Regional Studies in Marine Science
December 2023, Volume 68, Pages 103267 (15p.)
https://doi.org/10.1016/j.rsma.2023.103267 https://archimer.ifremer.fr/doc/00859/97053/

An application of electronic monitoring system to optimize onboard observation protocols for estimating tropical tuna purse seine discards

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Abstract :

Onboard observer programs have been implemented since the 2000's to monitor the impact of tropical tuna fisheries on pelagic ecosystems. The recent development of Electronic Monitoring Systems (EMS) offer new insights to improve the monitoring and estimation of discards at sea, which remains a challenge for observers on board purse seiners where catch handling occurs simultaneously at different places on the vessel and often represents large volumes discarded within a short amount of time. In this study, data collected through EMS installed on board French tropical tuna purse seiners operating in the Indian Ocean were used to examine the sorting process and test optimized observer sampling strategies to obtain robust estimates of discards. We used EMS "counts per minute" data to estimate the total amount of discards in numbers, as well as discards per taxa by fishing set. Results indicate differences in the flow of discards among species and sorting location with 82% of the individuals released through the discard belt in the lower deck, the rest being directly released from the upper deck. Observer sampling strategies were simulated with the aim of optimizing the total sampling duration and the duration of sampling sequences by assessing the bias and coefficient of variation of the estimates. Based on these results we recommend a protocol for onboard observers using a minimal coverage of 22 minutes of sorting operations in the lower deck, with sampling sequences of 2 to 4 minutes for large volumes of catch. Further strategies to improve the estimation of discards combining onboard and electronic observations are also discussed.

Keywords : Electronic Monitoring System, Observer program, Tuna purse seine fishery, Bycatch, Discards, Indian Ocean

1. Introduction

The development of fisheries worldwide has led to the monitoring and regulation of fishing activities to maintain marine populations at a sustainable level of exploitation (Botsford et al., 1997). Catch and fishing mortality estimates are necessary components of any management framework to understand the impact of fisheries on ecosystems and living marine resources (Hall, 1996; Bellido et al., 2011). This includes the monitoring of the catch of species and fish size categories that are either not targeted by the fishery (bycatch, FAO, 2011) or are returned to the sea, dead or alive (discards, FAO, 2011). Despite being essential to fisheries managers, discards can be inaccurately estimated or poorly reported by fishers in their logbooks due to lack of time or training (Gilman and Zimring, 2018; Suuronen and Gilman, 2019). Onboard observation programs have consequently been developed to provide accurate estimates of the fishing mortality of discarded species (Bellido et al., 2011). Such programs are considered as one of the most reliable source of information to monitor the fraction of the catch that is discarded and that can therefore only be accurately monitored at sea by professional observers (Davies, 2002; Babcock et al., 2003; Gilman et al., 2017).Yet, the numerous tasks assigned to observers (e.g., monitoring vessel activities, counting and measuring fish, collecting samples, etc.) on large vessels such as large tropical tuna purse seiners may hinder the quality of the estimation of the retained bycatch and discards, including endangered, threatened and protected (ETP) species (Gilman and Zimring, 2018). Reducing bias and improving the precision of discards estimates may however be possible through an increase in observer coverage, a better understanding of catch sorting operations to design appropriate sampling protocols taking into account both common and rare species (Babcock et al., 2003; Hall and Roman, 2013).

In the case of tropical tuna purse seine fisheries, a large part of observer tasks consists in estimating discards including target species unfit for human consumption and non-target species (Chavance et al., 2012; ISSF, 2016). Even though bycatch rates are lower for purse seine fisheries than for other tropical tuna fisheries (Pérez Roda et al., 2019; Gilman et al., 2020), they still represent a significant part of purse seine catches, that is inherently increased by the extensive use of Fish Aggregating Devices (Hall and Roman, 2013; Justel-Rubio and Restrepo, 2017). Bycaught and discarded species consist of minor tunas, various bony fishes, and various ETP species such as sharks, rays and turtles (Amandè et al., 2012). While some minor tunas and other bony fish species are retained for the local market or crew consumption, discards represent around 5 % of the total catch biomass (Gilman et al., 2020; Hall and Roman, 2013). Estimates of retained bycatch in purse seine fisheries are generally available in logbooks, sales notes on local markets or accessible through port sampling, but estimates of discards at sea are generally only obtained in the frame of observer programs (Amandè et al., 2011). Such information is particularly critical for all species considered as “data-poor” by tuna Regional Fisheries Management Organizations (RFMOs), such as small tunas, billfishes and sharks and it is then crucial for stock assessment and management plans of such species that estimates provided by scientific observers are accurate (Hall and Roman, 2013).

However, the estimation of bycatch remains a difficult task for observers onboard large tropical tuna purse seiners (60-100 m LOA in the case of French purse seiners of the Indian Ocean) since important volumes of catch are processed in a short amount of time and are sorted simultaneously at different locations of the vessels (Hall and Roman, 2013; Briand et al., 2022). Indeed, a fraction of individuals of ETP species are sorted and released from the upper deck while the rest of the catch (bony fishes and ETP species) is handled in the lower deck (Poisson et al., 2014; Forget et al., 2021), which can lead to two sources of bias. First, when collecting data in the lower deck observers may miss the ETP fauna that is directly released from the upper deck during the brailing process. Second, when the flow of discards is important below deck onboard observers can encounter difficulties to count discarded individuals exhaustively. As a result, various strategies have been recommended to onboard observers over time, ranging from sampling discards (IRD-Ob7, 2016; IOTC, 2021a) to exhaustive counting (IRD-Ob7, 2020; IOTC, 2021a). None of these methods are fully applicable or accurate and the trade-off between the feasibility of the protocol and the robustness of discard estimates still needs to be assessed. In particular, the accuracy of discards estimates obtained with sampling strategies has not been assessed so far.

In parallel, during the last two decades, electronic observation through Electronic Monitoring Systems (EMS) has been progressively implemented and tested in various tuna fisheries as a complement or an alternative tool to onboard observation, especially to increase regional coverage (Restrepo et al., 2014; Ruiz et al., 2014; Emery et al., 2018, 2019; Itano et al., 2019; Gilman et al., 2020; Helmond et al., 2020). In particular, various EMS projects have been implemented onboard European and associated flags tropical tuna purse seiners with the objective of reaching 100% coverage of fishing sets (Ruiz et al., 2014, 2017; Briand et al., 2018). So far, these pilot studies have confirmed that, provided that EMS is carefully configurated, electronic observation allows the monitoring of discards at an acceptable species identification resolution, especially for species and groups of species which are systematically discarded (Briand et al., 2018). Even though issues (e.g., blind spots, inappropriate camera configuration on deck, camera lens cleaning, etc.) remain for the monitoring of incidental catch of ETP species (Briand et al., 2018; Forget et al., 2021; Monteagudo et al., 2015), EMS has proven to be a valuable tool to sample bycatch on board tropical tuna purse seiners (Ruiz et al., 2014; Briand et al., 2018; Gilman and Zimring, 2018).

As several tuna RFMOs are currently discussing the use of EMS for science and control purposes (Ruiz et al., 2017; Murua et al., 2022), we examine here how this tool may be used to optimize observation protocols for discards on board large tropical tuna purse seiners. In this study, based on the analysis of the flow of discards observed through EMS, we aim to define optimal scientific onboard observation and sampling strategies. In particular, we aim to determine the appropriate balance between the accuracy and precision of discards estimates obtain through certain sampling protocols and the practicality of the protocols bearing in mind that an exhaustive counting of discarded individuals by onboard observers is sometimes unrealistic in the context of actual fishing operations. Using EMS "counts per minute" data collected over 50 fishing sets on board five French vessels of the Indian Ocean, we (i) describe the flow of discards both on the upper and lower decks, (ii) test a range of sampling methods to estimate discards per species at the scale of the fishing set, and (iii) make new recommendations for the observation of discards.

2. Material and Methods

2.1. Camera installation and overview of discarding areas

Purse seiners covered in this study are equipped since 2014 with the EMS solution developed by *Thalos*, constituted of at least four HD MOBOTIX digital cameras, a local server and storage devices (Fig. 1a). Detailed information on EMS functioning and data collection routine for this study can be found in Briand et al. (2018).

In this study, we focused on the cameras that are located at different strategic positions of the upper deck and lower deck to monitor the release of ETP individuals and the discard of bycatch (Fig. 1a). On the upper deck, where large ETP species are released, we primarily used the desk camera, that allows monitoring the first phase of sorting operations when the catch is loaded onboard, i.e., the fast removal of unwanted individuals from the hopper. In the lower deck, where smaller individuals of ETP and bycatch species are sorted, we used the camera that is placed at the end of the discard belt to monitor and count all discarded individuals returning to the sea.

It is important to note that the configuration of French purse seiners is different between vessels, and that camera installation is therefore customized for each type of purse seiner configuration. For example, some lower deck cameras focus directly on the discard belt whereas others record individuals falling in a discard chute, which can affect observation quality and species identification. In this study, EMS data were collected for the different vessel configurations to account for such differences.

2.2. EMS "counts per minute" data

In the frame of the routine electronic monitoring of French purse seiners equipped with EMS, *Bureau Veritas Living Resources* electronic observers received EMS records on hard drives at the end of each fishing trip.

Videos were analyzed by trained observers (with previous onboard experience) using the *OceanLive Analyst* software developed by *Thalos* (Fig. 1b). Most of the collected data is similar to the information routinely collected by onboard observers on fishing operations, discarding operations, and safe handling and release of ETP fauna (Briand et al., 2018).

For the present study, a specific data collection protocol was used, which consisted in counting discarded individuals per species and interval of one minute. The resulting dataset will be designated as "counts per minute" in the following sections of this study.

Since the present study aims at developing a robust protocol to estimate discards, we chose to focus on fishing sets on floating objects that typically involve larger amounts of non-target species compared to free-swimming tuna school fishing sets (Hall and Roman, 2013; Ruiz et al., 2018). We also aimed at covering (i) the 3 vessel configurations of EMS-equipped French purse seiners of the Indian Ocean, and (ii) the range of discard amounts to be estimated by the observer. We used the sorting duration, defined as the interval between the time when the first brailer opens ($\mathbf{T_0}$) and the time when the last fish $\mathbf{T_{LF}}$ is sorted, to reflect the variability in the volume of discards among fishing sets. The sorting duration was notably used in this study to define different classes of sorting durations (10-20 minutes, 20-30 minutes and more than 30 minutes ~ 30+) with a chosen representative number of fishing sets (at least 10) per class of sorting duration (Table 1).

In total, 50 fishing sets with sufficient image quality were selected for this analysis. Sorting operations of the fishing sets were then reviewed entirely over the whole sorting time on the upper and lower decks using respectively the desk and discard cameras. $\mathbf{T_0}$ was used as a common starting time of sorting operations for both the upper and the lower decks. Discards were counted exhaustively for each one-minute sequence between $\mathbf{T_0}$ and $\mathbf{T_{LF}}$, separately for the upper and lower decks. Discarded individuals were identified at the highest possible resolution level (species or species group). For example, in the case of tuna and tuna-like species, which are difficult to discriminate with the current EMS configuration (especially for lookalike species such as minor tunas and juvenile YFT-*Thunnus albacares* and BET-*Thunnus obesus*), counts per minute data were aggregated at the scale of the species group (TUN-Thunnini).

