Validating the fishing locations reported in the logbooks using the positional data of vessel monitoring systems in the multi-day fishery of Sri Lanka

Nuwan D.P. Gunawardane[1], Mapalagama M. Ariyarathna[1], Upali S. Amarasinghe[2] and M.D.S.T. de Croos[3]*

[1]*Department of Fisheries and Aquatic Resources, New Secretariat, Maligawatte, Colombo 10, Sri Lanka*
[2]*Department of Zoology and Environmental Management, University of Kelaniya, Kelaniya 11600, Sri Lanka*
[3]*Department of Aquaculture and Fisheries, Faculty of Livestock, Fisheries and Nutrition, Wayamba University of Sri Lanka, Makandura, Gonawila (NWP) 60170, Sri Lanka*

*Corresponding author (E-mail: dileepa_dc@yahoo.com; dileepad@wyb.ac.lk)

ORCID ID: https://orcid.org/0000-0003-4449-6573

Received: 07.11.2022 Revised: 27.02.2023 Accepted: 01.03.2023 Online: 15.03.2023

Abstract As part of monitoring, control and surveillance of marine fisheries, a logbook monitoring and vessel monitoring system (VMS) were introduced for multi-day fishing. The present study investigates the possibility of using VMS data to validate logbook records of fishing locations of multi-day fishing vessels. The data from 1,424 multiday vessels were fitted with VMS, which was operated from May 2017 to April 2018. During the period, there were 17,626 fishing trips and 66,717 fishing occasions. In the VMS tracks where the locations were flooded, drift gillnet-operated vessels were seen as a condensed zig-zag pattern, while longline fishing vessels as curve-shaped tracks, and ring net fishing vessels as condensed locations had irregular-shaped clumps. The differences in coordinates of fishing locations in the logbook records matched with the tracks predicted by VMS in multi-day boats of three gear types indicating that almost all fishing operations were within ±10º of both latitudes and longitudes and further around 70% of fishing locations had less than 1 arcminute of a difference. Therefore, VMS track data can be used to verify and validate logbook records of fishing locations in multi-day vessels.

Keywords: Indian Ocean Tuna Commission, IUU fishing, logbook data validation, MCS of marine fisheries

INTRODUCTION

After the adoption of the United Nations Convention on the Law of the Sea (UNCLOS) by maritime countries in 1982, a new legal framework for ocean resources provided rights and responsibilities for the coastal states to manage and use fishery resources within the areas of their national jurisdiction. Regional Fisheries Management Organisations (RFMOs), which have been established by countries with fisheries interests in a given geographical area, are generally responsible for managing fish stocks under the legal provisions of UNCLOS. In the Indian Ocean, the RFMO focuses on highly migratory fish species, (particularly tuna species), known as the Indian Ocean Tuna Commission (IOTC), which develops and provides guidelines for legally binding conservation and management measures for member states to implement (IOTC 2018).

In this regard, monitoring, control and surveillance (MCS) of marine fisheries, which is the mechanism for implementation of agreed policies, plans, or strategies for oceans and fisheries management (Flewwelling 1995), has been recognized globally for sustainable management of marine fisheries. Illegal, unreported and unregulated (IUU) fishing is treated as actions, which do not comply with national, regional, or global fisheries conservation and management obligations. The IUU includes, according to the definition of the FAO international plan of action to prevent, deter and eliminate IUU fishing (IPOA-IUU), *inter alia* fishing activities conducted by national or foreign vessels in waters under the jurisdiction of a state (i.e., exclusive economic zone or EEZ), without the permission of that state, or in contravention of its laws and regulations (FAO 2001). The IUU fishing is a major threat to the sustainable management and conservation of world fisheries (Petrossian 2015).

The international plan of action to prevent, deter and eliminate IUU fishing adopted by FAO in 2001 (FAO 2001), has been endorsed by the European Community. Accordingly, European Union has established a system to prevent, deter and eliminate IUU fishing (European Union 2008). Following non-legally binding international instruments framed under the UNCLOS, many maritime countries have implemented regulations to prevent IUU fishing under the national MCS strategies (Kao 2015). In Sri Lanka, a logbook monitoring system was introduced in 2012, as part of MCS for multi-day fishing. However, Sri Lanka failed to fulfill the international standards for preventing IUU fishing. As a result, European Commission (EC) issued a 'yellow card' to Sri Lanka in November 2012 under the legal provisions of EC Council Regulation No. 1005/2008 concerning the export of fish and fishery products to EU countries. The EC requested the fisheries authorities of the country, to avoid Sri Lanka being identified as a non-cooperating country, to establish and implement an action plan to rectify the shortcomings of plans to prevent IUU fishing. As the fisheries authorities have unheeded EU directives, EC issued a 'red card' to Sri Lanka in January 2015, specifying the number of shortcomings in Sri Lanka's efforts to act against IUU fishing (Gunawardane and Fernando 2016). These shortcomings include the failure to adopt an adequate legal framework to implement international law obligations, the lack of an adequate and efficient monitoring system, the lack of a deterrent sanctioning system, and the failure to comply with international obligations including the recommendations and resolutions of RFMOs, and the United Nations IPOA-IUU.

As part of the road map to revoke the EU fish export ban, fisheries authorities of Sri Lanka introduced a vessel monitoring system (VMS) in late 2015 and made it compulsory for all multi-day fishing vessels for obtaining certificates for the export of fish and fishery products. For the implementation of measures to prevent IUU fishing, which might include fishing in EEZs of other maritime states, illegal trans-shipment of fish catches without reporting, etc. several management measures have been taken by the Sri Lankan government, which included amongst others, making it compulsory submission of a logbook by every fishing boat to enter fisheries harbours (Sandaruwan and Weerasooriya 2019). As a result, however, upon realization of shortfalls in recording correct fishing locations in the logbook recording systems, attempts were made by fisheries authorities of Sri Lanka to validate logbook records using VMS data, as reported elsewhere (e.g., Gerritsen and Lordan 2011; Chang 2011).

Verification of logbook data using VMS data is a widely used procedure in many fisheries elsewhere. For example, in the California groundfish (i.e., demersal fish) fishery, attempts were made to assess the accuracy of logbook data using VMS data (Thomas-Smyth 2013). Palmer and Wigley (2009) have shown that VMS-based methods of the positioning of fishing locations, although not a replacement for logbook-based methods of reporting, could be used to validate and improve the accuracy of logbook data of fishing vessels in northeastern U.S. fisheries. In the Danish Skagerrak–Kattegat fishing fleets, 52–56% of the VMS positions were perfectly matched, 14–18% partially matched and 30% failed to match the logbook data (Bastardie et al. 2010). The worldwide need for processing, analyzing and visualizing logbook and VMS data for MCS of marine fisheries is exemplified by the availability of open-source software for the purpose (Anon. 2021a).

Although the EU lifted the fish import ban and delisted Sri Lanka (White 2016), to avoid the future risk of re-introduction of the EU ban, long-lasting solutions are needed to be introduced for effective national MCS strategies. Logbook records essentially consist of fishery-dependent data, but it is often proclaimed that scientific analyses based on them are questionable due to the notion that logbook data are unreliable and not verified as accurate (Gunawardane 2016). To our knowledge, falsification of logbook data may occur unintentionally due to the reason that fishers do not record fishing locations simultaneously with fishing operations, but at a later stage with a guestimate of latitude and longitude coordinates, making the recorded location potentially different from the actual fishing location. It was also not uncommon that there were instances of intentional misrepresentation of fishing locations, especially when fishing operations were performed illegally, for example in an illegitimate area such as an EEZ of another country. As VMS tracking data may contain duplicate values for a given fishing location, before matching logbook data with VMS data, certain cleaning-up procedures are necessary. In the present analysis, an attempt is made to investigate the possibility of using VMS data to validate logbook records of fishing locations of multi-day boats operated from 21 fisheries harbours of Sri Lanka over a period of 12 months from May 2017 to April 2018.

MATERIALS AND METHODS

The data in the present study were from 1,424 multiday vessels fitted with VMS and operated in both EEZ and high seas. They were operated from 21 fishery harbours of Sri Lanka over a period of 12 months from May 2017 to April 2018. During this period, 17,626 fishing trips having 66,717 fishing occasions, had been recorded by the Fisheries Monitoring Centre (FMC) in Sri Lanka. Raw VMS data (n = 2,262,340) of these fishing trips and fishing occasions were received from the FMC.

