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Electronic monitoring in fisheries: Lessons from global experiences and future opportunities

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Abstract

Since the beginning of the 21st century, electronic monitoring (EM) has emerged as a cost-efficient supplement to existing catch monitoring programmes in fisheries. An EM system consists of various activity sensors and cameras positioned on vessels to remotely record fishing activity and catches. The first objective of this review was to describe the state of play of EM in fisheries worldwide and to present the insights gained on this technology based on 100 EM trials and 12 fully implemented programmes. Despite its advantages, and its global use for monitoring, progresses in implementation in some important fishing regions are slow. Within this context, the second objective was to discuss more specifically the European experiences gained through 16 trials. Findings show that the three major benefits of EM were as follows: (a) cost-efficiency, (b) the potential to provide more representative coverage of the fleet than any observer programme and (c) the enhanced registration of fishing activity and location. Electronic monitoring can incentivize better compliance and discard reduction, but the fishing managers and industry are often reluctant to its uptake. Improved understanding of the fisher's concerns, for example intrusion of privacy, liability and costs, and better exploration of EM benefits, for example increased traceability, sustainability claims and market access, may enhance implementation on a larger scale. In conclusion, EM as a monitoring tool embodies various solid strengths that are not diminished by its weaknesses. Electronic monitoring has the opportunity to be a powerful tool in the future monitoring of fisheries, particularly when integrated within existing monitoring programmes.

Aloysius van Helmond and Lars O. Mortensen contributed equally to this work.

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catch documentation, discard monitoring, electronic monitoring, fully documented fisheries, video-based monitoring

1 | INTRODUCTION

Historically, fishing has largely been an unregulated industry, with fishers operating as independent explorers of the sea (Johnsen, Holm, Sinclair, & Bavington, 2009; Stevenson & Oxman, 1974). It was primarily governed by affective relations, often in local fishing communities (Johnsen et al., 2009). However, over the course of the 20th century, awareness of the impact of fishing on marine resources has grown, resulting in an increase in rules and regulations (Botsford, Castilla, & Peterson, 1997; Johnsen et al., 2009). Fisheries-dependent data collection has also increased, as more data are needed to assess fish stocks, and to monitor and regulate the environmental impact of fishing.

The value of fishery-dependent information in estimating the status of fish populations has regularly been called into question (Cotter & Pilling, 2007). Information may be biased because fisheries do not randomly sample fish populations and because fishing methods vary from place to place and time to time. Furthermore, landings do not provide information about all fish that are caught, since catch that is discarded at sea can represent a large proportion of the total catch (Borges, Zuur, Rogan, & Officer, 2004; Fernandes et al., 2011; Poos et al., 2013; Uhlmann et al., 2014; Ulleweit, Stransky, & Panten, 2010). Finally, misreporting may occur when fishers under-report problematic interactions with by-catch and quota-limited or "choke" species (Borges, 2015).

Despite the rapid increase in availability of new technology, such as GPS, network communication, digital cameras and image analysis software, the implementation of these innovations to monitor fisheries catches at sea has not evolved much. For instance, the vast majority of discard estimates are based on expensive fisheries observer programmes, and are associated with low coverage, often less than 1% of the fishing activities (Benoît & Allard, 2009; Depestele et al., 2011; Poos et al., 2013; Rochet, Péronnet, & Trenkel, 2002), often using subsamples of catches where fish are measured one by one on a measuring board and recorded with pencil and paper. Only within the last two decades, electronic monitoring (EM) has emerged as an additional approach for documenting catches in fisheries (Ames, Leaman, & Ames, 2007; Kindt-Larsen, Kirkegaard, & Dalskov, 2011; McElderry, Beck, & Anderson, 2011; Stanley, McElderry, Mawani, & Koolman, 2011). While the initial development of EM systems was largely an industry-led process to cope with management reforms and gear theft in the British Columbia crab fishery (Ames, 2005), it was quickly recognized that EM could also be used for monitoring and control in fisheries challenged by poor coverage by at-sea observations (McElderry, Schrader, & Illingworth, 2003). Electronic monitoring systems generally consist of various activity sensors, GPS, computer hardware and cameras (Figure 1) which allow for video monitoring and documentation of catches and detailed fishing effort estimation without requiring additional on-board personnel, unless additional biological data, for example otoliths, are needed (e.g. Needle et al., 2015; Ulrich et al., 2015). The data recorded can be reviewed at a later stage to obtain catch information, for example species composition, numbers, volume and lengths.

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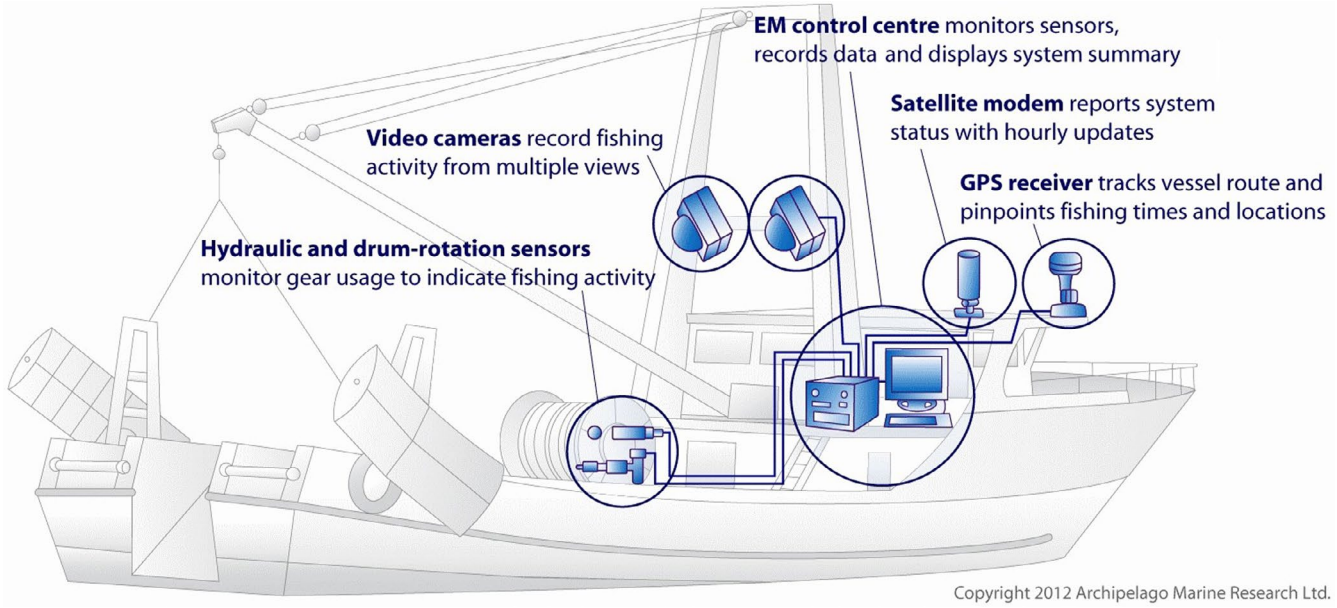

FIGURE 1 Overview of a standard remote electronic monitoring system set-up. Courtesy of Archipelago Marine Research Ltd [Colour figure can be viewed at wileyonlinelibrary.com]

In North America, the first EM trial was implemented in the Area "A" crab fishery in 1999 in British Columbia, Canada, to monitor vessel trap limits and to control catch and gear theft. As a result, the fisheries authorities implemented a full EM programme involving 50 vessels with a 36,000 fleet-wide trap limit. Subsequently, in 2002 EM was tested in the Alaskan longline fisheries to register catch and effort in the Pacific halibut (*Hippoglossus stenolepis*, Pleuronectidae) fishery and to test for compliance with regulations on seabird catch mitigation devices (Ames, Williams, & Fitzgerald, 2005; McElderry et al., 2004). In 2006, one of the largest EM programmes was introduced in the groundfish hook and line and trap fishery in British Colombia, Canada, to monitor compliance with self-reporting responsibilities on about 200 vessels.

In New Zealand, an EM programme was started to monitor marine mammals' and seabirds' interactions in gill net and trawl fisheries in 2003 (McElderry, McCullough, Schrader, & Illingworth, 2007). In 2005, EM trials started in Australian waters, monitoring fish handling and by-catch mitigation measures in several fisheries. Since 2012, EM has been tested in tropical tuna fisheries in the Atlantic and Indian Ocean, and during the same period, EM technology was introduced in trials on similar fisheries in the Western and Central Pacific Ocean with the aim to enhance sampling coverage of observer programmes for these vast fishing grounds.

European EM trials started in 2008, with the rising awareness of the vicious circle in which North Sea demersal fisheries were trapped (Rijnsdorp, Daan, Dekker, Poos, & Densen, 2007). A recovery plan for Atlantic cod (*Gadus morhua*, Gadidae) in the region had evolved into a complex and micromanaged regulation with multiple gear categories and exemptions (Kraak et al., 2013; Ulrich et al., 2012). Eventually, this resulted in the establishment of a new cod plan that included severe effort reductions. Several EU member states tried to incentivize cod discard reductions by making volunteer fishers accountable for their total catches rather than for their landings, in exchange for increased quota shares and, in some cases, exemptions from the effort reductions (Ulrich et al., 2015). Consequently, several EM trials were funded in order to verify declared catches, also known as "Fully Documented Fisheries" (FDF).

Electronic monitoring seems to be a good candidate for full catch documentation. However, in spite of the obvious advantages of EM, European managers have so far remained reluctant to use it because of its unpopularity among fishers. The fishers consider EM an intrusion in their private workspace (Baker, Harten, Batty, & McElderry, 2013; Plet-Hansen et al., 2017) and argue that camera surveillance reflects a governmental mistrust against them (Mangi, Dolder, Catchpole, Rodmell, & Rozarieux, 2013). This paper aimed to review the current status of EM worldwide and to discuss whether EM is a viable monitoring tool for fisheries. In addition, we summarize experiences with EM trials in northern Europe, where uptake of EM in monitoring programmes is slow, and compare them with experiences worldwide.

