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Increasing the functionalities and accuracy of fisheries electronic monitoring systems

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Abstract

1. Fisheries-dependent data underpin essential scientific and management applications. Electronic monitoring (EM) systems are increasingly being used to supplement human observer programmes and provide coverage where none previously existed.
2. Candidate methods were identified to expand EM functionalities to collect data fields of human observer programmes that contemporary EM systems either cannot collect or require improved accuracy. Options were also identified to enable EM systems to collect new data fields that human observers cannot collect, prioritized by scientists, managers and the catch sector.
3. Many EM limitations could be resolved through simple changes of repositioning existing or adding new cameras with suitable fields of view and resolution, integrating additional sensors, and making minor modifications to fishers' practices. Research, development and trials, however, are required for possible EM integration of some existing and emerging technologies.
4. Whether an EM improvement method should be pursued requires consideration of: the relative importance for meeting monitoring objectives; the accuracy and cost of alternative monitoring methods, such as data collection by fishers with EM auditing, and by dockside inspections; impacts on fishing operations and crew safety; and net costs.
5. Active support from fishers is necessary for EM collection of some data fields, where EM enables auditing fisher compliance with required procedures. Having EM systems supply data desired by the seafood industry could augment their support for EM and incentivize fisher cooperation.
6. EM systems have the capacity to collect most data fields collected by human observer programmes with high precision and in some cases improved accuracy, to supply information of interest to seafood companies, and to meet expanding data requirements as fisheries management frameworks continue to transition to implementing elements of ecosystem-based fisheries management.

KEYWORDS

camera, electronic monitoring, emerging technologies, fisheries-dependent data, observer, tuna fisheries

1 | INTRODUCTION

Fisheries monitoring programmes meet data requirements for fundamental scientific, compliance monitoring and sustainability assessment applications. Applications include conducting stock assessments, estimating bycatch and discards, assessing the performance of ecosystem-based harvest strategies, monitoring compliance with management measures and licence agreements, and conducting assessments against fisheries ecological sustainability and labour standards (Davies & Reynolds, 2002; Gilman, Weijerman, & Suuronen, 2017; Marine Stewardship Council, 2018). Data collected by observer programmes provide more accurate and comprehensive information than data self-reported in logbooks by fishers. This is because fishers may lack the time and training to conduct prescribed data collection methods and/or may have an economic or regulatory disincentive to record accurate data, for example, to avoid catch, effort and size limits (Brown, 2001; Davies & Reynolds, 2002; Legorburu et al., 2018; Walsh, Ito, Kawamoto, & McCracken, 2005; Walsh, Kleiber, & McCracken, 2002). Port sampling programmes supply data only on landed catch, and not on discarded (non-retained live released and dead discarded) catch or on effort within trips.

Electronic monitoring (EM) systems are increasingly being used to complement conventional human onboard observer programmes and to trial introducing at-sea coverage where none previously existed. EM systems typically use onboard cameras, global positioning systems, sensors and data loggers to collect information on fishing, transshipment and supply vessels (Legorburu et al., 2018; Lowman, Fisher, Holliday, McTee, & Stebbins, 2013; Restrepo, 2012). They include office-based staff who analyse imagery (video and/or single-frame still photographs) and sensor data and input data into a database, usually operated by a fisheries body or other independent organization. Several trials of EM systems have occurred in pelagic longline and tuna purse seine fisheries, including to monitor at-sea transshipments and activities of supply vessels (Australian Fisheries Management Authority [AFMA], 2011; Briand et al., 2017; Gilman, Schneiter, Brown, & Zimring, 2018; Hosken, Williams, & Smith, 2016; Hosken, Vilia, et al., 2016; Hosken, Williams, Smith, Loganimoce, & Schneiter, 2018; Legorburu et al., 2018; McElderry, Pria, Dyas, & McVeigh, 2010; Monteagudo, Legorburu, Justel-Rubio, & Restrepo, 2015; National Marine Fisheries Service [NMFS], 2017c, 2018; National Oceanic Resource Management Authority, 2017; Piasente et al., 2012; Western and Central Pacific Fisheries Commission [WCPFC], 2018b). Two tuna fisheries have fully operational EM systems. The Australia pelagic longline fishery has fleetwide EM to support an audit model, where a random subset of EM imagery is reviewed to validate the precision of logbook catch data (AFMA, 2012, 2015; Larcombe, Noriega, & Timmiss, 2016). And, the US Atlantic pelagic longline fishery has fleetwide EM to monitor Atlantic bluefin tuna (*Thunnus thynnus*) bycatch (NMFS, 2017b).

EM has several advantages over conventional human observer programmes. EM can overcome three main sources of statistical sampling bias faced by human observer programmes. First, fishers may alter their fishing practices and gear in response to the presence of a human observer or EM system (Babcock, Pikitch, & Hudson, 2003; Benoit & Allard, 2009; Gilman, Chaloupka, Merrifield, Malsol, & Cook, 2016; Hall, 1999; Liggens, Bradley, & Kennelly, 1997). The higher the observer and EM coverage rate, the lower the bias from an observer effect (Babcock et al., 2003). Having all vessels outfitted with EM equipment and analysing a random sample or all of the EM imagery could eliminate this source of bias. Furthermore, while the supply of human observers at some threshold will prevent scaling observer coverage to increase monitoring incrementally to the world's industrial and ~4.6 million total fishing vessels (Food and Agriculture Organization of the United Nations [FAO], 2018a, 2018b; Michelin, Elliott, Bucher, Zimring, & Sweeney, 2018), EM is scalable. Second, observers may not be placed on certain vessels for various reasons (undesirable conditions, too small, unsafe, skipper or crew are ill-disposed, mismatch in languages spoken by the fishers and observers, logistically challenging for placement and retrieval) (Benoit & Allard, 2009). Because vessel specification requirements for EM systems are much lower than for a human observer, EM enables avoiding an observer displacement effect so that sampling is random and balanced proportionately across ports and vessel categories (Bartholomew et al., 2018; Benoit & Allard, 2009; Bravington, Burridge, & Toscas, 2003). And, third EM systems are not subject to biased data resulting from coercion and corruption of human observers, and avoid risks to at-sea observers' safety. When at-sea observers collect sensitive information, the vessel captain and crew may hinder the observer from properly conducting their monitoring activities, threaten the observer's safety, or attempt to bribe the observer to not report damaging information (Levitz, 2013; Watling, 2012). Some observers may deliberately misreport industry-sensitive data fields due to friendships with the captain and crew. EM data can be independently verified through an audit of EM imagery and sensor data, which cannot be conducted for data collected by human onboard observers.

EM can overcome incomplete monitoring coverage within trips. EM systems allow analysts to monitor multiple fields of view on a vessel simultaneously. Human observers can monitor only one area of a vessel at a time (Kennelly & Hager, 2018; Monteagudo et al., 2015). For instance, whereas EM systems enable simultaneous monitoring of upper and lower tuna purse seine decks, a human observer monitoring the deck where target species are processed may not observe billfishes and other bycatch species that crew handle on a separate deck (Monteagudo et al., 2015). At-sea observers cannot collect data when sleeping, eating, going to the bathroom and during scheduled breaks (Hosken, Vilia, et al., 2016). Gear haulback may take over 12 hr, during which time some programmes allow observers to take breaks (Hosken, Vilia, et al., 2016). Observers may be required to schedule a day off following a specified period of working (Hosken, Vilia, et al., 2016). Human observers may be unable to collect data during rough weather and may have to stop working when they are ill, such as from seasickness (NMFS, 2017a). Whereas multiple at-sea observers are placed on individual vessels in some fisheries where operations are conducted continuously, or nearly so (NMFS, n.d.-a), this is not economically viable or practical in most fisheries. Although EM overcomes these gaps in monitoring, EM systems also do not achieve 100% coverage. For instance, equipment malfunctions occur, power can be interrupted, hard drives can reach capacity before the end of a trip, and crew can inadvertently or intentionally obstruct cameras and disable sensors. But these issues typically result in only a small proportion of effort going unmonitored. For example, only 0.8% and 4.6% of hours-at-sea were not monitored by EM systems during preliminary trials in the Hawaii and Solomon Islands longline fisheries, respectively (Hosken, Vilia, et al., 2016; McElderry et al., 2010). Furthermore, this rate of incomplete EM data collection is likely to decrease as fisheries transition from pilots to fully operational EM programmes, for instance, as regulations on the maintenance and operation of EM systems are adopted and implemented, and as EM technology continues to improve.

EM does not come with certain inconveniences of human observers, including logistics for receiving and delivering the observer, crowding on vessels, and the need to supply food and sleeping space (Kennelly & Hager, 2018). And, as a result of having a person onboard who is unfamiliar with the vessel, safety issues can arise from placement of human observers, both for the observer and crew (Kennelly & Hager, 2018).

For some fields, EM provides more accurate data than collected by human observers. For example, positional data, which can be automatically recorded by the EM reviewing software, are of higher resolution (Hosken, Vilia, et al., 2016). EM systems can automatically record the date, time and vessel position for each pelagic longline capture event (when a caught organism is retrieved during gear haulback), which might not be feasible for human onboard observers to record for each caught organism (Hosken, Vilia, et al., 2016). In addition, when an observer data record is flagged as questionable (discussed earlier), archived raw EM data can be audited by multiple analysts, which is not possible for data collected by human onboard observers, except when an observer has photographed the catch or retained a specimen—usually reserved for protected species captures.

EM systems could be used to reduce tasks of at-sea observers, enabling them to allocate time to collect data that EM systems cannot, such as biological samples. In addition to enabling direct communication with fishers, and meeting employment objectives, maintaining at-sea observer programmes in conjunction with EM programmes allows ongoing assessment of the precision of data collected by EM and at-sea observer programmes. This also provides experiential knowledge required by EM analysts (Restrepo, Ariz, Ruiz, Justel-Rubio, & Chavance, 2014).