The fishery

During 2017-2018, there were 1,281 -1,346 in-board multi-day boats (IMULs) engaged in high-seas fishing and 2,850-3,300 IMULs engaged in fishing within the EEZ (Anon. 2021b). These boats are mainly engaged in drift gillnetting, tuna longlines and flotsam-associated fisheries using surrounding nets. In Sri Lanka, fisheries authorities labeled these encircling nets as ring nets, although they exactly do not conform to the definition of the Food and Agriculture Organization of the United Nations (FAO 2022) (i.e., a form hybrid between a purse seine and a lampara net). In the present study too, the term 'ring net' is used to describe flotsam-associated surrounding nets. This fishing method is ubiquitous in the IMUL operated from the fishery harbours of southern Sri Lanka (Ariyarathna and Amarasinghe 2012). The total duration of a fishing trip of an IMUL varies from 5 to 30 days (Hewapathirana *et al.* 2015), which essentially depends on the fish holding capacity in the vessel, limited deck space and the manual operation of fishing gear.

Nature of data

The present analysis was based on two types of data from the multi-day fishing boats, i.e., log book data provided by multi-day boat skippers and VMS data of the FMC. Since 2012, the Department of Fisheries and Aquatic Resources (DFAR), Sri Lanka had introduced manual logbooks to collect location-wise catch data, to meet the obligatory requirements of IOTC resolutions and as a crucial step in managing IUU fishing. Furthermore, since 2015, logbook data were decisively combined with the offshore/deep-sea fisheries management process of Sri Lanka under the road map to revoke the EU fish export ban. Log sheets of each multiday fishing vessel were collected and verified in the fishery harbours. Here, the fisheries officer on duty at the harbour inspects the vessels and compares the harvest landed with the details given in log sheets. Certified log sheets related to the fishing operations/ trips are collected and data are entered into a database held in a SQL server. Logbook data consisted of, amongst others, data on the latitude and longitude of the fishing location.

Since 2015, fishing activities of all the vessels having licenses to fish in the offshore/deep-sea have been monitored by VMS. Although the VMS signals do not indicate whether a vessel is fishing, navigating, or stationary, there have been several attempts to use the information on vessel speed to infer whether a VMS record corresponds to fishing activity (e.g. Murawski *et al.* 2005; Walter *et al.* 2007; Palmer and Wigley 2009; Lee *et al.* 2010; Gerritsen and Lordan 2011).

Each vessel had a text file of VMS records of each fishing trip, which contained the data on the course speed of the boat in four-hour time intervals, latitudes and longitude of the position recorded in four-hour time intervals, and whether the boat is located within EEZ of Sri Lanka or high seas at a particular point. The text files of VMS records of the above vessels, collected from the FMC of Sri Lanka, contain various VMS signals or alerts including location data in every 4-hr time intervals coded as TPREP and 'all clears' coded as ALCLR, the signals received in less than 30-min time intervals that represent flooding in the map to identify fishing locations. Through the signal type TPREP, the location and the speed of the vessel can be used for the analysis.

Matching logbook data with VMS data

Data logs are generally required to be filled by the skipper of the boat at the sea during fishing operations. They contain, amongst others, details of fishing locations based on the readings of GPS available at the fishing boat. However, as mentioned above, the reliability of logbook data is questionable due to perceived malpractices of data log recording. As such, verification of data logs for their accuracy is important. For this purpose, fishing locations were inferred from VMS data assuming cruise speed could be determined from the nature of VMS records, which would represent whether the vessel is fishing, navigating, or stationary (Mendo *et al.* 2019). As mentioned above, VMS tracking data may contain duplicate values for a given fishing location. As such, VMS data were cleaned before analysis.

Cleaning the VMS data

In Sri Lanka, FMC treats the reference speed of 3 knots or less as the vessel's cruising speed during fishing. However, verification of fishing at this cruise speed was needed through auxiliary evidence such as statements of crew members and logbook data. This was necessary because low vessel speed could also occur due to reasons other than fishing such as cruising in search of a fishing location, slowing down due to weather conditions, engine troubles, etc. As the VMS tract corresponds to fish movement, the animal-movement tracking approach in wildlife research is appropriate for tracking fishing vessels using VMS data. As such, an approach similar to cleaning animal-movement tracking data in wildlife studies, where the speed, distance, and angle filter are used, was adopted in the present analysis (Gurarie *et al.* 2009). This process identifies maximum and minimum speed parameters, maximum distance traveled, and the angle that three consecutive points create. The speed of < 3 knots, which was considered the general vessel cruising speed during fishing, was filtered and included for the analysis of VMS data. For the angle filter, a conservative minimum angle size of 15° was used (Fig. 1), which was assumed to be useful to remove erroneous data points (i.e., spikes) in the data track. From this procedure, a zig-zag pattern or sudden changes in direction of the vessel could be detected. The instances that fishing locations are clearly shown in the track are known as VMS flooding. In these instances, instead of the standard time interval of 4 hrs for receiving VMS data, the system was adjusted to receive data for shorter time intervals (i.e., time intervals of a few minutes). VMS signal type, ALCLR represented the locations of the vessels that were received in less than 30 min. time intervals when flooding was plotted on a map to identify the fishing locations. The TPREP signals, which represented the standard location data for 4-hr time intervals were also plotted on the same map to calculate the angle of the consecutive data points of VMS data. Also, in this approach, points that did not contain heading (bearing) information could be included. In such instances, the haversine formula (Chang and Yuan 2014; see below), which would determine the great-circle distance (*d*) between two points on a sphere given their longitudes and latitudes was used to calculate a bearing field.

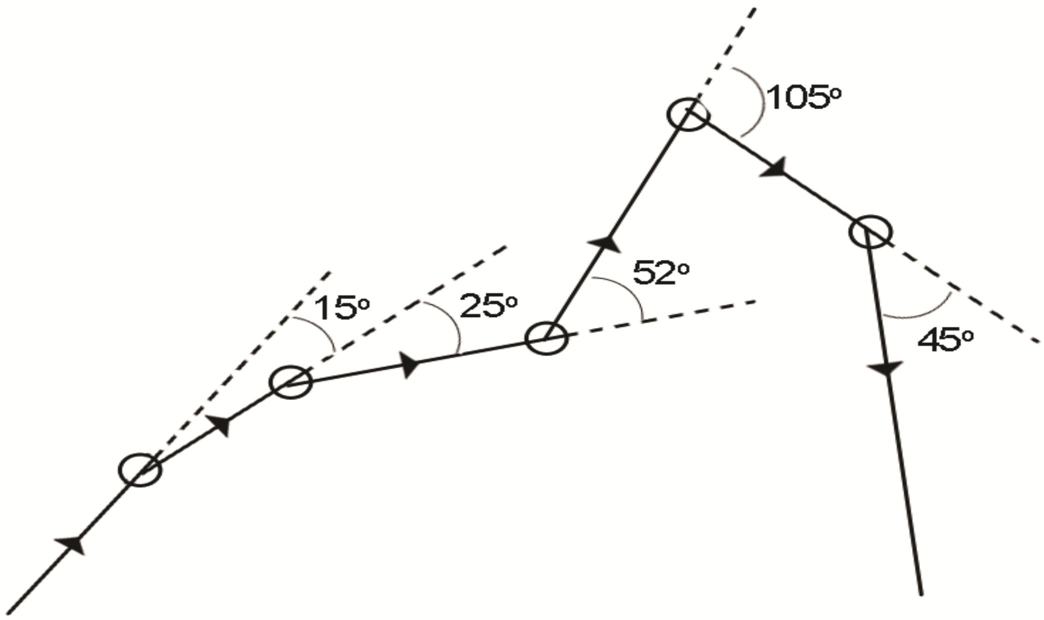

Fig 1 Diagrammatic representation of calculating the angle of the consecutive VMS location data

Haversine formula:

$$d = 2\mathrm{r}\ \mathrm{arcsine}\left[\sqrt{\sin^2\left(\frac{\emptyset_1 - \emptyset_2}{2}\right) + \cos\emptyset_1 \cos\emptyset_2 \sin^2\left(\frac{\partial_1 - \partial_2}{2}\right)}\right]$$

Here, the distance (*d*) was calculated using the haversine formula at two positions P1 = (ø1, ∂1) and P2 = (ø2, ∂2), where ø and ∂ represent their latitude and longitude, respectively.

