additional non-market species values

As discussed in section 3.3.3, the results of the main analysis use a small sample of representative bycatch species to estimate a potential value to society of any potential lower rate of bycatch motivated by the presence of EM. In reality, there is likely a higher societal value for this potential effect, as more species beyond the representative species may also have lowered mortality. While still not an exhaustive list, an expanded range of non-market species values can be found in Table 12, with the model results using a 20% observer coverage rate scenario are explored in Table 13:

Table 12: Expanded Range of Non-Market Species Values

		Low	High	Mean	Source

Marine Mammals					
	Spinner dolphin	$9.34	$65.63	$37.48	Wiener et al. 2020
Sharks & Rays					
	Dusky shark	$21.12	$29.12	$25.12	Booth et al. 2021
	Silvertip shark	$8.96	$19.52	$14.24	Booth et al. 2021
	Silky shark	$8.00	$9.44	$8.80	Booth et al. 2021
	Mobula rays	-$13.44	$12.00	-$0.64	Booth et al. 2021
	Thresher shark	$1.92	$8.96	$5.44	Booth et al. 2021
	Hammerhead sharks	$0.16	$4.16	$2.24	Booth et al. 2021
	Tiger shark	$6.72	$10.40	$8.64	Booth et al. 2021
	Mako sharks	$2.72	$15.84	$9.28	Booth et al. 2021
Sea Turtles					
	Leatherback turtle	$34.01	$43.78	$38.81	Booth et al. 2021
	Loggerhead turtle	$7.93	$8.95	$8.44	Wallmo and Lew 2012
	Hawksbill turtle	$14.87	$16.50	$15.68	Wallmo and Lew 2015
Seabirds					
	Seabirds (generic)	$5.22	$13.49	$9.35	Börger et al. 2020

Table 13. Static Model Results of 20% Observer Coverage Using Expanded List of Non-Market Values

category	**costs**			**benefits**			**net benefits**
		% of total			% of total		
observers - on board	$14,842,174	19.26%		$0	0.00%		-$14,842,174
observers - EM	$4,781,093	6.20%		$0	0.00%		-$4,781,093
vessel hardware	$56,257,168	72.99%		$0	0.00%		-$56,257,168
other management costs	$1,199,532	1.56%		$0	0.00%		-$1,199,532
price premium - EM	$0	0.00%		$43,339,332	12.63%		$43,339,332
scientific data value	$0	0.00%		$14,384,343	4.19%		$14,384,343
bycatch reduction	$0	0.00%		$172,180,148	50.19%		$172,180,148
IUU reduction	$0	0.00%		$113,135,759	32.98%		$113,135,759
Total	$77,079,966			$343,039,581			**$265,959,615**