EM also has the potential to collect new data fields that are of importance to scientists, managers and industry that are not possible to collect by human onboard observers. Data from EM can also support applications other than for science and compliance monitoring, including to implement seafood traceability programmes and monitor compliance with voluntary industry fishing practices (Organización de Productores Asociados de Grandes Atuneros Congeladores & Asociacion Nacional de Armadores de Buques Atuneros Congeladores, 2017; Pierre, 2018).

EM may currently be less expensive than conventional human observer programmes only in fisheries meeting narrow criteria, including having relatively high levels of fishing effort, high observer coverage rates, where a small proportion of EM raw data are sampled, with a large number of vessels, and with broad fishing grounds (Larcombe et al., 2016; Piasente et al., 2012; Sylvia, Harte, & Cusack, 2016). EM technology several years hence, however, is likely to become more efficient and EM operating costs are likely to fall, for instance, as the review of EM imagery and other data is increasingly automated through machine learning. The data collection efficiency of individual human observers, however, is relatively static, and costs may increase over time if observer wages increase (Kennelly & Hager, 2018; Sylvia et al., 2016). Assessed ins this study, EM may be able to supply information of interest to catch sector companies to support fishing, processing, sales and marketing operations, and may enable reduced insurance premiums and support processing insurance claims (Michelin et al., 2018; NMFS, 2017b), helping to offset industry contributions to covering EM costs.

Candidate methods were identified, including existing and emerging technologies, to expand EM functionalities to: (a) collect fields that are recorded by human observer programmes but cannot be collected by contemporary EM systems; (b) improve the accuracy of fields collected by contemporary EM systems; and (c) capture new fields prioritized by scientists, managers and the catch sector. Whether each candidate method is feasible to integrate into EM now or otherwise requires investment in research, development and trials was also identified. The data requirements of fisheries monitoring programmes have substantially expanded as management authorities throughout the world have begun to transition to implementing elements of ecosystem-based fisheries management (EBFM), with various degrees of success (Gilman et al., 2017; Gilman, Passfield, & Nakamura, 2014; Pitcher, Kalikoski, Short, Varkey, & Pramod, 2009). Data collection methods of many observer programmes, including what categories of information are collected and what data collection protocols are employed, could be substantially expanded and improved, including some fields that EM systems could collect but human observers cannot, to support more comprehensive and robust analyses required to implement EBFM (Gilman et al., 2017; Gilman & Hall, 2015). Improvements promise to enable EM systems to collect most fields of contemporary human observer programmes, to improve data quality for some fields, to collect information of interest to catch sector companies, and to broaden data collection fields to meet the expanding data requirements of fisheries monitoring programmes as management authorities continue to transition to implementing elements of EBFM.

2 | METHODS

Data fields collected by human observers of the 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 were included in the study (Gilman & Hall, 2015; Hosken, Vilia, et al., 2016; Pacific Community, 2014; Pacific Community & Pacific Islands Forum Fisheries Agency, 2017). Additional data fields were included that have been recommended for inclusion in pelagic longline and tuna purse seine observer programmes because the variables that these fields measure significantly affect catch and survival rates, and are of importance for other scientific and compliance monitoring purposes (Gilman & Clarke, 2015; Gilman & Hall, 2015; International Seafood Sustainability Foundation, 2012, 2015; Restrepo et al., 2014). Additional new data fields included in the study that are relevant to pelagic longline and tuna purse seine fisheries and are of interest to scientists, managers and industry were identified through consultation with experts, including observer programme staff, EM service providers and pelagic longline and tuna purse seine companies.

A determination of which of these observer data fields cannot be collected at all or infrequently by contemporary EM systems was made by reviewing the results of trials of EM systems in pelagic longline and tuna purse seine fisheries (Hosken, Vilia, et al., 2016; Kennelly & Hager, 2018; Larcombe et al., 2016; McElderry, 2008; McElderry et al., 2010; McElderry, Schrader, & Anderson, 2008; Monteagudo et al., 2015; Piasente et al., 2012; Pierre, 2018; Restrepo et al., 2014), and reviewing literature from non-tuna fisheries on the efficacy of EM systems at making species-level estimates of seabird counts attending vessels (Ames, Williams, & Fitzgerald, 2005; McElderry, 2008; McElderry et al., 2004). This determination was also informed by reviewing findings from a workshop that identified which fields of the SPC/FFA regional observer programme are not possible for EM systems to collect (Emery et al., 2018; SPC & FFA, 2017), and by surveying experts, including EM analysts and EM programme managers. For each observer data field included in the study, why some or all contemporary EM systems cannot collect the field was reported. Some fields were identified that clearly are not possible for EM systems to collect, such as taking biological samples. Other fields may be frequently collected in some but not all EM programmes, including fields that depend on the setup of the EM vessel equipment and require crew cooperation. The fields were categorized as being applicable to one of the following: catch, pre-catch, crew, environmental variables, fishing method, bycatch mitigation method, gear, bycatch mitigation gear, transshipment vessel characteristics and equipment, and other. Whether a field can be collected pre-trip through a dockside inspection was identified, where fields that either cannot be collected through dockside pre-trip observations or for which its value may vary during the course of a fishing trip are a relatively high priority for EM collection. The observer data fields were categorized as either: (a) not ever possible to collect using current EM systems; (b) infrequently possible to collect using current EM systems; or (c) able to be collected frequently in some but not all fisheries with EM systems. The study scope did not include reviewing the various applications and relative importance of individual observer data fields, which has been conducted in previous studies (e.g. Davies & Reynolds, 2002; Gilman et al., 2017; Gilman & Hall, 2015; International Seafood Sustainability Foundation, 2012, 2015).

Findings from relevant past studies (Emery et al., 2018; Gilman & Hall, 2015; Hosken, Vilia, et al., 2016; Restrepo et al., 2014; SPC & FFA, 2017) were reviewed to identify options, including the use of existing and emerging technologies, to expand the functionalities of existing EM systems to collect observer data fields that contemporary EM systems cannot, and to increase the accuracy of data collected by contemporary EM systems. Consultations with experts in EM systems and electronic technologies were also conducted to identify options. Observer data fields that may not be possible for EM systems to collect were identified. For each candidate method to augment the functionalities of EM systems, we identified whether the method is feasible to integrate into EM systems now or otherwise whether research, development and trials are needed.

3 | RESULTS: METHODS TO EXPAND DATA FIELDS AND IMPROVE THE ACCURACY OF DATA COLLECTED BY EM SYSTEMS

Supplementary Information Table S1 identifies data fields that are collected by some pelagic longline and tuna purse seine fisheries but are likely not possible to be routinely collected by contemporary EM systems. Table S1a identifies the subset of data fields that cannot be collected through pre-trip dockside observations, including fields for which the value may vary during the course of a fishing trip, such as occurs during relatively long trips by distant water longline vessels that may be resupplied at sea with gear components and crew. Table S1b comprises the subset of fields that can be collected dockside via pre-trip inspections and are not likely to change during the course of a trip.

Definitions are included for data fields in Table S1 for which the name of the field is not self-explanatory. Each field is categorized by: (a) the gear type(s) for which the field is relevant (pelagic longline, tuna purse seine, both); (b) field category; and (c) whether the field can be collected pre-trip by a dockside inspection and the value of the field is not likely to vary during a trip. For each field, Table S1 explains why the field is not always feasible to collect using existing EM systems, and identifies candidate methods to enable EM systems to collect it or to improve accuracy. For each candidate method identified in Table S1, Table 1 describes how it would be used when integrated into EM systems, and describes whether the method is feasible to integrate into EM systems now or otherwise whether research, development or trials are needed.

3.1 | Methods for EM collection of data fields that human observers collect that contemporary EM systems cannot collect or require improved accuracy

There are a growing number of studies comparing the quality of data collected by EM systems and by human observers, including from pelagic longline and tuna purse seine fisheries. Findings in most cases indicate that EM data have relatively high precision (i.e. the values for data fields derived from EM are consistent with and have low variability from those collected by onboard observers). Areas identified where EM systems require improvements include, for example, EM camera setup to view all locations where crew handle and discard catch, identification of catch that is released in the water distant from the fish door on longline vessels, species identification of relatively rare

TABLE 1 Candidate methods, including existing and emerging technologies, to augment the functionalities of fisheries electronic monitoring (EM) systems to enable the collection of data fields that contemporary systems are unable to capture, augment data accuracy for fields existing EM systems collect, whether the method is feasible to integrate into EM systems now or otherwise requires research, development or testing

EM improvement method	Status	Notes	References
Acoustic doppler current profiler	Ready	Integrate into EM	Beverly et al., 2003
Anemometer (wind-speed) sensor	Ready	Integrate into EM	NauticExpo, 2018
Automated identification systems (AIS)	Ready	Integrate AIS database into EM system and program to issue alert when specified thresholds (e.g. when within 20 m of another vessel) are exceeded; and enable detection of information (e.g. unique ID, vessel name, flag state) of vessels that come within the threshold distance of the fishing vessel	Girard & Du Payrat, 2017; International Telecommunication Union, 2014; Selbe, 2014
Automatic branchline coiler hydraulic sensor	Ready	Integrate sensor to detect when an automatic branchline coiler is used	McElderry, 2008; McElderry et al., 2008, 2010; Piasente et al., 2012
Bait caster hydraulic sensor	Ready	Integrate sensor to detect when a bait caster is used	McElderry, 2008; McElderry et al., 2008, 2010; Piasente et al., 2012
Bathythermograph	Ready	Integrate into the EM system to identify the depth of the thermocline, using data on the distribution of temperature by depth	Beverly et al., 2003
Camera position/field of view (or additional cameras)	Ready	Add new dedicated camera with suitable lens and resolution, adjust field of view of existing cameras	Briand et al., 2017; Restrepo et al., 2018; SPC & FFA, 2017
Cameras with wide angle up to 360° ‘fisheye’ lenses	Ready	Cameras with wide-angle lenses are commercially available, and several EM service providers already use wide-angle and 360° view ‘fisheye’ cameras	Kumler & Bauer, 2000
Colour sensor (e.g. spectrophotometers and spectroradiometers)	Ready	Integrated into EM to detect the hue, value and chroma of bait prior to pelagic longline setting. Variable lighting conditions can limit the applications of colour sensors	Gomez-Robledo et al., 2013; Gongal et al., 2015; Sikri, 2010
Compression of EM data for satellite transmission	R&D, testing	Improve the compression of digital imagery files collected by EM systems without loss of quality to enable lower cost for satellite data transfers to support near-real-time monitoring	Lohar et al., 2018; Xiao et al., 2018
Database of fishers—integrate into EM system	Development	Enable input into EM system through integration with electronic reporting (ER) tablet, or graphical user interface (GUI) to enable dockside observer or fishers to input, or link through facial recognition (see ‘facial recognition’ improvement method)	NA
Database of fishing vessels—integrate into EM system	Ready	When a vessel's unique ID is input into the EM system (established when the EM system is installed on the vessel, or through linking the EM system with ER or input using a GUI) the EM system automates populating fields on the vessel characteristics and equipment that remains relatively static (i.e. not likely to change over multiple years), and these fields are updated when the record for that vessel in the vessel database is updated	e.g. FAO, 2018; Restrepo et al., 2014; WCPFC, 2018a