For each fishing trip, selecting individual VMS points that represent the actual fishing activity would be necessary. For this purpose, a crude distance selection was made. The following three different 'matched' fishing data sets were used in the analysis (Thomas-Smyth 2013).

(1) In the first option, the fishing date and position given by the skipper of the boat were considered as the main reference value. The VMS alerts were generated in 4 hrs time intervals, and as such, the fishing location might not be 100% matched with the VMS location even if the skipper has recorded the exact catch location. Therefore, a buffer of 4 hrs was applied in the analysis. For this purpose, the time buffer was converted into distance assuming that the maximum distance of boat travel within 4 hrs (when fishing) was 12 nautical miles or approximately 0.020° (at a speed of maximum 3 knots). This was based on the distance between one degree of longitude, which was about 60 nautical miles at the equator. Since most of the fishing locations of multiday boats operating off Sri Lanka were close to the equator, the distance in nautical miles was divided by 60 to convert the distances to a degree of latitude and longitude.

(2) Secondly, it was possible that fishing operations of Sri Lankan multiday fishing vessels could be extended up to 10-12 hrs. The fishing location reported by the skipper thus could be any location within that time period. Therefore, the second option was to consider VMS points within a time period of 12 hrs from the fishing location provided, so that the buffer of 12 hrs was applied. Here, it was

assumed that the maximum distance of a boat travel during an operation (when fishing) was 36 nautical miles or approximately 0.60º (at a speed of maximum 3 knots per hrs). The distance buffer was calculated based on the same assumptions above.

(3) In the third option, all VMS points within the exact time frame of the logbook fishing date were selected. Here, the fishing date given by the skipper of the boat was considered as the reference value and all VMS points within that date (24 hrs) were considered as the possible catch locations. It was also possible that the skipper records one fishing location within a day, and this location might not necessarily be the location where the fishing took place. Therefore, it was necessary to consider the matches during the day to determine the possible catch locations. Here, no distance calculation was adopted since all possible locations were considered. However, the distance difference between the nearest VMS location and the reported location was calculated using a latitude/longitude distance calculator (NOAA 2019) to determine the accuracy of the skipper's records.

Speeds of greater than 10 knots were considered as outliers, and in any case, were automatically removed when the data were filtered by speed < 3 knots. Also, boats representing less than 0.05% of the dataset of speed limit distribution were removed from the analysis. Fishing locations from logbook records and those which were predicted by VMS tracks, having filtered by speed < 3 knots, were categorized into grid values of one-degree square (60 × 60 nm). If both values overlaid within a grid, the two location values were treated as similar.

In the multiday fishing fleet operating off Sri Lanka, there are three types of boats targeting large pelagic fish species, viz. drift gillnet boats, longline boats and ring net boats. In the VMS tracks, normal reporting locations and flooding locations (i.e., rare situations of generally <1% due to some technical problems in transponders), where fishing was assumed to be performed, could be easily identified. As such, all these locations were mapped using that data that were recorded in a single file of a SQL database. To judge the types of fishing operations in the flooding locations of the VMS tracking maps, their patterns were visually identified also using auxiliary evidence such as statements of crew members and logbook data. Here, the comparison of the VMS and logbook track data were done by MySQL script and Microsoft queries in MS excel (data merge function). Visualization of the overlap of the flooding and VMS tracks was performed via Google maps.

The above filters were then used to match the VMS locations with the fishing occasions reported by skippers via the logbook data. Here, both the logbook locations and VMS data were recorded in a SQL database. Both data sets were converted to MS Excel® tables. The three filters (i.e., speed, angle and distance buffers) were applied to VMS data and data that were not matched with them were removed. If a location matched with VMS data via the above three filters, such location was considered as a matched location, otherwise, it was categorized as an unmatched location. Matched locations were determined for all three filtered separately and in combination. Percentage-matched locations were then calculated as an index of the accuracy of the logbook data of skippers.

RESULTS

Distributions of speed limits recorded by VMS alerts matched with the nearest fishing locations for the boats of all three fishing methods are shown in Figure 2. There were 982 VMS alerts representing less than 0.05% of the dataset of speed limit distribution, which was removed from the analysis. The speed levels between 0.1- 3.0 knots were considered to indicate fishing activities, and those between 3.0 – 8.0 knots indicated steaming of the vessel.

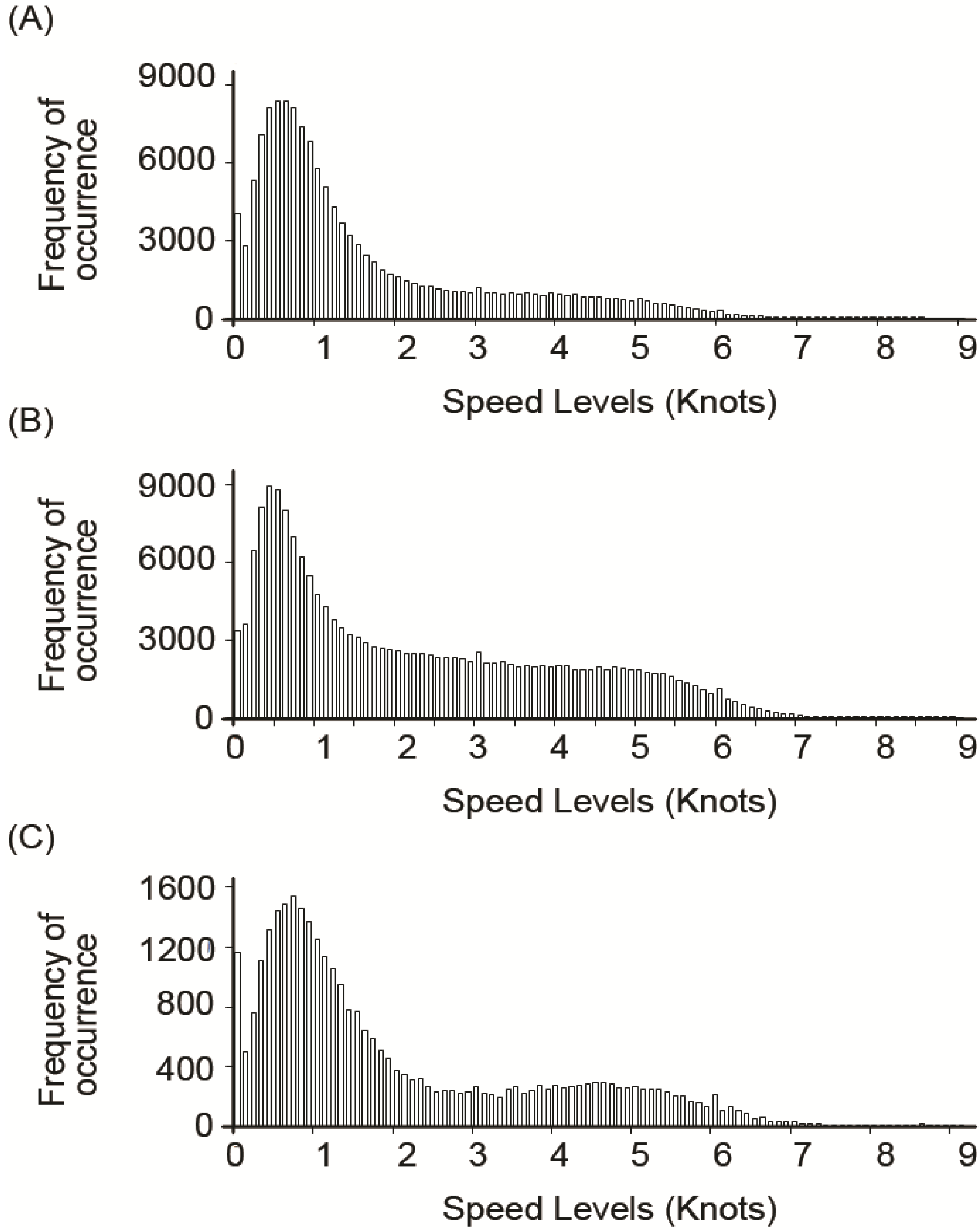

Fig 2 Frequency distribution of vessel speed by gear types. (A) Drift gillnet boats; (B) Longline boats; (C) Ring net boats

The patterns of VMS tracks of the three methods of fishing operations of multi-day boats are shown in Figure 3. Here, fishing operations of drift gillnet boats were illustrated as condensed zig-zag patterns (Fig. 3A). The VMS tracks of longline fishing vessels had curve-shaped tracks (Fig. 3B). The VMS tracks of condensed patterns having irregular-shaped clumps were considered as fishing operations of ring net fishing vessels (Fig. 3C).