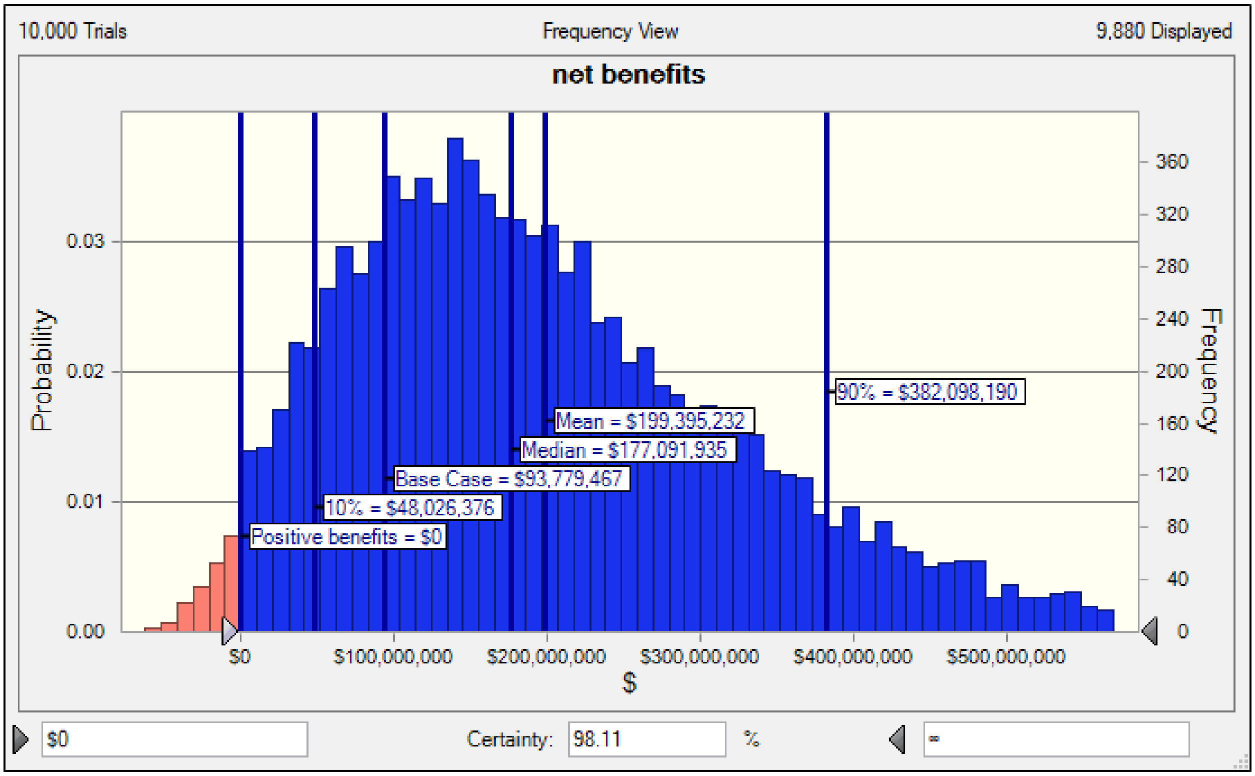
Compared to Table 6 – the comparable 20% observer coverage table in the main analysis – Table 13 displays exactly the expected result: identical outputs, with the sole exception of an increased bycatch reduction benefit value. This value has almost doubled, unsurprising given more than double the number of species are now included in the analysis.

B.3 Results with no non-market species values included

In contrast to section B.2 above, some stakeholders may take issue with the use of non-market values in this report. While there is general agreement that society gains *some* benefit from the lowering of bycatch mortality for non-market species, there can be disagreement with specific values selected, or the underlying techniques used to generate these values, despite strong theoretical underpinnings. The simplified per-species value approach used in this analysis could also generate skepticism, despite the goal of the application being to seed defensible starting values in the Monte Carlo simulation. A final source of skepticism could also stem from the underlying assumption of this section that the presence of EM might lower bycatch mortality, rather than merely reporting that same mortality more accurately.

To address any potential concerns and explore the impact these values have on simulation outcomes, an analysis of the 20% observer coverage scenario was conducted again, but this time holding the non-market values at $0 (in other words, this benefit category is removed from the analysis), the results of which can be found in Figure 7.

Figure 7: Results of the Monte Carlo simulation with zero non-market species values included, 20% observer coverage

