Meeting the objectives of fisheries observer programs through electronic monitoring

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CONTENTS

Abstract

Data from fisheries observer programs support fundamental research and management applications, ranging from conducting stock assessments to assessing the performance of ecosystem-based harvest strategies. Electronic monitoring (EM) systems are increasingly being used to augment conventional coverage by human onboard observers, as well as to provide at-sea coverage where none previously existed. Here we review findings from studies that compared the precision and accuracy of data fields collected by EM and onboard observers. EM data have relatively high precision to data collected by onboard observers, but with some areas identified where EM systems are in need of improvement, such as detection of some species of non-retained catch, life status of the catch and whether crew used specific fishing methods and equipment. We describe how data from EM systems, unlike at-sea observer program data, are not susceptible to intimidation, corruption, and observer placement that is not randomized and balanced (sampled proportionately across ports and vessel categories), so that fleet-wide extrapolations accurately characterize the entire fleet, and avoid statistical sampling bias. We discuss how a fisheries monitoring programs designed so that all vessels in a fleet are outfitted with onboard EM systems and where random and balanced samples of the raw data are analyzed would eliminate an 'observer effect', where the alternative of 100% human observer coverage to eliminate this source of bias is likely more costly. Fields collected by at-sea human observers of regional observer programs of the western and central Pacific Ocean for pelagic longline and tuna purse seine fisheries were analyzed, identifying 101 fields that are not possible to collect with contemporary EM systems. Of these, 45 fields could be collected by dockside monitoring, however, 7 of these fields might not remain static during the course of a trip, in particular for distant-water vessels. Innovations in EM technology could be feasible to collect 70 of the fields. Many of the identified changes to contemporary EM technology are likely feasible through simple changes, such as positioning existing or additional EM cameras to ensure that certain fishing activities are within the field of view. Others, however, are highly uncertain, require research and development, such as a probe that analyzes sex-specific genetic markers or hormones to determine the sex of the catch, and require trials to determine their accuracy, such as the use of thermal cameras to determine life status, and the use of underwater cameras and EM digital length software to estimate the dimensions of submerged gear. Tissue samples and information on gonad stage of the catch, which are not possible to collect by dockside inspections or EM, could potentially be collected by fishers. Having observer coverage of vessels receiving at-sea transshipped catch would be necessary to collect information on the receiving vessel. It may only be possible for human onboard observers to collect information on the fishers of distant-water vessels that exchange their captain and crew multiple times during a trip. Achieving the political will and capacity to transition to EM may be strengthened given the support of catch sector and other seafood companies. Examples are provided of industry-desired information that could be delivered by EM systems. Improvements in EM technology promise to enable EM systems to collect most fields collected by contemporary human onboard observer programs, to improve data quality for some fields, and to broaden data collection fields to meet the expanding data requirements of fisheries monitoring programs as management authorities continue to transition to implementing elements of ecosystem-based fisheries management.

***Keywords*:** Electronic monitoring; Fisheries-dependent data; Observer; Tuna fisheries

1. INTRODUCTION

Fisheries-dependent data from observer programs enable meeting fundamental monitoring requirements. Data collected from these programs support applications ranging from conducting robust stock assessments to assessing the performance of ecosystem-based harvest strategies by monitoring ecosystem pressure and state indicators (e.g., FAO, 2002; Gilman et al., 2017). Having data collected and reported by independent onboard human observers or by onboard electronic monitoring (EM) systems to meet scientific and compliance objectives produces more accurate and detailed information than data collected and reported in logbooks by fishers: fishers may lack the time and training to conduct prescribed data collection methods and may have an economic or regulatory disincentive to record accurate data, e.g., to avoid catch or size limits (Brown, 2001; FAO, 2002; Walsh et al., 2002, 2005; TNC, 2018). Port sampling programs obtain information on retained catch when unloaded in port, but not information on discarded (non-retained live released and dead discarded) catch or on effort within trips.

EM systems are increasingly being used to augment conventional coverage by human onboard observers, as well as to provide at-sea coverage where none previously existed. EM systems typically use onboard cameras, global positioning systems, sensors and data loggers to collect a variety of information (Restrepo, 2012). EM systems also include office-based staff who analyze raw EM video and sensor data and then input data into an observer program database, conducted by a fisheries body or other independent organization. Several trials of EM systems have occurred in tuna fisheries (e.g., McElderry, 2010; AFMA, 2011; Monteagudo et al., 2015; Hosken et al., 2016a,b; Briand et al., 2017; TNC, 2018). And several fisheries are now using EM systems as part of their observer programs (e.g., AFMA, 2012; Lowman et al., 2013).

This study reviews findings on the relative quality of data collected by EM and conventional human onboard programs for data fields that can be collected by both methods. This includes considerations for how installing EM systems on all vessels can address observer effects that occur in fisheries with < 100% coverage, and how EM is not subject to coercion and corruption of human onboard observers. Fisheries with vessels unsuitable for human observer placement, and fisheries that require continuous observer monitoring are presented as additional examples of how EM enables monitoring where human onboard observer coverage is either not practical or possible. Data fields that EM can capture but cannot be collected by human observers, drawn from pelagic longline and tuna purse seine fisheries, are summarized. Similarly, data that human onboard observers can collect but cannot be obtained through current EM systems, again for pelagic longline and tuna purse seine fisheries, are described. Of these fields that EM cannot currently capture, we identify those that could be collected by dockside observers before vessels depart on trips, identify possible innovations in EM technology that could enable their collection, and identify the subset that could be collected by fishers. The report also reviews considerations for defining minimum observer coverage rates as well as data collection fields and methods. Not reviewed here, previous studies have documented the extensive overlap in variables that both EM and human onboard observer programs can collect (e.g., SPC [2014], SPC and FFA [2017] for pelagic longline and tuna purse seine fisheries). The scope of this study also did not include reviewing the various applications and importance of individual observer data fields and data collection protocols, which has been previously reviewed (e.g., FAO, 2002; Gilman and Hall, 2015; Gilman et al., 2017).

2. RELATIVE DATA QUALITY

2.1. Estimates of Precision between EM and Human Onboard Observer Data

A comparison of data fields collected by EM and human onboard observers enables a determination of the degree of precision or how close two measurements are to each other. The assessment does not enable a determination of the accuracy, how close a measurement is to a true value, of the estimates derived by each monitoring method. If the mean and variance of estimates by EM and human observers are similar, this informs us that EM can collect data for that field at a similar degree of accuracy as can a human observer. If, however, estimates by EM and human observers differ significantly, additional studies, such as comparing estimates of retained catch made by EM and human observers with port sampling landings data, are needed to determine which of the two onboard monitoring methods is more accurate. However, studies of the precision of estimates by EM and human observers are useful, per se, because a finding that the two methods produce similar estimates indicates that they are of similar accuracy and therefore EM would be as acceptable a method for collecting that information as is conventional human onboard observers.

There is a growing number of studies comparing the quality of data collected by EM systems versus collected through traditional onboard observers, including from pelagic longline and purse seine tuna fisheries. Findings in most cases indicate that EM data have relatively high precision (i.e., are similar to data collected by onboard observers), but with some areas identified where EM systems are in need of improvement, such as detection of some species of non-retained catch (AFMA and Archipelago Marine Research, 2005; McElderry, 2010; AFMA, 2006, 2010, 2011, 2012; Arnande et al., 2012; Chavence et al., 2013; Ruiz et al., 2013; Hosken et al., 2016b; Monteagudo et al., 2015; Briand et al., 2017; Bartholomew et al., 2018). Detailed summaries of findings from two studies, one from a tuna pelagic longline fishery, and one from a tuna purse seine fishery, are provided.