On the upper deck, individuals disentangled from the net or sorted before $\mathbf{T_0}$ were also counted in our analysis and taken into account in the total number of discarded individuals. However, the overall flow of discards was only described between $\mathbf{T_0}$ and a maximum time defined at 60 minutes (no individual was sorted after 60 minutes in our dataset). The total number of individuals per fishing set and per species represents the "observed" value that was used as the reference value when testing various sampling strategies.

2.3. Optimization of onboard observer sampling strategies

2.3.1. Parameters of sampling strategies to optimize

During the fishing set, observers present on board tropical tuna purse seiners are advised to be posted in the lower deck the majority of the time, close to the discard belt or chute where the major part of discarded individuals are sorted (IRD Ob7, 2016; IOTC, 2021a). We therefore focused our analyses on optimizing the sampling protocol in the lower deck. We also prioritized major tuna species generally classified in electronic monitoring as unidentified individuals from the Thunnus genus (TUS-*Thunnus* spp), skipjack tuna (SKJ-*Katsuwonus pelamis*), and unidentified tunas (TUN-Thunnini), as well as the most common discarded bycatch species (Amandè et al., 2011; Hall and Roman, 2013), i.e., rough triggerfish (CNT-*Canthidermis maculata*), rainbow runner (RRU-*Elegatis bipinnulata*), mackerel scad (MSD-*Decapterus macarellus*), wahoo (WAH-*Acanthocybium solandri*), dolphinfish (DOL-*Coryphaena hippurus*), silky shark (FAL-*Carcharhinus falciformis*) and sea chub nei (KYP-*Kyphosus spp.*).

We simulated sampling strategies to be used by onboard observers to estimate the total number of individuals per species transiting on the discard belt. Two parameters of the sampling strategy to optimize were considered: (i) the total sampling duration and (ii) the duration of sampling sequences. For each simulation, the number of individuals (total and per species or species group) was calculated by extrapolating the number of individuals counted over a given period to the total sorting time (Eq. 1).

(Eq. 1) $$N_{estimated,s,i} = N_{sample,s,i} \times (T_{LF} - T_0)/T_{sample,i}$$

where $N_{estimated,i}$ is the estimated number of individuals for the species s in set i, $N_{sample,i}$ is the number of individuals counted within the sample, T_{LF} is the time when the last fish is sorted on the discard belt, T_0 is the time when the first brailer opens, and $T_{sample,i}$ is the duration of the sample.

For the total sampling duration, we tested a range of sampling durations to determine the minimum duration that should be covered by the observer to obtain robust estimates of discards. For each of the 50 fishing sets, we sampled random minutes (without replacement) from one minute to the total duration of sorting operations and then extrapolated the total number of discarded individuals.

For the duration of sampling sequences, we tested a range of duration to optimize the practicality of the protocol. We tested sampling sequences of 1 to 4 consecutives minutes randomly chosen over the total duration of each fishing set, that were repeated from 1 to the total number of possible sequences within each fishing set (depending on the duration of sorting operations).

2.3.2. Assessing the suitability of sampling strategies

The suitability of sampling strategies was assessed using various metrics: the bias of the extrapolated value $N_{estimated}$ to the reference value $N_{reference}$ (Eq. 2), the absolute bias (Eq. 3), and the coefficient of variation CV (Eq. 4).

(Eq. 2) $$Bias = N_{estimated} - N_{reference}$$

(Eq. 3) $$Absolute\ Bias = |N_{estimated} - N_{reference}|$$

(Eq. 4) $$CV = \frac{Standard\ deviation}{Mean\ of\ N_{estimated}}$$

The objective was to identify the (i) optimal total sampling duration and (ii) the duration of sampling sequences for which the absolute bias and CV of discard estimates would strongly decrease at a minimum acceptable level (20-30% following IOTC sampling performance guidelines; IOTC, 2021b).

We bootstrapped this operation 100 times (Efron and Tibshirani, 1994) for each fishing set so as to provide mean values and confidence intervals for these indicators. We expect the absolute bias and the relative dispersion (CV) will decrease with sampling duration, and will identify the inflexion point where both the bias and CV are sufficiently low so the sampling strategy can be considered accurate and precise (optimal).

3. Results

3.1. Overall releasing and discard flow

EMS records analyzed in this study indicate that about a fifth of discarded individuals (all species combined) is sorted on the upper deck while the large majority (81.9 %) is sorted below deck (Table 2). Moreover, counts per minute and cumulative counts per minute indicate that the discarding process is faster and more regular in the lower deck than on the upper deck (Fig. 2a,b, Appendix A**)**.

At the scale of the fishing set, the discard flow was observed to be heterogeneous over time. A wide range of shapes in the discard flow was obtained, with either repeated peaks in the number of discarded fishes throughout the sorting time (upper and lower decks) or a single large peak (lower deck only) (Appendix B, C).

Overall, all 50 fishing sets combined, the discard flow of the most common species and groups of species showed different patterns on the upper and lower decks with a greater irregularity over time on the upper deck compared to the lower deck (Fig. 2a,b). Sorting was also faster in the lower deck, with an average sorting duration of 30.2 minutes (S.D. 13.0) on the upper deck compared to 24.0 minutes in the lower deck (S.D. 10.7) and only 60 % of the individuals sorted within the first 20 minutes on the upper deck compared to 90 % in the lower deck.

For all fishing sets combined by classes of sorting duration, the discard flow is more intense during the first half of sorting operations (Appendix B). For fishing sets with sorting time shorter than 30 minutes, nearly 100% of the individuals (all species combined) were sorted within the 20 first minutes, compared to 80% for fishing sets which sorting duration lasted more than 30 minutes (Appendix B). However, this overall trend was slightly different between vessel configurations. For vessel 1 (N = 21) for example, the peak in discards was more concentrated in time than all other vessels combined. This sharper peak also tended to appear later when the duration of sorting operations increased (Appendix C).

In the lower deck, sorting duration also increased with the total catch but with relatively high variability among fishing sets (Appendix E).

Results also indicate large differences among species or groups of species in terms of arrival in the upper deck (Fig. 2a). DOL were mostly sorted at the beginning of catch handling operations compared to the other species, such as CNT that appeared to be discarded in small peaks throughout the sorting process. In the case of sharks, cumulative counts per minute showed that, regardless of the ability of electronic observers to identify the species on EMS records, sharks (FAL, RSK) appeared to be sorted quickly on the upper deck with 80 % of the individuals released in the first 7 minutes in all fishing sets (N = 50). Depending on the species or the species group, a certain level of species sorting prioritization may therefore occur on the upper deck. It is unclear, however, if these observations truly reflect an order in species arrival on the deck or in sorting species, and to what extent the lack of identification of bony fishes (87.2 % of bony fishes categorized as MZZ on the upper deck) at the scale of the species affects the results.

In the lower deck, a larger proportion of bony fishes and sharks could be identified at the scale of the species, with respectively 8.2 % of MZZ and ~ 0 % (only one) RSK. No clear pattern of species composition of discards was observed, suggesting that individuals placed on the discard belt are released at sea in their order of arrival on the conveyor belt (Fig. 2b). CNT, RRU, TUN and MSD contributed to a large proportion of discards and these species appeared in small peaks throughout the whole duration of sorting operations. This is also the case for less frequent species such as KYP and WAH. It is worth noting that silky sharks (FAL) appeared to be released relatively quickly in the lower deck. Indeed, cumulative counts per minute indicate that 70% of FAL were sorted in less than 10 minutes (Fig. 2b). This trend is particularly noticeable for vessel 1 (N = 21 sets), where a priority was probably be given to sorting FAL individuals in all fishing sets and for all sorting time categories (Appendix C). Overall, 80 to 90% of the FAL individuals were sorted in less than 10 minutes for sets under 30 minutes, and 90% in less than 12 minutes for sets above 30 minutes (Fig. 2b, Appendix C).

3.2. Optimal total sampling duration

Figure 3 and Table 3 summarize the effect of the total sampling duration on the accuracy and precision of estimated/extrapolated total number of individuals discarded from the lower deck during the 50 fishing sets analyzed in this study. Overall, the accuracy (absolute bias) and precision (CV) of estimated numbers of discarded individuals increase with the proportion of sorting time sampled. The mean absolute bias decreases and stabilizes at around 12 minutes (Tab. 3; Fig. 3). The variance of the bias and absolute bias also decrease when increasing the sampling time and becomes acceptable (IOTC, 2021b) after 15 minutes of cumulated sampling time (Fig. 3). After sampling for 15 minutes, the mean bias is below 8 individuals (median < 5 individuals) while the maximum bias remains below 60 individuals (Tab. 3). The mean coefficient of variation (CV) of the extrapolated total number of discarded individuals stabilizes at around 15 minutes of random sampling and remains low (< 0.2) as sampling time increases (Tab. 3).

Bootstrap results differ depending on the species transiting through the lower deck (Fig. 4). Results show that the CVs stabilize between 15 and 20 minutes of sampling (Fig. 4, Appendix D) for the most abundant bycatch species: CNT, MSD and RRU, as well as for KYP and for tuna discards SKJ, TUS and TUN. For these species the mean CV reaches 0.3 at ~16-17 minutes of sampling while the mean bias remains below 5 individuals (Appendix D, Table D). For less frequent species such as DOL, WAH and FAL, the mean CVs stabilize after a longer sampling duration (> 20 minutes) than the most common species (Fig. 4, Appendix D). For DOL and WAH, the mean CV reaches 0.3 at around 22 minutes of sampling (Appendix D). Note that for FAL, the mean CV remains variable even for larger sampling durations (Fig. 4, Appendix D).

3.3. Sampling sequences

Figure 5 shows the comparison of the absolute bias for the estimation of the total number of discarded individuals for sampling sequences of 1 to 4 minutes.

In all cases, the bias decreases with the total sampling duration (as well as associated confidence intervals) and flattens around 15 minutes, while mean CVs overlaps around 20 minutes. Despite marginal differences, the absolute bias of discard estimates and confidence intervals are comparable among the four tested sampling sequences. It is worth noting that between 2 to 20 minutes of total sampling the mean CV of the 1-minute-sequence strategy remains slightly below the CVs of the 2-, 3- and 4-minutes strategies, but that this difference remains relatively negligible. Moreover, the overlap of confidence intervals of 2, 3 and 4 minutes suggests that these differences are not significant and therefore that the duration of repeated sequences has no effect on discard estimates.