However, these patterns could only be seen in high-frequency flooding maps. In normal tracks based on 4-hr time intervals, all vessel movements were seen as zig-zag patterns. Hence, locations of zig-zag patterns recorded as angles <15°, were assumed to be of the speed of ≤3 knots representing fishing operations. As mentioned above, the VMS signal type, ALCLR represented flooding data. The positional data of the multi-day boats of three fishing methods of logbook records and corresponding positions predicted by VMS through three buffers (i.e., 4 hr, 10-12 hr and 24 hr) in selected grids are shown in Figure 4. They indicate the relative accuracy of VMS-based prediction of fishing positions.

Speed and cause (angle) were adopted for 24 hrs buffer to find out the possible matches (Thomas-Smyth 2013). Here, VMS positions of a speed of less than 5 or 3 knots with an average cause (angle) of ≥15º were compared with fishing locations provided by skippers of the boats of all three fishing gear types. Data harmonized with the above criteria within one day (24 hrs) were considered as matched. The mean deviations (in degrees) of reporting locations and matching with locations of VMS prediction for drift gillnet boats, long line boats and ring net boats were determined separately.

For occasions where the speed was ≤3 knots and the cause ≥15º, 12 hrs and 4 hrs filters were applied. Results for boats using each gear type are given in Table 1. It was, therefore, evident that 75.2% (= 100 – 24.8) boats were reporting fishing within 12-24 hrs after fishing and that 89.7% (= 100 – 10.3) boats were reporting their fishing location after 4 hrs (Table 1), which must have been resulted due to the differences of reporting of the fishing location.

The VMS location data matched with fishing locations provided by skippers for the boats in 24 hrs buffer for speed filter of ≤ 5 knots and of ≤ 3 knots categorized according to the three types of fishing gears used (Table 2). Based on the assumption that boats would be reducing their speed down to 3 knots when fishing, there were only 4.7% (= 85.1% - 80.4%) occasions, where boats were fishing within the speed range of 5 to 3 knots (Table 2).

The VMS location data matched with fishing locations provided by skippers for the boats of three gear types in a 24-hr buffer for speed and cause (angle) limits are given in Table 3. There were only 0.09% (= 81.6% - 81.5%) occasions where boats were fishing within the range of 5 to 3 knots with a cause (angle) of ≥15º (Table 3). Therefore the 3 knots limit could be applied as the reference limit for fishing speed for boats of all three gear types.

The mean deviations (in degrees) of reporting locations and matching with locations of VMS prediction for drift gillnet boats, longline boats and ring net boats were 0.963 ± 0.009, 1.142 ± 0.010 and 1.496 ± 0.022 respectively, with the overall mean deviation of 1.266 ± 1.856 (Table 4). Also, differences of greater than 10 degrees were considered as outliers. However, in 4 hrs buffer, only around 10% of the matching was possible. This was due to the reason that a single fishing operation that could last for a longer period, i.e., >12 hrs, would predict more than one VMS location for a single fishing occasion in 4 hrs intervals. In 12 hrs buffer, there was <25% matching with logbook records indicating that most of the fishermen were reporting fishing occasions 12-24 hrs after fishing. The difference in coordinates of latitude and longitude for matched VMS and logbook records of fishing locations of multi-day boats of three gear types are shown in Figure 4. They indicate that the differences in almost all fishing operations of multi-day boats of all three fishing methods were within ±10º of both in latitudes and longitudes. Of the vessel movements, there were 66,717 instances of fishing operations, 89,553 instances of potential fishing activities and 26,134 instances of potential cruising predicted by VMS alerts.

The percentage frequency distribution of the differences of fishing locations in the logbook records and VMS predictions of these 66,717 fishing operations by multiday boats is shown in Figure 5. This indicates that approximately 70% of fishing operations had a difference in a fishing location of less than 1 arcminute (1 arcminute ~ 1 nautical mile; Anon. 2003).

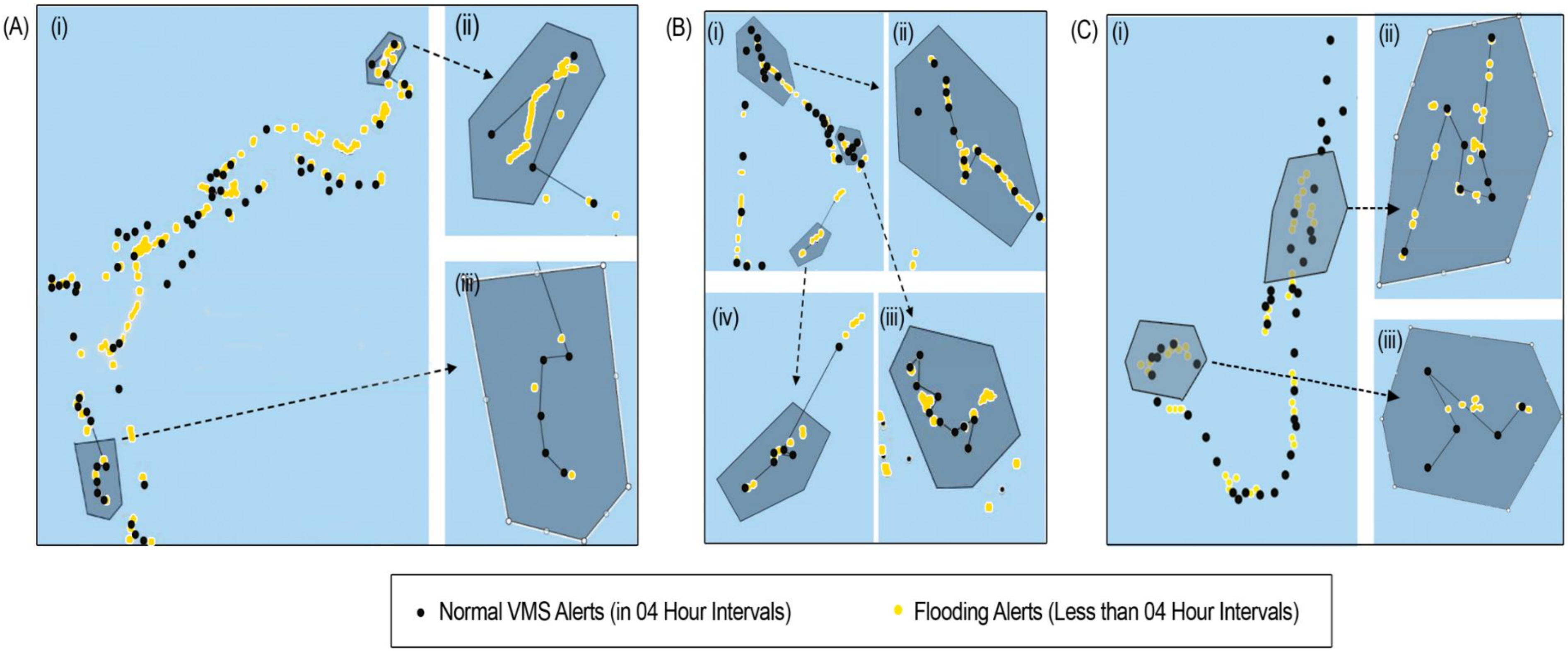

Fig 3 Flooding (yellow colour) and normal (black colour) VMS data of [A(i)] a drift gillnet vessel, [A(ii), (iii)] two enlarged portions of VMS track; [B(i)] a longline vessel, [B(ii), (iii), (iv] three enlarged portions of VMS track; [C(i)] a ring net vessel, [C(ii), (iii)] two enlarged portions of VMS track