Hosken et al. (2016b) compared the quality of data collected by EM systems and onboard human observers in the Solomon Islands pelagic longline fishery. The EM systems were manufactured by the company Satlink. Two vessels were outfitted with EM systems and assigned a human onboard observer. The study was conducted during four fishing trips of 199 sets. Estimates of catch and effort were largely consistent at the set level. There was high correlation in the observed number of caught organisms (Smean = 0.88, Sorensen method) and the same species were identified for 94% of the catch. Where differences did occur, the authors hypothesize that they may have resulted from differences in the proportion of hauls that were covered by the two monitoring methods, and from differences in species identification abilities of the onboard vs. office-based observers, and were not a result of differences in the capacity of the two monitoring approaches to obtain similar levels of catch and effort data quality. However, for some species, the EM analyst may have had difficulty differentiating between similar looking species by reviewing the raw video, such as for long snouted and short snouted lancetfish. The two methods also produced consistent estimates of species-specific rates of retention and discarding (Hosken et al., 2016b).

While the onboard observer recorded a single estimate for the field number of hooks between floats (HBF) for all sets in a trip, the office analysts review of EM data resulted in set-specific estimates. For example, for one trip, the mean trip-level estimate of HBF from the EM data (22.4) was over 17% lower than the estimate by the onboard observer (27) (Hosken et al., 2016b). The employment of the less rigorous data collection protocol by the onboard observer, however, could be feasibly addressed, such as by having the observer record the number of hooks between two floats for at least 20% of the baskets set (Gilman and Hall, 2015).

Positional data, which were automatically recorded by the EM reviewing software, were of a higher resolution by the EM system than by the onboard human observer (Hosken et al., 2016b). Furthermore, the EM system automatically recorded the date, time and vessel position for each capture event (when a caught organism is retrieved during gear haulback) (Hosken et al., 2016b). The date/time and position of each capture event is not recorded by the human onboard observer in this observer program, however, it would likely be feasible for the observer to record this additional information (Gilman and Hall, 2015).

There were differences in estimates of the hook number (on which hook between two pelagic longline hooks an individual organism was captured) between the EM analysis and the human onboard observer, with the office analyst estimates being higher than the onboard observer. In addition to having low precision, both methods are likely inaccurate, because both the onboard and office observers may lose count of the hook number, especially for baskets with >10 HBF (Hosken et al., 2016b).

A trial of a digital length measurement tool developed by the EM service provider was conducted during two fishing trips. A comparison of fish lengths made by the human onboard observer and the EM analysis indicated that consistency varied by species, where length estimates were closer for species with larger mean lengths (e.g., bigeye and yellowfin tunas) that for species with smaller mean lengths (e.g., albacore and skipjack tunas) (Hosken et al., 2016b).

There was low precision in estimates of the sex of shark species, where estimates were more consistent for males (ca. 76%) than females (ca. 53% match). A comparison of sex codes was conducted only for shark species because the recording of sex for non-shark species was very infrequently attempted by the EM analyst (Hosken et al., 2016b).

There was high precision in records on whether individual caught organisms were alive versus dead upon gear haulback. There was low precision in the degree of injury for live caught organisms, which was attributed to there being subjectivity and variability between observer determinations of this field, and thus the variability was not deemed to be due to any differences in the two monitoring methods (Hosken et al., 2016b).

Comparisons of fate codes (was the catch retained, discarded or escape, method for processing retained catch, method for discarding non-retained catch) for the catch were largely consistent. For non-retained catch, differences in fate records were due to there being more than one code that could be used to describe the event (e.g., discarded, struck off and discarded, cut free), and thus were not due to differences in the capacity for the quality of this data field by the two monitoring methods (Hosken et al., 2016b).

Monteagudo et al. (2015) compared the quality of data collected by EM systems and onboard human observers on tropical tuna purse seine vessels operating in the Atlantic Ocean. The EM systems were also manufactured by the company Satlink. Two vessels were outfitted with EM systems and assigned a human onboard observer. The study was conducted during four fishing trips of 103 sets.

Both the human onboard observer and EM analysts identified the same number and types of purse seine sets (set on a free-swimming school unassociated with a floating object vs. sets on fish aggregating devices). The EM analysts determined the purse seine set type by assessing the time of day of the set, evaluating the vessel's movements detected from a display of vessel monitoring system positional data, and the catch composition (Monteagudo et al., 2015). The addition of cameras that provide a view over the vessel side could enable a more definitive, objective method for EM analysts to determine purse seine set type (Restrepo et al., 2014; Monteagudo et al., 2015). Positional data from both EM and onboard human observers were extremely precise, where most pairs of latitude/longitude coordinates differed by 0.01 decimal degrees (about 1 km) (Monteagudo et al., 2015).

Estimates of total catch per set were also highly precise. Estimates of total catch per set from EM data were about 5% lower than the estimates from data collected by the human onboard observers. There was no significant difference between median catch per set estimates by the two methods based on the Wilcoxon signed Rank test. EM versus human observer estimates of the median proportion of the total catch per set made up of skipjack and of bigeye tunas were significantly different, while there was no significant difference in estimates of the median proportion of the catch made up of yellowfin tuna based on the Wilcoxon signed Rank test. These results were the same when applied to all set types, and by individual set type. Relative to the onboard human observers, the EM analysts had higher estimates of the proportion of the catch comprised of skipjack in all four trips, and lower yellowfin and bigeye in 3 of the 4 trips (Monteagudo et al., 2015).

There was no significant difference in the EM vs. human observer estimates of median tuna discards per set (in sets where catch was discarded) for combined tuna species, again based on the results of the Wilcoxon signed Rank test.

EM and human observer estimates of sea turtle, billfishes and manta ray captures per trip were similar. The EM estimates of shark captures per trip were lower in all four trips than the estimates by the human observers, but the estimates were of similar magnitudes. No statistical tests were conducted due to limited sample sizes (Monteagudo et al., 2015). In a similar study, Briand et al. (2017) found that EM produced lower estimates of purse seine shark and billfishes catch rates than onboard human observers, and hypothesized that because these species are handled at different locations onboard, that EM systems may not enable the EM analyst to view their retrieval due to camera distance or the camera not covering those areas. Thus, this could potentially be resolved through improvements in camera installations and crew collaboration.

Overall, the differences in catch estimates between the EM and human observers were small in magnitude, and possibly similar to the degree of precision that occurs for estimates that would be made by different human onboard observers when monitoring different purse seine trips (Monteagudo et al., 2015), as well as when different observers monitor the same purse seine effort. The authors recommended a study that compares retained catch estimated by EM and human observers to that estimated by port sampling in order to assess the accuracy of the EM and human observer estimates (i.e., how close the retained catch estimates are to a presumed true value as determined by port sampling) (Monteagudo et al., 2015).