2 | METHODS

A global review was conducted on published EM trials and fully implemented EM programmes. Published literature was searched through SCOPUS using the search query TITLE-ABS-KEY (("electronic monitoring" OR "video capture") AND fish*). Given that many trials and EM programmes are not documented in peer-reviewed journals, the literature search was augmented with the latest unpublished knowledge from principal scientists involved in trials worldwide. Studies using video monitoring techniques to capture images of catch or by-catch, but not necessarily described and referred to as EM, were included in the review. The global

TABLE 1 Overview of EM trials worldwide

Country, region	Source	No. trials	Years	Gears	No. vessels	Monitoring objectives (no. trials)[a]					
						EM[b]	CM[b]	CH[b]	PS[b]	GM[b]	VA[b]
Canada	McElderry (2002, 2006); McElderry et al. (2003), McElderry et al. (2011); Riley and Stebbins (2003); Stanley et al. (2015)	6	2001–2007	Bottom trawl, longline, seine, traps	1–19	5	4	1	2	1	
USA, Alaska	Ames (2005); Ames et al. (2007); McElderry et al. (2004), McElderry, Reidy, Illingworth, and Buckley (2005), McElderry, Reidy, and Pathi (2008), McElderry, Schrader, Wallin, and Oh (2008); Cahalan, Leaman, Williams, Mason, and Karp (2010); Haist (2008); McElderry (2008); Bonney, Kinsolving, and McGauley (2009); NOAA (2017a); Wallace et al. (2015); Henry et al. (2016); Buckelew et al. (2015); Saltwater Inc. (2017)	16	2002–2017	Bottom trawl, longline, traps	1–90	12	12		5	2	3
USA, West coast	Pria, McElderry, Oh, Siddall, and Wehrell (2008); Bryan, Pria, and McElderyy (2011); Carretta and Enriquez (2012); NOAA (2017d); Al-Humaidi, Colpo, Donovan, and Easton (2014); Damrosch (2017)	7	2006–2015	Bottom trawl, gill net, longline, midwater trawl, traps	5–10	7	6		1	1	
USA, Northeast	Pria, McElderry, Stanley, and Batty (2014), Kennelly and Hager (2018); NOAA (2017c); Baker (2012)	7	2004–2018	Bottom trawl, gill net, longline, midwater trawl, bandit	3–17	7	7		2		
USA, Southeast	Stebbins, Trumble, and Turris (2009); NOAA (2017ee)	3	2008–2014	Longline, shrimp trawl	1–8	2	2		3		
USA, Hawaii, American Samoa	McElderry, Pria, Dyas, and McVeigh (2010); NOAA (2017b)	5	2008–2018	Longline, gill net, purse seine	1–17	4	5		1	1	
Australia	McElderry, Illingworth, McCullough, and Stanley (2005), McElderry, Reidy, McCullough, and Stanley (2005) Piasente et al. (2011), Piasente, Stanley, and Hall (2012); Larcombe, Noriega, and Timmiss (2016); Lara-Lopez, Davis, and Stanley (2012); Evans and Molony (2011); Wakefield et al. (2017); Jaiteh et al. (2014); ARM (2005)	10	2005–2012	Bottom trawl, gill net, longline, midwater trawl, shrimp trawl	1–10	8	3		6	1	
New Zealand	McElderry, Schrader, McCullough, and Illingworth (2004), McElderry et al. (2007), McElderry, Schrader, and Anderson (2008), McElderry et al. (2011); Geytenbeek, Pria, Archibald, McElderry, and Curry (2014); Middleton, Guard, and Orr (2016); Middleton et al. (2016); Austin and Walker (2017)	9	2003–2016	Bottom trawl, gill net, longline, midwater trawl	1–12	6	5		8	4	
Fiji Islands	Million et al. (2016); Hosken, Williams, and Smith (2017)	1	2015	Longlines	31	1	1	1	1		
Cook Islands	Hosken et al. (2017)	1	2017	Purse seine	2	1	1	1	1	1	
FSM	Hosken et al. (2017)	1	2016	Longlines	5	1	1	1	1	1	
RMI	Hosken et al. (2017)	1	2017	Longlines	6	1	1	1	1	1	
Palau	Hosken et al. (2017)	1	2016	Longlines	7	1	1	1	1	1	

(Continues)

TABLE 1 (Continued)

Country, region	Source	No. trials	Years	Gears	No. vessels	Monitoring objectives (no. trials)[a]					
						EM[b]	CM[b]	CH[b]	PS[b]	GM[b]	VA[b]
Solomon Islands	Hosken et al. (2017)	1	2014	Longlines	2 (2014) 7 (2017)	1	1		1		
New Caledonia	Hosken et al. (2016)	1	2014	Longlines	1	1	1		1		1[c]
China (tuna fishery, Pacific)	Hosken et al. (2016)	1	2015	Longline	33	1	1				
Denmark	Dalskov and Kindt-Larsen (2009); Kindt-Larsen et al. (2011); Ulrich et al. (2015); Plet-Hansen et al. (2019); Mortensen et al. (2017), Mortensen et al. (2017)	3	2008–2016	Bottom trawl, gill net, purse seine	6–27	2	2		1	1	
Germany	Götz et al. (2015); Oesterwind and Zimmermann (2013)	2	2011–2016	Bottom trawl, gill net	2–3	2	1		1		
The Netherlands	van Helmond et al. (2015, 2017); Bryan (2015); Scheidat et al. (2018)	4	2011–2017	Bottom trawl, gill net, purse seine, midwater trawl	2–12	33	2		1		
Sweden	Tilander and Lunneryd (2009)	1	2008	Gill net	2	1			1		
UK	Needle et al. (2015); French et al. (2015); Course et al. (2011); Marine Management Organisation (2013a, 2013b, 2014a, 2014b, 2015a, 2015b, 2015c, 2016); Hold et al. (2015)	6	2008–2015	Bottom trawl, gill net, longline, trap	1–27	6	6				1
Spain (tuna fishery, Atlantic)	Chavance et al. (2013); Ruiz, Krug, Gonzalez, Gomez, and Urrutia (2014), Ruiz et al. (2015), Ruiz et al. (2016); Monteagudo, Legorburu, Justel-Rubio, and Restrepo (2015); Briand et al. (2017)	5	2012–2016	Purse seine	1–2	5	5		2		
Ghana (tuna fishery, Atlantic)	Million et al. (2016)	1	2016	Purse seine	11	1	1		1		
Spain (tuna fishery, Indian Ocean)	Legorburu et al. (2018)	1	2015	Supply vessel	5	1					
France (tuna fishery, Indian Ocean)	Ruiz et al. (2015); Briand et al. (2017)	2	2012–2015	Purse seine	1	1	1				
Peru	Bartholomew et al. (2018)	1	2015–2016	Gill net	5	1	1		1		
Mexico	NOAA (2017b); NOAA (2016)	1	2016	Gill net	87 net sets		1				
South Georgia	www.archipelago.ca	1	2014	Longline	2					1	
Indonesia	Kennelly and Borges (2018)	1	2016	Hand line	5		1		1		

[a]A single trial can have multiple monitoring objectives.
[b]EM = effort monitoring; CM = catch monitoring; CH = catch handling; PS = protected species; GM = gear modification (mitigation devices); VA = automated video analysis (computer vision technology).
[c]Some of the EM records collected from the NC EM trial vessel were used in an automated video analysis competition. At this stage, none of the EM trials in the WCPO include automated video analysis, although EM service providers are focusing their R&D in this area.

literature review summarized EM trials and programmes by region, describing the first year of implementation, number of vessels and objectives of the trials and programmes. The results of the global review were summarized for different regions and fisheries: North America, Tropical Tuna Fisheries, Australia and New Zealand, South and Central America and Europe. The global review was followed by a detailed review of EM performance in the European trials. All contributing authors of reports and publications were asked to provide summaries of their research. In addition to the aspects of EM covered in the global review, a more detailed review covered EM set-up and data flow, EM analyses, EM performance and EM costs in European trials.

3 | RESULTS

The comprehensive review collected information on 100 EM trials and 12 fully implemented EM programmes worldwide (Tables 1 and 2). Electronic monitoring is predominantly implemented in Canada and the United States of America (USA) (including Alaska, West Coast and East Coast), as well as Oceania, Europe and West Pacific. Full programmes are in operation for fisheries in the United States, Canada, Australia and tropical tuna fisheries in the Atlantic and Indian Ocean (Figure 2). Since 1999, there has been a steady increase in the number of EM systems deployed on vessels worldwide, with strong increases in 2006 and 2015 (Figure 3). These strong increases were caused by the implementation of the British Columbia Groundfish Hook and Line Catch Monitoring programme in 2006 (~200 vessels) and the Atlantic Highly Migratory Species programme for pelagic longlines in 2015 (112 vessels), and four Alaska trawl fisheries between 2007 and 2014 (~60 vessels). The United States and Canada are the two dominant countries in terms of numbers of vessels involved in EM (Figure 4). Longline and demersal trawl, for example bottom trawl, are the two main fishery types for which EM trials are conducted (Table 1). The number of trials on demersal trawls is worth noting, since EM is, intuitively, expected to be more efficient for gears that bring catch on deck one individual at a time, such as hook and line, rather than a mixed catch brought on deck at once, as is the case for demersal trawls (van Helmond, Chen, & Poos, 2015).

The main objective for the use of EM was the need for detailed effort and catch monitoring. Out of 100 trials, 82 used EM for effort monitoring and 75 tested EM for catch monitoring purposes (Table 1). In contrast, there were clear differences between regions for other EM objectives: there was more focus on the by-catch of megafauna such as dolphins, sharks, turtles and birds in the trials of Australia, New Zealand and the West Pacific compared with Canada and Europe. For example, 6 out of 10 (60%) EM trials and programmes in Australia had by-catch monitoring as key objective, whereas only 2 out of 6 (33%) trials and programmes in Canada monitored by-catch. Five programmes in the United States were designed to monitor by-catch of several species, including bluefin tuna, Pacific halibut and Chinook salmon. Likewise, the possibility to use EM to monitor compliance with technical regulations on gear mitigation measures was explored in almost half of the EM trials undertaken in New Zealand, but less often in Europe (Table 1). Below, we summarize the findings of the review for different areas and fisheries.

3.1 | North America

The majority of fully implemented comprehensive EM programmes, 9 out of 12 (75%) worldwide, run in both Canada and the United States (Table 2). All these programmes are management-driven monitoring schemes, where EM is officially used for compliance monitoring purposes. Vessels under these regulations are required to have some form of monitoring and may choose to use EM. The number of vessels

TABLE 2 Overview of EM fully implemented programmes worldwide

Country	Programme	Year	Gears	No. vessels
Canada	British Columbia, "Area A" crab fishery (Dungeness crab)	1999	Trap	50
	British Columbia, Groundfish Hook and Line/Trap Catch Monitoring Program (GHLCMP)	2006	Hook and Line/Trap	200
	British Columbia, Hake Fishery	2006	Midwater trawl	35
USA	Alaska EM programme Bering Sea & G. o. Alaska: Pollock, Non-Pollock, Rockfish, Cod	2014	Bottom trawl; longline	66
	Atlantic Tuna Longline Highly Migratory Species (HMS) Fishery, monitoring bluefin tuna by-catch.	2015	Longline	112
	Alaskan small boat fixed gear fishery	2018	Longline; trap	141
	West Coast, Pacific total catch accounting on fixed gear	2018		
	West Coast whiting fishery	2018	Midwater trawl	25
	West Coast groundfish bottom trawl	2018	Bottom trawl	11
Australia	Australian Fisheries Management Authority (AFMA) Electronic Monitoring Programme	2015	Longline; hand line; gill net; trap	75
Spain	ANABAC-OPAGAC Tropical tuna purse seine programme, Indian Ocean	2018	Purse seine	27
	ANABAC-OPAGAC Tropical tuna purse seine programme, Atlantic Ocean	2018	Purse seine	22

FIGURE 2 EM trials and fully implemented programmes on world map [Colour figure can be viewed at wileyonlinelibrary.com]

involved in a fully implemented programme varied widely, between 7 and 200 vessels. In most cases, EM proved to be a cost-effective reliable alternative for human observation: The costs of human observation were high, and mismatches between the availability of observers and vessel departures sometimes caused delays or additional costs. The latter was caused by, for example, bad weather conditions when fishing trips were on hold and observers had many down days waiting for good weather. The levels of monitoring coverage varied among the different programmes: some have 100% EM coverage of all trips on all vessels, for example in the British Columbia Groundfish Hook and Line Catch Monitoring programme and the Atlantic Tuna Longline Highly Migratory Species (HMS) fishery (Stanley et al., 2011). Others use EM as an alternative to on-board observers, for example in the whiting midwater and fixed gear programme on IFQ Fleets on the US West Coast (McElderry, Beck, & Schrader, 2014; NOAA, 2017d). Some use partial coverage with the possibility to opt into an EM selection pool for a period of time where they are only required to turn on the EM systems on randomly selected trips. This method is used to integrate EM into the existing observer programme for the Alaskan small boat fixed gear fishery. The funding of monitoring programmes varies as well. The Canadian programmes started under co-funding arrangements, but eventually moved to 100% industry funding. The programmes on the US West Coast are co-funded by government and fishing industry. Initially, the National Marine Fisheries Service (NMFS) covered a substantial part of the costs, but is transitioning to only cover specific costs. In Alaska, a combination of federal and industry funds is used for EM deployment (NOAA, 2017a), but this too will transition to industry funding.