Table 1 Number of matched occasions and percentages in each gear type with speed filter of ≤ 3 knots and the angle of ≥15º for two distance filters of 12hrs and 04 hrs

Gear Type	Fishing occasions	Number of matched occasions with speed filter of ≤ 5 knots and the angle of ≥ 15º		Number of matched occasions with speed filter of < 3 knots and the angle of ≥15º	
		No.	%	No.	%
Drift gillnets	26,424	21,818	82.6%	21,807	82.5%
Longline	33,817	27,451	81.2%	27,424	81.1%
Ring net	6,476	5,171	79.8%	5,160	79.7%
Overall	66,717	54,440	81.6%	54,391	81.5%

Table 2 VMS location data matched with fishing locations provided by skippers for the boats of three gear types in 24 hrs buffer for speed filter of ≤ 5 knots and of ≤ 3 knots

	Fishing occasions	Number of matched occasions with speed filter of ≤ 5 knots		Number of matched occasions with speed filter of ≤ 3 knots	
		No.	%	No.	%
Drift gillnets	26,424	23,001	87.1%	22,993	87.0%
Longline	33,817	28,366	83.9%	25,183	74.5%
Ring net	6,476	5,439	84.0%	5,428	83.8%
Overall	66,717	56,806	85.1%	53,604	80.4%

Table 3 VMS location data matched with fishing locations provided by skippers for the boats of three gear types in 24-hr buffer for speed and cause (angle) limits

Gear Type	Fishing occasions	Number of matched occasions with speed filter of ≤ 5 knots and the angle of ≥ 15º		Number of matched occasions with speed filter of < 3 knots and the angle of ≥15º	
		No.	%	No.	%
Drift gillnets	26,424	21,818	82.6%	21,807	82.5%
Longline	33,817	27,451	81.2%	27,424	81.1%
Ring net	6,476	5,171	79.8%	5,160	79.7%
Overall	66,717	54,440	81.6%	54,391	81.5%

Table 4 Deviation of reported fishing location from matched VMS locations (in degrees)

Gear type	Fishing occasions	Mean deviation (in degrees)	Standard deviation (in degrees)
Drift gillnet	26,424	0.963	1.413
Longline	33,817	1.142	1.930
Ring net	6,476	1.496	1.739
Overall	66,717	1.266	1.856

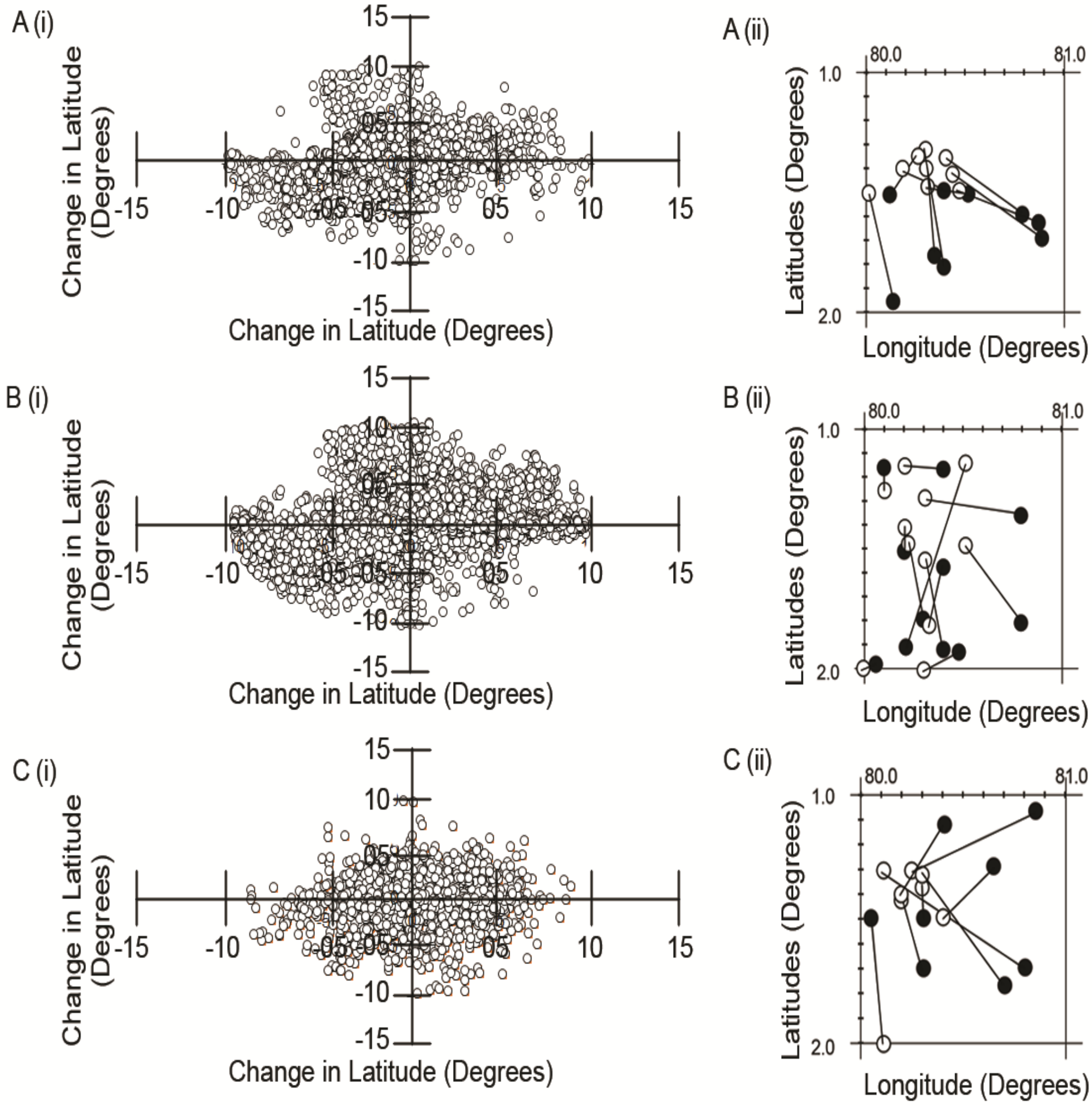

Fig 4 Graphical representation of the difference latitude and longitude coordinates for matched VMS and logbook records of multi-day boats of three gear types. [A(i)] drift gillnet boats; [B(i) longline boats; [C(i)] ring net boats. Representative grids showing deviation of fishing locations predicted by VMS (black dots) and those of logbook records (white dots), the corresponding locations of which are linked. [A(ii)] drift gillnet boats; [B(ii) longline boats; [C(ii)] ring net boats. Note: One degree is approximately 60 nautical miles near the equator.