Theoretically, EM may enable more accurate estimates of some routinely collected monitoring fields. For example, estimates of the number of seabirds within a specified distance of the vessel, in particular during nighttime, (see Gilman and Hall [2015] for a review of standardizing effort using data on seabird density during various fishing operations) might be more effective with video cameras with infrared (thermal) imaging capabilities than by onboard observers using the naked eye and binoculars. And hook number of the catch could be collected by EM systems through an automated process, where the time of day of each float upon retrieval and the time of retrieving each captured organism would be used to estimate hook number (Hoskens et al., 2016b; Williams, 2017). Onboard observers make rough estimates of hook number, where, except for hooks close to floats, estimates are likely of low certainty in sets with a relatively large number of hooks between two floats. EM data analysts currently count hooks between floats in order to determine the hook number of the catch, which likely results in more accurate estimates of hook number of catch events than estimates by human onboard observers, but this protocol makes EM data reviewing extremely inefficient (Hosken et al., 2016b). In addition, when a record of the species of a caught organism is flagged as questionable, EM data provides a means of reviewing archived raw video from that trip by experts (Hosken et al., 2016b), while it is not possible to validate questionable records recorded by human onboard observers, except when an observer has photographed the catch, usually reserved for rare-event protected species captures.

Some fields that are able to be collected by contemporary EM systems sometimes are not possible to estimate by the analyst reviewing the EM video and sensor data. For example, the species, length and sex of a caught organism may not be possible to determine if the image of the organism is obstructed or not clear, especially if the organism is not landed. Cooperation of the crew to follow procedures that enable clear camera views of the catch could reduce this problem (SPC and FFA, 2017). Also, the life status of the catch when retrieved during gear haulback and when returned to the sea if not retained can be difficult to observe, especially for smaller organisms (Hosken et al., 2016b; SPC and FFA 2017). Technological innovations such as image recognition software to identify species and length of the catch, and thermal imagery to determine life status, may improve the accuracy of EM data collection of these fields. Fields that document whether a fishing method or equipment was used, such as an underwater setting chute during pelagic longline setting, and longline branchline weighting design (mass of the weight, distance from the hook) may not be possible to detect when analyzing EM raw data (SPC and FFA, 2017). These latter issues may be resolved through better positioning of cameras or the addition of cameras, use of macro video, or other technological methods (Section 4.3). These and other EM technological innovations to enable EM systems to collect fields that are currently not feasible via existing EM technology are identified and discussed in Section 4.

2.2. Overcoming an Observer Effect

Observer data may be biased as a result of fishers altering their fishing practices (e.g., location and time-of-day of fishing, discarding practices, handling and release practices) and gear as a result of the presence of an onboard observer or EM system, referred to as an observer effect (Hall, 1999; Liggens, *et al*., 1997; Babcock *et al*., 2003; Benoit and Allard, 2009). For example, fishers in the Palau pelagic longline fishery made 33% shorter trips when the government assigned an observer to their vessel, which may have been a result of an observer effect, but also could have resulted from non-randomized or non-representative placement of observers and small sample sizes (Gilman et al., 2016a). As a result of an observer effect, monitoring data collected through observer programs with less than 100% coverage may be biased and not accurately characterize the fishery as a whole.

The higher the observer coverage rate, the lower the bias from an observer effect is, as the larger the proportion of fishing effort that is observed, the more accurately the monitoring data characterize or represent the fishery (Babcock et al., 2003). With 100% human onboard observer coverage, or 100% of vessels of a fishery having EM equipment onboard, there would be no bias resulting from an observer effect. For the latter, either 100% or a sample of the EM data could be analyzed without introducing an observer effect. If a sample of the EM data are analyzed, because fishers do not know whether a unit of their fishing effort will be reviewed, they are unable to alter their practices during a subset of their effort in order to avoid having it observed.

2.3. Overcoming Observer Coercion and Corruption

Human at-sea observers may be tasked with recording information that is sensitive to the fishing industry. For example, observer catch and effort records could result in the end of a fishing season for that individual vessel or seasonal closure of a fishery (e.g., reach an effort limit, reach a seasonal cap on the catch level of an endangered, threatened or protected species or total allowable catch level for a target or bycatch species) (Levitz, 2013). Observer programs that use at-sea observer data for compliance monitoring and enforcement can create a safety risk for the observer. Some observer data collection fields may identify a vessel as having violated a management measure (e.g., did not employ prescribed fishing gear design or method, violated a time/area closure, violated a retention restriction by size, sex or species). When these types of sensitive fields are collected by at-sea observers, the vessel captain and crew may hinder the observer from properly conducting their monitoring requirements, may threaten the observer's safety, and might bribe the observer to not report damaging information. Some observers may deliberately misreport industry-sensitive data fields due to friendships with the captain and crew. This could result in inaccurate or incomplete data collection and an unacceptable threat to the observer's safety (e.g., FAO, 2002; Levitz, 2013). EM systems, where office-based analysis of the raw EM data occurs, are not susceptible to these types of coercion and corruption issues.

2.4. Overcoming an Observer Nonrandom Deployment Effect

Random placement of observers on vessels in a fishery, and balancing (sampling proportionately) across ports and vessel categories, optimizes having fleet-wide extrapolations accurately characterize the entire fleet, so as to avoid statistical sampling bias (Bravington et al., 2003; Benoit and Allard, 2009). When observers programs do not have 100% coverage, if monitoring is nonrandom, then the resulting observer data will be biased due to this observer deployment effect.

An observer displacement effect can occur when observers are not placed on certain vessels because they have undesirable conditions, because of the ill disposition of the skipper or crew, or due to a mismatch in the languages spoken by the fishers and observers (Benoit and Allard, 2009). Some fishing vessels may be too small to accommodate an additional person, and may be determined to be unsafe for placement of an observer. Furthermore, it may be logistically difficult to place and retrieve observers on vessels when there are numerous seaports used by the fleet, and when vessels have variable use of different seaports, some of which are in remote areas.

In fisheries with vessels that are not favored by observers or are unsuitable to place a human observer (too small, unsafe, remote or unpredictable location for placing and retrieving observers), because vessel specification requirements for EM systems are much lower than what is needed to deploy a human observer, EM may offer a feasible method to collect monitoring data for scientific and compliance monitoring (e.g., Bartholomew et al., 2018).

2.5. Overcoming the Monitoring Capacity of a Single At-sea Observer

As-sea observers will not collect data when meeting requirements for sleeping, eating, going to the bathroom and during scheduled breaks (Hosken et al., 2016b). For example, gear haulback may occur over a period that exceeds 12 hours, during which time some observer programs allow for observers to take breaks (e.g., Hosken et al., 2016b). In some fisheries, observers are required to schedule a day off following a specified period of working (Hosken et al., 2016b). Human observers may be unable to collect data when there is rough weather and it is unsafe to be on deck (Hosken et al., 2016b). And, human observers may be unable to conduct monitoring activities when they are ill, e.g., from seasickness (NMFS, 2017). Furthermore, when an observer is busy measuring catch on deck or conducting some other task, they may not be able to simultaneously monitor the gear haulback activities. In these cases, the observer may be tasked with recording the proportion of the total gear retrieved during haulback and the concomitant proportion of total catch that they observed (e.g., SPC and FFA, 2016).

EM systems are not subject to these gaps in monitoring by human at-sea observers. Multiple at-sea observers are placed in some fisheries where fishing operations are conducted continuously, or nearly so (e.g., U.S. west coast hake fishery catcher/processor trawl vessels over 125 feet in length, NMFS, No Date), but this is not an economically viable or feasible solution to these lapses in human observer monitoring in most fisheries. EM systems do not achieve 100% coverage, such as when equipment malfunctions or is inadvertently or intentionally obstructed. However, typically results in a small proportion of effort to go unmonitored. For example, 4.6% of hours-at-sea were not monitored due to video camera malfunctions during an EM trial in the Solomon Islands longline fishery (Hosken et al., 2016b). The incidence of equipment problems may decrease over time if improvements in technology occur.