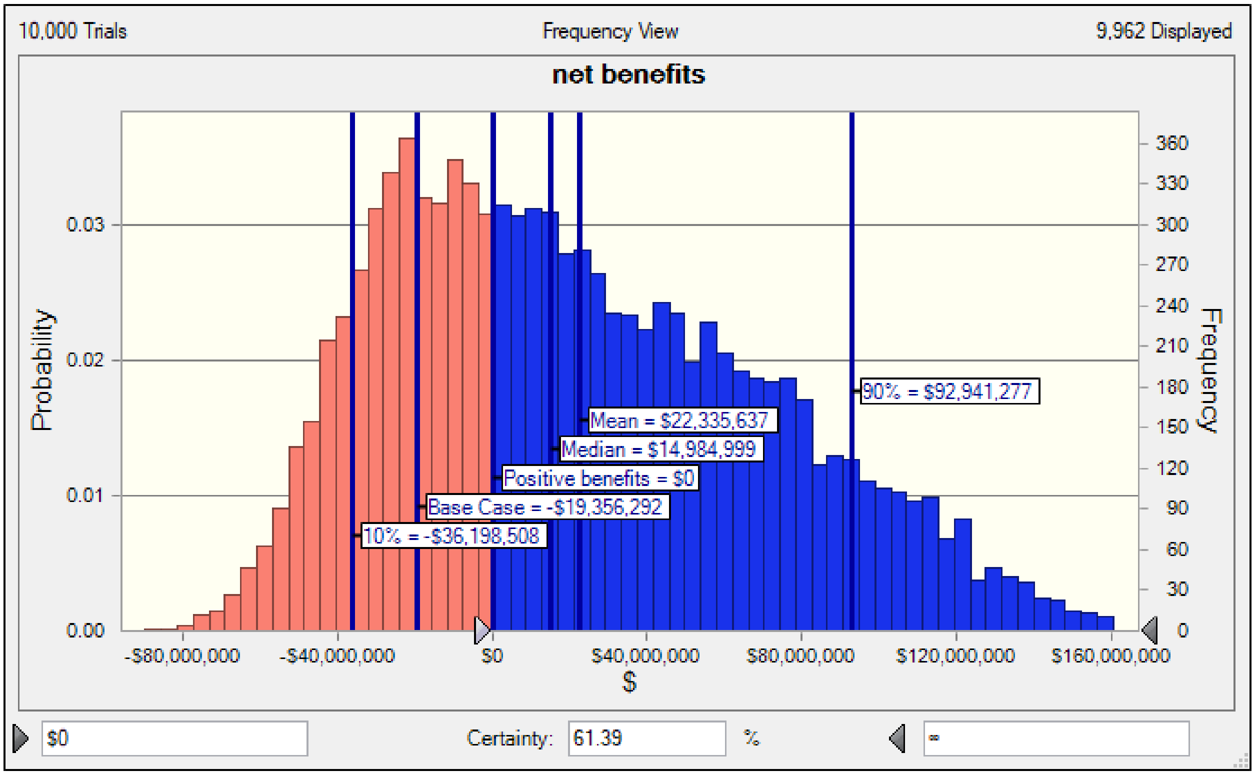


As displayed in Figure 7, the results of this additional analysis show that even with this benefit category completely excluded, 98% of scenarios still result in positive net benefits. While the value of net benefits is lower, as is expected from removing an entire category, the mean value of net benefits is now $199.4 million as compared to the original estimate (Figure 1) of $255.5 million. Thus, while there is little theoretical justification for entirely excluding a source of benefits to society, skepticism in regard to this benefit does not change the main finding of this report that there are positive economic benefits to an EM program.

B.4 Results with both non-market species and IUU reduction excluded

We extend the additional analysis in section B.3 even further by running the model again after eliminating *both* the bycatch reduction benefit *and* the IUU reduction benefit (as in Figure 3 of the main analysis).

Figure 8: Results of the Monte Carlo simulation with zero non-market species values included and zero IUU reduction benefits included, 20% observer coverage