The vast majority of the 43 American and Canadian EM trials tested the feasibility of EM to complement or (partially) replace

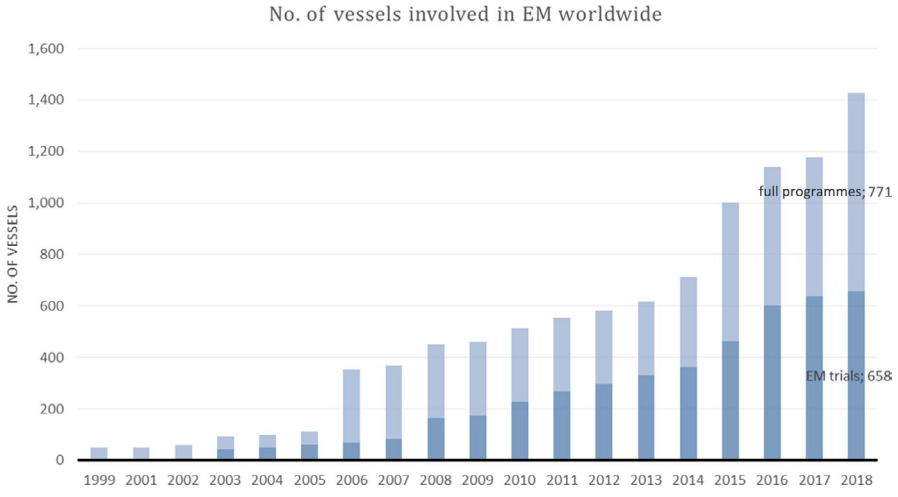

FIGURE 3 Number of fishing vessels involved in EM worldwide [Colour figure can be viewed at wileyonlinelibrary.com]

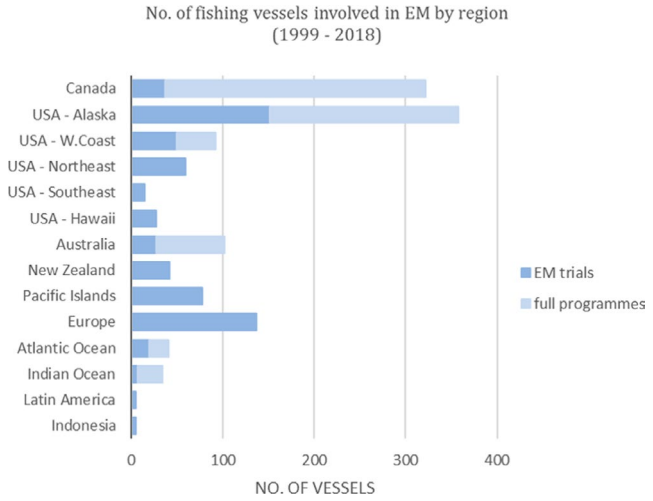

FIGURE 4 Number of EM trials and fully implemented programmes by region [Colour figure can be viewed at wileyonlinelibrary.com]

on-board observers in recording fishing activity, catch and discard composition. The results of almost all these Canadian and US studies demonstrated that EM is a promising tool for at-sea monitoring applications. It was repeatedly reported that EM differs from the more traditional observer programmes in terms of data collection capabilities and programme design issues (Kindt-Larsen et al., 2011; McElderry et al., 2014; Needle et al., 2015; Pierre, 2018; Plet-Hansen, Bergsson, & Ulrich, 2019). In comparison with observer programmes, EM has a number of advantages including its suitability across a broad range of vessels, the ability to review video for data verification, its presumed lower cost and higher scalability, and its ability to engage the industry in self-reporting processes. On the other hand, observer programmes are more suited as a tool for industry outreach, complex catch sampling operations and the collection of biological samples. In 14 trials, EM was successfully used to register interactions with or by-catches of marine megafauna and seabirds. In one trial, this included the registration of by-catch handling and release procedures. In 5 trials, the ability to monitor the use of gear mitigation devices to avoid by-catch was successfully tested. In 2014 and 2015, a series of American projects was initiated to develop automated image analysis for EM systems (Huang, Hwang, Romain, & Wallace, 2016, 2018; Wallace, Williams, Towler, & McGauley, 2015; Wang, Hwang, Rose, & Wallace, 2017, 2019; Wang, Hwang, Williams, Wallace, & Rose, 2016). It was concluded that achieving automated species recognition and fish counts potentially reduces the workload on video review, which is currently a manual, time-consuming and therefore expensive procedure.

3.2 | Tropical tuna fisheries

France and Spain conducted EM trials in tropical tuna purse seine fisheries in the Atlantic and Indian Oceans. Management organizations in both regions have management programmes that require a 5% observer coverage. While the International Seafood Sustainability Foundation requires participating companies to solely conduct transactions with large-scale purse seiners that have 100% observer coverage. Besides logistical constraints and high costs, there are serious security issues, as piracy makes it dangerous to place human observers on-board (James et al., 2019; Ruiz et al., 2015). The trials showed that EM was a promising tool to replace or to supplement current observer programmes (Briand et al., 2017; Ruiz et al., 2016). As a result, two Spanish tuna purse seiner associations started a 100% EM coverage of fishing activities in 2018. So far, these are the only fully implemented EM programmes worldwide that are not directly managed by national or subnational bodies, but are initiated by the fishing industry and where all fishers participate on a voluntary basis.

Electronic monitoring trials have also taken place in the tuna purse seine and longline fisheries in the Western and Central Pacific Ocean (Hosken et al., 2016). Trials are currently taking place in the Fiji Islands, Cook Islands, Solomon Islands, Palau, Federated States of Micronesia (FSM) and the Republic of the Marshall Islands (RMI). The objectives of these trials were to evaluate the efficiency of EM in monitoring effort, catch, catch handling and by-catch of protected species. One of the most recent EM trials on a topical tuna purse seiner was implemented in Ghana by the World Wildlife Fund for Nature (WWF) in cooperation with the Ghana Fisheries Commission and the International Seafood Sustainability Foundation (Million, Tavaga, & Kebe, 2016). There the objective was also to monitor effort, catch and by-catch.

3.3 | Australia and New Zealand

In 2015, the Australian Fisheries Management Authority (AFMA) implemented an EM programme covering the Eastern Tuna and Billfish Fishery, Western Tuna and Billfish Fishery, and the Gillnet Hook and Trap fishery for scalefish and shark. Electronic monitoring is used as a compliance tool and to assist fisheries management with accurate near real-time data on discards and by-catch and/or interactions with protected species (Table 2). AFMA requires that a minimum of 90% of fishing effort is covered by EM. In situations with an increased risk of by-catch of protected species, monitoring coverage is increased to 100%. The baseline audit rate for all fisheries is a minimum of 10% of hauls for each vessel. This includes analysis of full catch composition for each shot selected for review. Catch composition, discards and interaction with protected species on audited shots are compared to logbook records, and discrepancies are flagged and reported to the authorities. Initially, AFMA funded the equipment costs, installation and initial standard service events for EM. From a later stage, the costs of getting EM systems up and running were met by industry through annual quota levies collected by AFMA.

In total, 19 EM trials, 10 Australian and 9 New Zealand, were reviewed in this study. The earliest EM trials in New Zealand were documented in 2003. These were mainly to monitor the by-catch of protected species in an inshore groundfish set net fishery. In Australia, the first EM trials were conducted in 2005. In total, 14 trials with the objective to test the efficiency of monitoring the interaction with protected species were undertaken in a wide range

of different fisheries, making this the most common objective in this region. Based on a review of trials in New Zealand, Pierre (2018) pointed out the capabilities of EM to successfully monitor the capture of protected species in commercial fisheries and recommended developing standardized approaches around the review of EM imagery. The trials demonstrated that implementing data standards, review protocols and training materials will promote efficiency and harmonization of EM in monitoring by-catch. Remarkably, one trial successfully used an "in-trawl" video system to monitor by-catch: underwater video footage was recorded with high definition video cameras mounted inside trawl nets (Jaiteh, Allen, Meeuwig, & Loneragan, 2014).

3.4 | South and Central America

In total, three EM studies were conducted in South and Central America (Table 1). The results of the Peruvian trial indicate that EM was an effective alternative to human observers in monitoring catches of Peru's small-scale elasmobranch gill net fishery (Bartholomew et al., 2018). The Mexican trial, comparing the efficacy of video monitoring systems versus on-board observers, used the "Flywire Camera System," a low budget EM system developed for small-scale and artisanal fisheries using high-quality video linked to a GPS. The same system was used in a Hawaiian EM project for catch and by-catch monitoring (NOAA, 2017d). To enhance data collection on small-scale fisheries in developing countries, the World Wildlife Fund for Nature (WWF) supports the development of "affordable" EM systems for this region (www.worldwildlife.org). Such low-cost EM systems will help address the more challenging but globally significant fishing regions, for example Asia and Southern Europe (Michelin, Elliott, Bucher, Zimring, & Sweeney, 2018). For example, a very basic low-cost EM application, just using a camera mounted on a small fishing vessel and video recording the complete fishing trip, also proved to be successful in other regions, for example monitoring protected species interactions in the Indonesian hand-line fishery (Kennelly & Borges, 2018). Along the development of low budget, the Chilean government is in the process of implementing EM in a fleet-wide programme to monitor compliance as part of the "by-catch law and mitigation plans" (Cocas, 2019).

3.5 | Europe

In total, 23 published studies describing 16 different trials from 6 different nations (Scotland, England, Denmark, the Netherlands, Germany and Sweden) were reviewed (Table 3). Trials were mainly conducted in demersal fisheries using active gears (trawls and seines), although some passive gears (gill net and longline) have also been monitored. Different types of vessels have been involved, from larger beam trawlers and seiners to small-scale fisheries with vessels less than 10 m in length. The trials often lasted several years and generated large amounts of data. The first trials started in Sweden, Denmark and Scotland in 2008, and a spin-off of the Scottish trial was still ongoing at the time of writing. The number of vessels participating in each trial varied between 1 and 27 vessels. Evaluating the usefulness of EM as a monitoring tool was the most common research objective among the studies and countries, with 17 out of 23 (74%) studies sharing this objective (Table 3). In 7 (30%) cases, this objective was combined with an evaluation and feasibility study of a catch quota management (CQM) regime or landing obligation. Other studies' objectives focused on EM as an alternative method for, for example, scientific data collection, testing increased flexibility in technical fisheries measures, monitoring by-catches, analyses of high grading or estimation of discards. One study investigated the possibilities to use computer vision technology to automate the process of data collection in EM (French, Fisher, Mackiewicz, & Needle, 2015). Even though several studies briefly described the acceptance of EM in the fishing industry and among fisheries inspectors, there was only one comprehensive study on this aspect, Plet-Hansen et al. (2017).

3.6 | Review of European EM operations

In the period 2008–2016, results of European EM trials were reported in a manner that allowed a detailed review of EM on an operational level. The trials were summarized and compared for efficiency for EM set-up and data flow, EM analyses, EM performance and EM costs. In addition, levels of acceptance and objective for the trials were described.

3.6.1 | EM set-ups and data flow

In all trials, the EM system set-up consisted of (a) a GPS recorder supplying information on vessel location, (b) cameras supplying visual information on fishing activities and catches, and (c) hydraulic and drum-rotation sensors to mark deployment and retraction of gears. All data are conveyed into a computer, which saves the information (Figure 1). Vessels in all trials were initially equipped with the technology developed by the Canadian company Archipelago Marine Research (www.archipelago.ca). This system uses hard discs to store sensor data, geographical location and video recording. These hard discs were replaced manually before reaching data storage limits. The Danish and German trials switched to another provider that allowed the transmission of data using 4G cellular networks (www.anchorlab.dk).