3. DATA FIELDS THAT CONTEMPORARY EM SYSTEMS CAN COLLECT BUT HUMAN OBSERVERS CANNOT

Hoskens et al. (2016b), SPC and FFA (2017) and Monteagudo et al. (2015) documented fields that EM systems collect, and theoretically could collect given contemporary EM technology capabilities, and that human onboard observers cannot, for pelagic longline and tuna purse seine fisheries, which are summarized in Table 1. Several of the data fields are information related to the EM systems and EM data reviewing, which are not applicable to human onboard observer programs, such as identifying EM hardware components and the EM data reviewing software. Data on the position, date and time of individual captured organism is retrieved in pelagic longline fisheries is collected by EM systems but is likely not feasible to be collected for all catch events by human onboard observers, unless multiple observers are placed on a vessel (Hoskens et al., 2016b). See Section 2.5 for a discussion of why at-sea observers are unable to monitor entire fishing operations.

EM systems with near real-time satellite-based data delivery (including of date and time of fishing operations and geospatial positional data) could enable managers to detect near-real-time violations of time/area closures. Onboard human observers may not be able to determine when a vessel fished during a temporal closure or inside a closed area. Managers can monitor satellite-based vessel monitoring system vessel tracks to detect time/area closure violations, but, depending in part on the ping rate (the frequency that VMS signals are reported), it may be challenging for management authorities to differentiate between various fishing operations (sailing vs. fishing) and would have to wait to evaluate data collected by the onboard observer to make a determination.

4. DATA FIELDS THAT HUMAN OBSERVERS COLLECT BUT EM CANNOT

Table 2 identifies fields collected by onboard human observers of the Western and Central Pacific Fisheries Commission (WCPFC) Regional Observer Program and the Pacific Community (SPC) / Pacific Islands Forum Fisheries Agency (FFA) Regional Observer Program for pelagic longline and tuna purse seine fisheries that cannot be collected by current EM systems, based on a review of findings from SPC (2014), Gilman and Hall (2015), Hosken et al. (2016b) and SPC and FFA (2017). Table 2 also identifies the subset of these fields that (i) could be resolved by monitoring by dockside observers prior to vessels departing on trips, (ii) could be resolved through possible innovations in EM technology, and (iii) require collection by human onboard observers, as they cannot be collected pre-trip, by fishers or by contemporary EM systems or by the development and use of new EM technology. A sample of each of these four categories of observer fields are described in the following subsections.

4.1. Resolved via Dockside Observations

Pre-trip port inspections could enable the collection of 45 of the 101 compiled data fields that cannot be captured by EM systems and that are expected to remain static during an entire trip (Table 2). These include, for example, fields on vessel equipment; purse seine mesh size of the main net; and characteristics of the pelagic longline mainline, branchlines and floatlines (color, diameter, material, length).

Seven of the 45 fields for which it was indicated that dockside inspections could collect the information include a caveat that this would only be reliable for locally-based vessels, and not for distant-water vessels. There could be changes in the value for these fields during the course of a trip by distant-water vessels. For example, the captain and crew may disembark and the fishers may obtain new fishing gear during at-sea transshipments and when bunkering for fuel.

Dockside recording of information on drifting fish aggregating devices (FADs) (design, unique physical ID on FAD structure, presence/absence of satellite buoy and echo-sounder) on which a tuna purse seine vessel makes sets during a trip is not feasible. This is due to the prevalent practices of exchanging satellite buoys attached to, and the concomitant control over, drifting FADs used by tuna purse seine vessels, the deployment of FADs by support and other vessels, as well as the frequent refurbishment and replacement of dFAD components at sea (Gilman et al., 2018).

Most of the 57 fields that are not suitable for dockside collection are information on the catch (e.g., species, length, sex, life status, anatomical hooking position, tag data of longline catch event; purse seine brail weight), whether gear and equipment were used during fishing operations (e.g., longline bird-scaring tori line, longline bait casting machine), on fishing methods and gear designs that were used during setting and gear retrieval (e.g., longline offal management practices during gear haulback, purse seine net hanging ratio), and on environmental conditions during the trip (e.g., sea state, sea surface temperature, lunation). Only 3 of these 57 fields were identified as not likely being possible to detect using EM systems (Section 4.3).

4.2. Resolved via Fisher Collection

Logbook data, which are data on catch and effort collected by fishers, have been documented to be significantly different from data collected by EM and human onboard observers (e.g., Brown, 2001; Walsh et al., 2002, 2005; TNC, 2018). Mentioned in the Introduction, fishers may lack the time and training to conduct prescribed data collection methods and may have an economic or regulatory disincentive to record accurate data, e.g., to avoid catch or size limits (FAO, 2002; Walsh et al., 2002). Thus, we did not consider having fishers collect data collected by observers of the WCPFC and SPC/FFA regional observer programs that EM systems are unable to collect. However, there are some onboard human observer tasks that fishers may reliably conduct. For instance, there are examples of commercial fishers collaborating with fisheries research bodies to collect tags and tissue samples (otoliths and other fish hard parts, stomachs, gonads), and to tag organisms (e.g., California Sea Grant, 2013).

4.3. Resolved via Possible Innovations in EM Technology

Some fields that are not captured by contemporary EM systems may be possible to collect through innovations in EM technology. Of the 101 observer fields that were determined to not be possible to collect by contemporary EM systems, improvements in EM technology were thought possible for 70 (Table 2). Many of the identified changes to contemporary EM technology are likely very feasible, such as positioning existing or additional EM cameras to ensure that certain fishing activities are within the field of view. Others, however, are more uncertain, and may require research and development, such as a probe or scanner that analyzes genetic markers or hormones to determine the sex of the catch, a probe that conducts genetic analyses of tissue samples to determine the species of the catch, including for small tissue samples from behind the barbs of straightened hooks from which cetaceans escaped (NMFS, 2015), and trials to determine their accuracy, such as the use of thermal cameras to determine life status of organisms when retrieved and when returned to the sea, and the use of underwater cameras and EM digital length software to estimate the dimensions of the submerged components of FADs.

The positioning of EM cameras and use of specialized lenses (360 degree and macro) were identified as possible solutions for many of the fields. For example, the terminal tackle design that are variable within sets (e.g., if multiple types of hooks, types of bait, types of leader material, leader lengths, branchline weight amounts, and branchline diameters are used) on which individual endangered, threatened and protected species are captured may not be possible to detect by viewing EM raw video of contemporary EM systems, but the use of additional cameras with suitable lenses at the hauling station might resolve this gap. And for example the use of a 360 degree camera could enable office-based analysts to conduct seabird scan counts, which is necessary to standardize seabird catch rates (Gilman et al., 2003; 2016b). The addition of thermal cameras could enable determining the at-vessel condition (alive, dead) of catch, and condition if released alive or discarded dead. Thermal cameras might also enable determining if bait were thawed prior to setting. Underwater cameras could be used in combination with EM digital length software to estimate the dimensions of purse seine nets and submerged structures (appendage, submerged rafts) of FADs.