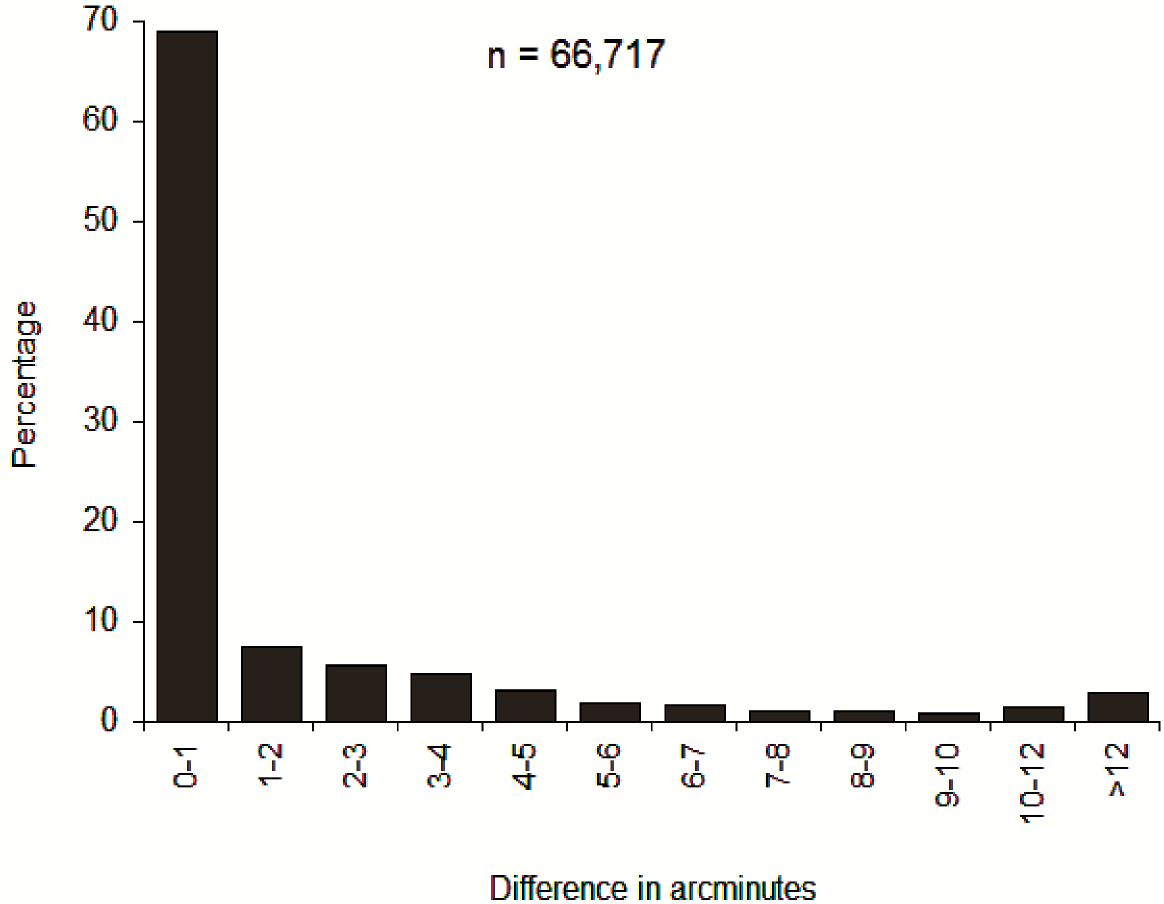

Fig 5 The percentage frequency distribution of the differences of fishing locations in the logbook records and VMS predictions of 66,717 fishing operations from multiday boats (1 arcminute ~ 1 nautical mile)

DISCUSSION

The present study shows that the accuracy of logbook records of fishing locations can be verified with reasonable reliability by using VMS track data based on the VMS alerts related to vessel speed of <3 knots and with the cruise angle records ≥ 15º. Although not strictly comparable, somewhat similar approaches are reported to be used elsewhere. For example, Gerritsen and Lordan (2011) used otter trawl data, and Thomas-Smyth (2013) and Marzuki (2017) used groundfish trawl data, which in all cases were with high resolutions. Validation of fishing locations reported in the logbooks for tuna fisheries using VMS is reported in the tropical Atlantic Ocean (Punzon *et al.* 2016), and in Seychelles (Nieblas *et al.* 2019). Also, the present study has shown a reasonable and cost-effective alternative for monitoring fishing activities of multi-day boats operating off Sri Lanka, based on the VMS validation procedure adopted by FMC. As evidenced from this study, around 70% of fishing operations were with a difference of <1 arcminute in fishing location between logbook records and VMS prediction. The mismatching of about 30% of fishing locations of logbook records with the VMS predictions should probably be due to wrong reporting by the skippers.

The present analysis, therefore, has shown that the fishing positions predicted by VMS through three buffers provided a fairly reasonable approach to improve positional data collection. VMS data further facilitates to identify and prevent possible illegal trans-shipment of catches of multi-day fishing vessels. Most multi-day boats operating in Sri Lanka, target migratory tuna and tuna-like large pelagic fish species using long line and drift gillnets (Hewapathirana *et al.* 2018), most notably yellowfin tuna, *Thunnus albacares* (Bonnaterre 1788) and skipjack tuna, *Katsuwonus pelamis* (Linnaeus 1758). These fisheries are of great importance to the national economy of Sri Lanka because the majority of the landings, especially *T. albcares*, are destined for the export market.

Further, the fishery of multiday boats using ring nets is essentially a flotsam-associated fishery (Ariyarathna and Amarasinghe 2012) targeting 'shade-philic' fish species such as Indian scad, *Decapterus russelli* (Rüppell 1830) and rainbow runner, *Elagatis bipinnulata* (Quoy and Gaimard 1825) that are by and large, locally consumed. As a member state of the IOTC, the RFMO that focuses on highly migratory fish species in the Indian Ocean, Sri Lanka is legally bound to implement guidelines for conservation and management measures (IOTC 2018). Apart from this, Sri Lanka being a major exporter of fish and fishery products to the European Union has to fulfill the international standards for preventing IUU fishing, stipulated under the mechanism of the European Commission Regulation (EC) No. 1005/2008 (European Union 2008). The implications of having a mechanism to detect correct positioning apart from monitoring of illegal fishing are that from the fisheries management point of view, such efforts would help control the utilization of the geographic, political and economic space by larger-scale economic and environmental conservation interests in the priorities in the ocean governance reforms, jeopardizing the substantial benefits of small-scale fisheries supporting many livelihoods (Cohen *et al.* 2019).

Therefore, having an improved logbook data system coupled with the VMS system might be useful for the enforcement of fisheries regulations under the guidelines of IOTC, which Sri Lanka has adopted to comply with. The logbook system that was introduced to the multiday fishery in 2011 took about 4 years to cover the multiday fleets. The logbook process was enhanced during the years 2015 and 2016 under the roadmap to revoke the fish export ban, imposed by the EU in January 2015, based on IUU fishing concerns (Gunawardane and Fernando 2016). However, there was no cost-effective method in Sri Lanka to validate the accuracy of fishing location records in fisheries logbooks, and subsequently, VMS was introduced in late 2015. Presently, the FMC of the Department of Fisheries and Aquatic Resources, Sri Lanka adopts the system depicted in Figure 6, for issuing catch certificates for exporting or for detecting IUU fishing, which facilitates issuing charge sheets for violating fisheries regulations. According to current practice, every vessel has to submit a departure form which is verified by a fisheries officer after inspection at the harbour, before departure. The details of the departure forms are verified by the coast guard at the harbour mouth. A copy of the departure form has to be kept in the vessel and will be re-checked with the conditions and details of the vessel upon arriving at the harbour. The catch data recorded in the log sheets are checked by the fisheries inspectors at the landing points. As a result, the effectiveness of this system for preventing IUU fishing has been evident due to a significant reduction in the rate of reported cases of IUU fishing from 35.2 per month to 1.25 per month respectively from September 2015 to January 2017 (Fisheries Monitoring Centre (FMC) records accessed by NDPG).