(Continues)

TABLE 1 (Continued)

EM improvement method	Status	Notes	References
Deck lighting, adjust angle and area coverage	Ready	To enable EM analysts to view catch and gear during gear haulback at night, that crew release in the water that are up to a branchline length away from the vessel. However, it may be problematic to have deck lighting reach areas where baited hooks become available to seabirds during gear haulback in fisheries that overlap with seabirds susceptible to capture	NA
Digital length-measurement tools	R&D, testing	Digital length-measurement tools using regular lenses have been developed and tested. In particular, improved length measurements are needed for smaller organisms and gear components viewed using macro lenses (e.g. hook wire diameter, bait length), which may be accomplished using fixed boards and measuring points	Archipelago Marine Research, 2018; Hosken, Vilia, et al., 2016; Huang et al., 2016; Satlink, 2016; Wallace et al., 2015; White et al., 2006
Echo sounders	R&D, testing	Develop echo-sounder buoys that enable accurate detection between species and lengths aggregated at drifting fish aggregating devices (FADs); integrated with instrumented buoys attached to FADs to provide real-time monitoring of the species composition and length frequency distribution of aggregations at FADs	Lopez et al., 2014, 2016
Electronic nose and other gas-based biosensors	R&D, testing	Biosensors for gases that indicate degree of freshness/spoilage	Ólafsdóttir & Kristbergsson, 2006; Thakur & Ragavan, 2013; Venugopal, 2002; Winquist, 2015
ER device	Ready	Integrate ER device (e.g. tablet, iPad, iPhone, computer) into the EM system to enable dockside observers and fishers to input data on crew, vessel characteristics and equipment (or alternatively use the EM user interface, discussed later)	NMFS, n.d.-b; WCPFC, 2018b
Electronic tongue and other liquid-based sensors	R&D, testing	Sensor for pathogens and toxins in liquid in the fish hold	Thakur & Ragavan, 2013; Venugopal, 2002; Winquist, 2015
E-tagged branchline	R&D, testing	Attach electronic tags, such as radio-frequency identification (RFID) tags, to branchline clips to enable automated detection of hook number (the position of each branchline in between two floats) of each caught organism	e.g. RFIDs: *RFID Journal*, 2016; Savi Technologies, 2007; Theiss et al., 2005; Williams, 2017
E-tagged drifting FADs	R&D, testing	Electronic tag that enables a unique ID of a drifting FAD to be read and transmitted by an attached satellite buoy, integrate into EM systems	e.g. RFIDs: *RFID Journal*, 2016; Savi Technologies, 2007; Theiss et al., 2005; Williams, 2017
E-tagged floatline	R&D, testing	Attach electronic tags, such as RFIDs, to each floatline to enable automatic recording of the time when floatlines are retrieved	e.g. RFIDs: *RFID Journal*, 2016; Savi Technologies, 2007; Theiss et al., 2005; Williams, 2017

(Continues)

TABLE 1 (Continued)

EM improvement method	Status	Notes	References
Facial recognition software	Ready	Integrate facial recognition software into EM systems to enable identification of unique fishers, and link with a database of all fishers participating in the fishery being monitored	e.g, Andreotti et al., 2017; Moya et al., 2015
Genetic marker, protein and chemical probes	R&D, testing	Probe to conduct genetic, protein and/or chemical analyses of tissue samples to determine species and sex	Angers et al., 2017; Ashoor & Knox, 1985; Clark, 2015; Hyde et al., 2005; Knuutinen & Harjula, 1998; Liu et al., 2018
GUI in vessel EM system	Ready	Integrate a GUI into the EM system so that dockside observers and/or fishers could input data, including document ID numbers, names, nationalities, duration of fishing experience, and position on the vessel	Martinez, 2011
Hormone marker probe	R&D, testing	Probe to analyse hormones to determine sex	Devlin & Nagahama, 2002
Image analysis software to detect colour properties, luminance and sea state	Ready	Integrate software that automates measurements of the colour properties (e.g. the proportion of the sky that is blue vs. cloud-covered during daylight, the hue, value and chroma of bait to determine if it is dyed to prescription), luminance and sea state of EM imagery	Giusti et al., 2017; Schneider et al., 2012; Troscianko & Stevens, 2015
Image recognition software	R&D, testing	Existing software requires further development to detect all species susceptible to capture in tuna and other multispecies fisheries and to improve accuracy. Interim objectives of identifying when catch events occur, distinguishing between higher taxonomic groups, and generating a short list of species, are closer to being ready for implementation in multispecies fisheries. Beyond automated species recognition, software could identify unique individuals that are recaptured in a fishery (see Facial recognition software)	Andreotti et al., 2017; Bicknell et al., 2016; FishVerify, 2018; Kumar et al., 2012; MacLeod, 2008; Moya et al., 2015; Rossi et al., 2016; The Nature Conservancy, 2017; Zhuang et al., 2017
Integrate vessel radio into EM system, or make the EM system capable for use as a radio	R&D, testing	To enable EM analyst to determine what international safety radio frequencies were monitored	NA
Lunar phase	Ready	Integrate lunar phase database into EM system	e.g. Astronomical Applications Department, 2017; Gilman, Chaloupka, Peschon, et al., 2016
Lux meter	Ready	Automate measurements of illuminance during fishing operations, including lunation during night-time; sensor would need to be located where unaffected by deck lighting at night	International Organization for Standardization, 2014; PCE Instruments, 2018
Macro lens	Testing	Cameras with macro lenses are commercially available. Testing to determine accuracy for collection of various desired observer data fields is required	Davies, 2010
Mainline hauler hydraulic sensor	Ready	Integrate hydraulic sensor to detect when the line hauler is used	McElderry, 2008; McElderry et al., 2008, 2010; Piasente et al., 2012

(Continues)

TABLE 1 (Continued)

EM improvement method	Status	Notes	References
Mainline line shooter hydraulic sensor	Ready	Integrate hydraulic sensor to detect when the line shooter is used, and sensor to detect the line shooter setting speed	McElderry, 2008; McElderry et al., 2008, 2010; Piasente et al., 2012
Mixed-layer and thermocline depth satellite imagery	Ready	Integrate satellite data to estimate the depth of the mixed layer/top of the thermocline	Chassot et al., 2011; OCENS, 2018; ROFFS, 2018; SeaView, 2018
Radio buoy data	R&D, testing	Integrate radio buoy data into EM system	Beverly et al., 2003; Pacific Ocean Producers, 2018
RFID tag	Ready	Integrate RFID data into EM system, program EM software to automate generating daily retained catch logs, and data on fishers onboard, and transmit via satellite	*RFID Journal*, 2016; Savi Technologies, 2007; Theiss et al., 2005
Real-time alarm for distance from other vessels	R&D, testing	Integrate real-time regional AIS data and program EM software to trigger an alarm when the fishing vessel is within certain distance of another vessel	International Telecommunication Union, 2014; Kroodsma et al., 2018; Miller et al., 2018
Real-time alarm for spatial/temporal thresholds	Ready	Program EM software to create a geo-fence and, using VMS or GPS, trigger an alarm when a vessel enters a designed area and/or during a specified time period	LTFV, 2017, and see Vessel Monitoring Systems
Satellite buoy data	Ready	Obtain parallel data feed from satellite buoy service provider of unique ID and positional data for each buoy being tracked by the fishing vessel, and integrate into EM systems. Or "EM compatible" satellite buoys could be fully integrated into EM systems to enable data feeds directly from the satellite buoy to the EM system on all fishing and supply vessels that are tracking them. Identify if echo-sounder is attached to FAD.	Escalle et al., 2017; Gilman, Bigler et al., 2018; Santiago et al., 2017; Satlink, 2018
Sea surface concentration of chlorophyll-a satellite imagery	Ready	Integrate satellite imagery of sea surface concentration of chlorophyll-a into EM systems	Beverly, 2011; CATSAT, 2018; Chassot et al., 2011; OCENS, 2018; SeaView, 2018
Sea surface height satellite imagery	Ready	Integrate satellite altimetry data on sea surface height measurements, and on the speed and direction of surface currents, into EM systems	Beverly, 2011; CATSAT, 2018; Chassot et al., 2011; OCENS, 2018; ROFFS, 2018; SeaView, 2018
Sea surface temperature gauge	Ready	Integrate a thermistor, dedicated sensor or integrated into sonar transducer, into EM system	Beverly et al., 2003; WMJ Marine, 2018
Sea surface temperature satellite imagery	Ready	Integrate satellite imagery of sea surface temperature into EM systems	Beverly, 2011; CATSAT, 2018; Chassot et al., 2011; National Climatic Data Center, 2018;

(Continues)

TABLE 1 (Continued)