In all trials, the cameras were usually installed in a way that crew workflow was minimally affected. The number of cameras deployed depended on the size and the specific characteristics of the vessels. The layout and selection of camera models and settings was the result of an optimization between quality and data storage requirement. The number of cameras, their field of view, the resolution (pixel density) and the frame rates were considered against the specific monitoring objectives. It was always necessary to dedicate time to optimize camera locations on each vessel. Locations were chosen in order to maximize the vision given the vessel layout, the workflow and the position of the crew, while avoiding moisture, dirt and blind spots. Meanwhile, electrical wiring locations sometimes limited the possible locations for cameras. Typically, there were 4 cameras used

TABLE 3 Overview of European EM trials, including references and study objectives for the studies describing the trials

Study	Trial	Years	Vessels	Fisheries	Reference	Study objectives
1	German North Sea CQM	2011–2016	2	Demersal trawl	Götz et al. (2015)	1. Evaluate and develop the reliability of information on discards by EM. 2. Test the feasibility of a management approach using a reversal of the "burden of proof."
2	German trial on by-catch registration of harbour porpoise and seabirds	2011–2013	3	Gill nets	Oesterwind and Zimmermann (2013)	Assess by-catch levels of harbour porpoise and sea birds in gill nets using EM.
3	Dutch North Sea cod CQM trial	2011–2015	12	Demersal trawl and seine	van Helmond et al. (2015)	Evaluate the efficacy of EM as control tool for mixed bottom trawl fisheries.
4					van Helmond et al. (2016)	Provide insight into the effect of the landing obligations prior to implementation and investigate the effect of CQM on fishing behaviour.
5	Dutch trial on by-catch registration of harbour porpoise	2013–2017	12	Gill nets	Scheidat et al. (2018)	Assess the by-catch rates and numbers of porpoises in the Dutch commercial bottom-set gill net fishery.
6	Dutch trial on pelagic freezer trawler	2014	1	Midwater trawl	Bryan (2015)	Develop a methodology to use EM to confirm full retention of catch on-board a freezer trawl vessel (compliance with discard ban).
7	Dutch sole EM trial	2015	2	Beam trawl	van Helmond et al. (2017)	Evaluate the efficacy of EM as control tool for discard of undersized sole in beam trawling.
8	Scottish CQM trial	2008–current	6–27	Demersal trawl	Needle et al. (2015)	1. Focus on the science that can be achieved with EM systems. 2. Preferable system for monitoring the landings obligation (rather than alternatives such as on-board observers).
9					French et al. (2015)	Reduce the viewers' workload as much as possible by automating this tedious and expensive procedure
10	English CQM trials for otter trawls and gill nets North Sea and Western Channel	2010–2015	6–16	Longline, otter trawl, gill net	Course et al. (2011); Marine Management Organisation (2013a, 2015c, 2016), Elson et al. (in press)	1. Test impact of a discard ban 2. Investigate the potential of using market grading data for reference fleet monitoring 3. Development of EM verification method for full documentation of plaice discards.
11	English CQM trials for beam trawls in the Western Channel	2011–2015	7–9	Beam trawl	Marine Management Organisation (2015a)	1. Explore the implications of the landing obligation in this mixed demersal beam trawl fishery; 2. Investigate European plaice discard levels by using EM verified self-reported data; 3. Explore CQM trial on demersal species.

(Continues)

TABLE 3 (Continued)

Study	Trial	Years	Vessels	Fisheries	Reference	Study objectives
12	English EM trials for vessels < 10 m	2012	2	Demersal trawl	Marine Management Organisation (2013b)	Test the reliability of EM equipment on-board commercial fishing vessels and to determine whether this technology could be used to monitor and quantify catches.
13	English CQM trials for Western haddock	2013–2014	1	Twin-rig otter trawl	Marine Management Organisation (2014a, 2015b)	To test impact of discard ban
14					Marine Management Organisation (2014b)	1. Provide insight into the level of high grading and discarding that is typical of the fleet 2. Explore measures to protect recruitment and reduce total haddock catches while maintaining profitable landings in the context of a landing obligation
15	English trial on video capture of crab and lobster catch	2014	4	Crustacean fisheries	Hold et al. (2015)	Evaluated the use of on-board camera systems to collect data from *Cancer pagurus* and *Homarus gammarus*.
16	Danish FDF trial for CQM	2008–2016	6–27	Trawl, seine, gill net	Dalskov and Kindt-Larsen (2009); Kindt-Larsen et al. (2011)	Establish whether EM can supply the sufficient documentation for a CQM. Discuss implementation of CQM, in regard to new technologies
17					Ulrich et al. (2015); Plet-Hansen et al. (2015)	Collate and assess the data collected during the FDF trials and estimate discard rates.
18					Bergsson and Plet-Hansen (2016); Bergsson et al. (2017); Plet-Hansen et al. (2019)	Development of EM as a documentation measure for fisheries applicable to the landing obligation. Assessment of whether data can be transmitted by means of 4G network, satellite or WI-Fi.
19					Plet-Hansen et al. (2017)	Describe specific areas of convergence or divergence of perceptions between fishery inspectors and fishers.
20	Minimizing discards in Danish fisheries (MINIDISC project)	2014–2015	14	Trawl, seine	Mortensen et al. (2017)	Analyse the effect of a free gear selection in a CQM setting, using EM as documentation tool. Analyse observer bias in EM
21					Mortensen et al. (2017)	Evaluate the discard estimates made by EM video inspectors for several species and contrast the estimates with the reports of fishers and on-board observers to estimate precision and accuracy of the EM observations
22	Danish trial on by-catch registration of harbour porpoise	2010–2011	6	Gill nets	Kindt-Larsen et al. (2012)	Assess by-catch levels of harbour porpoise in gill nets using EM.
23	Swedish trial on by-catch registration	2008	2	Gill nets	Tilander and Lunneryd (2009)	To test whether EM is more efficient in by-catch monitoring than on-board observers.

(Figure 5). The general systems among the reviewed trials had at least one camera pointed directly at the discard chute and sorting belt, one camera to cover the processing area or the deck on smaller vessels, one camera to observe net hauling and one camera to cover the catch in the hoppers. Meanwhile, recent EM systems have been able to store data from up to eight cameras. These additional cameras have been used for larger vessels in Scotland and Denmark to get a better coverage of the vessel and to limit blind spots (Mortensen, Ulrich, Eliasen, & Olesen, 2017; Needle et al., 2015; Ulrich et al., 2015). On smaller vessels, the sorting areas may be small or absent and positioning the cameras was often challenging. Installing custom mounting infrastructure to improve camera positions was useful in trials on small vessels with open decks (Marine Management Organisation, 2013b; Mortensen et al., 2017; Needle et al., 2015). Also, the availability of electrical power on small vessels may be limited by battery capacity when the engine is not running, thereby limiting the scope for implementation on some smaller inshore vessels. Meanwhile, autonomous systems have been developed that are powered by solar panels and batteries (Bartholomew et al., 2018).

Cameras can be set to record at different resolutions. For many applications, low resolution may be adequate. In current systems, low-resolution camera feeds are able to record at higher frame rates, which offers a smoother view and allows for the detection of abnormal behaviour in the handling process or when counting fish. However, using low-resolution images hampers species recognition and measuring fish lengths. High-resolution camera feeds have lower frame rates and use considerably more hard disc space than low-resolution camera feeds. In several studies, for example #10 and #18 in Table 3, the cameras directed at the discard chute or processing area were set to record at maximum resolution. This resulted in high-quality images, but frame rates were limited to 5 frames per second (Bergsson, Plet-Hansen, Jessen, & Bahlke, 2017; Course, Pasco, Revill, & Catchpole, 2011). With the declining cost of high-resolution cameras and high-capacity data storage, recent studies have used higher resolution and higher frame rates compared with earlier studies. Also, the introduction of digital cameras had significant implications for data storage. Digital cameras process and store all imagery in compressed data files. Higher resolution and increased frame rates are, therefore, less of a problem. In earlier EM systems, imagery of analog cameras was processed by the central computer, limiting resolution and frame rate by the processing capacity of the computer.

In the standard EM set-up, vessels were fitted with hydraulic pressure and drum-rotation sensors. Data from these sensors allow interpretation on gear use. This contributes to data review because it directly marks events of interest in the analysis software. The deployment and retrieval times are registered in the data flow, enabling accurate estimates of haul duration. Another purpose of sensors is to automatically start and stop camera recording outside of the active fishing operations, which could save storage capacity of the system or to respect the privacy of crew members. However, sensor data have not been systematically used. For example, in the English and Danish trials on trawlers, video recording started when fishing gear was deployed for the first time during a trip and stopped only when vessel returned to the port (Kindt-Larsen et al., 2011; Marine Management Organisation, 2013a). For another trial with gill net vessels, recording started when the net was hauled and stopped after 40 min because all catches in this fishery were processed rapidly and continuous recording was unnecessary (Course et al., 2011).

In all EM set-ups, GPS information was collected with high frequency (generally every 10 s) (Needle et al., 2015; Ulrich et al., 2015). This is a much higher temporal resolution than the typical 0.5- to 2-hr interval used in the obligatory EU vessel monitoring system (VMS) (Deng et al., 2005; Hintzen et al., 2012; Lee, South, & Jennings, 2010). The high spatial and temporal resolution of GPS position data, combined with the hydraulic and drum-rotation sensors, allows for accurate effort calculation for vessels equipped with EM. This was demonstrated in the study by Needle et al. (2015), pointing out the differences in perceived fishing activity as indicated by either VMS or EM data for a Scottish seine vessel. The VMS-derived fishing path underestimated the area impacted by the vessel, whereas the true path was accurately recorded by the EM data, showing the characteristic triangular pattern of seine fishing. Similarly, Götz, Oesterwind, and Zimmermann (2015) showed that haul durations indicated in fishing logbooks were imprecise when compared to those estimated using EM information. In their trial for two vessels, the towing times listed in the logbooks for one vessel were generally longer than the times recorded by EM (96% of hauls in 2012, 60% in 2013 and 86% in 2014), while for the other vessel the opposite was true (84% in 2012, 95% in 2013 and 89% in 2015).

3.6.2 | Data storage

Data collected from the various sensors and cameras are all linked to a central computer, which files the data onto a hard drive. All trials started with EM data being stored on exchangeable hard drives. Once full, hard drives were replaced by empty drives to continue recording. Drives were usually replaced by authorized persons, for example fisheries inspectors (Götz et al., 2015; Needle et al., 2015) or by staff of the institutes responsible for the projects (Dalskov & Kindt-Larsen, 2009; Kindt-Larsen et al., 2011), although in some cases fishers were instructed to change hard drives themselves (Course et al., 2011; van Helmond et al., 2015). Particularly, in case of compliance monitoring data encryption is provided to ensure data protection in the chain of custody.

To avoid the manual replacement of hard drives, a new system was developed in Denmark that allows wireless transmission of data via 3G, 4G or Wi-Fi networks, and this was progressively implemented in the Danish trials. This switch to wireless transmission of data considerably reduced the operational costs of the EM compared with the exchangeable hard drive technology (Bergsson & Plet-Hansen, 2016; Mortensen et al., 2017; Plet-Hansen et al., 2019). However, wireless transmission is dependent on the availability of sufficient Wi-Fi networks and the quantity of data to transmit. A potential issue is that data reviewers are wanting more comprehensive data, while data

FIGURE 5 Example of camera views from EM trials. Camera views show different angles of the sorting process and the hauling area [Colour figure can be viewed at wileyonlinelibrary.com]

transmission seeks lower volumes. West coast programmes in North America still rely on manual replacement of hard drives.