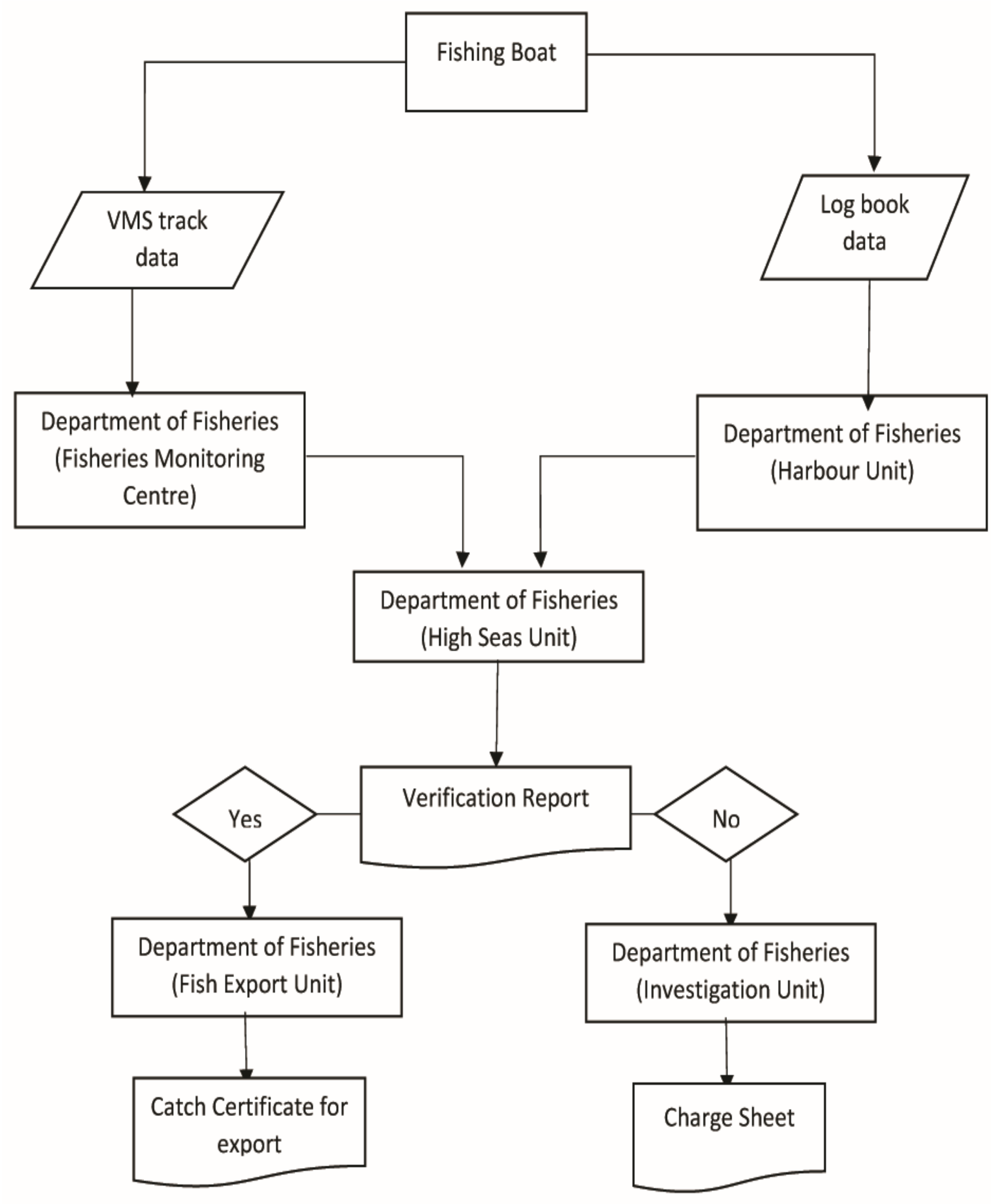

Fig 6 Fisheries data management system for multi-day boats in Sri Lanka

Even the logbook data recording system suffers its inherent weaknesses such as erroneous fishing locations that fishermen manually enter in the log sheets, and the practical difficulty of manually entering location data under the harsh conditions at sea especially due to the artisanal nature of the multi-day fishing vessels, validation of logbook records of fishing location is necessary to comply with IOTC guidelines and other international guidelines for monitoring high seas fisheries. This is of particular importance because, during the last 15 years, there has been a phenomenal expansion in the size of the multi-day fishing fleet in the Sri Lankan fisheries sector (Haputhantri and Maldeniya 2011). Thus, monitoring multi-day vessels has become a challenge in the current measures of fisheries management.

Moreover, the MCS of marine fisheries is a critical issue for the sustainable management of marine fisheries (Flewwelling 1995). This has become essential more than before due to the reason that after implementing the road map to revoke the EU fish export ban, mechanisms to combat IUU fishing have to be in place as management measures. Further, the VMS data are normally transmitted at 4-hr time intervals, but logbook data are occasionally reported just after the fishing operation is concluded. Therefore, it is not possible to automate the verification, unless the VMS can be transmitted in a 30-minute time interval, which is impracticable due to the associated cost.

Although this process is sufficient for fishing vessels to comply with legal requirements and law enforcement processes, it does not provide fishermen with a commercial advantage. As such, to seek the active participation of fishermen, possibilities of extending VMS-based monitoring for making other economic benefits to fishermen should be sought. It is reported that based on the cruise data of catch and effort of multi-day boats, VMS monitoring could be used to establish effective fish catch forecasting methods and catch allocation (Palmer and Wigley 2009). However, the overall difference in matched VMS and logbook records was narrower in ring net boats than in longline boats and drift gillnet boats (see Figure 4). This is mainly because the mode of operation of ring net in Sri Lankan waters is that the boat is allowed to drift with the ocean currents for several days until the crew members are convinced that a substantial quantity of fish is attracted to the flotsam before starting operation of ring net to encircle the fish schools (Ariyarathna and Amarasinghe 2012). As such, unlike in the boats of the other two fishing methods, skippers in ring-net boats have sufficient time for keeping accurate logbook records.

The current manual logbook recording system is adequate for multi-day fishing vessels to comply with the fisheries management regulations of the FMC and their enforcement. Although this system is bound to false reporting, mainly due to practical difficulties encountered by fishermen working on relatively small vessels, after fisheries authorities have taken steps to verify logbook records using VMS data, fishermen are compelled to avoid false reporting. However, it must be noted that VMS should not be an alternative to replace logbook-based methods of reporting.

Logbook data recording is mandatory for multi-day boats operating from Sri Lanka. Logbook and VMS data are now being used for the data verification system at the 'High Seas Operation Unit' of the DFAR of Sri Lanka. A verification report is now a compulsory requirement for fish exports. However, filling in the departure form, logbook data collection and verification and inspections are currently being conducted and reported manually. There are over 200 fisheries staff members assigned for the purpose, who are required to work in fisheries harbours 24 hours over a week on a rotational basis. Due to these inherent weaknesses in the logbook-based MCS of marine fisheries, an effective mechanism is necessary.

The present study shows that VMS data can effectively be used for logbook data verification of multi-day fishing boats landed in fisheries harbours of Sri Lanka. The findings of the present study are of global significance for MCS of marine fisheries, especially to contribute to the global effort to deter IUU fishing. In fact, the carding system of the European Commission Regulation (EC) No. 1005/2008, i.e., issuance of 'yellow card'. motivated countries such as Thailand and Ghana to take action on IUU fishing (Sumaila 2019). Sumaila (2019), based on his analysis, also stated that the economic risk to fish exporting countries would increase significantly if the United States and Japan also instituted similar carding systems, which would in turn help to reduce IUU fishing worldwide.

ACKNOWLEDGEMENTS

The authors are thankful to former Director General, Mr. M. C. L. Fernando and the present Director General, Mr. S. J. Kahawatta of the Department of Fisheries and Aquatic Resources for providing necessary approval for the study and information gathering. Special thanks are due to officials of the Fisheries Monitoring Centre, High Seas Operation Unit and Information Technology Division of the Department of Fisheries and Aquatic Resources for their kind assistance during the data-gleaning process.

REFERENCES

Anon. 2003. Ocean Navigator. Retrieved from http://www.oceannavigator.com/January-February-2003/Nautical-mile-approximates-an-arcminute/ (accessed April 2020)

Anon. 2021a. VMSTools R package to analyse VMS and Logbook data. Retrieved from http://nielshintzen.github.io/vmstools/ (accessed April 2021).

Anon. 2021b. Fisheries Statistics 2021. Ministry of Fisheries, Colombo, Sri Lanka. https://fisheries.gov.lk/web/images/statistics/annual_report/Fisheries_Statistics_2021_FINAL_PDF_compressed.pdf (accessed November 2022)

Ariyarathna, M.M. & U.S. Amarasinghe 2012. A fishery associated with floating objects in the Indian Ocean off Southern Sri Lanka. Asian Fisheries Science 25: 278-289. https://d oi.org/10.339 97/j.afs.20 12.25.4.001

Bastardie, F., J.R. Nielsen, C. Ulrich, J. Egekvist & H. Degel 2010. Detailed mapping of fishing effort and landings by coupling fishing logbooks with satellite-recorded vessel geo-location. Fisheries Research 106(1): 41–53. https://doi.org/10.1016/j.fishres.2010.06.016

Chang, S.K. 2011. Application of a vessel monitoring system to advance sustainable fisheries management benefits received in Taiwan. Marine Policy 35(2): 116–121. https://doi.org/10.1016/j.marpol.2010.08.009

Chang, S.K. & T.L. Yuan 2014. Deriving high-resolution spatiotemporal fishing effort of large-scale longline fishery from vessel monitoring system (VMS) data and validated by observer data. *Canadian Journal of Fisheries and Aquatic Science* 71(9): 1363-1370. https://doi.org/10.1139/cjfas-2013-0552

Cohen, P.J., E.H. Allison, N.L. Andrew, J. Cinner, L.S. Evans, M. Fabinyi, L.R. Garces, … B.D. Ratner 2019. Securing a just space for small-scale fisheries in the blue economy. Frontiers in Marine Science 6: 171. https://doi.org/10.3389/fmars.2019.00171

European Union 2008. Council Regulation (EC) No 1005/2008 of 29 September 2008, establishing a Community system to prevent, deter and eliminate illegal, unreported and unregulated fishing, amending Regulations (EEC) No 2847/93, (EC) No 1936/2001 and (EC) No 601/2004 and repealing Regulations (EC) No 1093/94 and (EC) No 1447/1999. Official Journal of the European Union L 286/1-L 286/32. Retrieved from https://eur-lex.europa.eu/legal content/EN/ALL/?uri=celex%3A32008R1005 (Accessed April 2021).