EM improvement method	Status	Notes	References
			OCENS, 2018; ROFFS, 2018; SeaView, 2018
Sensor on hatch of fish hold, or in the fish hold	Ready	Sensor indicates when fishers open the hatch, walk through the hatch (break beam alarm), or trigger a motion sensor in the fish hold. Integrate with EM system	EasylinkUK, 2018a, 2018b; Woznowski et al., 2016
Sensor to measure purse seine net depth	Ready	Linear measurement sensor such as acoustic transponders, camera-based bar code positioning system, laser length-measurement sensors, measuring wheels and tachometers, or sonar imagery, to measure maximum possible depth, and actual depth during individual sets	e.g. Kongsberg Maritime, 2013; SICK, 2018; Tenningen et al., 2015; Trumeter, 2018
Sensor to measure purse seine net headline length	Ready	Linear measurement sensor, such as acoustic transponders, camera-based bar code positioning system, laser length-measurement sensors, measuring wheels and tachometers, or sonar imagery, to measure maximum possible length and actual length during individual sets	e.g. Kongsberg Maritime, 2013; SICK, 2018; Tenningen et al., 2015; Trumeter, 2018
Sensors on vessel equipment that affect fishing efficiency	Ready	Integrate sensors on vessel equipment that affect fishing efficiency, such as technology aids for fish finding and equipment used for gear deployment and retrieval that affect effective fishing power, so that the EM system detects if the equipment was used during each set	e.g. Beverly et al., 2003; Torres-Irineo et al., 2014
Temperature sensor	Ready	Integrate a temperature sensor located in the fish hold, and an engine temperature sensor, into the EM system and program the EM system to trigger an alarm if the temperature in the hold exceeds a specified threshold.	Crowley et al., 2005; NauticExpo, 2018
Thermal or infrared IR night vision camera	Testing	Cameras are commercially available, including with visible image fusion (e.g., Forward-looking Infrared thermal imagery). Testing to determine accuracy is required, in particular for ectothermic species, organisms far from the vessel in the water, and for seabird scan counts within 137 m of a longline vessel.	Havens & Sharp, 2016; Jin et al., 2017; Musyl, 2018; Swann et al., 2004
Time–depth recorder (TDR)	R&D, testing	TDRs are commercially available. Need to adapt the design to enable the TDR to be incorporated into a pelagic longline branchline component that does not adversely affect crew ability to coil, store and deploy branchlines	Fedak et al., 2001; Star Oddi, 2017
Underwater camera	R&D, testing	Underwater cameras are commercially available, but new designs and housings, with suitable fields of view for desired applications for purse seine gear and drifting FADs require R&D and testing	e.g. CRISP, 2016; Sheehan et al., 2016; Simrad, 2013; Underwood et al., 2014
Vessel monitoring system (VMS)	Ready	Integrate into EM and program to issue alert when specified thresholds (e.g. vessel enters a specified area during a certain season) are exceeded. Integrate regional VMS database into EM system to detect when the fishing vessel comes within a threshold distance of another vessel, enabling detection of a transshipment receiving vessel information (e.g. unique ID, vessel name, flag state)	Beverly et al., 2003; Girard & Du Payrat, 2017; Indian Ocean Tuna Commission, 2016; Satlink, 2018

(Continues)

TABLE 1 (Continued)

EM improvement method	Status	Notes	References
Weight sensor, motion compensated	Ready	Integrate into EM system to automate recording of weight of all catch (retained and discarded) that are landed on deck	Girard & Du Payrat, 2017; Kennelly & Hager, 2018; SPC & FFA, 2017
Weight sensor, motion compensated, on crane	Ready	Integrate into EM system to automate recording of weight of transshipment	Girard & Du Payrat, 2017
Weight sensor, motion compensated, on in-line scale	Ready	Integrate into EM system to automate recording of weight of individual fish when landed on deck, or when being transshipped to another vessel	Girard & Du Payrat, 2017
Weight sensor, motion compensated, on purse seine brail winch	Ready	Integrate into EM system to automate recording of weight of brailed catch	Girard & Du Payrat, 2017

non-retained catch, identification and enumeration of seabirds to the species level during scan counts, life status (i.e. condition, alive, degree of injury, dead) of the catch and whether crew used specific fishing methods and equipment (Table S1) (AFMA, 2006, 2010, 2011, 2012; AFMA & Archipelago Marine Research, 2005; Arnande et al., 2012; Bartholomew et al., 2018; Briand et al., 2017; Chavence et al., 2013; Hosken, Vilia, et al., 2016; Larcombe et al., 2016; McElderry et al., 2008, 2010; Monteagudo et al., 2015; NMFS, 2018; Ruiz et al., 2013). EM collection of catch data with high precision compared with that collected by human observers is relatively more difficult in fisheries where very large volumes are landed simultaneously (e.g. trawl, purse seine) (e.g. Damrosch, 2017; Kennelly & Hager, 2018). Most of the candidate methods to improve EM systems to augment the accuracy of data that contemporary systems collect are also methods identified to enable EM to capture fields that contemporary EM systems are unable to collect but are collected by human observer programmes.

Of 123 observer data fields that are not possible to routinely collect by contemporary EM systems, expansions of EM functionalities were determined to be possible to resolve for all but two: collection of biological samples and determination of whether safety equipment meets requirements (Table S1). Of fields that are not possible to routinely collect by contemporary EM systems, 44 could be collected through pre-trip dockside inspections, including the adequacy of safety equipment (Table S1a). An additional 11 fields could be collected dockside, pre-trip, under certain circumstances (for vessels that do not re-provision gear or fishers at sea, and only for fish aggregating devices [FADs] deployed by the fishing vessel during that trip) (Table S1b). EM or conventional human observer coverage of transshipment events could enable collecting some fields with values that vary within a trip when vessels reprovision gear and crew at sea. Some fields on landed catch (species, sex, length, weight, tag data) could also be collected post-trip through port sampling and sales records. Of 56 methods identified to augment EM functionalities, 38 are ready now for integration into EM systems. The remaining 18 methods require research, development and testing (Table 1).

3.1.1 | Image recognition software

Image recognition software (Bicknell, Godley, Sheehan, Votier, & Witt, 2016; FishVerify, 2018; Kumar et al., 2012; MacLeod, 2008; The Nature Conservancy, 2017; Zhuang, Xing, Liu, Guo, & Qiao, 2017) could enable more efficient reviewing of EM imagery and possibly more accurate species identifications (Kennelly & Hager, 2018; Pierre, 2018). The ultimate aim is to use deep learning to fully automate species recognition of the catch. For instance, for some species, EM analysts may have difficulty differentiating between similar looking species when reviewing EM imagery, such as between juvenile bigeye (*Thunnus obesus*) and yellowfin tunas (*T. albacares*) caught in purse seine fisheries and between long-snouted (*Alepisaurus ferox*) and short-snouted lancetfish (*A. brevirostris*) caught in pelagic longline fisheries (Hosken, Vilia, et al., 2016). For these species, especially for less experienced analysts, image recognition software theoretically may be able to provide more accurate identifications. Image recognition software that can support accurate species-level identifications in multispecies fisheries may be several years hence, as the machine-learning process requires tens of thousands of images (Kennelly & Hager, 2018; Kumar et al., 2012). Image recognition software in the near term, however, may meet interim objectives. This includes automating the detection of when an organism is retrieved during gear haulback (i.e. a Boolean variable of catch/no catch) for gear types where catch events occur as singletons or small volumes. Another interim objective for automating the identification of the catch is to develop automated image recognition for high-level taxonomic groups to enable differentiating between seabirds, bony fishes, sharks, rays, marine mammals and sea turtles, and software that can identify categories of species within defined groups (e.g. classes of fish from cloud-based processing, Rossi et al., 2016). This latter function, in turn, could be combined with near real-time satellite data transmission of protected species interactions. Getting closer to fully automated species-level identification, software could automate the identification of a short list of likely species, where the analyst would then manually select the correct species, aided through the software providing sample images and descriptions of each of the short-listed species (e.g. Leafsnap, using leaf images to identify tree species; Kumar et al., 2012). And, going beyond fully automated species identification, programs similar to facial recognition software could be used within EM systems to identify individual organisms that are recaptured in a fishery (including endangered, threatened and protected [ETP] species) (Andreotti et al., 2017; Moya et al., 2015), to augment the understanding of post-release survival and population sizes, similar to mark and recapture studies.

3.1.2 | Thermal or infrared night-vision cameras

EM analysts are restricted to making a determination of the life status of the catch by reviewing EM imagery, whereas human at-sea observers can employ numerous additional techniques. The life status of the catch when retrieved during gear haulback, and when returned to the sea if not retained, for some captured organisms, may be even more difficult for EM analysts to estimate than it is for human onboard observers (Davis, 2002; Gilman, Suuronen, Hall, & Kennelly, 2013; Musyl et al., 2015; Musyl & Gilman, 2018). This is especially the case for smaller organisms and for caught organisms that are released in the water (Hosken, Vilia, et al., 2016; SPC & FFA, 2017). Thermal or infrared (IR) night-vision cameras (Havens & Sharp, 2016; Jin et al., 2017) may enable more accurate estimates for this data field for both endo- and ectothermic species (Musyl, 2018). Several studies have documented that it is possible to detect differences in temperature between the ambient sea surface temperature and the body core temperature of endothermic species but not of ectothermic species (Boye, Musyl, Brill, & Malte, 2009; Malte, Larsen, Musyl, & Brill, 2007; Musyl et al., 2003). In addition, research on the heat dissipation and warming rates in live and dead blue sharks (Carey & Gibson, 1987) suggests that it should also be possible theoretically to differentiate between live and dead endotherm fishes (Havens & Sharp, 2016).