3.6.3 | Supplementary information

Supplementary catch information, for example logbook, haul-by-haul catch and observer data, was collected in all trials, with the purpose to evaluate and compare the efficacy of EM in a variety of management and scientific objectives. In the case of catch quota management trials for cod, all catches, including undersize individuals, were recorded. During trials in Germany and Denmark, extra information on discards was provided in official electronic logbooks (Götz et al., 2015; Ulrich et al., 2015). In several trials, data from on-board observer programmes were used in comparison with EM data (Marine Management Organisation, 2013b; Mortensen et al., 2017; Needle et al., 2015). In the Netherlands and England, fishers were requested to record catches by species or size category on a haul-by-haul basis (Course et al., 2011; van Helmond, Chen, & Poos, 2017).

3.6.4 | EM data analysis

Most of the EM studies have collected thousands of hours of video footage, thus requiring a structured approach for the review and interpretation of sensor and image data. Data analyses have been conducted by video observers, whose training have ranged from small introductory courses and cooperative training (Mortensen et al., 2017) to more formal training courses (Needle et al., 2015). Video observers were often trained at-sea fisheries observers (van Helmond et al., 2015, 2017) or have systematically been trained to recognize species and to operate the EM software. In some trials, they have also been trained in length measurement (Needle et al., 2015). This training improved the quality of the video review (Needle et al., 2015).

The analysis is generally aided by dedicated review software that merges the multiple data formats in EM (GPS, sensors, time, video, etc.), so that all can be visualized together. When inspecting EM data sets, users can fast forward, rewind or pause with synchronous views of all active cameras, along with normal video viewing tools such as zoom. The review time depends on the quality of the data set, the quality of the review software, the monitoring objective and the type of operation observed.

When monitoring for rare and highly visible events, such as the catch of cetaceans, all footage was reviewed when played at a higher rate (10–12 times faster than real time) (Kindt-Larsen, Dalskov, Stage, & Larsen, 2012). Monitoring catches of commercial species aboard demersal trawlers is generally time-consuming and in response to the large quantity of data most trials developed strategies where a random 10%–20% of the camera footage was validated against (self-) recorded catch data in logbooks (Course et al., 2011; van Helmond et al., 2015; Kindt-Larsen et al., 2011; Needle et al., 2015; Ulrich et al., 2015). Attempts to identify all fish and invertebrates discarded from one trip of a Scottish trawler resulted in prohibitively long review times: the trip took 1 week and the analysis took 3 months (Needle et al., 2015). This would clearly not be sustainable for ongoing monitoring purposes and budgets.

Different procedures have been used in improving estimates of catches from EM video material in the different trials (Table 4). The first approach required crews to sort discards into baskets (Figure 6) and show the baskets to the cameras before discarding (Marine Management Organisation, 2015a, 2015b; Ulrich et al., 2015). Viewers estimate discard quantities by counting the number of baskets, using a standard weight of 22–25 kg for full baskets. This approach relies on consistent and thorough sorting of the catch by the crew. The second approach aims to estimate discards directly on the sorting belt where possible (van Helmond et al., 2015; Marine Management Organisation, 2013a; Mortensen et al., 2017; Needle et al., 2015), which is a less invasive catch estimation method,

TABLE 4 European EM video data analysis overview

Trial	Method used to estimate catch from video recordings	Selection procedure of video data	Catch validation data	Monitored catch (species)
German North Sea CQM	Directly from sorting belt. Discards that were sorted outside camera view should be displayed by crew after the sorting process.	Random-selected sequences were observed.	Official logbooks (eLog).	Landings and discards of cod
Dutch North Sea cod CQM trial	Directly from sorting belt/area.	Random selection 10% of hauls with sufficient image quality.	(Self-)recorded catch by haul	Landings and discards of cod
Dutch trial on by-catch registration of harbour porpoise	Directly from net hauling and sorting table/deck	Census of video data, played at a rate of 8–10 times faster than real time.	(Self-)recorded by-catch by haul	Harbour porpoise
Dutch pelagic freezer trawler trial	Directly from wet deck and in the factory (sorting belt/area).	Census of video data, playback speed form frame-to-frame up to 16 times real time.	Not applicable in this study	Discards (discarding events)
Dutch sole EM trial	Landings directly from sorting belt. Discards sorted and displayed on sorting belt by crew after the soring process.	Random selection 5% of hauls with sufficient image quality.	(Self-)recorded catch by haul	Landings and discards of sole
Scottish CQM trial	Directly from sorting belt/area	Random selection 20% of hauls	Scientific observer scheme	Discards of cod, haddock, whiting, saithe, hake and monkfish
English CQM trials for otter trawls and gill nets North Sea and Western Channel	Directly from sorting belt/area	Random selection 10% of hauls/fishing operations	Observer trips, dock-side monitoring and (self-)recorded catch by haul	Discards of cod, plaice, sole, hake, megrim and monkfish
English CQM trials for beam trawls in the Western Channel	Discards sorted in baskets and displayed by crew	Random selection 5% of hauls	(Self-)recorded catch by haul	Discards of sole, megrim, monkfish and plaice
English EM trials for vessels < 10 m.	Directly from sorting belt/deck	A random selection of one haul per trip	(self-)recorded catch	Landings and discards of all fish species
English CQM trials for Western haddock	Directly from sorting process (counting haddock thrown into baskets)	Random selection 10% of hauls	Observer trips and (self-)recorded catch by haul	Landings and discards of haddock
English trial on video capture of crab and lobster catch	Pass catch across defined area under the field of view	Census of video data	Scientific observers	Crab and Lobster
Danish FDF trial for CQM	Catch/discards sorted in baskets and displayed by crew. From 2015 and onwards directly from sorting belt.	Random selection of minimum of 10% of hauls	Official logbooks (eLog).	Discards of cod, from 2015 discards of cod, haddock, whiting, saithe and hake
Minimizing discards in Danish fisheries (MINIDISC project)	Catch/discards sorted in baskets and displayed by crew	56% of hauls was inspected in chronological order	(Self-)recorded catch by haul	Discards of cod, hake, haddock, whiting, saithe, plaice and Norway lobster
Danish trial on by-catch registration of harbour porpoise	Directly from sorting belt/deck (no interference of working processes on-board)	Census of video data, played at a rate of 10–12 times faster than real time	Supplementary logbook	Harbour porpoise
Swedish trial on by-catch registration	Directly from net hauling and sorting table/deck	Census of video data. For one vessel, footage was independently analysed by two different members of staff.	Fishing journal with recordings of fishing activities, catches, by-catches and seal and bird damage, following the protocols of the Institute of Coastal Research.	Harbour porpoise, seals and birds. In addition, damaged catch by seals and birds was recorded

FIGURE 6 Sorting into baskets. Black basket contains discard and one basket has already been emptied on the conveyer belt. The picture also illustrates the issue with droplet formation on the glass dome of the camera [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 7 Placing individual specimens on the sorting belt (van Helmond et al., 2017) [Colour figure can be viewed at wileyonlinelibrary.com]

because crews do not have to alter their workflow. However, challenges with estimating large volumes of catch were encountered in the Dutch studies (van Helmond et al., 2015). The use of the "on the band" estimation method is thus prompting the development of automated image analysis (French et al., 2015) and automated counting of fish being discarded. A third approach to monitor catches was also implemented in an attempt to improve the accuracy of video observations (van Helmond et al., 2017). A simple protocol was used in which individual specimens were arranged and clearly displayed on the sorting belt in front of the cameras after the catch was processed (Figure 7). Counts were recorded from footage taken during this process. When using this protocol, video review of undersized sole improved substantially, with a very high agreement observed between the discards recorded on-board and the video observations.

An additional advantage of the "on the band" approach is the possibility to make on-screen length measurements, which can then later be converted into weights. Careful planning is needed if making measurements from display because recorded imagery will have optical distortion. Several methods for making on-screen length measurements have been reported. The most straightforward method relied on comparing the length of each fish with a size reference in the picture frame, for example a colour-coded tape fixed alongside the sorting belt of the fishing vessel (van Helmond et al., 2015, 2017). Additional tools have been developed for the video inspection, such as on-screen length measurements or image capture by supplying the dimensions of the sorting band to the software and subsequently relating the length measurement to the known size of the sorting band (Marine Management Organisation, 2013a). In the Danish CQM trial, a digital grid overlay has been used in the video audit software. Based on the size of known objects at the conveyor belt, the grid overlay could be set to add lines at known intervals (Bergsson & Plet-Hansen, 2016; Bergsson et al., 2017). Additionally, a measurement line could be added to the grid and in cases where fish lay in a curved position, this line could be extended and wrought to fit the full length of the fish (Bergsson & Plet-Hansen, 2016; Bergsson et al., 2017; Plet-Hansen et al., 2019). Linear allometric models were used in cases where the total length of a fish cannot be observed in a video image; total length could be estimated by inference of lengths of other body parts (Needle et al., 2015).

3.6.5 | EM performance

Most trials studied the performance of EM as a reliable source of catch information (Table 3). This performance depends on the technical reliability of the EM systems and the ability to correctly estimate catches. Technical EM failures and loss of data due to poor video quality were reported in 11 (out of 15) trials. However, not all technical errors were reported in similar detail. During the review, reported errors were classified in three different categories: system failure, storage failure and obstructed view. Where possible, errors were quantified as a percentage of data loss (Table 5). System failures were recorded in seven trials, with the main reason being broken cameras and non-functional drum-rotation sensors. Two studies (#12 and #22) mentioned system failure caused by power supply issues. Storage failure was recorded in three trials, caused by corrupted EM data, mainly video data, on the exchangeable hard drives. During the German trial, a hard drive began to burn during the copy process in the Institute and data were lost (Götz et al., 2015). Another form of storage failure occurred in the Dutch CQM trial; storage failure occurred because full hard drives were not replaced in time. This was not related to a technical failure of the EM system itself, but due to insufficient management of exchanging hard drives when vessels entered ports. A similar situation was described in the German trial where logistical and technical problems were encountered in relation to the exchange of hard drives, when vessels entered distant ports (Götz et al., 2015). Nevertheless, no data losses were reported in this trial because of these situations.

Obstructed view was reported in six trials. In these situations, the EM system worked properly; however, the footage recorded could not be used for further analysis because the view was blocked or unclear. The primary reported reason for EM data loss was unclear views because of dirty lenses, in some cases responsible for

TABLE 5 Technical EM failures and loss of data for European trials

EM failure description	Recorded in	Detailed information on failure, including estimated data loss (%), if reported[a]
System failure	7 trials	Camera failure: vessel A 2%–8%; vessel B 0%–25% Hydraulic sensor: <1% vessel A (German CQM trial)
		35% EM data loss in total, system failure was mentioned as one of the reasons (Dutch CQM trial)
		21% data loss in total, system failure was mentioned as one of the main reasons (Dutch sole EM trial)
		17% due to failure of cameras, 12% due to rotation sensors, 7% due to control boxes, also insufficient power supply was mentioned (English CQM trial for trawls and gill nets)
		2.5%, rotation sensor and camera failure (English EM trial for vessels < 10 m)
		0.7% of catch processing set for audit had camera breakdowns or video gaps either rendering the video useless or hampering the audit. An additional 1.2% of all video footage was lost due to hard drives being damaged or lost while being transported from vessels to video audit. This loss stopped after 2014 when manual data transmission was replaced by transmission via the Internet (Danish FDF trial for CQM)
		Unstable power supply (Danish trial on by-catch documentation for harbour porpoise)
Storage failure	4 trials	7% vessel A; 17% vessel B, corrupted hard drives (German North Sea CQM)
		Failed to replace full discs on time (Dutch CQM trial)
		13%, corrupted hard drives (English CQM trial trawls and gill nets)
		Corrupted files when power was switched off (Swedish trial in by-catch)
View obstructed	6 trials	Dirty lenses: 25% (Dutch CQM trial)
		21% data loss in total, dirty lenses was mentioned as one of the main reasons (Dutch EM trial on sole)
		"Skipper's duty to keep lenses clean is not always been fulfilled"; "Droplets obscure image"; "View being obscured by fishers working" (Scottish CQM trial)
		Crew catch handling: 31% view obscured other than crew: 12%; lack of maintenance or cleaning: 48% (English CQM trial trawls and gill nets)
		"Image quality can be affected by a number of different factors including moisture in the lens, sun shield blocking view, water drops, low light conditions and bad sun glare." (Danish FDF trial for CQM)
		4.2% of catch processing set for audit had the camera view obstructed by crew; water droplets on lenses; sun glare; and smudge on lenses. An additional 2.0% of the video footage had blurry imagery which hampered the discard estimates (Danish FDF trial for CQM)
		"…hauls with defected or dirty cam-eras were not analysed…" (Danish MINIDISC project)