FAO 2001. International Plan of Action to prevent, deter and eliminate illegal, unreported and unregulated fishing. FAO, Rome. 24 p.

FAO 2022. Fishing Gear types. Ring nets. Technology Fact Sheets. Fisheries and Aquaculture Division [online]. FAO, Rome.[Cited 6th November 2022]. https://www.fao.org/fishery/en/geartype/250/en

Flewwelling, P. 1995. An introduction to monitoring, control and surveillance for capture fisheries. FAO Fisheries Technical Paper No. 338. FAO, Rome. 217 p.

Gerritsen, H. & C. Lordan 2011. Integrating vessel monitoring systems (VMS) data with daily catch data from logbooks to explore the spatial distribution of catch and effort at high resolution. ICES Journal of Marine Science 68 (1): 245–252. https://doi.org/10.1093/icesjms/fsq137

Gunawardane, N.D.P. 2016. Electronic logbook and electronic data verification module to enhance the standards of high seas fisheries management process of Sri Lanka. IOTC-2016-WPDCS12-14. Session of the IOTC Working Party on Data Collection and Statistics, 28-30 November 2016, Victoria, Seychelles. Indian Ocean Tuna Commission, Victoria, Mahé, Seychelles.

Gunawardane, N.D.P. & M.C.L. Fernando 2016. Significant modifications of the administrative structure and procedures to revoke the EU fish export ban. Symposium on Best Practices and

Innovations in Public Administration for Public Administrators, 18th August 2016, Colombo, Sri Lanka. Sri Lanka Institute of Development Administration (SLIDA), Colombo, Sri Lanka.

Gurarie, E., R.D. Andrewa & K.L. Laidre 2009. Novel method for identifying behavioural changes in animal movement data. Ecology Letters 12: 395–408. https://doi.org/10.1111/j.1461-0248.2009.01293.x

Haputhantri, S.S.K. & R. Maldeniya 2011. A review on billfish fishery resources in Sri Lanka. IOTC–2011–WPB09–28. Indian Ocean Tuna Commission, Victoria, Mahé, Seychelles.

Hewapathirana, H.P.K., N.D.P. Gunawardane & M.M. Ariyarathna 2018. Sri Lanka: National report to the scientific committee of the Indian Ocean Tuna Commission, 2018. IOTC-2018-SC21-NR25. Indian Ocean Tuna Commission, Victoria, Mahé, Seychelles.

Hewapathirana, H.P.K., R. Maldeniya, & U.L.K. Perera 2015. Sri Lanka: National report to the scientific committee of the Indian Ocean Tuna Commission, 2015. IOTC-2015-SC18-NR26. Indian Ocean Tuna Commission, Victoria, Mahé, Seychelles.

IOTC 2018. Implementation of IOTC conservation and management measures – Part A: Understanding IOTC and the international fisheries management framework. Indian Ocean Tuna Commission, Victoria, Mahé, Seychelles. 80

Kao, S.M. 2015. International actions against IUU fishing and the adoption of national plans of action. Ocean Development & International Law 46(1): 2-16. https://doi.org/10.1080/00908320.2014.957989

Lee, J., A.B. South & S. Jennings 2010. Developing reliable, repeatable, and accessible methods to provide high-resolution estimates of fishing-effort distributions from vessel monitoring system (VMS) data. ICES Journal of Marine Science 67(6): 1260–1271. https://doi.org/10.1093/icesjms/fsq010

Marzuki, M.I. 2017. VMS data analyses and modeling for the monitoring and surveillance of Indonesian fisheries. Computer Vision and Pattern Recognition. Retrieved from https://tel.archives-ouvertes.fr/tel-01801769, Ecole nationale supérieure Mines-Télécom Atlantique, Nantes CEDEX, France.

Mendo, T., S. Smout, T. Photopoulou, & M. James 2019. Identifying fishing grounds from vessel tracks: model-based inference for small scale fisheries. Royal Society Open Science 6: 191161. https://doi.org/10.1098/rsos.191161

Murawski, S.A., S.E. Wigley, M.J. Fogarty, P.J. Rago & D.G. Mountain 2005. Effort distribution and catch patterns adjacent to temperate MPAs. ICES Journal of Marine Science 62(6): 1150–1167. https://doi.org/10.1016/j.icesjms.2005.04.005

Nieblas, A.E., J. Barde, J. Louys, J. Lucas, C. Assan, T. Imzilen, C. Dalleau, C. Gerry & E. Chassot 2019. Seychelles VMS/logbook comparison for tuna fisheries (FAO Area 51). pp. 79-108. In: Taconet, M., Kroodsma & J. A. Fernandes, (eds.) Global Atlas of AIS-based fishing activity - Challenges and opportunities. Food and Agriculture Organization of the United Nations, Rome, Italy.

NOAA 2019. Latitude/longitude distance calculator. National Hurricane Center and Central Pacific Hurricane Center. National Oceanic and Atmospheric Administration. Retrieved from https://www.nhc.noaa. gov/gccalc.shtml (accessed September 2019)

Palmer, M.C. & S.E. Wigley 2009. Using positional data from vessel monitoring systems to validate the logbook-reported area fished and the stock allocation of commercial fisheries landings. North American Journal of Fisheries Management 29(4): 928-942. https://doi.org/10.1577/M08-135.1

Petrossian, G.A. 2015. Preventing illegal, unreported and unregulated (IUU) fishing: A situational approach. Biological Conservation 189: 39-48.https://doi.org/10.1016/j.biocon.2014.09.005

Punzon, A., J. Lopez, M. Soto & H. Murua 2016. Validation of VMS data and identification of fishing activities of the Spanish tuna purse seine fleet. IOTC Working Paper, IOTC-2016-WPTT18-39. Indian Ocean Tuna Commission, Victoria, Mahé, Seychelles. DOI: 10.13140/RG.2.2.36696.49922

Sandaruwan, K.P.G.L. & S.A. Weerasooriya 2019. Non-tariff measures and sustainable development: The case of the European Union import ban on seafood from Sri Lanka. ARTNeT Working Paper Series, No. 185, May

2019, Bangkok, ESCAP. Retrieved from: http://artnet.unescap.org and http://hdl.handle.net/10419/197319

Sumaila, U.R. 2019. A carding system as an approach to increasing the economic risk of engaging in IUU fishing? Frontiers in Marine Science 6: 34. https://doi.org/10.3389/fmars.2019.00034

Thomas-Smyth, A. 2013. Assessing the Accuracy of Logbook Data Using VMS Data in the California Groundfish Fishery. (Master thesis), Environmental Management, Nicholas School of the Environment, Duke University, Durham, North Carolina, USA.

Walter, J.F. III, J.M. Hoenig & T.Gedamke 2007. Correcting for effective area fished in fishery-dependent depletion estimates of abundance and capture efficiency. ICES Journal of Marine Science 64(9): 1760–1771. https://doi.org/10.1093/icesjms/fsm147

White, C. 2016. European Commission removes red card from Sri Lanka, warns others. Retrieved from https://www.seafoodsource.com/news/environment- sustainability/ european-commission-removes-red-card-from-sri-lanka-warns-others (accessed April 2020)