4. Discussion

This study confirms that electronic observation through EMS is a powerful tool to monitor bycatch and complement onboard observer programs in tropical tuna purse seine fisheries, as already suggested in various recent studies and reviews (Ruiz et al., 2014; Briand et al., 2018; Gilman et al., 2020; Michelin et al., 2020; Stobberup et al., 2021). The results we obtained here further demonstrate that EMS can be used to provide valuable scientific information on sorting and discarding practices, notably interactions with ETP species. Here, we also demonstrated how electronic observation can be used to further optimize onboard observation sampling protocols through a better understanding of the flow of discards in the lower and upper decks of tropical purse seiners.

As expected, EMS records showed that most discards (82 %) transit through the lower deck of large tropical tuna purse seiners. This confirms that, to monitor the main discard flow, onboard observers need to concentrate their observation effort in the lower deck, keeping in mind that one single observer is usually more efficient if stationed in either one of the two decks (Forget et al., 2021).

For bony fishes, the results we obtained in this study also indicate that the majority of individuals are discarded during the first half of sorting operations, while the intensity of the discard flow decreases progressively during the second half of the sorting process. This can be related to the fact that brailers are usually more filled at the beginning of hauling operations (Briand et al., 2022), resulting in a decreasing discard flow at the end of sorting operations. In terms of onboard observation protocol, this would indicate that onboard observers should monitor discards in the lower deck throughout the whole sorting process. In case sampling is performed, samples should be collected evenly or in a random fashion over time to avoid biased estimates due to the irregularity of the discard flow in the lower deck. This would allow as well to deal with the effect of vessel configuration on the shape of the discard flow, with a methodology that can be applicable to all configurations of fishing sets and vessels.

Regarding the duration and organization of the sampling task, the simulation of random sampling strategies showed that sampling a total of around 22 minutes in the lower deck (not necessarily consecutive minutes) is necessary to obtain robust estimates of the number of discarded individuals (all species combined and separately for each species considered in this study). Simulations using sampling sequences of 1 to 4 minutes suggested that the length of sampling sequences does not affect much the accuracy of the estimates. Sampling using random single minute sequences appears to give slightly lower dispersion than the other sampling methods but may not be feasible in practice for onboard observers. In comparison, sampling in sequences of 2 to 4 minutes would be a more reasonable and pragmatic method for onboard observers.

However, when looking into the details, our results indicate differences in the flow of discards among species that may need to be better considered in the methodology recommended to observers. Indeed, in the context of a field experience where a great variability of situations can be encountered with uncontrolled conditions, the minimum acceptable level of coefficient of variation can be set around 0.3 (Gomez and Gomez, 1984; Patel et al., 2001; IOTC, 2021b). In our case, the mean coefficient of variation reached 0.3 after 16 minutes of sampling for the most common species (CNT, RRU, MSD) or group of species (TUN) while for rarer species such as DOL and WAH, a longer sampling duration (~ 22 minutes) would be needed to reduce the risk of missing some occurrences and ultimately obtain robust estimates. In terms of sampling protocol on board, this indicates that longer sampling time or even exhaustive counts would be necessary to obtain robust estimates of discards especially for rarer species. Such recommendations would also apply to the rarest species (including ETP species) whose discarding patterns were not investigated in this study, except for FAL. It is worth noting that monitoring exhaustively ETP species such as sharks, turtles, and some billfishes is suggested in observer guidelines provided by RFMOs (e.g., IOTC, 2021a) and is required in “Best Practices” programs (Poisson et al., 2014b). Exhaustive counts and post-release monitoring of sharks and other ETP species are indeed crucial to estimate fishing mortality (Hutchinson et al., 2015; Musyl and Gilman, 2019) in order to provide rigorous advice for effective management and sustainable fisheries.

In addition, the application of a 22-minute sampling in sequences of 2 to 4 minutes in the lower deck still requires further examination. In this study, we examined 50 fishing sets selected for a "balanced" design among sorting time categories (10-20 minutes, 20-30 minutes and more than 30 minutes, Tab. 1), however, this does not necessarily represent the actual distribution of sorting durations in operational conditions. Indeed, recommending to sample at least 22 minutes would therefore imply an exhaustive counting of discarded individuals in the majority of cases. Besides, recommending exhaustive counting by onboard observers may not be applicable in cases where the flow of discards is too important to be handled in real time, or when the configuration of the conveyor and discard belts in the lower deck makes it difficult to monitor discards.

Therefore, the results we obtain here should be seen as guidelines for onboard observers, rather than as a strict methodology. A potential approach would then be to propose the following guidelines to onboard observers: prior to the brailing of the catch, exchange with the captain to obtain an estimate of the expected volume of fish that will be loaded on board, if (i) the expected amount of catch is relatively low and therefore sorting operations are expected to be under 22 minutes, count exhaustively individuals discarded through the lower deck, and if (ii) the expected amount of catch is relatively high and sorting operating expected to last more than 22 minutes, sample at least 22 minutes in sequences of 2 to 4 minutes. This approach would first require determining a threshold between relatively low and high amount of catch and how a given amount of catch translates into an expected sorting duration. In the case of French tropical tuna purse seiners, the joint analysis of counts per minute and fishing logbooks indicated that this threshold could be set around 30 tons of expected catch, that corresponds to sorting durations of 22 minutes or more (Appendix E). Note that in 2021 the proportion of sets with catches greater than 30 tons corresponded to 38% of fishing sets (L. Floch, IRD-Ob7, *pers. comm.*). This approach would also require that onboard observers adapt their observation strategy to the configuration of the vessel and the sorting strategy of the crew. In any case, obtaining robust estimates for discards will remain challenging for onboard observers and their level of experience and adaptability will still be critical to obtain sound estimates.

Moreover, as shown in the present study, ETP species such as sharks are released simultaneously from the upper and the lower decks which is challenging for onboard observers that have to navigate between the lower and upper deck or rely on information communicated by the crew (IRD-Ob7, 2020). In this study, information collected on sharks (FAL, RSK) indicate that such species are generally released during the first seven minutes both on the upper and the lower decks, with differences among vessels and fishing sets. Such a pattern may either reflect a prioritization of the release of sharks in application of the so-called "Best Practices" for the fast and safe release of ETP species (Poisson et al., 2014b) or reflect the stratification of species composition in the sack. Indeed, some studies have shown shallow vertical distribution for species such as dolphinfish and juvenile silky sharks associated with floating objects (Merten et al., 2014; Whitney et al., 2016; Hutchinson et al., 2019) that may explain quicker discard of these species due to earlier order of arrival onboard. In any case, this pattern is informative for onboard observers, to appropriately organize their time between the exhaustive observation of ETP species on the upper deck (especially at the beginning of fishing operations) and the observation of all species in the lower deck. This however does not solve the issue of simultaneously monitoring both decks by onboard observers.

Having electronic and onboard observation working all together would be ideal to observe ETP species as EMS would complement missing observations in one or the other location. The combination of both methods to improve the quality of scientific data in fisheries observer program has been suggested in a recent study (Gilman and Zimring, 2018) but not been applied to date. Indeed, trips with both EMS and onboard observers remain rare due to cost and logistic reasons. Also, for purse seiners, limitations related to the current EMS installations such as the issue of blind spots (Briand et al., 2018; Forget et al., 2021) and poor ability to identify individuals at the species level on the upper deck (Briand et al., 2018) first need to be solved. This would imply installing more cameras, using recording footages with a higher resolution in the discarding areas, or placing cameras closer to the main catch sorting areas. Using EMS records on lower deck while on board observer is on the upper deck may also be a possibility but reviewing EMS records exhaustively is also time consuming and tedious for electronic observers. Note that the sampling methodology developed in this study could also be adapted for electronic observation with the goal of identifying the proper balance between the robustness of discard estimates and the time/cost for reviewing EMS records. These guidelines will not necessary be the same as those developed for onboard observers since the sorting duration is known in advance when EMS records are reviewed by electronic observers. Instead of recommending a total sorting duration, the guidelines would therefore recommend a percentage of the sorting duration to be reviewed by electronic observers.

Once such improvements to the EMS configuration are made, and knowing that scientific protocols require regular updates, the methodology developed in this study may be used for further recommendations on optimizing discard observation protocols.

5. Conclusions

Our study demonstrates that EMS is a promising complementary tool to onboard observation for the monitoring of discarded bycatch in tropical tuna purse seine fisheries. EMS counts per minute allowed to unravel the discarding process on the upper and lower decks on board French purse seine vessels operating in the Indian Ocean. This analysis provides first benchmarks for a reliable onboard sampling strategy for which we recommend a total of 22 minutes of sampling in random sequences of 2 to 4 minutes at convenience on the discard belt. This protocol can be used by onboard observers in the lower deck especially for large volumes of catch when exhaustive counts are not possible.

Our work also highlights the value of EMS within scientific observer programs to improve the overall capability of monitoring ETP species on the upper deck. Alternatives such as the combination of electronic observation on the upper deck and onboard observation in the lower deck should be considered in the future, when the associated costs will become reasonable. The combination of the two could be advantageously used to improve scientific estimates of discards for RFMOs fish stocks management. It is important however, that EMS configuration on board is improved in the meantime (additional cameras, better camera configuration and resolution), in particular to guarantee the exhaustive observation of ETP species on the upper deck and their identification at the species level.

Finally, observation methods could also greatly beneficiate from Artificial Intelligence (AI) algorithms that could be used to determine the species on EMS records to speed up the work of observers and thereby improve discard estimates per species in routine. Future innovations of EMS are then likely to further improve existing observation protocols.

6. Acknowledgements

This study was supported by co-funding from ORTHONGEL and IRD through EU's Data Collection Framework. We would like to thank Thalos teams for their technical support on EMS both onboard and on land. We also thank purse seine fleet managers and crew members from CFTO for their collaboration on the OCUP program and electronic monitoring program studies. Finally, we thank Bureau Veritas Living Resources for providing counts per minute datasets.

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Table 1. Number of sets per vessel, configuration, trip and sorting time category (in minutes).