[a]Percentages are calculated on different premises, for example total number of hauls, fishing days or fishing hours.

significant amounts of data loss, up to 48% (Table 5). The principal problem was the positioning of the cameras. To get a sufficient view of the catch and to be able to identify species, and count and measure individuals, the cameras were directed at the catch sorting areas. However, the working space in fishing vessels is generally extremely limited with low ceilings, and it can be difficult to position a camera in a way that can enable a wide, clear and undistorted view of the sorting area without the risk of water and fish waste splashing up onto the camera casing (Bergsson et al., 2017; Needle et al., 2015). Although the fishers had a duty to keep camera lenses clean, this was not always fulfilled. Another important factor that influences the usefulness of video data was crew that blocked the view on the sorting area, for example hands taking fish from the sorting belt (Plet-Hansen et al., 2019). Despite efforts to install cameras in the best positions, it was not always possible to prevent crew members accidentally or intentionally blocking the view. In particular, it was difficult to analyse footage on-board smaller vessels which sort directly on the open deck or use sorting tables (Marine Management Organisation, 2013b; Needle et al., 2015).

Van Helmond et al. (2017) concluded that to increase the technical reliability of EM, more emphasis should be put on the importance of camera maintenance (e.g. regular cleaning of the lenses and checks of EM systems). Plet-Hansen et al. (2015) found a steady decrease in the number of errors and data loss during the Danish trial. This suggested that there could be an adaption as fishers became acquainted with the presence of cameras, together with the increased training and experience of video auditors, increased experience in proper handling of EM equipment and optimization of maintenance of EM equipment. In addition, digital transfer of EM data via cellular (4G) and Wi-Fi networks eliminated malfunctions caused by incorrect hard drive exchange, damage to hard drives during transport or the loss of hard drives. Likewise, systems of this type have not been forced to stop recording because of insufficient disc space, as was the case in some other trials (Bergsson & Plet-Hansen, 2016). Overall, EM systems in European

trials have been sufficiently reliable to fulfil the goals of the studies, provided there was ongoing attention to maintenance.

All European trials had the objective to evaluate the ability of EM to estimate catches in commercial fisheries (Table 3). Different methods were used to estimate catch from video footage (Table 4). To test the efficiency of EM, catch estimates based on video review were compared with recordings of fishers and/or on-board observers. In the Danish and German CQM trials, catch weights were obtained from EM with the use of fishing crews that collected catches in baskets and showed those to the cameras (Table 4). The Danish CQM trial observed discrepancies between fishers' and video observers' discard estimates that were often less than 5 kg per haul, without systematic bias and with clear improvements of the accuracy over time (Ulrich et al., 2015). The Scottish, Dutch, German, English and in some years Danish CQM trials estimated catch directly from sorting belt or discard chute (Table 4). The English trials demonstrated good overall agreement between fishers' records and video observers (Marine Management Organisation, 2013a). In the Dutch trial, the video observations and logbook records for large cod catches were more strongly correlated than for the smaller catches, especially in highly mixed catches (van Helmond et al., 2015). This suggested that distinguishing small numbers of cod in large volumes of bycatch, particularly when similar-looking species are targeted in mixed fisheries, could be difficult. In addition, based on another Dutch EM trial, van Helmond et al. (2017) concluded that EM for small fish in mixed fisheries is not as effective as it is for large fish. Video review of the standard catch processing routines on-board bottom trawlers significantly underestimated the number of discarded sole less than 24 cm in length, while for landed sole greater than or equal to 24 cm, no significant difference was found between on-board records and video observations. Likewise, in Denmark Mortensen et al. (2017) found a tendency of EM to underestimate discards of smaller fish by 32% compared with on-board observations. This supports the findings in a few trials which suggest that, despite offering a promising way to use EM to monitor catch, the accuracy of video observation should be monitored and improved where needed (Needle et al., 2015; Ulrich et al., 2015).

The Scottish trial was able to estimate discards with no effective change to the catch processing systems used on each vessel (Needle et al., 2015). This was not the case in all trials, and protocols were developed to improve the registration of catches for vessels participating in EM in Denmark and in the Netherlands (van Helmond et al., 2017; Ulrich et al., 2015). Fishers were able to follow the protocols to improve video review, and when mismatches occurred, it has generally been sufficient to point to the issue in order to get the return to full compliance. These protocols substantially increased the accuracy of EM. However, for both trials it was reported that the protocol could be a burden for the crew. For example, the Danish basket system has been criticized by fishers, because it imposes additional work on crews. Moreover, baskets take much space on deck and they are heavy to move. In the Dutch case, the protocol required on average an additional 3 min of processing time per haul for a single species. Consequently, van Helmond et al. (2017) concluded that given the large number of species under the landing obligation for this fishery, implementing even a simple protocol come with a cost for the fishing industry; the extra time needed to conduct such a protocol under the landing obligation would exceed 12 hr per fishing trip. A reduction in this effort in a monitoring programme may be possible by means of industry-driven innovations.

Also, the use of EM video data to provide length–frequency data is not always straightforward, as it is not always possible to view the full body of each fish due to occlusion by other fish or waste materials (Needle et al., 2015). However, a morphometric length inference model for fish of which the full body was not visible on footage was successfully tested in the Scottish trial (Needle et al., 2015). Also, developments in automated measurement of fish by computer vision may improve length measurements based on video data even further (French et al., 2015; Huang, Hwang, Romain, & Wallace, 2018; White, Svellingen, & Strachan, 2006). Nevertheless, even fully accurate length measurements would have to be converted into weight using length–weight relationships rather than being weighed directly on-board, which could contribute to some discrepancies with observer estimates.

In summary, the EM performance depends critically on whether the operating specifications of the technology, the monitoring objectives, the vessel layout and the responsibilities of the vessel personnel in supporting the monitoring effort are considered.

3.6.6 | Cost-efficiency

The price of an EM system per vessel, including installation, in the trials has been around 9–10.000 €, and systems in the trials have typically lasted between 3 and 5 years (van Helmond et al., 2015; Kindt-Larsen et al., 2011; Marine Management Organisation, 2013b; Needle et al., 2015). Running costs include data transmission costs, maintenance costs, data review and software licences. Unfortunately, the different components of running costs are not always explicitly documented in the different studies. Reported total running costs for systems where hard drives needed to be exchanged manually were in the order of 4,000–7,000 € per year per vessel (van Helmond et al., 2015; Kindt-Larsen et al., 2011; Marine Management Organisation, 2013b; Needle et al., 2015). If data transfer was arranged by manual exchange of hard drives by scientific staff, the costs for this transfer were a considerable part of the running costs. The transmission of data by 4G network allowed these transmission costs to be considerably reduced, down to ~100 € per year per vessel (Mortensen et al., 2017). However, the costs depend on the quantity of data, the operation area of the vessel and the possibilities to transmit data. Plet-Hansen et al. (2019) estimate the initial costs of fitting all Danish vessels above 12 m in length (396 vessels) with EM to 3.3 million € and estimate the total running costs to amount to 1.7 million € annually based on the setup used in 2016 for a Danish EM trial. Needle et al. (2015) concluded that, although the initial costs of EM are high, EM is a more cost-effective monitoring method than an on-board observer programme in

the mid-to-long term as running costs are much lower, consequently, that would allow for a wider sampling coverage for a given monitoring budget along with truly random sampling. Another important aspect regarding the cost–benefit of EM is the involvement of fishers in reporting their catches. Electronic monitoring is often used to validate self-reported catches or discards. Even though only a minority of these reports are audited with video, the fishers do not know which hauls will be audited and when, which creates an incentive to report all catches accurately. Consequently, even with a low audit rate, observation costs are expected to be largely internalized by fishers (James et al., 2019). It should be noted, however, that these cost analyses were based on EM trials and that we did not encounter cost analyses based on large-scale monitoring programmes.

3.6.7 | EM acceptance

All the reviewed EM trials have been based on voluntary participation, albeit with substantial incentives in most cases. The participation in CQM schemes has usually been good, with most vessels participating for several years in the trials (Course et al., 2011; van Helmond, Chen, Trapman, Kraan, & Poos, 2016; Marine Management Organisation, 2013a; Ulrich et al., 2015). In Scotland, the scheme ran in full from 2009 to 2016 (a reduced scheme is still in operation at the time of writing), and was always oversubscribed, with an average of 25 vessels taking part each year (Needle et al., 2015). Noticeably, incentives to participate in the North Sea CQM trials were enshrined in the EU TACs and quota regulation (EU, 2010), with participating fishers receiving additional national quota shares. In the initial CQM feasibility trial, a 100% quota increase was offered (Kindt-Larsen et al., 2011), which was then reduced to 30% after 2010 (EU, 2010). CQM vessels were also exempted from days-at-sea regulations in most trials. Other trials outside of the remits of the North Sea CQM offered a more diverse perspective on participation. In the Scottish trial, vessels were permitted to enter parts of the nationally imposed real-time closures intended to protect juvenile cod (Needle & Catarino, 2011). The trials by Mortensen et al. (2017) and van Helmond et al. (2017) offered an additional quota taken from the quota share reserved to scientific experiments. Meanwhile, the studies of Tilander and Lunneryd (2009) and Kindt-Larsen et al. (2012) show that EM trials can also be conducted without tangible reward; fishers participated only for the benefits of demonstrating that their by-catches of harbour porpoise (*Phocoena phocoena*, Phocoenidae) were minor.

The concerns voiced against EM are mainly of ethical nature, related to the potential misuse of video data and to the "Big Brother" intrusion of the constant presence of video equipment (Mangi et al., 2013). On the other hand, increase in public goodwill, better stock assessment and the possibility to induce a more sustainable fishery have also been stated as reasons for participation (Marine van Helmond et al., 2016; Scotland, 2011; Plet-Hansen et al., 2017). A notable observation in the Danish trials, described in the study of Plet-Hansen et al. (2017), was that fishers who had participated in EM trials were generally positive about EM and its possibilities; 58% of interviewed EM-experienced fishers expressed positive views on EM. In contrast, fishers without any first-hand experience with EM remain largely negative about it; 90% of the interviewed fishers without EM experience were against it. Whether this division resulted from participating fishers being more in favour of EM prior to trial participation or whether participation in the trial had changed the opinion of the fishers was not studied. The fact that fishers were rewarded to fish with EM in most trials may also have been an influence. In addition, some studies indicated that protocols to improve video review can be a burden on the crew (van Helmond et al., 2017; Ulrich et al., 2015). The success of monitoring the landing obligation with EM likely depends, at least for a large part, on the workload that it imposes on skippers and crews for monitoring and registration of catches. Similar observations were made during the process of EM data review and analysis of Götz et al. (2015) and Mortensen et al. (2017). However, the development of technologies to improve the implementation and reduce this burden of EM has been ongoing in the Scottish trial (French et al., 2015; Needle et al., 2015).