Furthermore, thermal and IR night-vision cameras could enable detecting whether pelagic longline bait were frozen or partially or fully thawed during setting (which affects baited hook sink rate and affects seabird bycatch risk; Gilman & Hall, 2015), a field not possible to determine by contemporary EM systems. And, at night, seabird scan count estimates (the number of seabirds within a specified distance of the vessel), which is used to standardize effort in estimating seabird catch risk (Gilman, Boggs, & Brothers, 2003; Gilman, Chaloupka, Peschon, & Ellgen, 2016; Gilman & Hall, 2015), might be more accurate when using thermal or IR night-vision cameras (Swann, Hass, Dalton, & Wolf, 2004) than estimates made by onboard human observers using the naked eye and binoculars and by EM analysts viewing raw EM imagery using visible light. Thermal and IR cameras may be less effective for species identification than conventional colour visible-light cameras. One trial of an infrared camera found that it was more difficult to identify the species for some catch (e.g. to differentiate between blue *Prionace glauca* and thresher sharks *Alopias* spp.) due to IR imagery having low saturation (i.e. showing less colour/more grey scale) (Matthew Carnes, JIMAR, personal communication, 14 August 2018).

3.1.3 | Probes to analyse genetic markers, proteins, chemicals and hormones

Probes or scanners that analyse genetic markers, proteins, chemicals or hormones to determine the species and sex of the catch (Angers et al., 2017; Ashoor & Knox, 1985; Devlin & Nagahama, 2002; Hyde et al., 2005; Knuutinen & Harjula, 1998; Liu et al., 2018) could be developed and integrated into EM systems. Chromatography, various DNA-based analyses and protein-based analyses can be used to identify fish species (Angers et al., 2017; Ashoor & Knox, 1985; Clark, 2015; Galimberti et al., 2013; Knuutinen &Harjula, 1998). Depending on the species-specific sex determination system, analyses of hormones, proteins and genes could be used to determine the sex of the catch (Devlin & Nagahama, 2002; Liu et al., 2018). A probe could be used to detect the sex of species that lack sexual dimorphism with externally visible differences between sexes (e.g. claspers on male sharks and rays, sexual dimorphism in the pectoral girdle of older/larger opah *Lampris guttatus*, sexual dimorphism in the neurocranium of older/larger mahi mahi *Coryphaena hippurus*; Ditty, Shaw, Grimes, & Cope, 1994; Hawn, Seki, & Nishimoto, 2002; Jones et al., 2005) for which sex cannot be determined using contemporary EM systems. Probes may also enable more accurate estimates of the sex of the catch for species that do exhibit externally visible sexual dimorphism than estimated by EM analysts by reviewing imagery. However, see Section 4 for a potentially more practical and economical approach of using EM systems to audit fisher collection of these and other data fields.

3.1.4 | EM camera positions and lenses, deck lighting and crew cooperation

It may not be possible for EM analysts to determine whether a particular fishing method, gear component or equipment was used, such as various longline seabird bycatch mitigation methods (bird scaring *tori* line, side setting, etc.) when reviewing contemporary EM imagery (SPC & FFA, 2017). This could be resolved through better positioning of existing cameras or by adding cameras to ensure that the fishing method, gear and equipment are within the cameras' fields of view (e.g. Restrepo, Justel-Rubio, Koehler, & Ruiz, 2018). Using cameras with macro and wide-angle (up to 360° fisheye) lenses would also contribute to addressing this problem (Davies, 2010; Kumler & Bauer, 2000). Camera setup with appropriate lenses might enable EM detection of transshipment activities, sightings of ETP species, gear marking, and exchanges of satellite buoys attached to drifting FADs (Table S1). Adding cameras with wide-angle lenses up to 360°, correcting camera positions and adding additional cameras could also enable or improve the accuracy of seabird scan counts (discussed previously). Furthermore, optimally positioned cameras with suitable lenses could enable EM detection of purse seine main mesh size and the proportion of each type of longline gear component used in each set. This might also enable EM identification of longline terminal tackle (hook shape, hook size/minimum width, hook offset, bait type, leader material, leader length, branchline diameter, etc.) on which individual organisms are captured (Table S1).

A camera with a wide-angle lens, adjusting positions of existing cameras and adding additional cameras may also enable more accurate determinations of purse seine set type by EM analysts. EM analysts can determine tuna purse seine set type by assessing the time of day of the set, the vessel's movements detected from a display of satellite-based vessel monitoring system (VMS) 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 (Monteagudo et al., 2015; Restrepo et al., 2014).

In addition to adjusting camera positions, adding or adjusting deck lighting may also contribute to enabling EM analysts to view caught organisms and the gear on which they were caught that crew release in the water that are up to a branchline length away from the vessel during gear haulback at night (Figure 1). However, it may be problematic to have deck lighting reach areas where baited hooks become available to seabirds during gear haulback in fisheries that overlap with seabirds susceptible to capture (Brothers, Cooper, & Lokkeborg, 1999; Commission for the Conservation of Antarctic Marine Living Resources, 2016).

EM cameras and deck lighting should be able to be configured using existing technologies to detect any object that is reasonably visible from a point on the vessel. However, there is a limit to how many cameras an EM analyst can effectively review. Thus, in addition to optimizing the camera setup, simple modifications to crew practices can in some cases tremendously augment the ability of EM to collect certain data fields, such as where on deck they process retained and discard non-retained catch (Table S1; Figure 2). For instance, Briand et al. (2017) found that EM produced lower estimates of purse seine shark and billfishes catch rates than onboard human observers did. They hypothesized that, because these species are handled by crew at different parts of the vessel, the EM systems may not enable the

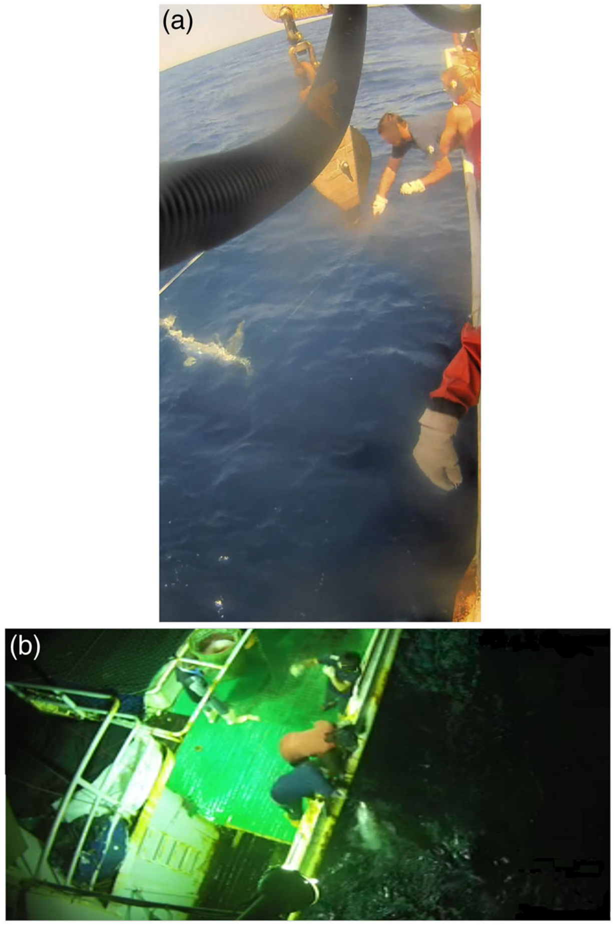

FIGURE 1 Examples of the fields of view of cameras on pelagic longline vessels showing the outboard side of the rail off the hauling station. When the camera view covers a portion of the area where catch may be released in the water, it is possible for the electronic monitoring analyst to identify the species only when crew bring the catch within this field of view (a, b), and during night-time hauling if the catch is within the area covered by deck lighting (b). (a) Courtesy of National Marine Fisheries Service, Greater Atlantic Regional Fisheries Office, Highly Migratory Species Management Division. (b) Courtesy of Luen Thai Fishing Venture, Ltd)

EM analyst to view their retrieval due to camera distance or fields of view not covering those areas. This could potentially be resolved through improvements in camera installations, as well as through crew assistance. For example, when practical (e.g. when purse seine brail sizes are sufficiently small, when deck space is adequate), crew could empty the catch from the brail into a hopper tray to enable EM analysts to identify the species and measure the length of the catch, instead of crew transferring the fish directly from the brail to the lower well deck.

The ability of EM systems to collect many observer data fields is dependent, in part, and in some cases entirely, on the setup of the EM cameras and/or on crew cooperation (Table S1). For 70% of the data fields in Table S1, frequent EM analyst collection would be supported through camera positioning and/or crew cooperation. For example, the camera setup determines whether EM analysts can

FIGURE 2 Crew cooperation is necessary to make some electronic monitoring (EM) data collection possible, including (a) when separating bycatch—in this case on a purse seine conveyor belt-crew can display the ventral side of adult sharks to enable EM analysts to detect the presence or absence of claspers to determine the sex of the fish, and (b) crew can wipe camera lenses when obstructed. (b) Courtesy of Programme Observateur de la Nouvelle-Calédonie

observe all areas, on deck and in the water, where crew handle and release non-retained catch. And crew compliance with certain protocols (requested or legally required), such as discarding catch that are landed on deck from designated areas of the vessel and placing scale-readout displays within an EM camera field of view, determines whether EM analysts can observe these fields. For example, for species with sexual dimorphism of external features, crew cooperation is needed to clearly display these features within the camera field of view so that EM analysts can detect them (Figure 2). This type of crew cooperation is required to resolve the low precision in estimates made by human observers versus by EM analysts of the sex of sharks (Hosken, Vilia, et al., 2016) and other species.

The species, length and sex (for species with distinguishing external anatomical features) of a longline-caught organism may not be possible for EM analysts to determine if the image of the organism is obstructed or not clear, especially if the organism is not landed (i.e. released in the water) and the field of view of the camera showing the area off the hauling station is limited or has partial coverage by deck lighting (Figure 1; Table S1; Larcombe et al., 2016; McElderry et al., 2008, 2010; Piasente et al., 2012). A comparison of catch data collected by human onboard observers and EM in the Hawaii longline fishery found that EM detected only 45% of caught sharks (NMFS, 2018). These missed shark catch events were likely due to crew releasing sharks in the water, where EM analysts were able to detect that a catch event occurred, and in some cases that a shark was caught, but could not definitively identify the species of the catch, in some cases because the shark was outside of the camera field of view (NMFS, 2018; WCPFC, 2018a).