Vessel	Configuration	Fishing trip	10-20	20-30	30+	Total
V1	C1	1a,1b	12	7	2	21
V2	C2	2	4	3	5	12
V3	C2	3a,3b	2	3	0	5
V4	C3	4a,5a	1	3	0	4
V5	C3	6,7a,7b	3	2	3	8
			22	18	10	50

Table 2. Number of discarded individuals by species from a) the upper deck, and b) the lower deck.

a)

FAO code	Scientific name	Common name	N discarded

MZZ	Osteichthyes	Marine fishes nei	3453
CNT	Canthidermis maculata	Rough triggerfish	165
RSK	Carcharhinidae spp	Requiem sharks nei	104
DOL	Coryphaena hippurus	Common dolphinfish	87
RRU	Elagatis bipinnulata	Rainbow runner	73
FAL	Carcharhinus falciformis	Silky shark	19
WAH	Acanthocybium solandri	Wahoo	13
TUN	Thunnini	Tunas nei	12
BIL	Istiophoridae	Marlins,sailfishes,etc. nei	11
GBA	Sphyraena barracuda	Great barracuda	7
XXX*	Unknown	Unknown	5
TUS	Thunnus spp	True tunas nei	3
BAO	Platax teira	Longfin batfish	1
BEN	Belonidae	Needlefishes, etc. nei	1
COM	Scomberomorus commerson	Narrow-barred Spanish mackerel	1
CXS	Caranx sexfasciatus	Bigeye trevally	1
KYP	Kyphosus spp	Kyphosus sea chubs nei	1
MSD	Decapterus macarellus	Mackerel scad	1
UKK	Uraspis spp	Cottonmouth jack	1
Total			**3959**

b)

FAO code	**Scientific name**	**Common name**	**N discarded**
CNT	Canthidermis maculata	Rough triggerfish	5544
TUN	Thunnini	Tunas nei	3447
RRU	Elagatis bipinnulata	Rainbow runner	2250
MSD	Decapterus macarellus	Mackerel scad	1737
MZZ	Osteichthyes	Marine fishes nei	1474
SKJ	Katsuwonus pelamis	Skipjack tuna	905
DOL	Coryphaena hippurus	Common dolphinfish	746
TUS	Thunnus spp	True tunas nei	476
KYP	Kyphosus spp	Kyphosus sea chubs nei	425
WAH	Acanthocybium solandri	Wahoo	300
FAL	Carcharhinus falciformis	Silky shark	183
FRZ	Auxis spp	Frigate and bullet tunas	95
BAO	Platax teira	Longfin batfish	77
UKK	Uraspis spp	Cottonmouth jack	72
LOB	Lobotes surinamensis	Tripletail	39
GBA	Sphyraena barracuda	Great barracuda	35
ALM	Aluterus monoceros	Unicorn leatherjacket filefish	30
CXS	Caranx sexfasciatus	Bigeye trevally	17
YTL	Seriola rivoliana	Longfin yellowtail	15
ALN	Aluterus scriptus	Scribbled leatherjacket filefish	8
BEN	Belonidae	Needlefishes, etc. nei	5
KAW	Euthynnus affinis	Kawakawa	2
XXX*	Unknown	Unknown	2
RSK	Carcharhinidae spp	Requiem sharks nei	1
Total			**17855**

Table 3. Summary of bootstrap statistics (N = 100) of the Absolute Bias (Eq. 3) for the total number of species averaged for all sets (N = 50) on the lower deck with increasing total sampling duration in minutes (CI^{sup} = 95% upper confidence interval; CI^{inf} = 95% lower confidence interval; CV = mean coefficient of variation).

Minute	Max	Median	Mean	ICsup	ICinf	CVMean	CVICsup	CVICinf
1	165.98	13.50	30.73	160.70	0.84	1.36	2.40	0.75
2	198.00	13.59	27.33	136.42	0.47	0.91	1.62	0.46
3	87.26	8.00	18.59	77.72	0.42	0.73	1.41	0.40
4	47.87	7.95	14.86	44.38	0.32	0.64	1.12	0.33
5	64.35	5.91	12.21	55.47	0.31	0.53	1.03	0.28
6	101.82	4.95	11.38	53.36	0.49	0.47	0.93	0.25
7	98.44	5.03	10.18	70.65	0.17	0.42	0.79	0.20
8	106.95	2.65	11.83	81.20	0.03	0.38	0.77	0.18
9	40.81	4.32	8.64	29.53	0.20	0.34	0.74	0.13
10	79.46	2.73	7.44	51.33	0.17	0.30	0.59	0.10
11	48.20	3.84	7.65	34.94	0.00	0.27	0.64	0.00
12	48.40	3.02	6.27	38.88	0.00	0.26	0.56	0.00
13	84.68	3.38	7.92	28.44	0.00	0.25	0.57	0.00
14	110.11	4.16	8.21	30.14	0.09	0.24	0.51	0.08
15	48.82	2.49	6.85	38.42	0.00	0.21	0.47	0.04
16	40.90	1.81	6.02	30.31	0.00	0.20	0.41	0.00
17	55.18	1.98	7.07	52.03	0.00	0.18	0.44	0.00
18	23.17	1.70	3.52	16.96	0.00	0.18	0.42	0.00
19	35.91	2.26	4.77	23.26	0.02	0.18	0.39	0.05
20	42.76	2.64	6.10	30.74	0.00	0.16	0.36	0.00
21	33.46	1.28	5.57	32.95	0.03	0.16	0.37	0.03
22	30.81	3.01	6.80	26.64	0.00	0.14	0.34	0.00
23	57.45	3.80	7.62	46.15	0.06	0.13	0.35	0.03
24	26.27	1.22	4.83	22.07	0.00	0.12	0.30	0.00
25	20.43	2.68	5.01	17.45	0.00	0.12	0.33	0.00
26	21.15	1.35	3.80	19.18	0.00	0.12	0.29	0.00
27	29.04	3.10	7.34	28.34	0.11	0.12	0.32	0.01
28	29.93	1.26	6.96	28.24	0.00	0.11	0.29	0.00
29	21.91	3.69	6.12	19.22	0.07	0.13	0.31	0.04
30	24.32	3.68	5.13	20.12	0.00	0.11	0.27	0.00
31	36.85	2.43	6.80	32.12	0.05	0.12	0.26	0.01
32	10.39	1.81	3.74	10.32	0.56	0.11	0.22	0.04
33	13.31	0.95	5.08	13.05	0.17	0.11	0.22	0.03
34	10.27	4.35	4.06	9.92	0.07	0.10	0.23	0.01
35	12.83	1.66	3.45	11.75	0.08	0.10	0.19	0.04
36	7.60	0.64	2.28	7.49	0.00	0.08	0.17	0.00
37	3.23	1.44	1.43	3.07	0.16	0.11	0.20	0.05
38	16.32	0.97	4.49	15.33	0.06	0.10	0.21	0.04
39	5.77	2.83	3.07	5.75	0.18	0.09	0.19	0.04
40	2.32	1.23	1.13	2.26	0.03	0.07	0.18	0.00
41	4.74	1.02	1.48	4.40	0.03	0.08	0.17	0.03
42	4.75	0.71	1.72	4.54	0.06	0.05	0.15	0.00
43	1.65	0.51	0.67	1.60	0.00	0.05	0.15	0.00
44	7.10	3.90	3.90	6.94	0.87	0.10	0.15	0.04
45	2.61	1.66	1.66	2.57	0.75	0.07	0.12	0.02
46	3.91	1.95	1.95	3.81	0.10	0.07	0.13	0.00
47	1.91	1.91	1.91	1.91	1.91	0.12	0.12	0.12
48	2.39	2.39	2.39	2.39	2.39	0.13	0.13	0.13
49	0.84	0.84	0.84	0.84	0.84	0.12	0.12	0.12
50	1.65	1.65	1.65	1.65	1.65	0.11	0.11	0.11
51	0.38	0.38	0.38	0.38	0.38	0.11	0.11	0.11
52	0.78	0.78	0.78	0.78	0.78	0.10	0.10	0.10
53	1.12	1.12	1.12	1.12	1.12	0.10	0.10	0.10
54	2.04	2.04	2.04	2.04	2.04	0.10	0.10	0.10
55	0.19	0.19	0.19	0.19	0.19	0.08	0.08	0.08
56	0.34	0.34	0.34	0.34	0.34	0.06	0.06	0.06
57	0.08	0.08	0.08	0.08	0.08	0.06	0.06	0.06
58	0.77	0.77	0.77	0.77	0.77	0.05	0.05	0.05

59	0.97	0.97	0.97	0.97	0.97	0.04	0.04	0.04
60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

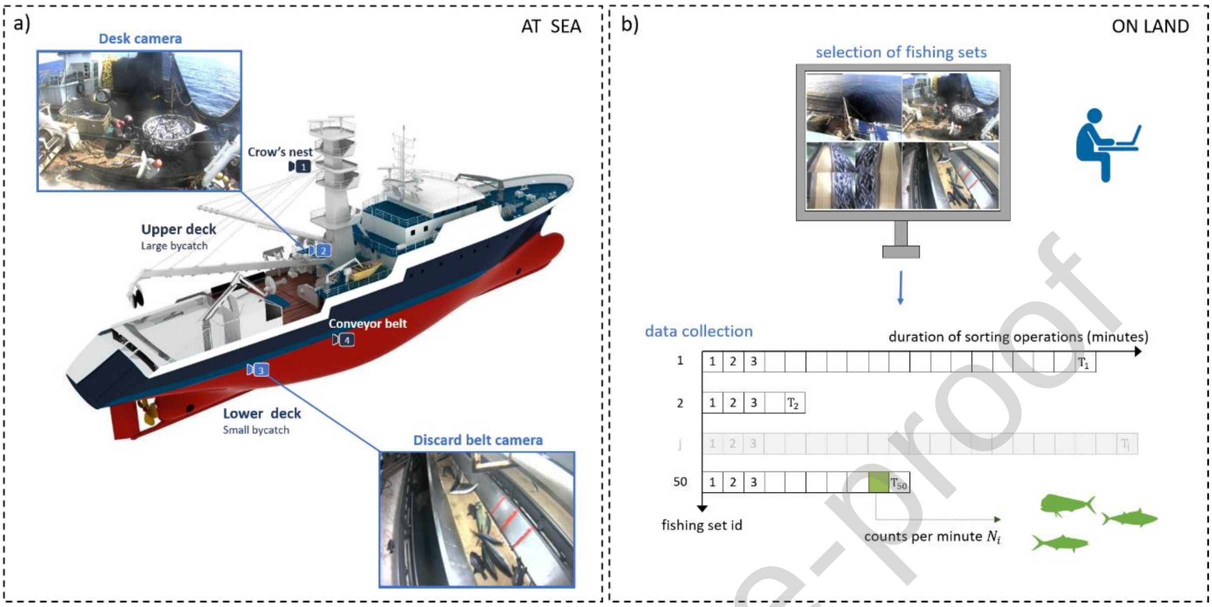
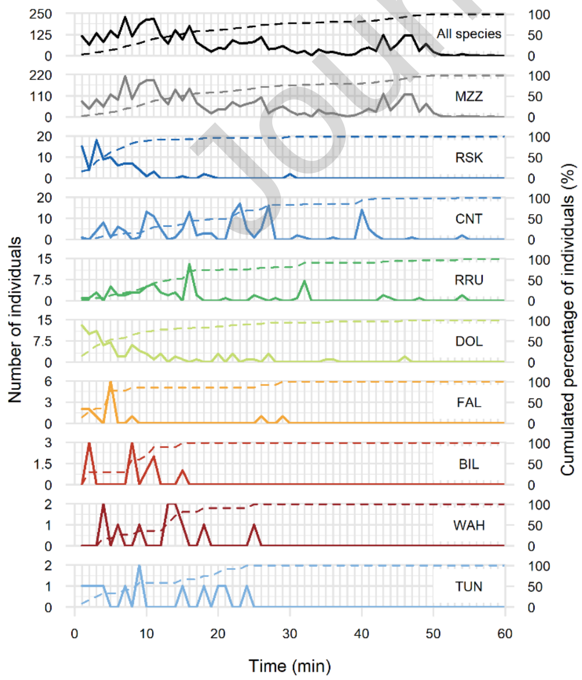