It is noteworthy that the first decisions to use EM in the EU did not come from the fishing industry, but from a strong political will. Based on the results of the first CQM trials in Denmark and Scotland, political representatives of Scotland, England, Denmark and Germany signed the Aalborg Statement on the 8 October 2009, which presented a joint position recommending the use of EM in fisheries monitoring. Following the Aalborg Statement, the Scottish Cabinet Secretary for Rural Affairs and the Environment emphasized that the intentions of the Scottish EM scheme were twofold: to facilitate monitoring of fishing and discarding activity for compliance purposes, but also (and equally) to provide valuable data to fisheries scientists to increase understanding of fleet dynamics, population distribution and structure, and ecosystem components (Needle et al., 2015). Also, the European Council mentioned the use of EM as a means to ensure compliance with the landing obligation in its regulations (EU, 2013). This top-down approach implies the fishing industry only got involved at the end of the implementation phase. However, based on Canadian EM studies in British Columbia, both Koolman, Mose, Stanley, and Trager (2007) and Stanley, Karim, Koolman, and McElderry (2015) emphasized the importance of involvement and participation of fishers already in the initial (design) phase of EM implementation. Also, the fact that EM is perceived as a compliance monitoring tool has a negative impact on the acceptance of EM within the fishing industry. A key aspect of this reluctance is the introduction of a (potentially) more robust monitoring of catches compared with the current reporting systems and thus a perceived higher probability of being caught if non-compliant. While only penalizing fishers in case of differences between logbooks and EM will be counterproductive, a continuous dialogue about these differences may help improve data quality and acceptance of EM as a monitoring tool.

In the context of the adoption of EM in Europe, there is still no obligation for EU Member States to use EM as a verification or monitoring tool. If EM is required in some Members States but not in others, there will be no "level playing field" between European fishers. This concept of a "level playing field" potentially imposes an extra

obstacle for the implementation of EM in European fisheries management (Plet-Hansen et al., 2017).

The acceptance of EM will improve if benefits of EM for the fishing industry are greater than just improving compliance (Michelin et al., 2018). Such benefits could include improved data quality through EM, allowing for more efficient management measures and, eventually, improved financial performance for industry, and increased flexibility in regulations as a result of improved accountability from EM. The Danish trial on free gear selection (Mortensen et al., 2017) is a good example of this, alternative uses for EM data, for example, improved business analytics, such as identifying and avoiding by-catch hotspots, support of (eco-) certifications by increasing traceability in seafood supply chains.

3.6.8 | EM objectives

Of the reviewed studies, 9 studies had the objective to evaluate the efficacy of EM as a monitoring tool (Table 3). Of these 9 studies, 8 concluded that EM is an effective monitoring tool compared with other existing monitoring methods such as at-sea observers, VMS and electronic logbooks (eLogs). One study of the 9 mentioned was not conclusive of the efficiency of EM as a monitoring tool compared with other methods, but indicated that EM delivered an appropriate coverage of fish catches and fishing time.

In addition, EM proved to be a successful tool to test alternative management regimes, for example catch quota management (CQM) trials and "unrestricted gear" trials (Mortensen et al., 2017). In several studies, changes in fishers' behaviour were observed because of a change in management regimes in combination with EM. In some cases, there was a shift in behaviour towards greater avoidance of undersized fish (van Helmond et al., 2016), reduced high grading (Kindt-Larsen et al., 2011) and generally greater compliance with rules and regulations in recording discards (Ulrich et al., 2015). Thus, EM triggered compliance and provided a rich source of information that can be used to inform on the outcome of management measures. In general, detailed spatiotemporal information on catches of unwanted fish and the ability to fully document fisheries with EM were of crucial importance for the evaluation of management measures in these studies, something that could only be achieved with on-board observers at substantially higher costs.

In the English trial, EM was used to assess the performance of new fishing gear (Marine Management Organisation, 2013a). As part of the English Marine Management Organization CQM scheme, a participating skipper voluntarily altered the selectivity of his trawl. Comparative catch weight data from the skipper using different net designs were corroborated using EM (Marine Management Organisation, 2015a). These data were used to optimize the modified trawl design prior to a detailed catch comparison trial. The validated skipper data supported results from the trial, demonstrating the efficiency of EM in evaluating and developing modified fishing methods or fishing gears. Considering the cost-efficiency in the mid-term and long term (see above), EM could be a relevant monitoring method for gear trials in comparison with the more expensive on-board observer option.

In two of the reviewed trials, the Dutch CQM and the Danish MINIDISC trials (studies #4 and #20, Table 3), changes in fishing activity and behaviour were analysed when vessels were under different management regimes (van Helmond et al., 2016; Mortensen et al., 2017). The wider monitoring coverage of the fleet, in essence a 100% coverage (Kindt-Larsen et al., 2011), created a unique opportunity to investigate fishers' gear choices, mesh sizes and fishing locations at broader (macro) and finer (micro) geographical scale. Rather than relying on model predictions on the potential outcome of catch quota management, the 100% recording of total catch (landings and discards) and fishing activity allows the observation of actual fishing behaviour (van Helmond et al., 2016). This was further supported by interviews to help interpret the results, giving a detailed insight in the decision-making processes and reasoning of fishers in the study.

The monitoring of marine mammal by-catch represents a special case in the use of EM. Such monitoring is needed worldwide due to growing concerns regarding the population status of marine mammal species. In Europe, 4 trials (studies #2, #5, #22 and #23, Table 3) have been conducted to evaluate the feasibility of using EM to observe incidental by-catch of marine mammals or seabirds in gill net fisheries (Kindt-Larsen et al., 2012; Oesterwind & Zimmermann, 2013; Scheidat, Couperus, & Siemensma, 2018; Tilander & Lunneryd, 2009). Commercial gill-netters (10–15 m in length) were equipped with EM systems. The results revealed that harbour porpoises, seals and birds could easily be recognized on the video footage. The studies highlighted the importance of having one camera covering the position where the nets break the surface as many porpoise carcasses tend to drop out of the nets at that specific point due to their heavier weight in air. Comparisons between EM results and fishers' logbooks showed that the EM system gave reliable results. In the Danish trial, EM was more reliable since fishers, in many cases, did not observe the by-catch while working on the deck (as the by-catch had already dropped out of the net before coming on-board). Furthermore, the studies concluded that very high coverage percentages at low cost, compared with on-board observers, could be obtained with EM. Similar conclusions were drawn in a review on EM studies by Pierre (2018): EM has been widely tested and proven effective in monitoring protected species interactions in fishing gears.

3.7 | Summary of European trials, operational benefits of EM

The three major benefits of EM perceived in the European trials were as follows: (a) cost-efficiency, (b) the potential of EM to provide much wider (and more representative) coverage of the fleet than any observer programme will likely achieve and (c) EM registration of fishing activity and position of much greater detail.

With the potential to enhance data collection programmes, EM has the ability to improve the scientific stock assessment and risk assessment processes. In particular, the assessments of data-limited stocks (DLS) would benefit from a system like EM, the wider

coverage of the fleet enabling data collection from less abundant species or specific fisheries, for example long-distance or small-scale fisheries, which are notably difficult to cover with a traditional observer programme. However, age and maturity data can only be collected through direct physical sampling. Observers can also collect sex data for some species by external observation (e.g. plaice, Elasmobranchs and Nephrops) which is not possible with existing EM systems. Therefore, EM cannot fully replace all the data needs currently provided by observers and it should be explored how observer and EM programmes could be integrated, as this would enable the benefits from both approaches to be utilized. An alternate possibility would be to continue development of length-based assessment methods, which would not require age data to the same extent as currently used in stock assessment methods (Needle et al., 2015). In addition, EM species identification for similar-looking species was difficult for small species and when large concentrations of fish were processed (van Helmond et al., 2015). In contrast, observers can accurately identify all fish, crustacean and cephalopod species to the species level as required for stock assessments. However, there is potential for improving species identification in EM by making use of computer vision technology (Allken et al., 2019; French et al., 2015; Hold et al., 2015; Storbeck & Daan, 2001; Strachan, Nesvadba, & Allen, 1990; White et al., 2006).

The results of the EU review are summarized using a SWOT (Strengths–Weaknesses–Opportunities–Threats) analysis in the context of the current data collection framework (Table 6) of the EU. The strength of EM is the substantially higher sampling coverage compared with current monitoring programmes at the same costs. At the same time, EM offers a better estimation of fishing effort through high-resolution spatiotemporal GPS data combined with accurate recording of fishing activity, for example setting and hauling. The observations of the catches made by video can be independently verified by different reviewers by replaying the video material. The EM systems had a high approval rate among participating vessels in one of the trials (Plet-Hansen et al., 2017). This means that EM can incentivize compliance through fleet-wide monitoring, creating the same regulatory framework for all fishers. Thus, the current EM systems could be a valuable addition to existing personnel-intensive monitoring methods. However, there is a range of weaknesses that still needs to be addressed when discussing the applicability of the EM. First, switching to EM requires a substantial investment, especially when compared to the revenue of smaller fishing enterprises. Thus, despite being cost-efficient in the medium-to-long term, EM can represent an initial economic burden. Secondly, fishing vessels differ widely from each other in terms of size and set-up of working spaces, meaning that each EM system must be tailored to the individual vessel to provide optimal monitoring. Additionally, time has to be dedicated to adjusting the set-up after the first trips, and camera lenses have to be regularly cleaned, affecting the workflow of the crew. The set-up also requires decisions on whether to have high resolution with low frame rate or vice versa, with both options requiring a substantial data storage demand. Also, as with all technical systems, EM can fail resulting in missing data. Even with ideal EM set-ups, it can be difficult to distinguish similar-looking species in high volume catches of mixed fisheries. But above all remains the reluctance to have cameras on-board. As most fishers see the fishing vessel both as a place of work, but also as a place of privacy, EM can easily be seen as a "Big Brother" system, intruding on the sanctity of the fishing vessel and representing a governmental mistrust in the fishers. Nevertheless, EM is currently a viable alternative to on-board monitoring of CQM regimes. If the

TABLE 6 SWOT analysis of EM compared with the European data collection framework of the EU in the context of the EU landing obligation

Strengths • High and randomized coverage • Cost-efficient • High spatial and temporal GPS resolution. • High precision on effort estimation • Provides verifiability of observations (replay) • Support tool for eLog verification • Independent recording of catch information • High acceptance among former EM users. • Equal playing field. • Inform on by-catch of marine mammals and seabirds.	Weaknesses • Intrusion of privacy • Requires investment in equipment • Challenging set-up on small vessels • Have to dedicate time to adjust set-up to match workflow, set-up unique to each vessel • Cameras have to be cleaned • High data storage demand. • Requires training of video inspection personnel. • High resource requirement for viewers (unless automated) • Can affect workflow for crew • Risk of system failures • Difficult to distinguish similar-looking species in mixed catches. • Low acceptance in the fishing industry in general
Opportunities • Fleet-wide coverage • Better assessments, especially of data-limited stocks • Potential for obtaining length–frequency distribution • Non-invasive monitoring • Assist in a better planning of the individual fishery. • Mapping of by-caught marine mammals and seabirds. • Can be combined with existing observer programmes	Threats • Misuse of data • Hacking • Confusion of data ownership • Changing political interest in EM

initial installation costs can be overcome, EM offers the potential for fleet-wide monitoring coverage, with substantially more data than currently gathered in the various monitoring schemes, including the potential for length-distribution estimation of target species and a mapping of by-catch. In summary, EM as monitoring tool contains a range of solid strengths, that are not diminished by its weaknesses and EM has the opportunity to be a powerful tool in monitoring fisheries, integrated with existing data collection programmes, as long as a range of issues are addressed.