$0

Certainty: 61.39 %

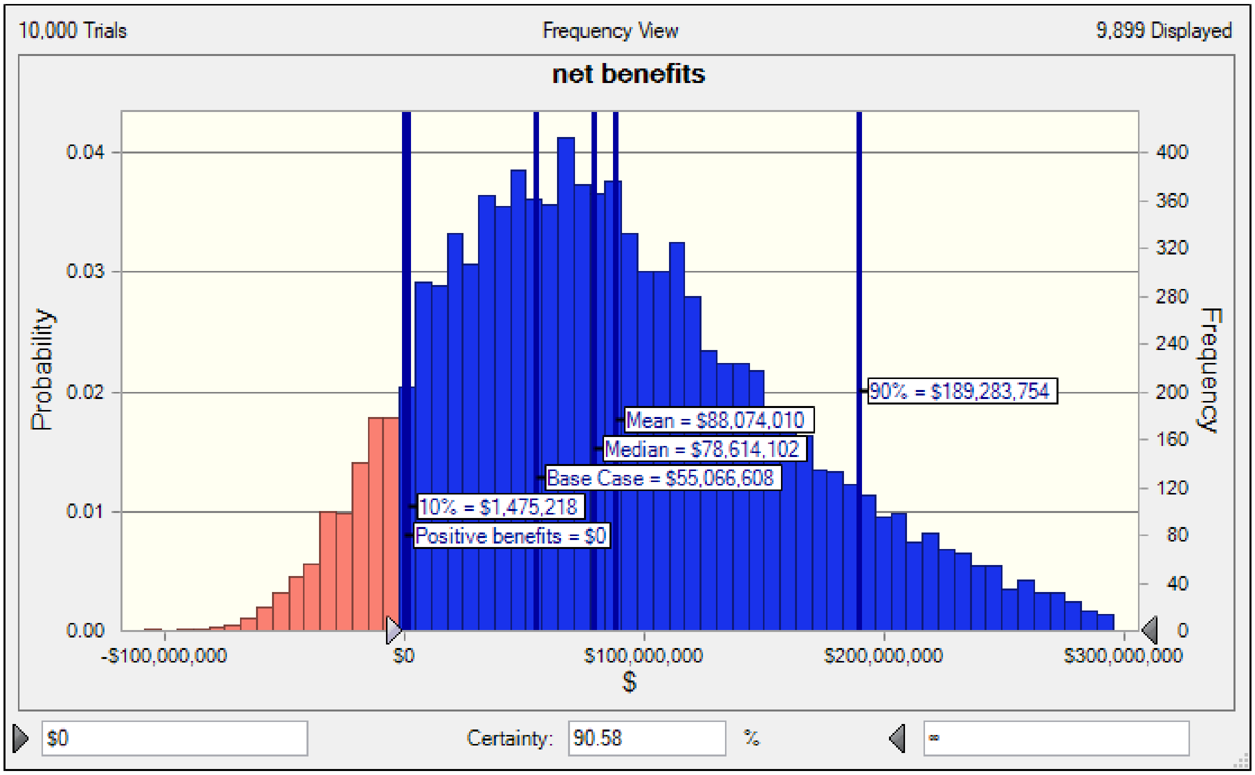
∞

As seen in Figure 8, the results of the Monte Carlo simulations with both of these benefits categories excluded still produce positive net benefits more than 61% of the time. Though the Base Case (static model output) value is negative at -$19.4 million – in other words, costs are higher than benefits in the base case – the mean output value across all runs of the model is a positive value of $22.3 million. In other words, even those potentially skeptical of values used in the both the IUU and bycatch reduction sections of the main analysis will still see there are significant positive economic benefits in more than half of all potential cases.

B.5 Results with benefits reduced by half, and by 3/4

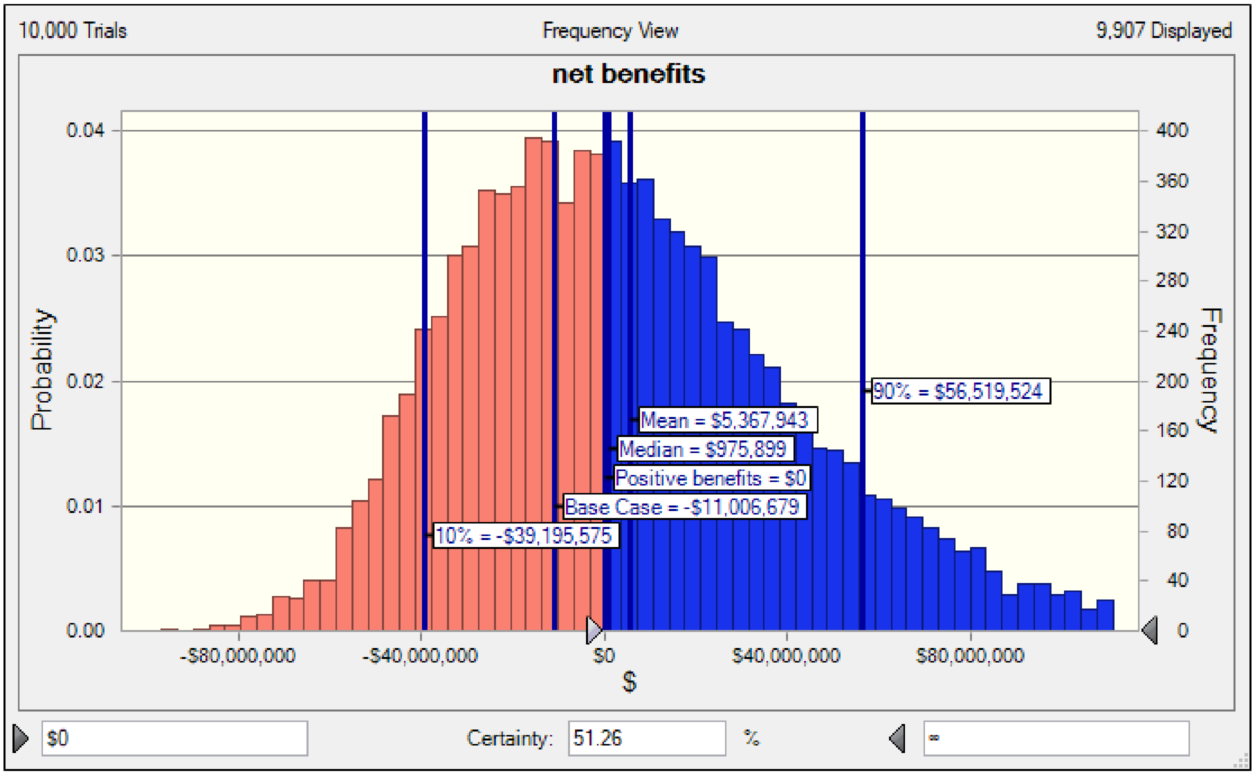
Finally, an additional analysis was conducted to explore the effects of simply lowering the value of all net benefits. This could, for example, address concerns that the benefit categories in the main analysis are all theoretically sound, but (despite being grounded in reported empirical values) may in some way be overestimating the value of each. To explore the impact of such a concern on the findings of this report, two additional analyses were conducted: all benefits halved, and all benefits reduced by 3/4. The results of these analyses can be seen in Figures 9 and 10, respectively.