Figure 1. Schematic representation of the EMS installation on French purse seine vessels with examples of associated views of discarding areas a) and summary of observer 'counts per minute' data collection b).

a)



b)

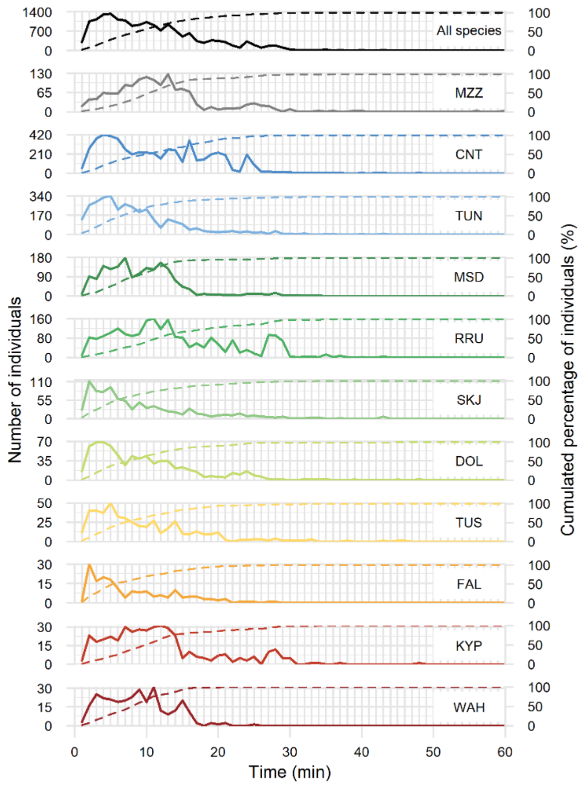


Figure 2. Counts per minute and cumulated percentage of discards combining all 50 fishing sets from a) the upper deck, and b) the lower deck. Total individuals are displayed with the solid black line and counts by species are displayed in solid colored lines.

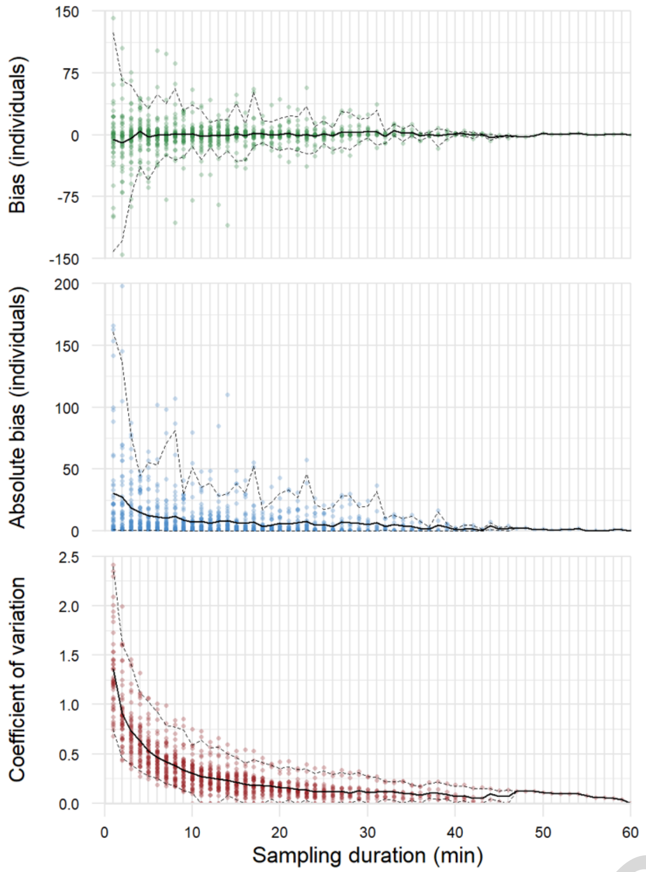


Figure 3. Bias, absolute bias and coefficient of variation (CV) of the total number of discards estimated as a function of sampling duration for the lower deck (N=50). The bias and CV were calculated on 100 bootstraps (resampling without replacement) for each fishing set. The solid line represents the mean and the broken lines the 95% confidence intervals.

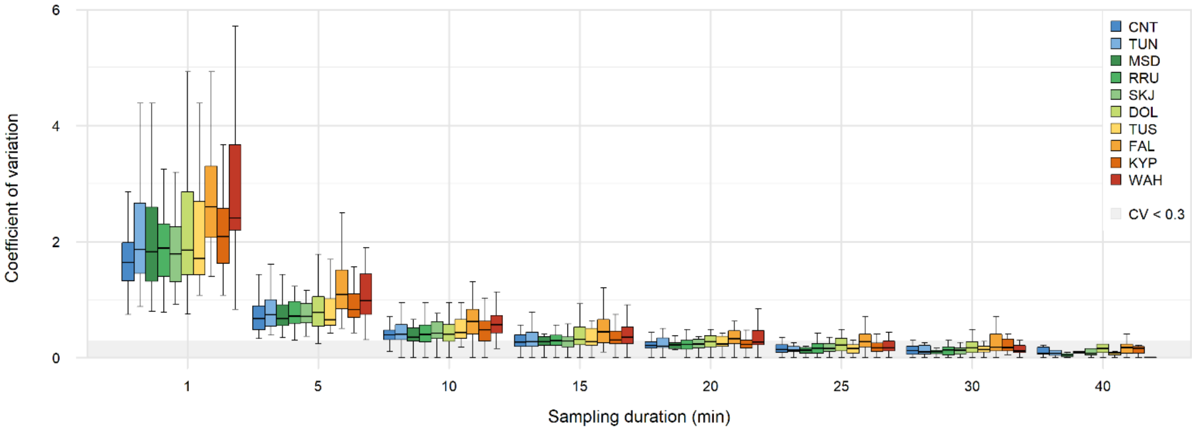


Figure 4. Distribution of the coefficient of variations (CV) in the extrapolated number of discards by species (CNT, MSD, RRU, SKJ, DOL, FAL, KYP, WAH) and groups of species (TUN, TUS) in the lower deck as a function of the sampling duration.

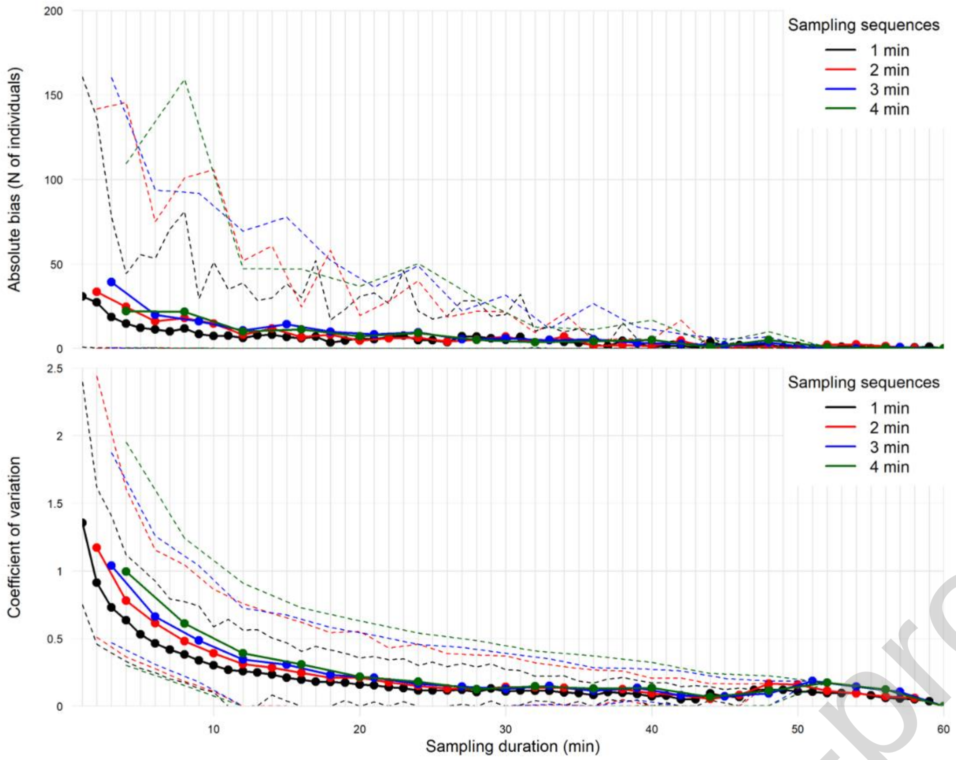
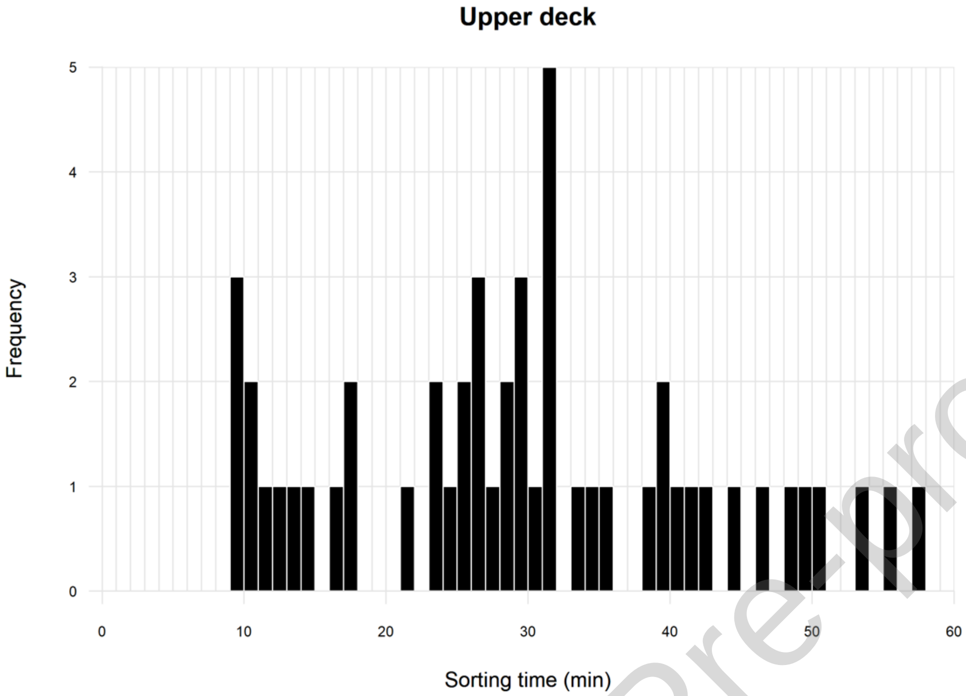


Figure 5. Mean absolute bias and CV of the total number of discards estimated as a function of cumulated sampling duration when random sampling sequences are 1, 2, 3 and 4 minutes in the lower deck.