Several additional observer data fields are difficult to collect for organisms that are released in the water, including anatomical hooking position and life status of the catch. As is often the case for human observers, the catch may not be visible to EM analysts when gear haulback is at night and crew release catch in the water by cutting or dropping a branchline with the catch far from the vessel's fish door, outside of the field of view of the camera covering the hauling station (Figure 1). This is especially likely to occur if the catch is directly behind the vessel and outside of deck lighting (Table S1). Cooperation of the crew to follow procedures (e.g. bringing the catch close to the fish door, when safe and if this will not increase injury to the catch; Figure 1) that enable clear camera views of catch released in the water could reduce the occurrence of these problems. Adjusting deck lighting for night-time gear haulback and camera positions (e.g. to have a dedicated camera on the outboard side of the rail near the hauling station so that catch that are release when crew cut a branchline are more likely to be within the field of view) would enable EM analysts to be more likely to detect catch events in these situations (discussed earlier and in Table S1).

3.1.5 | Digital length-measurement tools

Improvements to digital length-measurement tools (Archipelago Marine Research, 2018; Huang, Hwang, & Rose, 2016; Satlink, 2016;

Wallace, Williams, Towler, & McGauley, 2015; White, Svellingen, & Strachen, 2006) have been identified as a priority, in particular for species with smaller mean lengths (Hosken, Vilia, et al., 2016). Length measurement tools could provide adequate precision and accuracy of length estimates made with cameras with macro lenses, such as for the wire diameter of a hook, line diameter, and bait length in longline fisheries, and for purse seine net mesh size, using fixed boards and measuring points designed to measure relatively small dimensions.

3.1.6 | E-tagged floatlines and branchlines, and radio-frequency identification tags

Estimates of the hook number of individual catch events (on which hook between two pelagic longline floats an organism was captured), both by human observers and EM analysts, are likely highly inaccurate. Both onboard human observers and EM analysts may lose count of the hook number, especially for baskets with more than 10 hooks between floats (Hosken, Vilia, et al., 2016). Onboard observers make rough estimates of hook number, where, except for hooks close to floats, estimates are likely to be of low certainty in sets with a relatively large number of hooks between floats. EM analysts in some programmes count hooks between floats in order to determine the hook number of the catch, which likely results in more accurate estimates of hook number than estimates made by human onboard observers. But this protocol makes EM data reviewing extremely inefficient and expensive (Hosken, Vilia, et al., 2016). EM systems could enable automating the collection of this data field, where the time of day of retrieval of each float and of each captured organism could be used to estimate hook number (Hosken, Vilia, et al., 2016; Williams, 2017). This could be accomplished by electronic tagging floatlines with automated recording by the EM system of the time when floats are retrieved.

Radio-frequency identification (RFID) tags could be used to e-tag the floatlines (*RFID Journal*, n.d.; Savi Technologies, 2007; Theiss, Yen, & Ku, 2005). RFID tags have been used in some government EM fishery programmes to assign a unique ID to pots to monitor compliance with input controls (Course, Pasco, O'Brien, & Addison, 2015; EcoTrust, 2015; McElderry, 2008; Northwest Indian Fisheries Commission, 2015; Quinault Indian Nation, 2015). RFID tags have also been tested for identifying the ownership of fishing gear (Brickett & Moffat, 2004; La Velley, Brickett, & Moffat, 2010; Patton & Cromhout, 2011).

When combined with data on the time of the haulback of each captured organism, either recorded manually by EM analysts or otherwise from also e-tagging branchlines to automate collecting date/time and hook number data for each hauled branchline, data reviewing software could be programmed to use these data to determine the hook number of each capture event (Williams, 2017). E-tagging individual branchlines would also enable precise counts of hooks between floats within sets.

There are several potential sources of error in estimates using an automated method to estimate hook number if individual branchlines are not e-tagged. For instance, crew may have variable branchline setting rates, and fishers will periodically halt the haulback temporarily (e.g. to fix a tangle, when crew are not keeping up with coiling). Also, branchlines can tangle with fish hooked and/or tangled in the line, and it can be difficult to estimate hook number for catch on untended lines (when crew temporarily attach a branchline to the vessel rail while busy dealing with something else, such as processing catch on deck). However, the small error introduced from automating the EM data reviewing for this field with manual EM analyst recording of the time of branchline retrieval would likely be much smaller than the uncertainty of estimates by onboard observers.

3.1.7 | VMS and automated identification systems

EM systems integrated with data from satellite-based VMS and automated identification systems (AIS) (Beverly, Chapman, & Sokimi, 2003; Girard & Du Payrat, 2017; Indian Ocean Tuna Commission, 2016; International Telecommunication Union, 2014; Satlink, 2018) enable determining the vessel speed when setting. EM systems could be programmed to use information on vessel speed to estimate whether a purse seine set was on a free-swimming school versus an aggregation at a drifting or anchored floating object. Integrating regional VMS and AIS datasets could enable EM systems to automate the detection of other vessels that come within a certain threshold distance of the fishing vessel and obtain information on these other vessels (e.g. vessel unique ID, name, flag state).

3.1.8 | Colour sensor for blue-dyed bait

A colour sensor (e.g. spectrophotometers and spectroradiometers; Gomez-Robledo et al., 2013; Gongal, Amatya, Karkee, Zhang, & Lewis, 2015; Sikri, 2010) could be integrated into the EM system to determine if bait was dyed to the prescribed hue, value and chroma prior to setting in pelagic longline gear, for fisheries where blue-dyed bait is prescribed or used voluntarily.

3.1.9 | Radio

The vessel radio could be integrated into the EM system, or the EM system could be designed to be used as a radio to enable EM analysts to determine what international safety radio frequencies were monitored.

3.1.10 | Sensors to detect use of equipment that affect fishing efficiency

Sensors installed on vessel equipment that affect fishing efficiency, such as technology aids for fish finding (e.g. sonar to detect the deep scattering layer) and equipment used for gear deployment and retrieval that affect effective fishing power (Beverly et al., 2003; Torres-Irineo, Gaertner, Chassot, & Dreyfus-Leon, 2014) could be integrated into the EM system to enable detecting whether the equipment was used during each set. Some EM systems already include sensors on some equipment that affect fishing efficiency, such as an optical sensor on purse seine winches, a rotation sensor on longline mainline drums and purse seine conveyor belt drums, and hydraulic pressure sensors on longline line shooters and line haulers (used to detect when setting and hauling are occurring and trigger camera recording; AFMA, 2015; McElderry, 2008; Piasente et al., 2012; Restrepo et al., 2018). Other fields that are frequently but not always able to be collected by contemporary EM systems could have data collection automated by integrating the following additional sensors: hydraulic pressure and magnetic sensors to detect the use of pelagic longline automatic branchline coilers, bait caster machines, and mainline shooters and haulers, and a sensor to detect the speed of a mainline shooter (McElderry, 2008; McElderry et al., 2008, 2010; Piasente et al., 2012) (Table S1).

3.1.11 | Weight sensors

Weight sensors could be added to purse seine brail winches and integrated into EM systems to estimate individual brail weights and the total catch (Restrepo et al., 2014; SPC & FFA, 2017). Similarly, contemporary EM systems cannot estimate the weight of transshipped catch. This could be resolved by adding a weight sensor on cranes or on an in-line scale that could be integrated into the EM system (Restrepo et al., 2014; SPC & FFA, 2017).

3.1.12 | Equipment to estimate net dimensions

Some tuna purse seine vessels use sonar imagery to view the three-dimensional shape of the net during setting, which could be integrated into the EM system. To detect the maximum possible dimensions (length and depth) of tuna purse seine nets, and actual dimensions during individual sets, a sensor to measure the depth and headline length, such as a camera-based barcode positioning system, laser length measurement sensor (SICK, 2018), measuring wheels, and tachometers (Trumeter, 2018) could be incorporated. For example, sonar imagery and positional data from acoustic transponders have been used to estimate the dimensions of small pelagics purse seine nets (Kongsberg Maritime, 2013; Tenningen, Pena, & Macaulay, 2015). Time–depth recorders or temperature–depth recorders (TDRs; e.g. Fedak, Lovell, & Grant, 2001; Star Oddi, 2017) could be installed on the purse seine and downloaded at the end of each set to obtain the depth profile. Underwater cameras could also enable monitoring of the dimensions of the purse seine during setting (e.g. CRISP, 2016; Sheehan et al., 2016; Simrad, 2013; Underwood, Rosen, Engas, & Eriksen, 2014). For example, underwater cameras are being developed to enable real-time monitoring of catch in trawl codends (Simrad, 2013) and as catch pass through trawls (CRISP, 2016; Underwood et al., 2014). To achieve the desired applications for tuna purse seine fisheries, underwater cameras would need to be developed that enable a much larger field of view than devices developed for use in trawls, with long-term trials to determine the amount of maintenance required for ongoing use.

3.1.13 | Equipment, software and databases to collect data on vessels, vessel equipment and fishers

For data fields on vessel characteristics and equipment, and on the captain and crew, such as ID numbers, names, nationalities, duration of fishing experience, position on the vessel and the number of crew onboard during a trip, an electronic reporting (ER) device (tablet, iPad, iPhone, computer; e.g. NMFS, n.d.-b; WCPFC, 2018b), could be integrated into the EM system. Alternatively, the EM system could include a graphical user interface (GUI) (e.g. Martinez, 2011) that enables fishers and dockside observers to input these data. Another option is that each fisher could be assigned a two-dimensional matrix Quick Response (QR) code or an RFID that is programmed with these data, and a QR or RFID reader on the vessel could be integrated into the EM system. Alternatively, EM systems could collect the fields on the captain and crew if a record of all fishers was created and facial recognition software was integrated into EM systems to enable those systems to detect each unique fisher that comes within a camera field of view during a trip, and link to their record, in which case privacy issues would need to be carefully addressed. Integration of ER and EM systems could also enable the EM analyst to audit logbook data to determine if the captain recorded individual events (e.g. ETP capture event, transshipment event) on logsheets that were detected by the EM analysts. This would also enable the EM analyst to identify any events recorded on logsheets that were not detected by the EM analyst. Integrating a database of fishing vessels (e.g. FAO, 2018a; WCPFC, 2018a) into the EM system, so that when a vessel's unique ID is input into the EM system (through linking the EM system with ER, input using a (GUI), or established when the EM system is installed on the vessel) the EM system automates populating fields on the vessel characteristics (e.g. vessel name, owner, length, weight, fish hold capacity, engine power, flag state) and equipment that remains relatively static (i.e. not likely change over multiple years, such as refrigeration method, helicopter range, skiff horsepower). These fields would be automatically updated when the record for that vessel in the vessel database is updated (Restrepo et al., 2014).