4 | DISCUSSION

4.1 | Review of EM studies

There has been only limited coordination between the various trials between different regions in the world, and therefore, this review represents a step forward into synthetizing the outcomes of the various studies. Results of the studies have been documented in scientific peer-reviewed journals and technical reports. A challenge in this review was that not all trials have been well reported: some trials may never be documented, while others may not yet be documented because of a time delay in reporting results. Hence, it is not possible to include all trials in a global review. Another challenge in evaluating the performance of EM is that the technology has evolved over trials. Likewise, EM performance will evolve within trials and a perspective on the potential for EM may be more informed at the end of a trial rather than across a trial. Also, there is a difference in the level of detail in the methodology and results published in manuscripts or reports. Direct comparison between studies is, therefore, not always straightforward.

4.2 | Successes of EM worldwide

Based on continuity and expansion, EM has been successful in several different regions around the globe. Currently, EM programmes in Alaska, British Columbia, West and East Coasts of the United States and Australia are already well developed with comprehensive sampling schemes covering up to 100% of fleets, in some cases involving hundreds of vessels and thousands of fishing days. Clearly, the technical weaknesses of EM that were revealed in European trials have been encountered and solved in these examples where EM has been operationalized. In those cases, acceptance from the fishing industry was a crucial element for successful implementation of a full EM programme. Fully implemented programmes are often driven by the existence of a strong compliance or management issue that needs to be solved, for example gear theft or rampant discards, an example being the British Columbia, "Area A" crab fishery programme. In this case, EM is the best cost-effective solution and the efficiency of EM for these fisheries is demonstrated (McElderry, 2006). Full programmes can be adopted optimally if three components are present: (a) acceptance in the industry, (b) a strong incentive to monitor and (c) proven efficiency of EM.

Another component of successful EM implementation is government support. Electronic monitoring trials in the United States are subsidized by the government. A good example is the EM programme on the US Atlantic Highly Migratory Species longline fishery that was designed, approved and implemented in a little over a year (Michelin et al., 2018); such speed can be attributed to this being a fully government-funded EM programme. This initial investment by the government can help EM programmes develop, even if the long-term plan is to transition to industry cost allocation once a programme is fully implemented. On the other hand, system maintenance and longevity tend to be increased when fishers are investing in the systems themselves. A general factor in all fully implemented programmes (Table 3) is that EM cannot work in isolation and is often integrated with other monitoring elements, such as dockside monitoring, self-reported logs, observers and dealer reports. Various data types can provide useful information each with different strengths and weaknesses (Stanley et al., 2015).

In the field of research on interactions or by-catch of marine megafauna in commercial fisheries, EM is generally accepted as a reliable tool (Kindt-Larsen et al., 2012; Pierre, 2018). The high level of spatial and temporal coverage and the fact that megafauna is easily spotted on video records makes EM a very efficient tool for this purpose. This efficiency of EM in the field of by-catch registration of cetaceans is also reflected in the increasing number of activities organized by the Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS). The US regulatory programme to mitigate impacts on marine mammals in commercial fisheries potentially will also have an impact on the uptake of EM in the future (Michelin et al., 2018).

A fast-growing area of EM application is fisheries in remote areas, where monitoring fisheries is challenging, inefficient and costly. Examples are the West and Central Pacific Islands, Indian Ocean and South Georgia. Electronic monitoring is a solution for enhancing existing observer programmes in these fisheries where extreme weather conditions, high safety risks and long distances make administering observer programmes difficult and EM is much less of a financial burden than an on-board observer (Ruiz et al., 2015; Stanley et al., 2015). Also, issues of on-board accommodation, food, getting an observer in and out of remote locations do not exist with EM. In situations where the fishing industry has the responsibility, also financially, to monitor fishing activities, and where monitoring coverage is high, monitoring costs are a factor for an increased adoption of EM. In addition, EM put less constraints on the planning of fishing trips. Of course, when monitoring levels are minimal, the cost of buying and installing EM is higher than having an observer once every other year.

4.3 | Uptake of EM worldwide

Despite the apparent advantages of using EM systems in pilot studies, and successful EM programmes in some areas, fleet-wide implementation in globally important fishing regions is progressing slowly. This slow uptake of EM can be attributed to several factors:

1. EM is often proposed as a compliance tool. This works well in situations when there is a common need to solve a compliance

issue in the industry, for example the British Columbia, "Area A" crab fishery programme (McElderry, 2006) and the Groundfish Hook and Line Catch Monitoring programme in British Columbia (Stanley et al., 2015). However, in several cases EM was presented as a promising tool to monitor compliance in situations where full accountability seemed like an existential threat to the viability of the fishing industry (Michelin et al., 2018). This is especially true in fisheries with strong restrictions on discards and by-catches, like fisheries under the landing obligation in the EU, where fishers have become dependent on discarding the most limiting quota that would lead to early closures of the fishery, the "choke" species. Not surprisingly, EM has faced significant opposition from parts of the fishing industry in this region (Michelin et al., 2018; Plet-Hansen et al., 2017).

2. Costs of EM adoption are clear for the fishing industry, but the long-term benefits are not. While implementation costs are often covered through government funds, running costs and data analysis costs are generally at the expense of the industry (NOAA, 2017a). Meanwhile, potential benefits for individual fishers, for example market access, sustainability claims, improved traceability and data licensing, are not well documented and not always of direct interest to them.
3. Most pilot studies were not designed to initiate broad implementation. Commitment on what successful trials would trigger was lacking, and there was no plan for further development into full EM programmes (Michelin et al., 2018).
4. Most fisheries government agencies lack capacity and expertise, for example people capable of programme design and video review, to run fully implemented fleet-wide EM programmes. The implementation of such programmes requires large IT infrastructures to deal with the amount of data that EM generates in, for example, data transmission, data storage and data review. Many fisheries management agencies have no experience in setting up these infrastructures and are hesitant to commit to this effort. In the absence of support, individual fishery managers or regulators can be reluctant to implement EM schemes at scale (ICES, 2019; Michelin et al., 2018).
5. There is a strong perception of intrusion on the fishers' privacy. Mangi et al. (2013) point out that a large proportion of the fishing industry is not supportive in using EM for this reason. Besides privacy issues, the industry fears sensational use of footage, for example dolphin by-catch, liability and video manipulation (Michelin et al., 2018). Also, liability issues in the context of safety standards of work environment on-board can be an issue for vessel owners in cases where government institutions are requiring footage to monitor occupational health and safety regulations. Reluctance against EM regarding privacy issues and mistrust of data use is stronger for the proportion of the fishing industry without experience with EM (Plet-Hansen et al., 2017). Once EM is implemented and fishers have actual exposure to EM, they generally have a more positive perception of the tool and it is easier to have an informed dialogue about applications (Michelin et al., 2018; Plet-Hansen et al., 2017). In other words, most fishers that are familiar with camera set-ups on their vessels did not experience an intrusion of privacy because of EM.
6. In some cases, EM raises concerns about employment impacts, especially when it is likely that at-sea observer sampling schemes will be scaled back with EM. These concerns are more concrete in regions with higher unemployment levels and where observer programmes enhanced job creation, but can be mitigated by employing experienced observers for video review, fisher liaison, data processing and following up on anomalies in imagery (Michelin et al., 2018). This may be preferable in the context of work–life balance, health and safety, since it allows staff to remain onshore.

4.4 | EM and the European Landing Obligation

A phased implementation of a landing obligation (LO) (EU, 2013) is implemented in the context of the European Common Fisheries Policy (Borges, 2015; Holden, 1994). Fully implemented and enforced the LO require fishers to report all catches of TAC species to be deducted from the quota. However, in practice non-compliance is potentially introduced (Batsleer, Poos, Marchal, Vermard, & Rijnsdorp, 2013; Borges, Cocas, & Nielsen, 2016; Condie, Grant, & Catchpole, 2013; Msomphora & Aanesen, 2015). Fishers are incentivized to continue to illegally discard low-valued fish to retain quota to fish for more valuable catches of the same species later and to prevent exhaustion of the most limiting quota that would lead to early closures of the fishery, the so-called "choke" effect (Batsleer, Hamon, Overzee, Rijnsdorp, & Poos, 2015; Baudron & Fernandes, 2015; Eliasen, Papadopoulou, Vassilopoulou, & Catchpole, 2014; Hatcher, 2014; Mangi & Catchpole, 2013; Ulrich, Reeves, Vermard, Holmes, & Vanhee, 2011). Without additional or alternative tools for control and monitoring and/or a different set of incentives for fishers to fish more selectively, it has been anticipated that the LO will thus introduce more uncertainty into stock assessments and potentially jeopardize the chances of success of achieving the maximum sustainable yield (MSY) objective.

Electronic monitoring is often considered a potential candidate and, more importantly, the only financially affordable alternative, for full catch documentation under the LO (Aranda et al., 2019). An important constraining factor of implementing a full EM programme, within the context of the LO, is that EM is considered as a mechanism to monitor compliance. Such compliance-driven measures involving EM were only successful when there was support from the fishing industry. Incentives to gain support for EM would potentially improve the situation under the LO. For example, experiments with increased flexibility in gear choice (Mortensen et al., 2017), individual quota uplifts (van Helmond et al., 2016; Kindt-Larsen et al., 2011; Needle et al., 2015) and permission to enter closed areas (Needle & Catarino, 2011) have proved that incentives can make EM successful.

With regular feedback to the fishers, EM data can be used to inform on discard avoidance, and spatial distribution of unwanted catches, and could be disseminated on knowledge sharing platforms (Bergsson & Plet-Hansen, 2016; Bergsson et al., 2017; Needle et al.,

2015). Electronic monitoring systems would have the potential to become a valuable information stream, for example, for the fishing industry to enable them to avoid unwanted catches or inform each other about real-time move-on rules.

4.5 | Enhancing the implementation of EM

Electronic monitoring as a monitoring tool contains a range of solid strengths that are not diminished by its weaknesses and EM has the opportunity to be a powerful tool in the future monitoring of a wide range of different types of fisheries. Electronic monitoring can be used to fully document a fishery or be integrated with existing data collection programmes, for management and compliance purposes or scientific data collection. Nevertheless, the viability of EM depends largely on how a range of threats are dealt with. Changes in the political landscape make the future of EM unpredictable; the end of the Fully Documented Fisheries programme in Denmark was the result of governmental change with a different view on fisheries management. Another important liability is its very low acceptance by the fishing industry. If EM is to be implemented as a monitoring tool, then turning this threat into an opportunity is the biggest challenge for EM, shifting the perception that EM is only fit for fisheries management and compliance objectives. In other words, changing the association of EM from being a "Big Brother" perspective to "giving the responsibility back to the fishing industry" in a results-based approach. During the whole process of implementation, including the design and planning phases, involvement and participation of fishers are crucial (Stanley et al., 2015). In such a results-based approach, fishers are accountable for the impact they create on the marine environment (full documentation of catches), and EM should be used as a way for them to prove the reliability of their documentation, in the spirit of the "black boxes" used in trucks and flights. Also, a marketing role is foreseen for EM: consumers would like to know the provenance or sustainability of the product they are buying. A growing number of seafood retailers are planning to link EM with traceability systems that allow for complete and transparent "net-to-plate" origin stories (Michelin et al., 2018). As part of this paradigm shift, additional issues such as hacking and data misuse will need to be addressed before a wide implementation can be completed, which requires discussions on data ownership, data storage facilities and access. Another underlying threat is the lack of evidence that EM is, in fact, less expensive than on-board observers in large-scale monitoring programmes.

In summary, EM as monitoring tool contains a range of solid strengths, that are not diminished by its weaknesses and EM has the opportunity to be a powerful tool in the future monitoring of the fisheries, integrated with existing data collection programmes.

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DATA AVAILABILITY STATEMENT

The data, summarized information subtracted through literature review, that support the findings of this study are available from the corresponding author upon reasonable request.

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