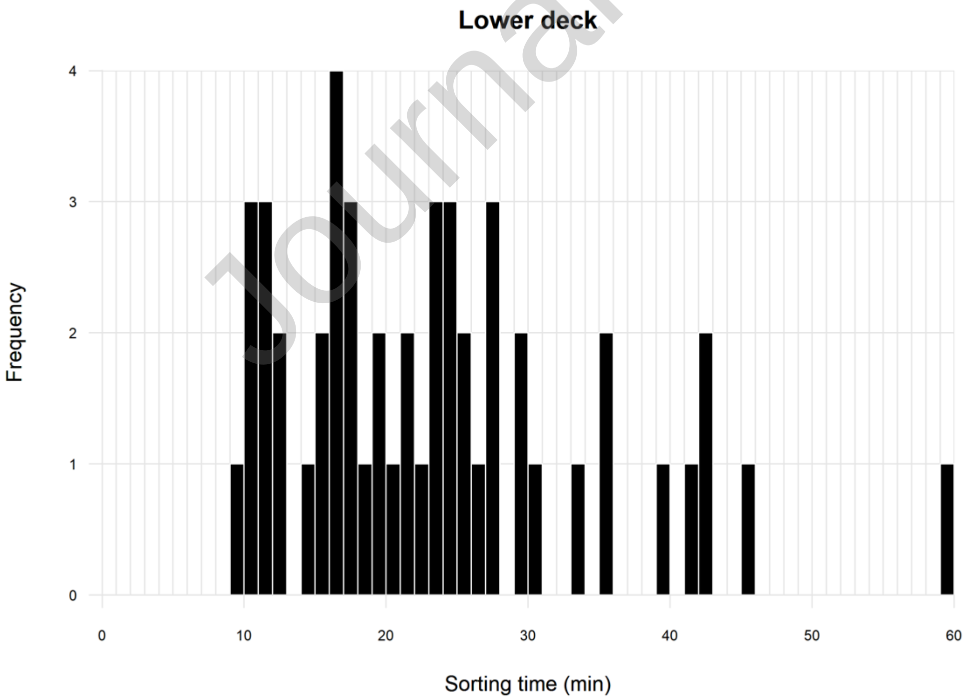
Appendix A.

Figure A. Distribution of discards sorting time in minutes on a) the upper deck and b) the lower deck.

a)



b)



Appendix B.

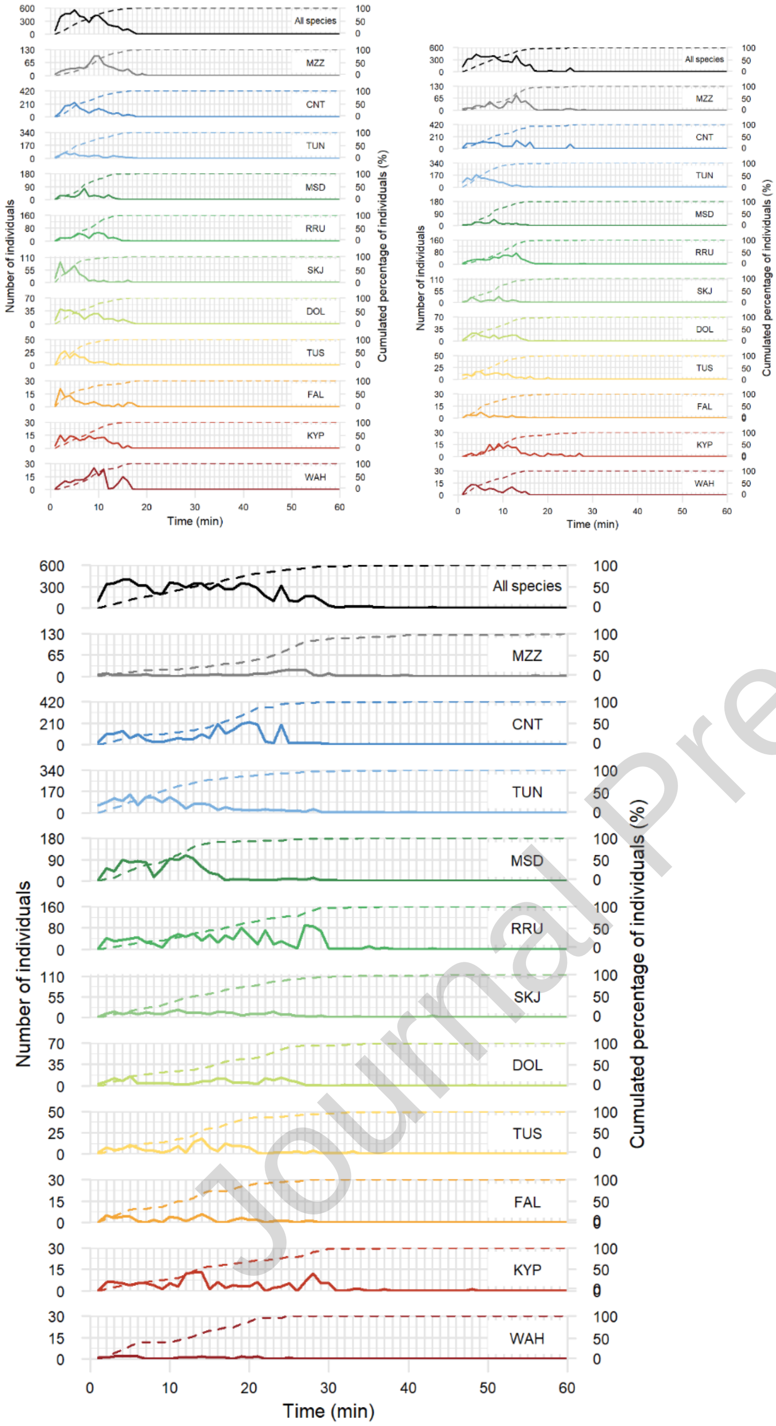


Figure B. Counts per minute (solid lines) and cumulated counts per minute (dashed lines) of discards in the lower deck of all vessels (N=50) per category of sorting time duration: 10-20 minutes (a); 20-30 minutes (b) and more than 30 minutes (c).

Appendix C.

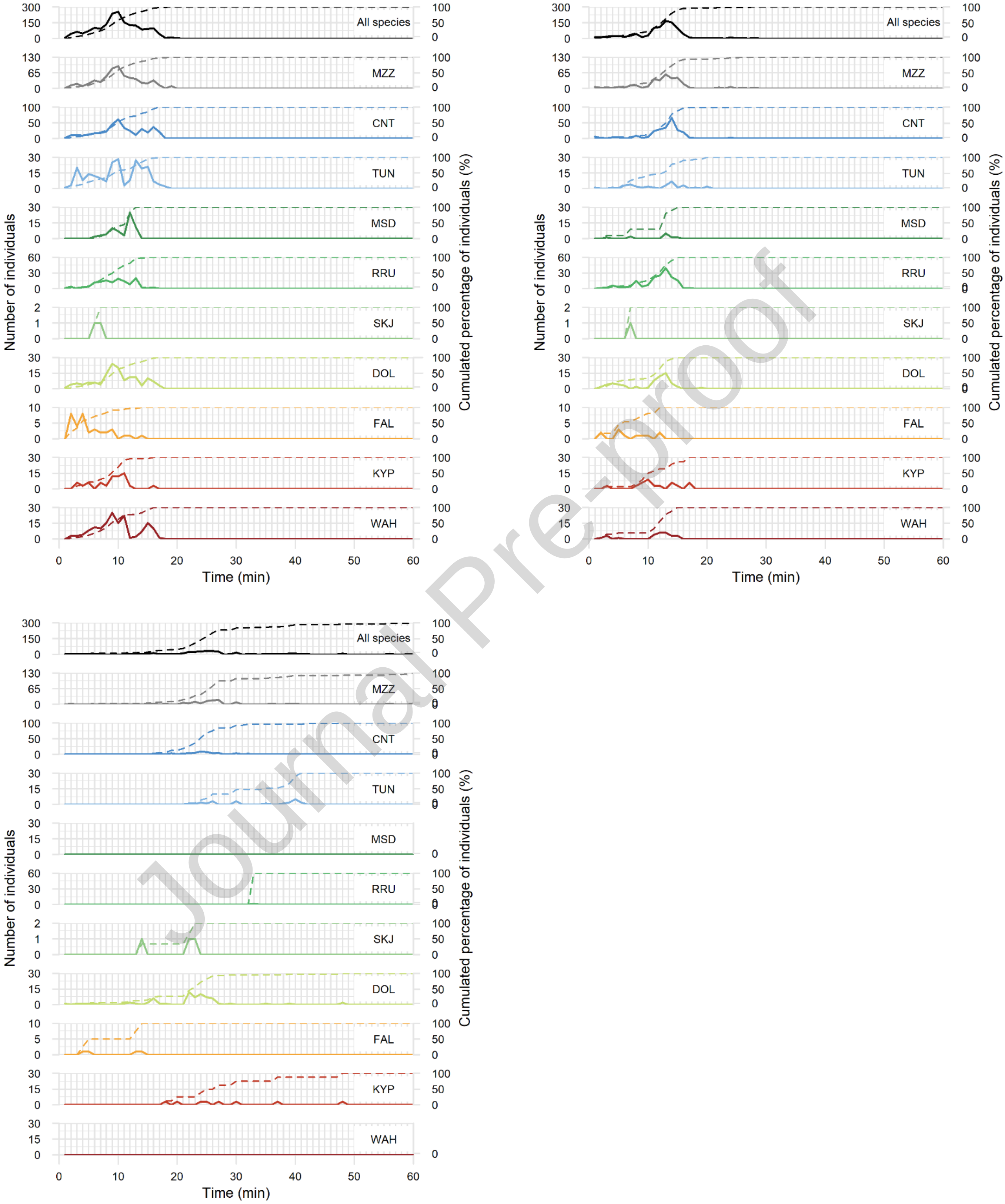
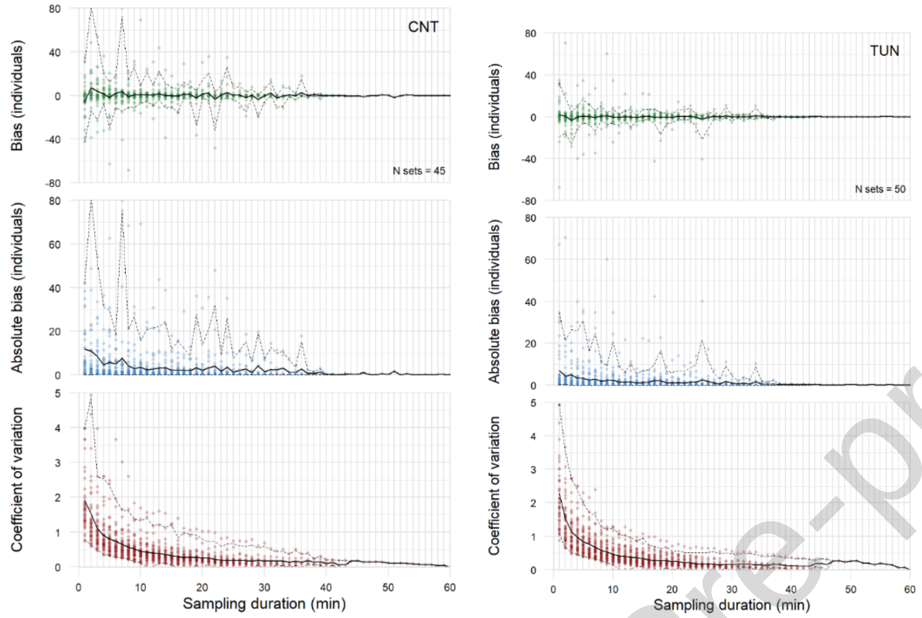
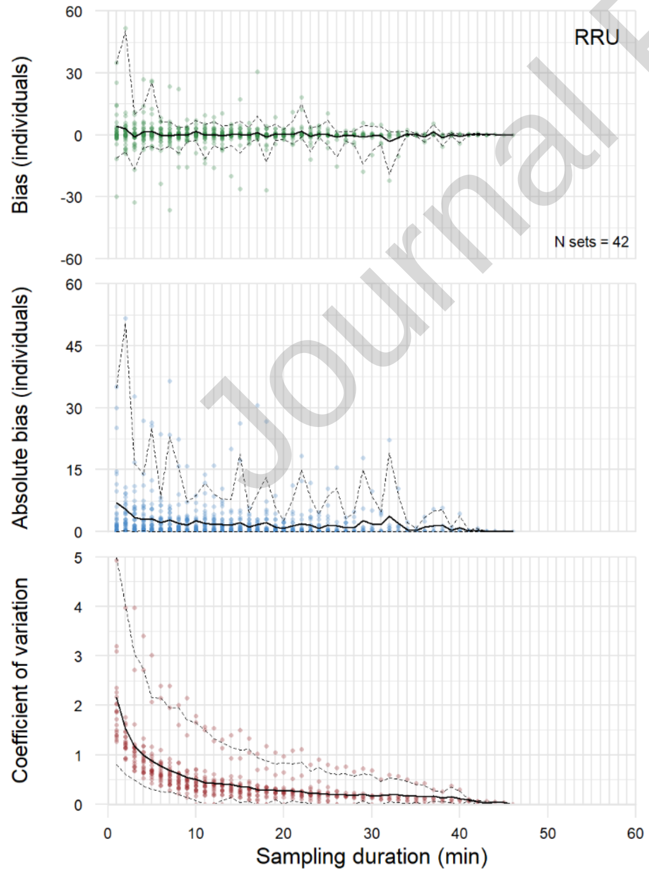