3.1.14 | Equipment, software and databases to collect environmental variables

A sea surface temperature gauge (thermistor, dedicated sensor or integrated into sonar transducer), acoustic doppler current profiler (to measure current speed and direction over a depth range), lux meter (to measure illuminance, an indicator of cloud coverage during the day, and at night provides an indication of lunar illumination, cloud coverage and deck lighting), anemometer to measure wind velocity, and bathythermograph (to identify the depth of the thermocline, using data on the distribution of temperature by depth) (Beverly et al., 2003; International Organization for Standardization, 2014; NauticExpo, 2018; PCE Instruments, 2018; WMJ Marine, 2018) could be integrated into EM systems to automate recording of these environmental variables. Software that measures colour properties of an image (e.g. the proportion of the sky that is blue vs. cloud covered during daylight; the hue, value and chroma of bait to determine if it is dyed to prescription), software that automates estimates of luminance of an image, and software that automates estimates of sea state (Giusti, Wrolstad, & Smith, 2017; Schneider, Rasband, & Eliceiri, 2012; Troscianko & Stevens, 2015) could be integrated into EM reviewing software. Environmental data from satellite imagery and other databases, and through satellite imagery service providers, such as for sea surface concentration of chlorophyll-*a*, lunar phase, sea surface temperature, sea surface height, depth of the mixed layer and thermocline, and speed and direction of surface currents (Astronomical Applications Department, 2017; Beverly, 2011; CATSAT, 2018; Chassot et al., 2011; Gilman, Chaloupka, Merrifield, et al., 2016; National Climatic Data Center, 2018; Ocean and Coastal Environmental Sensing [OCENS], 2018; ROFFS, 2018; SeaView, 2018) could also be integrated into EM systems. This could be done post-trip when being analysed by the EM analyst, or in real time during the trip so that the information could be used for near-real-time dynamic spatial management. Some of the data fields can be collected by analysts reviewing EM imagery, such as illumination. However, integrating these sensors, software and satellite imagery databases into the EM system would enable automating the measurements of these environmental variables to produce more efficient reviewing, and more accurate estimates than produced by the EM analyst viewing EM imagery.

3.2 | Methods for EM collection of new data fields prioritized by scientists and managers

3.2.1 | Underwater cameras and echo-sounder buoys to collect data fields on drifting FADs and aggregations at FADs

Pre-trip dockside recording of information on drifting 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 drifting FAD components at sea (Gilman, Bigler et al., 2018). When a tuna purse seine vessel makes a set on a drifting or anchored FAD, it is possible for observers (both human observers onboard and analysts reviewing EM imagery) to view submerged components only when the FAD is lifted out of the water. As discussed earlier, in addition to monitoring the dimensions of the purse seine during setting, underwater cameras could enable collecting information on the dimensions, design and materials of the FAD appendage (e.g. depth of the appendage, whether synthetic or biodegradable materials are used, whether the design is entangling, less entangling or non-entangling), detect fields (number and length of catch by species) of capture events in the FAD appendage, and determine the dimensions, design and materials of submerged rafts used for some FADs. Furthermore, underwater cameras could be integrated with satellite buoys attached to drifting and anchored FADs to provide real-time information on the biomass, species composition and length frequency distribution of the aggregation, if the field of view and resolution were adequate. Improvements in echo-sounder buoy technology could also provide information on the species composition of aggregations at FADs. Current echo-sounder buoys provide rough estimates of the biomass aggregated at FADs, but not accurate estimates of the species composition (Lopez, Moreno, Boyra, & Dagorn, 2016; Lopez, Moreno, Sancristobal, & Murua, 2014).

3.2.2 | TDRs to collect longline fishing depth and hook sink rates

EM systems may be augmented to collect information on the depth range and sink rate of pelagic longline hooks between floats. Information on pelagic longline baited hook sink rate over the upper ~ 0.5 m of the water column is used to determine the catch risk of seabirds with relatively limited diving capacity. Sink rate information over deeper depths (to ~30 m) is used to estimate the capture risk of deeper diving species as well as the risk of 'secondary' interactions, where small species of deep-diving seabirds retrieve baited hooks from depths and return them to the surface where larger species of seabirds with poorer diving capabilities can become hooked (Agreement on the Conservation of Albatrosses and Petrels, 2017; Gilman & Hall, 2015). EM systems may be able to collect sink rates if integrated with TDRs (discussed previously). TDRs would need to be developed that can be incorporated into a pelagic longline branchline component, such as a weighted swivel or clip, so that deployment does not rely on a change in crew behaviour for building, storing, deploying and retrieving gear. A TDR reader would need to be developed that scans and downloads data from TDRs during gear haulback without being impractical for fishers. The TDR unique ID could identify the hook number on which the TDR is attached. Finally, EM software could be developed to calculate various statistics, such as the mean depth, maximum depth, depth where the hook spent the maximum proportion of time and sink rate over different depths during the gear soak of individual sets, and across sets within a trip.

3.2.3 | EM software time stamps to collect longline branchline coiling times

EM reviewing software could be designed to support having analysts record the time taken by crew to coil pelagic longline branchlines during gear haulback. This could be conducted by analysts by time stamping when branchlines are unclipped from the mainline and when the crew complete retrieving the branchline. This variable may significantly explain seabird catch risk during gear retrieval (Gilman & Musyl, 2017).

3.2.4 | Integrating satellite buoy data into EM systems to collect satellite buoy unique IDs

EM systems could be designed to capture the unique IDs of all satellite buoys attached to drifting FADs being tracked by a tuna purse seine vessel, this in addition to the unique ID of satellite buoys attached to FADs on which a vessel makes a set (Gilman, Bigler et al., 2018). These data could be collected remotely, through parallel feeds from satellite buoy service providers (Escalle, Brouwer, Phillips, Pilling, & PNA, 2017; Gilman, Bigler et al., 2018; Santiago, Murua, Lopez, & Krug, 2017) integrated into the EM system. As with external databases of regional environmental data, the satellite buoy datasets could be pooled post-trip with the EM dataset during reviewing. Alternatively, 'EM-compatible' satellite buoys could be fully integrated into EM systems to enable data feeds directly from the satellite buoy to the EM system on all fishing and supply vessels that are tracking the satellite buoys. The satellite buoy data could include information on whether an echo sounder is attached to the FAD and other FAD instrumentation. Radio buoys and self-call buoys (e.g. Beverly et al., 2003; Pacific Ocean Producers, 2018) are largely no longer used by tuna purse seine vessels (Gilman, Bigler et al., 2018). However, for vessels still using them, it might be possible to integrate radio buoy data into EM systems.

3.2.5 | E-tagged drifting FADs to collect data on individual FADs

With electronically tagged drifting FADs, the unique ID of the FAD could be read and transmitted by an attached satellite buoy. These data could be integrated into EM systems of the vessel that is tracking the satellite buoy. This would enable tracking the history of fishing companies successively exchanging satellite buoys on individual drifting FADs, and the spatial location of the FAD during its lifetime (Gilman, Bigler et al., 2018). As with data on the unique IDs of satellite buoys, data on the unique ID of drifting FADs could also be remotely accessed, through parallel feeds from satellite buoy service providers or from EM-compatible satellite buoys.

3.3 | Methods for EM collection of new data fields prioritized by industry

There are many existing and potential new EM applications that could generate information of interest to catch-sector companies. Luen Thai Fishing Venture (LTFV), a company that owns and manages pelagic longline vessels that are based in small island developing states in the Pacific, developed and is using video cameras and sensors for various company applications. This provides a starting point to identify applications that could be supported by EM systems that are of interest to fishing companies. These applications illustrate the types of information that potentially could be obtained by expanding the functionalities of currently used government EM systems. Many of these industry-desired functionalities could not be practically obtained through human onboard observers.

3.3.1 | Real-time satellite-based data transfer to monitor activities on the vessel

The LTFV equipment includes three digital video cameras that allow the company to monitor activities on deck, including to detect if/when the captain and crew tranship catch at sea in violation of company policy and government licence terms (LTFV, 2017). The equipment is designed to enable remote, real-time video monitoring via satellite-based data transfer, but LTFV is not currently using this feature due to the high cost of data transmissions through satellite providers (around US$8 per megabyte). Instead, staff review samples of video after the completion of trips (Garland Shen, LTFV, personal communication, 13 July 2018). Thus, a technological improvement priority may be to reduce the cost for satellite data transfers, perhaps through improvements in compressing the digital imagery files (Lohar et al., 2018; Xiao et al., 2018).

In addition to enabling industry management to monitor activities on deck, captains also might find it useful to monitor certain areas of the vessel from the wheel house. For instance, many existing EM systems have cameras installed in areas of interest to the captain, such as in the engine room (Kennelly & Hager, 2018; McElderry et al., 2010).

3.3.2 | VMS and AIS to monitor real-time vessel position within restricted areas

LTFV uses satellite-based VMS and AIS to alert fishers as well as fleet managers in real time through an alarm that is triggered when a vessel enters designated areas during periods when they are closed to fishing, or fishing grounds where catch does not qualify for Marine Stewardship Council certification (LTFV, 2017). The VMS and AIS systems are not integrated with the video monitoring system, but could be fully integrated, as some EM systems have geofencing capabilities.