Integrating existing and new sensors was an additional potential solution for several fields. For instance, EM systems could be designed to capture the unique IDs of satellite buoys attached to drifting FADs that are being tracked by a tuna purse seine vessel (Gilman et al., 2018). Weight sensors could be included on purse seine brail winches and integrated into EM systems. And sea surface temperature sensors could be integrated into EM systems.

In fisheries where shark finning (retaining shark fins and discarding the remainder of the carcass) is prohibited, and where fins are not required to be naturally attached to the body, some management authorities established thresholds for fin-to-carcass weight ratios to ensure that retained shark fins correspond to the retained shark carcasses and not those of discarded shark carcasses (e.g., WCPFC, 2010). However, the precision and accuracy of estimates of this ratio are likely very low, as there can be high variability in the weight ratio depending on the shark species, whether a subset or all fins were removed and included in the fin weight, whether the wet or dry weight for fins is used, whether and how the carcass was processed (e.g., headed, gutted), and how fishers cut the fins from the body (Cortes and Neer, 2006). Discussed in Section 2.5, at-sea observers are unable to monitor entire fishing operations, and thus may not detect all shark finning events. Also, it may be challenging for onboard observers to weigh fins and carcasses of all retained sharks when a large number are retained. If EM camera positions are adequate, EM analysts might detect and record all shark finning events, eliminating the need to estimate shark fin-to-carcass weight ratios to assess compliance with a ban on shark finning. Or, analysts could use EM digital length software to measure fin and carcass length dimensions and management authorities could either use species-specific ratios of fin-to-carcass lengths, or lengths could be converted to weight estimates enabling estimates of fin-to-carcass weight ratios. These length or weight ratio estimates may be of similar accuracy as those derived by at-sea observers.

4.4. Require Collection by Human Onboard Observers

Of 31 observer fields for which innovations in EM technology are not likely feasible to enable their collection, 3 were also determined to not be possible to collect via dockside inspections: tissue samples, gonad stage, and information on the vessel receiving at-sea transshipped catch. Discussed in Section 4.2, it could be possible for fishers to collect the first two fields, and having observer coverage of vessels receiving at-sea transshipped catch could collect information on the receiving vessel.

An additional 5 fields were identified as not being possible to collect via dockside inspections for distant-water vessels, as the values for these fields might vary during the course of a relatively long, distant-water trip, such as during at-sea transshipment and bunkering: captain and crew names, nationalities, document unique IDs, duration of fishing experience, and name of crew in each position (e.g., chief engineer, first mate). These could be collected during port-sampling, when the vessel returns to port, but the captain and crew could be exchanged multiple times during the course of a single trip. These fields may only be possible to collect by human onboard observers.

5. OBSERVER COVERAGE RATES, DATA COLLECTION PROTOCOLS AND FIELDS

There is no unequivocal answer to the question, 'What is an acceptable minimum observer coverage rate?' (Hall, 1999; Lennert-Cody, 2001; Babcock et al., 2003). The necessary observer coverage rate, as well as data collection fields and methods, for a fishery will depend on (i) the objectives of analysis, including required levels of accuracy and precision of catch rates, and (ii) aspects of each individual fishery – such as how many vessel classes exist, how many ports, the spatial and temporal distribution of effort, the frequency of occurrence of catch interactions for each species of interest, the amount of fishing effort, and the spatial and temporal distribution of catch - to enable avoiding statistical sampling bias (Hall, 1999; FAO, 2002; Gilman and Hall, 2015). In general, the variability in precision and biases in bycatch estimates decrease rapidly as the observer coverage rate increases to 20%, assuming that the sample is balanced and there are no observer effects (Hall 1999; Lennert-Cody 2001; Lawson 2006; Arnande et al. 2012). At 5% coverage, the threshold employed for many tuna longline fisheries, catch estimates will likely have large uncertainties for species with low capture rates, and may result in high uncertainty even for species that are more commonly caught if a small sample size is observed per stratum (e.g., by port, vessel category, season), but likely would be sufficient to enable determining when and where bycatch occurs (Bravington et al., 2003).

6. EM INNOVATIONS FOR INDUSTRY APPLICATIONS

Achieving the political will and capacity to transition to EM may be strengthened given the support of catch sector and other seafood companies. Seafood sector support for EM, in turn, would be strengthened if EM supplied information to industry that supported their fishing operations.

Luen Thai Fishing Venture, a company that owns and manages pelagic longline vessels in several Pacific small island developing states, developed and are using low-cost electronic monitoring technology for various company applications (Garland Shen, LTFV, personal communication, 2 January 2018), which provides a starting point for identifying EM applications of interest to catch sector companies. The Luen Thai EM system enables the company to conduct remote, real-time monitoring of activities on deck to detect when illegal and unreported at-sea transshipment occurs. Their system provides real-time summaries of the species, number and weight of retained catch, information that supports the work of marketing and sales teams. Alarms are triggered real time when the vessel enters areas closed to fishing, or fishing grounds where catch does not qualify for Marine Stewardship Council certification. And, their system enables remote monitoring of the temperature in the fish hold, where alarms are triggered when temperature thresholds are exceeded, similar to remote temperature monitoring systems in use in other fisheries sectors (e.g., shellfish trawl fisheries, Crowley et al., 2005).

These electronic monitoring applications exemplify types of information that potentially could be met by expanding EM systems that are used for observer programs. Many of these industry-desired EM data fields could not be practically obtained through human onboard observers. Expanding EM systems to provide these and other applications of interest to catch sector companies (e.g., sensors on the hatch to the hold to inform owners when fishers open the hatch; biosensors to provide near-real-time monitoring of fish quality, Venugopal, 2002; Thakur and Ragavan, 2013) might develop seafood company support for broad EM system use, where the benefits to seafood companies of these EM applications might offset any costs to industry of EM systems that are in excess of costs currently covered by the fishing industry for onboard human observers.

7. CONCLUSIONS

Observer program data support applications ranging from conducting robust stock assessments to assessing the performance of ecosystem-based harvest strategies (e.g., FAO, 2002; Gilman et al., 2017). Data fields required from fisheries monitoring programs have been substantially expanding as management authorities have been transitioning to assessing and managing broader ecological effects of fishing, from genotypes to ecological communities (Pitcher et al., 2009; Gilman et al., 2017). EM systems are increasingly being used to augment conventional coverage by human onboard observers, as well as to provide at-sea coverage where none previously existed, in order to meet these increasing demands for fisheries monitoring data.

A review of findings from studies comparing the data collected by EM and onboard observers indicated that, for most fields, EM and human at-sea observers produce estimates with high precision. Species identification by EM systems, in particular for predominantly discarded species, was found to be in need of improvements in several studies (AFMA and Archipelago Marine Research, 2005; McElderry, 2010; AFMA, 2006, 2010, 2011, 2012; Arnande et al., 2012; Chavence et al., 2013; Ruiz et al., 2013; Hosken et al., 2016b; Monteagudo et al., 2015; Briand et al., 2017; Bartholomew et al., 2018). Furthermore, estimates of fish lengths by EM digital length software for relatively small species and of the sex of sharks, in particular for females, require improvements (Hosken et al., 2016b). For some fields, EM data were of higher quality, such as positional data (which can be automatically captured by some EM reviewing software) and the number of hooks between floats in pelagic longline fisheries (Hosken et al., 2016b).