Figure C. Counts per minute (solid lines) and cumulated counts per minute (dashed lines) of discards in the lower deck of vessel 1 (N=21) per category of sorting time duration: 10-20 minutes (a); 20-30 minutes (b) and more than 30 minutes (c).

Appendix D.

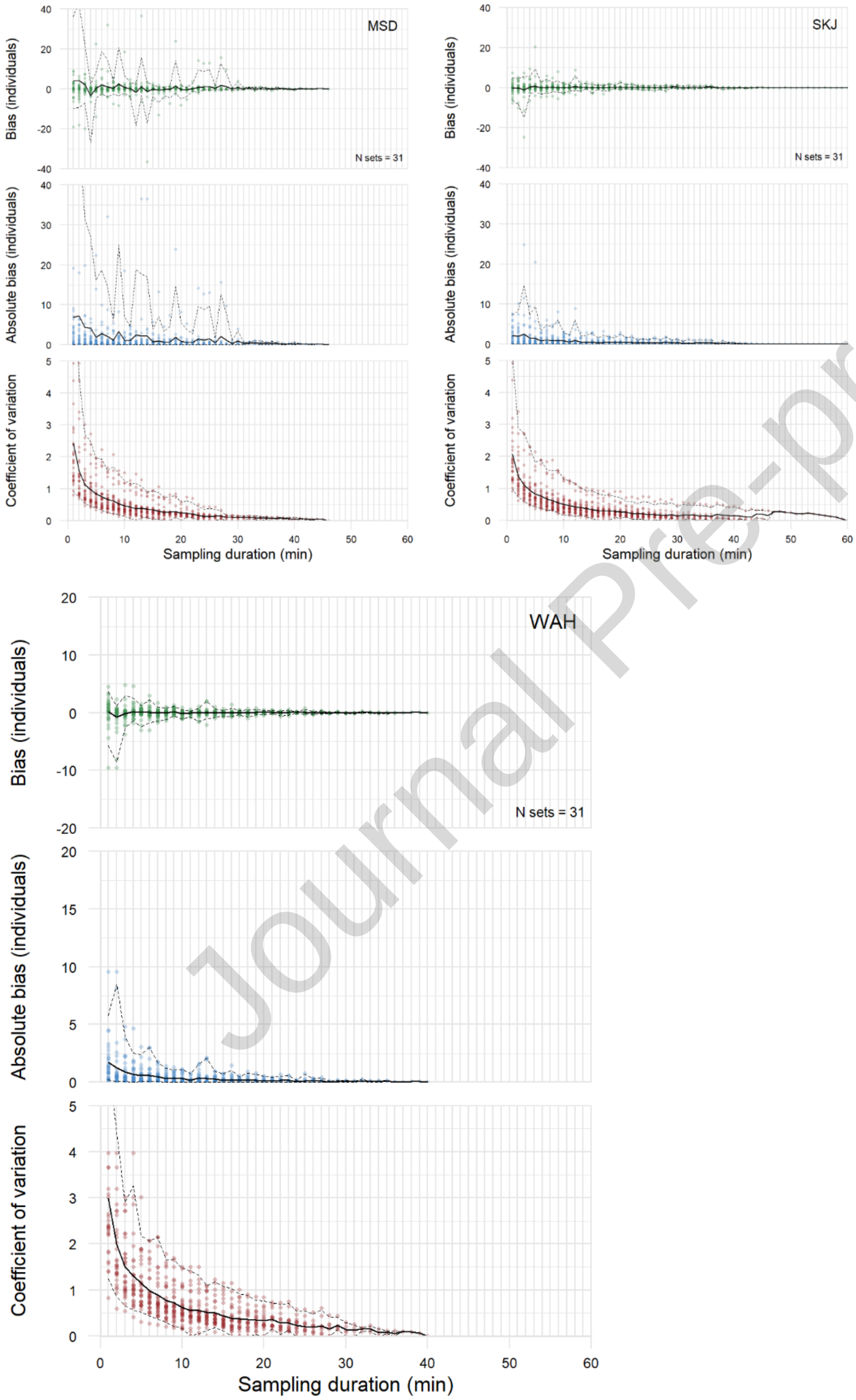
Figure D.1. Bias, absolute bias and coefficient of variation (CV) of the extrapolated number of CNT, TUN and RRU as a function of sampling duration on lower deck. The bias, absolute bias and CV were calculated on 100 bootstraps (sampling random minutes without replacement) for each fishing set. The solid line represents the mean and the broken lines the 95% confidence interval. The scale of Y-axes may differ among species.





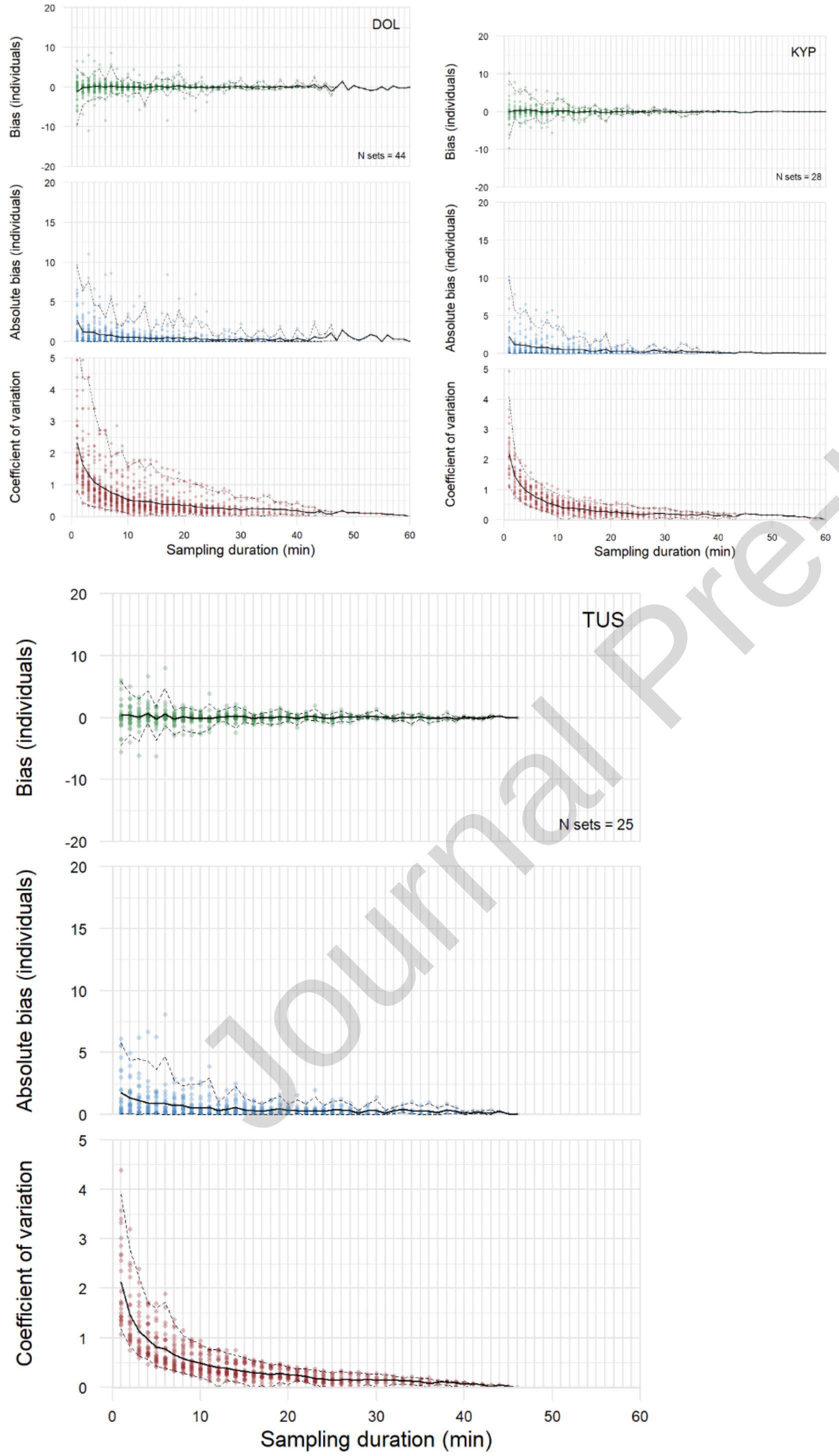
Appendix D.