3.3.3 | Temperature sensors to monitor fish hold and engine temperature thresholds

LTFV's monitoring equipment includes a temperature sensor in the fish hold, where the system is programmed to provide emergency warnings if the temperature exceeds a threshold. This is similar to remote temperature monitoring systems in use in other fisheries sectors (e.g. shellfish trawl fisheries; Crowley et al., 2005). Integrating engine temperature sensors (e.g. NauticExpo, 2018) into EM systems may also be of interest to skippers and fleet managers.

3.3.4 | RFID tags to monitor retained catch

LTFV's monitoring equipment includes an RFID system, providing daily summaries to the company's management staff on the retained catch by each vessel during a fishing trip—information that supports the work of their marketing and sales teams. When a species of tuna is landed onboard and will be retained, the crew record on an RFID tag information on the vessel name, species, weight, vessel position when the fish was hauled aboard, and date and time when the fish was hauled aboard and affix the RFID tag to each tuna. The LTFV system uses the RFID data to generate a daily catch logbook (using the SPC/FFA regional longline logsheet form), which is transmitted via satellite (LTFV, 2017). The RFID retained-catch data could similarly be integrated into an EM system and transmitted via satellite-based data transfer.

3.3.5 | Regional AIS data to detect proximity to another vessel

Also of interest to fisheries management authorities, the LTFV system uses regional AIS data to trigger an alarm when the fishing vessel is less than 20 m from another vessel while at sea (see methods for using AIS data to detect when fishing and transshipment vessels come within a threshold proximity; Kroodsma et al., 2018; Miller, Roan, Hochberg, Amos, & Kroodsma, 2018). This may indicate that the vessel is about to transship catch at sea (which may violate company policy and government licence terms) or conduct other illicit activities. Once alerted, vessel managers can review video, in real time if the system has this functionality, or otherwise post-trip, to determine whether the vessels came alongside and what activities occurred while alongside. However, the function is disabled if one of the vessels turns off their AIS or does not have an AIS device. Vessels larger than 300 gross tons (longer than ~37 m) that make international voyages are required by the International Maritime Organization to carry and operate an AIS device, and the EU, the USA and other countries have adopted more restrictive rules (International Maritime Organization, 2002; Kroodsma et al., 2018; McCauley et al., 2016). Also, theoretically, for all vessels with EM systems, it would be feasible to detect when two vessels come within a threshold distance from each other using positional data.

3.3.6 | Sensors to detect when crew enter the fish hold

EM systems, and industry monitoring systems, could include a sensor on the hatch to the fish hold or in the fish hold to detect during a fishing trip, again in near real time via satellite data transmission, when fishers open the hatch, walk through the hatch (break beam alarm) or trigger a motion sensor in the fish hold (EasylinkUK, 2018a, 2018b; Woznowski, Kaleshi, Oikonomou, & Craddock, 2016). This may indicate that catch is being transshipped which vessel managers could investigate through review of imagery. However, because crew frequently open the hatch to the fish hold to conduct routine operations, most obviously when fish are caught during gear haulback, but also to transfer fish from the quick-freezing compartment, investigating each incidence of the hatch being opened may be inefficient (Garland Shen, LTFV, personal communication, 13 July 2018).

3.3.7 | Biosensors to monitor fish quality in the hold

Biosensors could be added to the fish hold and integrated with industry monitoring systems and/or EM systems to provide near-real-time monitoring of fish quality. Sensors located in the hold could detect levels of certain gases ('electronic nose') and of pathogen- and toxin-related compounds in liquids ('electronic tongue') that are indicators of the degree of freshness/spoilage of the catch for vessels that supply fresh chilled seafood (Ólafsdóttir & Kristbergsson, 2006; Thakur & Ragavan, 2013; Venugopal, 2002; Winquist, 2015).

4 | DISCUSSION AND CONCLUSIONS

In the near future, EM systems could be improved to a point where they collect most data fields of some pelagic longline and tuna purse seine human observer programmes, and with similar precision (Table S1; Emery et al., 2018). Currently, EM may be less expensive than human onboard observer programmes only in fisheries with very narrow conditions of having relatively high levels of fishing effort, high observer coverage rates, a small proportion of EM data sampled, and a large number of vessels with broad fishing grounds (Larcombe et al., 2016; Piasente et al., 2012; Sylvia et al., 2016). In several years hence, if technology enables increasingly automated processing and review of EM imagery and other data, EM systems may become vastly more efficient, and concomitantly much less expensive, than a much broader range of conventional human observer programmes, making EM suitable for mass uptake to substantially supplement or supplant human observer programmes (Kennelly & Hager, 2018; Kumar et al., 2012). EM functionalities could be vastly expanded to collect additional data fields, helping to meet the expanding data requirements of fisheries monitoring programmes as management authorities begin or continue to transition to implementing elements of ecosystem-based fisheries management (Gilman et al., 2014, 2017; Pitcher et al., 2009).

A next step is to prioritize which candidate methods to pursue to expand EM functionalities to collect additional data fields and improve accuracy. There are several criteria that can inform this prioritization process:

1. The relative importance for meeting defined objectives of research, management and industry applications of individual domestic and regional fisheries monitoring programmes.
2. Whether other monitoring approaches could collect priority data fields more cost-effectively and with similar levels of accuracy as expanded EM systems. Integrated monitoring could entail various combinations of EM and conventional at-sea observer coverage, pre-trip dockside inspections, fisher collection with EM auditing of prescribed data collection protocols, EM or human observer coverage of at-sea transshipment and activities of supply vessels, and post-trip data collection from port sampling and sales records of landed catch. Integrated monitoring could also employ an audit model, described in Section 1, where a random subset of EM data is reviewed to validate logbook data (AFMA, 2012; Larcombe et al., 2016; Stanley, McElderry, Mawani, & Koolman, 2011; Stanley, Olsen, & Fedoruk, 2009), or where vessels are required to retain certain species of fish, monitored by port sampling, with EM used to verify compliance with the full retention requirement (maximum retention model; Kennelly & Hager, 2018).

3. The impacts of the method on fishing operations and crew safety. For instance, requiring crew to bring catch that they plan to release in the water near the fish door, so that it is within a camera field of view, might increase the risk of having fly-backs of pelagic longline branchline weights hit crew when a shark severs the leader. And, for instance, prescribing a deck position where all discarding must occur, again to ensure that the activity is captured by a camera, may be impractical for crew.
4. Costs for any required research, development and testing, for the initial outlay and maintenance of new equipment, for storing additional imagery and sensor data, and for EM analysts to review additional EM data.
5. Whether integration of the new method would automate some of the EM data analyses, increasing EM data reviewing efficiency and thus reducing EM operational costs.

Achieving the political will and capacity to transition to EM may be strengthened given the support of the catch sector and other seafood supply chain companies. Seafood sector support for EM, in turn, would be strengthened if EM delivered industry-desired information that benefited their fishing, processing, sales and marketing operations (e.g. McElderry, 2008; Michelin et al., 2018). EM may also reduce a fishing company's insurance premiums and support processing insurance claims (NMFS, 2017b). These potential industry benefits may provide an incentive for vessel owners and fleet managers to have their fishers comply with procedures that are necessary for effective EM data collection (Figure 2). Benefits to seafood companies from EM applications might offset costs to industry from EM systems that are in excess of industry costs for conventional human observer programmes.

Logbook data, self-reported by fishers, can be significantly different from data collected by EM and human observers (Brown, 2001; Legorburu et al., 2018; Gilman, Bigler et al., 2018; Walsh et al., 2002; 2005). Fishers could be tasked as part of an EM programme to collect data, such as to record the contents of tags attached to catch that will be released alive, retain tags attached to catch that will be retained or dead catch that will be discarded, and collect tissue samples (otoliths and other fish hard parts, stomachs, gonads). EM systems could be used to audit fisher compliance with data collection methods in order to achieve a level of precision similar to that of data collected by at-sea human observers (McElderry, 2008). As is the case for data collection by onboard human observers, fisher cooperation is also required for many existing as well as candidate new EM data collection methods. In some cases, simple modifications to crew practices can tremendously augment the ability of EM to collect certain data fields (Table S1; Figure 2). For example, existing EM systems rely on crew to periodically wipe condensation from camera lenses. It is necessary for crew to display within EM camera view the relevant body part of species that exhibit externally visible sexual dimorphism (Figure 2), and to discard catch only from positions on deck that are within EM cameras' fields of view. For catch that will be retained, where the sex cannot be determined through external visual inspection, fishers could be required to dissect and display the gonads within an EM camera field of view, enabling EM analysts to determine the sex and gonad stage. EM systems, therefore, are not wholly passive but require active support from fishers. Legal and regulatory frameworks that require fisher actions needed to implement certain EM data collection methods, in combination with effective enforcement and outcomes (penalties and sanctions) resulting from enforcement actions when infractions are identified, may be needed to ensure adequate fisher compliance. Using EM to audit fisher cooperation and data collection might be more cost effective and practical than augmenting EM systems to collect some fields, such as determining the sex and species of the catch by integrating into the EM system a probe that conducts genetic, protein, chemical and hormone analyses.

Observer coverage rates remain at very low levels in most marine capture fisheries. For instance, 47 of 68 fisheries that catch marine resources managed by regional fisheries management organizations have no observer coverage (Gilman et al., 2014). To avoid statistical sampling bias, the necessary observer coverage rate, as well as data collection fields and methods, for a fishery depend on: (a) the objectives of analysis, including required levels of accuracy and precision of catch rates, and (b) aspects of each individual fishery—such as how many vessel classes exist, how many ports are used, 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 (Davies & Reynolds, 2002; Gilman & Hall, 2015; Hall, 1999). In general, 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 (Arnande et al., 2012; Hall, 1999; Lawson, 2006; Lennert-Cody, 2001). 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) (Bravington et al., 2003).

We can be cautiously optimistic that EM technology will incrementally be suitable for use on the world's 4.6 million fishing vessels (FAO, 2018b; Michelin et al., 2018), from artisanal, small-scale fisheries 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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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of the article.

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