Figure 9: Results of the Monte Carlo with each benefit reduced by 50%



$0 Certainty: 90.58 % ∞

Figure 10: Results of the Monte Carlo with each benefit reduced by 75% in value



$0

Certainty: 51.26 %

∞

In the 50% reduction scenario, 90.6% of all model outputs still produced net positive economic benefits, with a mean output value of $88.1 million in net benefits. In the 75% reduction scenario, benefits are still positive in 51.3% of all scenarios, with a mean net benefits value of $5.4 million. In other words, even if the value of all benefits are reduced by 75%, more than half of all scenarios will still produce positive net economic benefits.

Appendix C. Recommendations for Extending This Analysis to the Purse Seine Fishery

This analysis has focused on the potential costs and benefits flowing from a future adoption of EM in the longline fishery operating in the Eastern Pacific Ocean, particularly given the relatively low attention paid to longline fisheries in previous EM cost-benefit analyses. It is unlikely, however, that IATTC will separately pursue EM programs for the longline and purse seine fisheries. A truly comprehensive cost-benefit framework for EM adoption in the EPO, that provides IATTC members with a full framework for assessing the likely costs and benefits across both fisheries, will require two major components in addition to a longline-centered analysis: (1) a cost-benefit analysis similar to the one presented in this report, but instead focused on the purse seine fishery; and (2) an analysis of these two systems together, to identify potential cost savings or co-benefit opportunities across one unified system.

Here we provide recommendations for components and details to consider when undertaking these future analyses, informed by some of the specific choices made and information gathered over the course of this analysis.

Recommendations Specific to the Purse Seine Fishery

- While this analysis provides a solid foundation that can be used for a similar analysis of the purse seine fishery, many specific details of EM (e.g., the number of cameras required for full vessel coverage) will be different for purse seine vessels, and will likely be somewhat dependent on vessel size – although some of these details will simply require inputting the specific purse seine version of those parameters
- Observer coverage is much higher in the purse seine fishery, meaning there are significant differences in established costs and employment
- Some of the benefits identified in this analysis, such as the generation of scientific data and IUU reduction, may be diminished due to the comparatively higher level of existing data related to the purse seine fishery; other benefits, such as changes in vulnerable species detection rates, may be just as beneficial as in this analysis
- The higher observer coverage in the purse seine fishery may also afford new opportunities to explore benefits related to finding synergies between EM and onboard observers; for example, EM could conceivably “free up” human observers to conduct more time-intensive types of data collection (e.g. biological sampling)
- Some of the unquantified benefits in this analysis, such as EM’s ability to afford a “bird’s eye view” of vessel operations, likely represents a more significant economic benefit for the much larger purse seine vessels

Co-Benefits and System-wide Considerations

- Familiarity with implementing an EM program on one type of vessel will likely produce tangible operational and institutional benefits (e.g. for IATTC) in the other fishery as well (i.e. learning by doing)

- Many of the startup costs identified related to management – such as IT equipment, infrastructure, etc. – will be used across any fishery equipped with an EM program, considerably reducing the average cost of these expenses if an EPO-wide EM management system is jointly launched to serve both longline and purse seine vessels