Observer data may be biased as a result of fishers altering their fishing practices and gear due to the presence of an onboard observer or EM system. The higher the observer coverage rate, the lower the bias from an observer effect, as the larger the proportion of fishing effort that is observed, the more accurately the monitoring data represent the fishery (Babcock et al., 2003). With 100% onboard human observer coverage, or likely more cost effective, having all vessels in a fleet outfitted with onboard EM systems and analyzing random samples, can eliminate this observer effect.

When sensitive fields are collected by at-sea observers, the vessel captain and crew may hinder the observer from properly conducting their monitoring requirements, and might bribe the observer to not report damaging information. Some observers may misreport industry-sensitive information due to friendships with fishers. EM systems, where office-based analysis of the raw EM data occurs, are not susceptible to these types of coercion and corruption issues.

In fisheries where placement of at-sea observers is not able to be randomized and balanced (e.g., some vessels are too small to accommodate an observer, are unsafe, have relatively undesirable conditions, or are logistically difficult to access), resulting observer data are biased. Because vessel specification requirements for EM systems are much lower than what is needed to deploy a human observer, EM is not likely to result in this type of deployment effect.

At-sea observers are unable to monitor all fishing operations, for example, due to requirements for sleeping and breaks, and during rough weather. While EM does not achieve complete coverage, as there can be equipment malfunctions and fishers may inadvertently or intentionally obstruct EM equipment, this represents a small proportion of unmonitored fishing effort relative to that of human onboard observer.

There are very few data fields for pelagic longline and tuna purse seine fisheries that contemporary EM systems collect that may not be able to be collected by human onboard observers. This includes the position, date and time of each organism caught by pelagic longline vessels, as human observers might lack the time to record the position for each caught organism, and for vessels with single observer placements, observers typically do not monitor the entire gear haulback. And, while human observers may not be able to determine real-time violations of temporal and spatial fishery closures, EM systems with near real-time satellite-based data delivery could enable managers to detect close to real time when a vessel violated a time/area closure.

Based on an assessment of fields collected by onboard human observers of the WCPFC Regional Observer Program and the SPC/FFA Regional Observer Program for pelagic longline and tuna purse seine fisheries, we identified 101 fields that are not possible to collect with contemporary EM systems. Dockside monitoring would cover 45 of these fields. A small subset of these 45 fields may vary within trips, in particular for distant-water longline vessels, where innovations in EM technology could enable their collection. Most of the 57 fields that are not suitable for dockside collection are information on the catch, whether gear and equipment were used during fishing operations, on fishing methods and gear designs that were used during setting and gear retrieval, and on environmental conditions.

Of the observer fields that were determined to not be possible to collect by contemporary EM systems, improvements in EM technology were thought possible for 70. The positioning of EM cameras and use of specialized lenses, the addition of thermal and underwater cameras, and integrating existing and new sensors were identified as potential solutions.

Of 31 observer fields for which innovations in EM technology were determined to likely not be feasible, 3 were thought to not be possible to collect by dockside inspections: tissue samples, gonad stage, and information on the vessel receiving at-sea transshipped catch. An additional 5 fields were identified as not being possible to collect via dockside inspections for distant-water vessels, as the values for these fields might change during a trip when the vessel conducts at-sea transshipment and bunkering: captain and crew names, nationalities, document unique IDs, duration of fishing experience, and name of crew in each position. These fields may therefore only be possible to collect by human onboard observers.

Examples are provided of industry-desired information that could be delivered by EM systems. Achieving the political will and capacity to transition to EM may be strengthened given the support of catch sector and other seafood companies. Seafood sector support for EM, in turn, would be strengthened if EM supplied information to industry that supported their fishing operations.

Current EM systems can contribute to meeting objectives of fisheries observer programs. Priority improvements in EM technology could augment the quality of data being collected, enable collecting additional data fields, and support meeting the expanding data requirements of fisheries monitoring programs as management authorities begin or continue to transition to implementing elements of ecosystem-based fisheries management (Pitcher *et al*., 2009; Gilman *et al*., 2014, 2017). We can be cautiously optimistic that EM technology will soon be suitable for use in all capture fisheries, from artisanal/small scale to industrial/large scale fisheries, and from fisheries with relatively rudimentary management systems with relatively low institutional and financial resources to fisheries with relatively robust management systems and ample resources. This tremendous increase in fisheries monitoring will in turn support drastic improvements in ecological risk assessments, the science-based design of conservation and management measures and compliance monitoring.

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Table 1. Data fields for pelagic longline and tuna purse seine fisheries that contemporary EM systems collect that may not be able to be collected by human onboard observers (Monteagudo et al., 2015; Hosken et al., 2016b; SPC and FFA, 2017).

Data field	Gear	Field category	How could be collected by a human observer	Citation	Notes
Geospatial position of individual catch events (i.e., vessel position when an organism is retrieved during gear haulback)	Pelagic longline	Catch	Multiple observers	Hosken et al., 2016b	One at-sea observer might not have time to record for all catch events, might not observe the entire gear haulback
Date/time of individual catch events	Pelagic longline	Catch	Multiple observers	None	One at-sea observer might not observe the entire gear haulback and might miss some catch events
EM data reviewing software version	All	EM equipment	Dockside	SPC and FFA, 2017	
EM hardware components	All	EM equipment	Dockside	SPC and FFA, 2017	
Full coverage	All	EM equipment	Multiple human onboard observers	None	EM systems can monitor fishing operations full time; would require multiple at-sea human observers to cover 24 hour operations
Office EM data analysis duration	All	EM observer	NA	SPC and FFA, 2017	
EM office observer analyst name	All	EM observer	NA	SPC and FFA, 2017	
Near-real-time determination of violations of time/area restrictions	All	Fishing methods	Human observers record positional and temporal data, but may not be able to determine real-time if a vessel did not comply with a time-area closure.	Monteagudo et al., 2015	EM systems with near real-time satellite-based data delivery could enable managers to detect near-real-time violations of time/area closures.

Table 2. Pelagic longline and tuna purse seine fields that are collected by onboard human observers that cannot be collected by contemporary EM systems (Gilman and Hall, 2015; Hosken et al., 2016b; SPC and FFA, 2017).

Data field	Gear	Field category	Can collect pre-trip via dockside inspection (and value is unlikely to vary during trip)?	EM tech fix options (theoretical and known)	Reference	Notes
Count of each seabird species within 137 m of vessel during all fishing operations (set, soak, haul, transit)	All	Other	N	360 degree camera - during day	Gilman and Hall, 2015	
Wind velocity	All	Environmental variables	N	Additional sensor	Gilman and Hall, 2015	
Sea surface temperature	All	Environmental variables	N	Additional sensor	Gilman and Hall, 2015	
Method used to detect fish school for each set	All	Fishing methods	N	Additional sensors	SPC and FFA, 2017	
Vessel equipment used during trip (make, model) (including technology aids for fish finding and gear deployment and retrieval that affect effective fishing power)	All	Vessel characteristics and equipment	N	Additional sensors	Gilman and Hall, 2015; SPC and FFA, 2017	
Logsheet recording (did captain record in logsheet - e.g., transshipment, catch event)	All	Other	N	Automated comparison between EM and logbook data could be conducted by set and trip	SPC and FFA, 2017	

Turtle curved carapace length	All	Catch	N	Automated estimate from species recognition software and EM digital length software	None	
Anatomical hooking position	Pelagic longline	Catch	N	Camera position	Gilman and Hall, 2015	
Terminal tackle remaining attached to live released organisms	Pelagic longline	Catch	N	Camera position	Gilman and Hall, 2015	
FAD deployment information (date, location)	Purse seine	Gear	N	Camera position	SPC and FFA, 2017	Cannot detect deployments of FADs tracked by this vessel that are deployed by other vessels
Design of bird-scaring tori line when deployed (e.g., aerial coverage, height of tori line above deck, spacing and length of streamers)	Pelagic longline	Gear-bycatch mitigation	N	Camera position and lens	Gilman and Hall, 2015	
Terminal tackle (hook shape, hook size, hook offset, bait type, leader material, leader length, branchline diameter, etc) on which individual organisms (including ETP species) are captured	Pelagic longline	Catch	N	Camera position and lens type	Gilman and Hall, 2015	
Sea state (Beaufort wind force scale)	All	Environmental variables	N	Camera position and lens type	Gilman and Hall, 2015	
Visibility	All	Environmental variables	N	Camera position and lens type	Gilman and Hall, 2015	
Interactions with ETP species that occur during fishing operations other than setting and hauling	All	Other	N	Camera position and lens type	SPC and FFA, 2017	May not be included in EM analyses - which may be restricted

						to setting and hauling
Information on sightings of ETP species (number adults, number juveniles, length, distance from vessel, behavior, vessel activity during sighting, etc.), and of other vessels (distance from vessel, vessel activity)	All	Other	N	Camera position and lens type	SPC and FFA, 2017	
Cloud cover	All	Environmental variables	N	Camera position and lens type, illumination sensor	Gilman and Hall, 2015	
Shark line, number per set	Pelagic longline	Gear	N	Camera position could enable viewing crew attaching branchline to floatline	Gilman and Hall, 2015	
Lightsticks, number per set	Pelagic longline	Gear	N	Camera position could enable viewing crew attaching lightsticks to branchlines	Gilman and Hall, 2015	
Offal management practice (retained, discharged, during setting, hauling, other operations)	Pelagic longline	Gear-bycatch mitigation	N	Camera position, e.g., some fisheries require offal discharge on opposite side of vessel from hauling station	Gilman and Hall, 2015	
Handling and release methods for ETP species	All	Catch	N	Camera position, including when recovering on deck	Gilman and Hall, 2015	
Weight catch transshiped at sea from vessel	All	Transsipment	N	Camera position, sensor on hold, sensor on cranes	SPC and FFA, 2017	

Discarded pollution (garbage, waste) length/area/volume	All	Other	N	Cameras position to enable analyst to see and estimate the amount of pollution discarded overboard	Hosken et al., 2016b; SPC and FFA. 2017	Some pollution discarding may be conducted outside the viewing range of the EM cameras
Species of catch, and of escaped catch	All	Catch, escaped (pre-) catch	N	Probe that conducts genetic analyses of tissue samples to determine the species of the catch	None	May be possible to collect tissue samples from hooks on which an organism had been hooked but escaped prior to gear haulback (NMFS, 2015)
Sex of catch of some species with no visible anatomical features (e.g., claspers on sharks, and mahi mahi and opah have external differences by sex)	Pelagic longline	Catch	N	Probe/scanner to analyze sex-specific genetic markers or hormones	Hosken et al., 2016b	Juvenile fishes require abdominal analysis. Crew required to display underside of sharks and rays if EM to view.
Ratio of weight of shark fin-to-carcass	All	Catch	N	EM analysts could record shark finning events (retain fins, discard the remaining carcass) precluding the need to estimate shark fin-to-carcass weight ratios. And, with the cooperation of crew to ensure removed fins and the associated carcass are within camera view, EM digital length software could measure fin	None	

				and carcass length dimensions and either convert to estimates of weight, or establish new species-specific length ratios.		
Seabird bill length, tip of wing to wrist	All	Catch	N	EM digital length software	SPC and FFA, 2017	
Shark fin weight	All	Catch	N	EM digital length software, use length-to-weight conversion factor	SPC and FFA, 2017	
shark carcass weight	All	Catch	N	EM digital length software, use length-to-weight conversion factor	SPC and FFA, 2017	
bird curtain used	Pelagic longline	Gear-bycatch mitigation	N	Ensure EM camera provides view of gear setting and hauling operations	None	
Bird-scaring tori line used	Pelagic longline	Gear-bycatch mitigation	N	Ensure EM camera provides view of gear setting and hauling operations	None	
underwater setting chute used	Pelagic longline	Gear-bycatch mitigation	N	Ensure EM camera provides view of gear setting operations	SPC and FFA, 2017	
Branchline weight amount	Pelagic longline	Gear-bycatch mitigation	N	E-tag, sensor during set or haul, video marco	SPC and FFA, 2017	Could be altered during course of trip thus dockside observation may not be valid
Weight of individual organism	All	Catch	N	Image or serial connection of weight	SPC and FFA, 2017	

				from motion-compensated scales. Estimate from length estimate using a length-weight ratio.		
Sightings of other vessels, aircraft (latitude, longitude, date, time, activity of other vessel, etc.)	All	Other	N	Include camera with suitable specs to enable detecting vessels/aircraft in distance	SPC and FFA, 2017	
Purse seine net hanging ratio	Purse seine	Fishing methods	N	Include underwater camera positioned to detect the dimensions of the net	SPC and FFA, 2017	
Tag data	All	Catch	N	Macro view of tag on catch may enable office analyst to read and record the tag contents.	SPC and FFA, 2017	
Type of tag	All	Catch	N	Macro view of tag on catch may enable office analyst to read and record the tag contents.	SPC and FFA, 2017	
Tissue samples	All	Catch	N	None known	None	
Gonad stage	All	Catch	N	None known	SPC and FFA, 2017	
Transshipment receiving vessel information (unique identificaton number, etc)	All	Transsipment	N	None known	SPC and FFA, 2017	Could be obtained via analyses of VMS and AIS data, pre-notificatoin
Current strength	All	Environmental variables	N	Sensor	Gilman and Hall, 2015	

Current direction	All	Environmental variables	N	Sensor	Gilman and Hall, 2015	
Mainline line shooter speed	Pelagic longline	Fishing methods	N	Sensor	SPC and FFA, 2017	
Max depth of purse seine net in each set	Purse seine	Fishing methods	N	Sensor on net	SPC and FFA, 2017	
Did fishers monitor international safety frequencies	All	Vessel characteristics and equipment	N	Sensor on radio	SPC and FFA, 2017	
Sea surface concentration of chlorophyll-a	All	Environmental variables	N	Sensor, integrate with relevant satellite imagery databases for rough scale	Gilman and Hall, 2015	
Thermocline depth	All	Environmental variables	N	Sensor, integrate with relevant satellite imagery databases for rough scale	Gilman and Hall, 2015	
Lunation	All	Environmental variables	N	Sensor	Gilman and Hall, 2015	
FAD design (materials, dimensions, less- and non-entangling designs for appendage and surface structure)	Purse seine	Gear	N	Submerged design characteristics may be possible for EM cameras to capture for FADs on board and within camera view. Design and materials of surface structures may be able to be detected by EM for deployed FADs if close enough to the vessel and within camera view.	SPC and FFA, 2017	Not possible for EM cameras to detect submerged structure of FADs that are deployed. Vessels routinely set on FADs deployed by other vessels.
Bait thawed completely before set	Pelagic longline	Fishing methods -	N	Thermal signature?	Gilman and Hall, 2015	

		bycatch mitigation				
Life status of catch at haulback (alive, dead, degree of injury)	All	Catch	N	Thermal signature?	Hosken et al., 2016b	Can be particularly difficult to identify life status for smaller organisms
Life status of catch upon release if not retained (alive, dead, degree of injury)	All	Catch	N	Thermal signature?	SPC and FFA, 2017	Can be particularly difficult to identify life status for smaller organisms
Bait dyed blue	Pelagic longline	Fishing methods - bycatch mitigation	N	Video macro during set	Gilman and Hall, 2015	In particular, for fish species used for bait, likely not possible to determine if are blue-dyed based on review of video
Leader length	Pelagic longline	Gear-bycatch mitigtion	N	Video macro during set	SPC and FFA, 2017	Could be altered during course of trip thus dockside observation may not be valid
Hook shielding device used	Pelagic longline	Gear-bycatch mitigation	N	Video macro during set or haul	None	
Brail weight	Purse seine	Catch	N	Weight sensor on brail winch	SPC and FFA, 2017	
Vessel length	All	Vessel characteristics and equipment	Y	360 degree camera	Gilman and Hall, 2015	
Purse seine net strips	Purse seine	Gear	Y	Camera field of view	SPC and FFA, 2017	

Purse seine main mesh size	Purse seine	Gear	Y	Camera position, EM digital length software	SPC and FFA, 2017
Hook ring or not	Pelagic longline	Gear	Y	Camera with macro lens in suitable position	Gilman and Hall, 2015
Hook shape	Pelagic longline	Gear	Y	Camera with macro lens in suitable position	SPC and FFA, 2017
Satellite buoy and radio beacon unique ID	Purse seine	Gear	Y	Could be collected remotely, through parallel feed from satellite buoy service provider to management authority	SPC and FFA, 2017
Target species	All	Other	Y	Determine from EM-derived data on retained catch composition	SPC and FFA, 2017
Vessel flag	All	Vessel characteristics and equipment	Y	EM camera position	Gilman and Hall, 2015
Branchline length	Pelagic longline	Gear	Y	EM digital length software, with crew cooperation to have sample of branchlines, showing entire branchline, within camera view	Gilman and Hall, 2015
Floatline length	Pelagic longline	Gear	Y	EM digital length software, with crew cooperation to have sample of branchlines, showing entire	SPC and FFA, 2017

				branchline, within camera view	
Information on helicopter (make, model, registration number, range)	Purse seine	Vessel characteristics and equipment	Y	EM imagery may enable collecting some of these fields	SPC and FFA, 2017
Bait live vs. dead	Pelagic longline	Gear	Y	EM may be able to detect when live bait are taken from vessel well by crew during setting, when a mix of live and frozen bait are used	Gilman and Hall, 2015
Floatline material	Pelagic longline	Gear	Y	None known	Gilman and Hall, 2015
Floatline diameter	Pelagic longline	Gear	Y	None known	Gilman and Hall, 2015
Buoy material	Pelagic longline	Gear	Y	None known	Gilman and Hall, 2015
Mainline length on vessel	Pelagic longline	Gear	Y	None known	Gilman and Hall, 2015; SPC and FFA, 2017
Mainline diameter	Pelagic longline	Gear	Y	None known	Gilman and Hall, 2015
% each branchline weight type	Pelagic longline	Gear	Y	None known	Gilman and Hall, 2015
Mainline material	Pelagic longline	Gear	Y	None known	SPC and FFA, 2017
Branchline material	Pelagic longline	Gear	Y	None known	SPC and FFA, 2017
Branchline diameter	Pelagic longline	Gear	Y	None known	SPC and FFA, 2017
% each hook type	Pelagic longline	Gear	Y	None known	SPC and FFA, 2017

Hook minimum width	Pelagic longline	Gear	Y	None known	SPC and FFA, 2017
Hook manufacturer and model	Pelagic longline	Gear	Y	None known	SPC and FFA, 2017
Vessel unique ID	All	Vessel characteristics and equipment	Y	None known	Gilman and Hall, 2015
Vessel weight	All	Vessel characteristics and equipment	Y	None known	Gilman and Hall, 2015
Information on skiff (make, horsepower)	Purse seine	Vessel characteristics and equipment	Y	None known	SPC and FFA, 2017
Vessel name	All	Vessel characteristics and equipment	Y	None known	SPC and FFA, 2017
Vessel owner	All	Vessel characteristics and equipment	Y	None known	SPC and FFA, 2017
Vessel equipment onboard (make, model)	All	Vessel characteristics and equipment	Y	None known	SPC and FFA, 2017
Refrigeration method	All	Vessel characteristics and equipment	Y	None known	SPC and FFA, 2017
Valid license document onboard	All	Vessel characteristics and equipment	Y	None known	SPC and FFA, 2017
Safety equipment meet requirements	All	Vessel characteristics and equipment	Y	None known	SPC and FFA, 2017
Were required materials displayed on the vessel to	All	Vessel characteristics and equipment	Y	None known	SPC and FFA, 2017

remind fishers about MARPOL regulations?						
Vessel marking	All	Vessel characteristics and equipment	Y	None known	SPC and FFA, 2017	
Max length of purse seine net	Purse seine	Fishing methods	Y	Sensors on headline of net during operation	SPC and FFA, 2017	
Echo-sounder on FAD	Purse seine	Gear	Y (for FADs deployed), N (for FADs deployed by other vessels)	Integrate satellite buoy and echo-sounder buoy data into EM system. Camera position may enable detection of echo-sounder on drifting FAD if the FAD is close to the vessel and within camera view.	None	Presence/absence of echo-sounder on drifting FADs can be detected dockside for FADs that the vessel has onboard, but not for FADs that the vessel is tracking but are deployed by other vessels or that are obtained by the vessel by exchanging the satellite buoys attached to the FAD.
Number of crew onboard during trip	All	Crew	Y (locally-based), N (distant-water)	Camera positions cover entire vessel	SPC and FFA, 2017	Could be altered during course of trip thus dockside observation may not be valid, and some crew may not be captured by cameras
Bait weight and length	Pelagic longline	Gear	Y (locally-based), N	EM digital length software and camera with macro lens to detect	SPC and FFA, 2017	Distant-water vessels may resupply bait when

			(distant-water)	species, and use length-to-weight conversion to estimate weight		transshipping at sea.
Captain and crew names	All	Crew	Y (locally-based), N (distant-water)	None known	SPC and FFA, 2017	Crew may change during a trip on distant-water vessels
Captain and crew nationalities	All	Crew	Y (locally-based), N (distant-water)	None known	SPC and FFA, 2017	Crew may change during a trip on distant-water vessels
Captain and crew document ID number	All	Crew	Y (locally-based), N (distant-water)	None known	SPC and FFA, 2017	Crew may change during a trip on distant-water vessels
Name of crew conducting each job position	All	Crew	Y (locally-based), N (distant-water)	None known	SPC and FFA, 2017	Crew may change during a trip on distant-water vessels
Crew duration of fishing experience	All	Crew	Y (locally-based), N (distant-water)	None known	SPC and FFA, 2017	Crew may change during a trip on distant-water vessels
Gear marking	All	Gear	Y (pelagic longline), N (purse seine FADs)	Camera position to enable view of exchanging satellite buoys attached to drifting FADs	SPC and FFA, 2017	Gear marking for pelagic longline likely is adequate to conduct dockside, but not adequate for purse seine FADs.