Figure D.2. Bias, absolute bias and coefficient of variation (CV) of the extrapolated number of MSD, SKJ and WAH as a function of sampling duration on lower deck. The bias, absolute bias and CV were calculated on 100 bootstraps (sampling random minutes without replacement) for each fishing set. The solid line represents the mean and the broken lines the 95% confidence interval. The scale of Y-axes may differ among species.



Appendix D.

Figure D.3. Bias, absolute bias and coefficient of variation (CV) of the extrapolated number of DOL, KYP and TUS as a function of sampling duration on lower deck. The bias, absolute bias and CV were calculated on 100 bootstraps (sampling random minutes without replacement) for each fishing set. The solid line represents the mean and the broken lines the 95% confidence interval. The scale of Y-axes may differ among species.



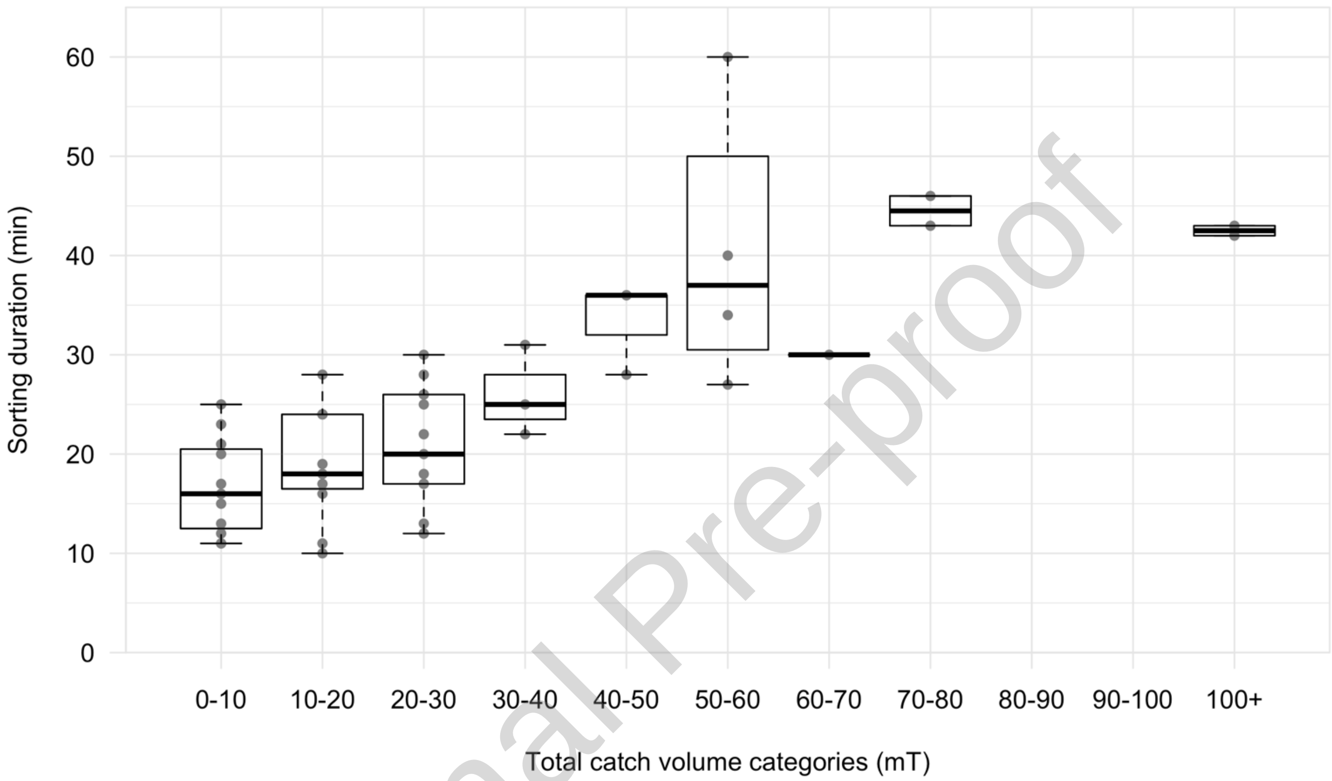
Appendix D.

Table D. Mean coefficient of variation computed for each discarded species or group of species found on the lower deck with increasing total sampling duration in minutes. CVs were calculated on 100 bootstraps (sampling random minutes without replacement) for each fishing set where the species was found.

Minute	CNT	RRU	MSD	SKJ	TUS	TUN	KYP	DOL	WAH	FAL
1	1.907	2.158	2.415	2.068	2.278	2.278	2.202	2.321	2.987	2.921
2	1.531	1.530	1.562	1.386	1.532	1.532	1.449	1.635	1.989	2.090
3	1.096	1.175	1.122	1.115	1.137	1.137	1.181	1.317	1.505	1.620
4	0.912	1.004	0.975	0.948	0.975	0.975	0.976	1.089	1.314	1.392
5	0.805	0.878	0.840	0.825	0.846	0.846	0.870	0.976	1.152	1.244
6	0.740	0.777	0.756	0.762	0.764	0.764	0.744	0.866	0.989	1.051
7	0.648	0.685	0.655	0.676	0.675	0.675	0.675	0.753	0.893	0.928
8	0.577	0.620	0.618	0.621	0.587	0.587	0.572	0.702	0.784	0.819
9	0.518	0.544	0.528	0.561	0.527	0.527	0.514	0.612	0.722	0.760
10	0.448	0.508	0.466	0.506	0.467	0.467	0.466	0.529	0.627	0.661
11	0.422	0.446	0.433	0.471	0.418	0.418	0.402	0.491	0.560	0.603
12	0.398	0.429	0.380	0.428	0.396	0.396	0.392	0.497	0.555	0.566
13	0.392	0.421	0.395	0.407	0.380	0.380	0.393	0.466	0.517	0.587
14	0.366	0.406	0.360	0.380	0.362	0.362	0.360	0.473	0.500	0.541
15	0.324	0.362	0.333	0.335	0.334	0.334	0.345	0.432	0.446	0.499
16	0.293	0.348	0.301	0.317	0.298	0.298	0.313	0.394	0.384	0.442
17	0.274	0.294	0.259	0.296	0.276	0.276	0.288	0.376	0.372	0.403
18	0.274	0.289	0.271	0.295	0.274	0.274	0.272	0.383	0.362	0.413
19	0.280	0.290	0.284	0.288	0.268	0.268	0.281	0.376	0.345	0.424
20	0.261	0.273	0.230	0.274	0.248	0.248	0.240	0.340	0.344	0.395
21	0.254	0.277	0.237	0.256	0.241	0.241	0.270	0.347	0.368	0.368
22	0.221	0.258	0.211	0.227	0.211	0.211	0.223	0.306	0.289	0.348
23	0.201	0.222	0.173	0.209	0.203	0.203	0.220	0.296	0.287	0.331
24	0.188	0.225	0.136	0.203	0.178	0.178	0.210	0.258	0.238	0.293
25	0.192	0.206	0.135	0.181	0.166	0.166	0.188	0.265	0.213	0.303
26	0.189	0.201	0.146	0.182	0.168	0.168	0.176	0.260	0.200	0.333
27	0.185	0.200	0.138	0.169	0.172	0.172	0.197	0.261	0.218	0.314
28	0.174	0.181	0.100	0.158	0.147	0.147	0.202	0.221	0.161	0.297
29	0.192	0.212	0.102	0.178	0.170	0.170	0.212	0.259	0.233	0.293
30	0.169	0.172	0.093	0.142	0.150	0.150	0.206	0.209	0.140	0.250
31	0.174	0.178	0.088	0.166	0.168	0.168	0.180	0.236	0.135	0.286
32	0.175	0.200	0.107	0.179	0.178	0.178	0.199	0.263	0.150	0.260
33	0.172	0.190	0.090	0.163	0.165	0.165	0.169	0.242	0.162	0.258
34	0.142	0.174	0.074	0.148	0.145	0.145	0.146	0.240	0.075	0.214
35	0.175	0.173	0.087	0.157	0.139	0.139	0.180	0.248	0.087	0.223
36	0.141	0.155	0.066	0.133	0.125	0.125	0.145	0.219	0.057	0.185
37	0.185	0.164	0.085	0.196	0.167	0.167	0.190	0.240	0.102	0.249
38	0.146	0.131	0.074	0.171	0.151	0.151	0.186	0.221	0.087	0.197
39	0.152	0.151	0.063	0.150	0.132	0.132	0.147	0.188	0.070	0.217
40	0.106	0.115	0.045	0.146	0.115	0.115	0.126	0.181	0.000	0.178
41	0.128	0.089	0.064	0.150	0.119	0.119	0.169	0.159		0.205
42	0.070	0.048	0.049	0.121	0.099	0.099	0.132	0.112		0.158
43	0.065	0.022	0.025	0.110	0.107	0.107	0.106	0.122		0.118
44	0.175	0.051	0.051	0.207	0.185	0.185	0.164	0.177		0.189
45	0.185	0.037	0.036	0.197	0.194	0.194	0.214	0.091		0.190
46	0.143	0.000	0.000	0.156	0.162	0.162	0.181	0.080		0.111
47	0.145			0.272	0.262	0.262	0.179	0.135		0.265
48	0.158			0.289	0.275	0.275	0.153	0.177		0.253
49	0.141			0.263	0.233	0.233	0.157	0.112		0.240
50	0.120			0.253	0.256	0.256	0.150	0.132		0.222
51	0.110			0.213	0.270	0.270	0.156	0.120		0.216
52	0.116			0.205	0.203	0.203	0.143	0.101		0.188
53	0.107			0.240	0.191	0.191	0.115	0.103		0.199
54	0.096			0.203	0.156	0.156	0.124	0.089		0.149
55	0.076			0.177	0.192	0.192	0.090	0.088		0.161
56	0.068			0.161	0.174	0.174	0.103	0.065		0.130
57	0.070			0.128	0.142	0.142	0.072	0.069		0.099
58	0.045			0.109	0.062	0.062	0.059	0.046		0.087
59	0.047			0.047	0.075	0.075	0.047	0.037		0.074
60	0.000			0.000	0.000	0.000	0.000	0.000		0.000

Appendix E.

Figure E. Distributions of sorting time duration in the lower deck in relation to the volume of total catch in logbooks. Total catches by set (N = 50) are grouped by 10 mt categories with 100+ representing catches above 100 mt.



CRediT authorship contribution statement

Karine Briand: Methodology, Formal analysis, Writing- Original draft preparation. **Philippe S. Sabarros:** Methodology, Formal analysis, Visualization, Writing- Reviewing and Editing. **Alexandra Maufroy:** Visualization, Writing- Reviewing and Editing. **Anne-Lise Vernet*:*** Investigation, Data curation. **Arthur Yon:** Investigation, Validation. **Antoine Bonnieux*:*** Resources. **Michel Goujon:** Funding Acquisition. **Pascal Bach**: Conceptualization, Methodology, Funding Acquisition, Writing- Reviewing and Editing.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: