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Original Research Article

Can modelling the drift of bycaught dolphin stranded carcasses help identify involved fisheries? An exploratory study

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ABSTRACT

Between the 1st of February and the March 31, 2017, 793 stranded cetaceans were found along the French Atlantic coasts. Common dolphins made up 84% of these strandings, and most of these presented evidence of death in fishing gear. The aim of this work is to test an approach that could help identify the fisheries potentially involved in a given stranding event. To do this we examined how the distributions of likely areas of mortality of bycaught dolphins, inferred from carcass drift modelling, coincide with fishing effort statistics of various fleets, generated from the Vessel Monitoring System, in the area over the same dates. Using reverse drift modelling, two main mortality areas were identified. A total of 3690 common dolphins (IC95% [2230; 6900]) were estimated to have died in fishing gear within the Bay of Biscay during this unusual stranding event. There was a positive correlation between the origin of stranded bycaught dolphins and the fishing effort distribution of French midwater pair trawlers, Spanish otter bottom trawlers and French Danish seiners. This co-occurrence highlights a risk and identifies fisheries that require further investigation (through observers or e-monitoring). These fisheries differed in their fishing gear, but two characteristics appear to be shared: they targeted predatory fishes (sea bass and hake) in winter and used high vertical opening gear.
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1. Introduction

The catch of non-target or non-commercial species in fishing gear, defined as bycatch, affects most marine species (Davies et al., 2009; Hall, 1996; Reeves et al., 2013; Soykan et al., 2008). The impact of bycatch on marine mega-vertebrates can be

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direct, such as additional mortality at unsustainable levels for populations, or indirect, including depletion of prey, habitat destruction and disturbance of physical and chemical processes (Hall et al., 2000; Kumar and Deepthi, 2006; Read, 2008). Bycatch is a potent threat for long-lived species with slow population growth rates, low fecundity or low survival to adulthood such as seabirds, sharks, sea turtles and marine mammals (hereafter defined as mega-vertebrates) (Hall et al., 2000; Lewison et al., 2004a, b; Mannocci et al., 2012; Read, 2008). Uncertainties around the true magnitude of bycatch often delays management decision-making, and reducing bycatch remains a challenge for the effective conservation of mega-vertebrate populations (Lewison et al., 2004a, b; Thompson et al., 2013; Lewison et al., 2014). Recent studies on the impact of fisheries on mega-vertebrate demography and population genetics revealed pessimistic conservation scenarios (Mannocci et al., 2012; Mendez et al., 2010; Saavedra et al., 2018). Most types of fishing vessels, including pelagic or bottom trawls, bottom-set gillnets and longlines, contribute to this worldwide threat to large marine vertebrates (Gilman et al., 2005; Lewison et al., 2004a, b; Lewison and Crowder, 2003; Read et al., 2006). Bycatch has been a major conservation issue since the 1970s and although it is one of the most important man-induced threats to marine mega-vertebrates it still remains largely unresolved (Breen et al., 2017; Cox et al., 2007; Cruz et al., 2018; Davies et al., 2009; Hamel et al., 2009).

Bycatch issues have long been ignored and under-documented, mostly because the occurrence of it is hard to monitor as it takes place far from ports and fish markets (Hall et al., 2000). Fisheries management has focused for decades on commercial species only, but a rising awareness of the detrimental effects of bycatch on species persistence and ecosystem functioning has occurred due to charismatic species (marine mammals, sea turtles, etc.). Bycatch occurs far from the public eye and affects species for which public concerns can quickly become salient, yet obtaining reliable estimates of its magnitude at a population scale remains a difficult endeavour (Read, 2008).

Mega-vertebrate bycatch is conventionally estimated through the stationing of on-board observers that sample a fraction of the fishing effort (Amandè et al., 2012). This approach has been considered successful in a number of cases (Beerkircher et al., 2002). When vessels are too small to accommodate an additional crew member, this approach can be replaced by port surveys that sometimes enable bycatch estimates (Goetz et al., 2015) or rapid bycatch assessments (Moore et al., 2010; Poonian et al., 2008). However, even when the fleet is composed of vessels that are large enough to accommodate observers, a variety of factors can prevent the deployment of observers as designed in the sampling scheme, thereby precluding any extrapolation to the fleet (Benoît and Allard, 2009). In the case of the common dolphin in the eastern North Atlantic, the ICES working group on bycatch in fisheries (WGBYC) recently concluded that despite more than a decade of monitoring in several EU countries it was impossible to conduct a bycatch risk assessment on this species (ICES, 2017a, page 4).

Stranding records are an important source of information on marine mega-vertebrates, and can provide critical information with which to estimate a minimum level of bycatch across fisheries (Adimey et al., 2014; Leeney et al., 2008; Lopez et al., 2003; Silva and Sequeira, 2003). Several recent studies suggested relevant indicators of mega-vertebrate populations based on strandings while accounting for drift conditions and observation pressure (Authier et al., 2014; Epperly et al., 1996; Koch et al., 2013; Peltier and Ridoux, 2015). Stranding monitoring schemes can provide data on cetacean bycatch that are complementary to more conventional approaches like on-board observer programmes, and in some circumstances observer programmes and stranding scheme datasets could ground-truth each other (IWC, 2016).

In the northeast Atlantic, the short-beaked common dolphin (*Delphinus delphis*) is one of the most abundant small cetaceans (Hammond et al., 2013; Laran et al., 2017; Murphy et al., 2013), yet also one of the most vulnerable to bycatch by fisheries (Fernández-Contreras et al., 2010; Leeney et al., 2008; N. de Boer, 2012; Peltier et al., 2016; Silva and Sequeira, 2003). In the Bay of Biscay and the English Channel, common dolphin bycatch is mostly reported in pelagic fisheries targeting seabass (*Dicentrarchus labrax*) or albacore tuna (*Thunnus alalunga*), but also in fisheries using gillnets and trammel nets, as shown by compulsory observer programmes conducted under regulation EC 812/2004. Very high estimations of bycaught common dolphins have been reported in the past (Morizur et al., 1999; Rogan and Mackey, 2007; ICES, 2018). Observer programs have estimated that up to 2000 common dolphins have died per year as a result of European fisheries in the 90s and later again in 2009 (Murphy et al., 2013), while estimations using stranding data and reverse drift modelling over the period 1990–2009 suggested that as many as 3650 (IC95% [2250; 7000]) common dolphins were bycaught annually in the Bay of Biscay and Celtic Sea (Peltier et al., 2016). For the year 2016, the estimated bycatch levels of short-beaked common dolphins in the ICES subarea VIII of the Bay of Biscay ranged from 1607 to 4355 animals based on the observer programme, and from 1400 to 4800 based on stranding data (ICES, 2018, pages 61–62).

This situation has been at a standstill for decades. Very high levels of common dolphin strandings with bycatch evidences were already being recorded along French Atlantic coasts in the 1990s, and since then 350 to 550 carcasses were recorded annually (1997–2002, 2012–2014, 2016). Two unusual multiple stranding events occurred recently along the French Atlantic coast, in February and March 2017, and most of the necropsied common dolphins were established as having been bycaught. These events constituted a timely reminder of the importance of the bycatch issue for common dolphins in the eastern North Atlantic. Understanding the ecological relationship between dolphins and fishing activities is integral to conservation management and decisions regarding bycatch reduction. Due to the difficulties involved in implementing the EC 812/2004 regulation that requires each Member State to design and implement a monitoring scheme for incidental catches of cetaceans (ICES, 2017a; Peltier et al., 2016), the use of additional datasets to improve the understanding of the cetacean bycatch issue is highly encouraged.

The aim of this work is to test an approach that could help to identify the fisheries potentially involved in a given stranding event. We tested this approach on the unusual stranding events observed in February and March 2017 along the French Atlantic coasts. To do this we examined how the likely distributions of mortality areas (the locations where fatal incidents were estimated to have occurred) of bycaught dolphins coincided with fishing effort statistics in the area over the same dates for different fleets. The at-sea mortality areas of stranded common dolphins with bycatch evidence were predicted using reverse drift modelling (Peltier et al., 2016; Peltier and Ridoux, 2015). Fishing effort data were generated from the Vessel Monitoring System (VMS), which automatically collects positional data of fishing vessels, and data on the types of fishing gear used and species targeted were attained from other official sources (Leblond et al., 2008). The mortality area and fishing effort datasets were analysed under a General Additive Model (GAM) framework to identify potential cetacean-fishery interactions in the Bay of Biscay.

2. Materials and methods

2.1. The stranding scheme

The French stranding network (*Reseau National Echouage*, RNE) is coordinated by *Observatoire Pelagis*. The network currently includes over 400 trained volunteers distributed along the entire French coast that collect information on stranded marine mammals according to a standardized protocol, including details of species, sex, measurements, external marks, stranding date and location (Van Canneyt et al., 2015). Observation pressure has been stable since the late 1980's. Cases where death was caused by fishing gear were identified by members of the volunteer network or *Observatoire Pelagis*, and these cases were validated by *Observatoire Pelagis* following Kuiken (1994) and Bernaldo de Quirós et al. (2018). The major evidence of lethal encounters with fishing gear include: net marks; good nutritional condition; evidence of recent feeding; jaw and rostrum fractures; froth in the airways; oedematous lungs; and dorsal fin, pectoral fin or tail fluke amputations. Body condition was established by evaluating the whole animal visually and measuring the thickness of the blubber layer. Froth, hematoma and oedematous lungs can only occur *ante-mortem* and are related to asphyxia. Bleeding around fractures was examined to confirm *ante-mortem* trauma. Fin and fluke amputations usually occur *post-mortem* as a result of disentangling the bodies from fishing gear. Bycatch was determined to have been the cause of death only among fresh and slightly decomposed carcasses that had stranded between the Gironde and Loire estuaries (Fig. 1) (decomposition codes 1–3 (Table 1), as defined in Van Canneyt et al. (2015), inspired by Geraci and Lounsbury (2005)). The presence of epidermis and intact viscera in very fresh to slightly decomposed carcasses allowed the observers to carry out the full sampling protocol and therefore establish the cause of death.

2.2. Estimating the mortality areas of stranded carcasses

The at-sea origins of animals that stranded during the unusual mortality events of February–March 2017 were determined following the methodology described in Peltier and Ridoux (2015) and Peltier et al. (2016). The reverse trajectories of

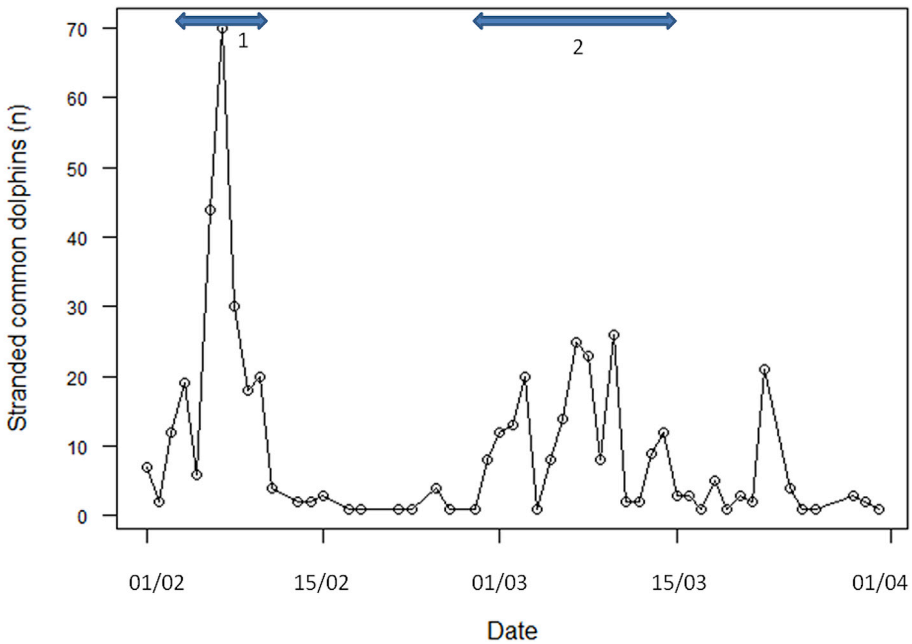

Fig. 1. Time series of common dolphin strandings in February and March 2017 along the French Atlantic coast, between the Gironde and Loire Atlantique departments (n = 483). Blue arrows highlight the two most important stranding events (1 = February event; 2 = March event).

Table 1
Decomposition codes assigned to stranded cetaceans with criteria, time after death and photographic examples of carcasses (Van Canneyt et al., 2015, inspired by Geraci and Lounsbury, 2005).

Decomposition code	Criteria	Time after death (drift)	Example
1 – < 48 h	-Seen alive <48h before examination -Unhaemolysed serum -No protrusion -Blood cells intact -Viscera intact -Clear eyes	<2 days	
2 – Fresh	-Haemolysed serum -No protrusion -Viscera intact -Glazed eyes	2 to 5 days	
3 – Slight decomposition	-Tongue and penis protruted -Viscera intact -Eyes sunken or missing -Skin cracked and sloughing	5 to 15 days	
4 – Advanced decomposition	-Epidermis can be entirely missing -Viscera friable, difficult to dissect -Gas pockets	15 to 30 days	
5 – Skeletal remains or mummified	-Skin may be draped over skeletal remains -Tissues desiccated	>30 days	

bycaught animals were calculated from their stranding locations using the drift prediction model MOTHY (Modèle Océanique de Transport d'Hydrocarbures), which was developed by MétéoFrance to predict the drift trajectory of a floating object under the influence of tides and wind (Daniel et al., 2002), and from this trajectory the likely area of mortality at sea was identified. MOTHY includes atmospheric forcing from a global meteorological model. Carcass immersion was set at 90% in volume, following previous *in situ* and modelling experiments (Peltier et al., 2012). The death-to-stranding time was determined for each individual from visual criteria describing skin erosion (from Peltier et al., 2012). Experiments were carried out in winter (January to March) in the Bay of Biscay to ensure compatibility with decomposition and drift conditions during winter mortality events. Animals categorized as "fresh" were estimated to be < 5 days *post-mortem* and animals classified as "slightly decomposed" were 5–15 days post-mortem. One location was retained for each day within the time window corresponding to the decomposition code of each individual, and locations were weighted in order to obtain a total weight of 1 per drift. In order to ensure a thin resolution and ease of reading, weighted fixes of dead animal drifts were summed in a 0.4° × 0.4° grid. Four sub-sets of data were defined according to stranding month and decomposition status: February - fresh animals; February - slightly decomposed animals; March - fresh animals; and March - slightly decomposed animals.

To obtain spatially smoothed estimates of mortality we used a "block averaging" method (Petitgas et al., 2014). This method allowed us to average the data by block over the 0.4° × 0.4° grid, ranging from 43°N to 47°N, and from 1°W to 4°W. The value in the first block (block 0, origin = x_0) is the sum of the weighted locations encountered within its edges. The point origin (x_0) from block 0, in the lower left corner, was randomized 100 times. At each randomization k, the grid origin x_k varies and the sum of animals that died in each cell is calculated. Each block then has 100 sums associated with it. The mean of all 100 sums was then calculated and located at the centre of the block. This block-averaged data is similar to a kernel interpolation (Petitgas et al., 2014).

Analyses and cartography were performed using R software, version 3.4 (Ihaka and Gentleman, 1996; R Core Team, 2017) and bathymetric maps were plotted with the R library *marmap* (Pante and Simon-Bouhet, 2013).

2.3. Estimating mortality at sea

The observed number of stranded animals is a function of several parameters (Peltier et al., 2016):

$$N_{stranding} = f(\,Abundance,\ mortality, buoyancy,\ drift,\ discovery) \tag{1}$$

The observed number of strandings was corrected using various parameters to estimate total mortality at sea. The discovery rate was set to 1, since observation pressure has been stable since 1990 and since the public's and authorities' awareness (*e.g.* municipalities, prefecture, police, marine safety) during these events likely allowed for the detection and reporting of all carcasses. Previous published work spatially corrected the stranding numbers using the probability of stranding (itself a function of drift) in the area (Peltier et al., 2016, 2014; Peltier and Ridoux, 2015). We assumed that almost all drifting cetacean carcasses were brought ashore by storms occurring days and hours before the unusual stranding events, so the probability of stranding was conservatively set to 1. The buoyancy rate of dolphin carcasses (the proportion of all carcasses that float) was previously estimated at 17.9% [9.3%; 28.8%] in the North-East Atlantic (Peltier et al., 2016).

2.4. Fishing effort data

Fishing effort data were provided by the French Institute for Marine Research and Exploitation (*Institut Français de Recherche et d'Exploitation de la Mer* - Ifremer) and the Directory of Marine Fisheries and Aquaculture (*Direction des Pêches Maritimes et de l'Aquaculture* – DPMA - from the ministry in charge of agriculture and fisheries), as agreed by the working group on cetacean bycatch. Following the unusual stranding events of February–March 2017, the French ministry in charge of the environment convened a meeting with the main stakeholders of the cetacean-fisheries interaction network in order to identify and resolve the issue of common dolphin bycatch in the Bay of Biscay. The working group is composed of representatives from: 1) the DPMA, 2) the Directory of Water and Biodiversity (*Direction de l'eau et de la Biodiversité* - DEB - Ministry in charge of the environment), 3) Ifremer, 4) the industry from the Committee for Marine Fisheries and Fish Farming (*Comité National des Pêches Maritimes et des Elevages Marins* - CNPMEM), 5) the French Agency for Biodiversity (*Agence Française pour la Biodiversité* - AFB), 6) regional groupings of professional fishermen (*Pêcheurs de Bretagne, OP Vendée, Pêcheurs d'Aquitaine*), 7) Interregional Maritime Directions and 8) *Observatoire Pelagis* (University of La Rochelle and CNRS). The terms of reference of the working group are (1) to improve knowledge of small cetacean bycatch in the Bay of Biscay, (2) to develop mitigation strategies to prevent bycatch, and (3) to raise awareness among fishers on the bycatch issue.

All European fishing vessels over 12 m are required under EU regulation to be equipped with Vessel Monitoring System (VMS) transmitters that provide information of their positions and activity. Data are gathered and archived by Ifremer and administered by the DPMA.

Ifremer's Fisheries Information System (SIH-Système d'Informations Halieutiques, http://sih.ifremer.fr/) covers all fisheries operating in French waters and is part of Ifremer's aim to build an operational and multidisciplinary monitoring network, allowing a comprehensive view of fishery systems including their biological, technical and economical components. Available information includes VMS data, declarative landing statistics (log-books and sales provided by the ministry in charge of fisheries) and Ifremer survey data.

The VMS location data were converted into in fishing effort on the basis of vessel speed by Ifremer (Leblond et al., 2008). Raw positional data were collected at 1-h intervals. To estimate the speed of fishing vessels, vessel displacement between two successive points was assumed to have been rectilinear at a constant speed. Linear segments were mapped on a $0.05^\circ \times 0.05^\circ$ grid. Mean speed was estimated from the time difference between each segment extremity. For each segment, the vessel was considered to be in transit if the mean speed was >4.5 knots or if the segment was less than two nautical miles (NM) from a fishing harbour. The vessel was considered to be fishing if the mean speed was <4.5 knots. The activity was unknown when speed was 0 or when the time interval between two locations exceeded 6 h. Non-fishing operations were removed from VMS dataset. The daily sums of fishing effort in hours were provided in a $0.05^\circ \times 0.05^\circ$ grid, and the information was split by fishing gear type, flag, vessel length and registration harbour. Fishing effort during mortality events was aggregated within the $0.4^\circ \times 0.4^\circ$ grid (44.2°N to 47.4°N and −0.8°W to −4°W) used for aggregating carcass drift locations. The fishing effort was split according to fishing gear type, following the blocking procedure described in section 2.2 (Petitgas et al., 2014) to ensure spatial consistency between estimated densities of dolphin mortality areas and observed fishing effort. Moran's I statistics for spatial autocorrelation was computed for each group of fishery effort data.

Only trawls, nets and seines were considered as longline fishing, pots and dredges are not suspected to generate small cetacean bycatch in the Bay of Biscay. Ten fisheries operating in the Bay of Biscay at the time under different flags and equipped with different gear types were considered (Table 2).

2.5. Generalised Additive Models (GAMs)

Generalised Additive Models (GAMs) were used to explore the spatial overlap between fishing effort and the distribution of estimated bycaught common dolphins at sea as obtained by carcass drift back-calculation. The densities of bycaught dolphins, and fishing effort in hours were $\log(1+x)$ transformed.

Table 2
Fisheries analysed during the four stranding events. Moran's I statistics for spatial autocorrelation is reported (null expectation: I = −0.019 ± 0.010). Statistically significant Moran's I statistics (at the 5% level) are in bold.

Fishery	Flag	Code	February		March	
			Fresh	Slightly decomposed	Fresh	Slightly decomposed
Danish seines	French	SDN_FR	**0.757**	**0.696**	**0.696**	**0.709**
Drift nets	French	GND_FR	**0.654**	**0.701**	**0.723**	**0.677**
Set gillnets	French	GNS_FR	**0.545**	**0.559**	**0.693**	**0.724**
Trammel nets	French	GTR_FR	**0.520**	**0.518**	**0.486**	**0.537**
Otter twin trawls	French	OTT_FR	**0.697**	**0.652**	**0.705**	**0.683**
Pair trawls midwater	French	PTB_FR	**0.671**	**0.573**	**0.641**	**0.640**
Pair trawls bottom	French	PTM_FR	**0.654**	**0.650**	**0.660**	**0.661**
Otter trawls bottom	German	OTB_DEU	NA	NA	**0.660**	**0.693**
Otter trawls bottom	Spanish	OTB_ESP	**0.783**	**0.805**	**0.769**	**0.764**
Otter trawls bottom	French	OTB_FR	**0.548**	**0.609**	**0.578**	**0.620**

In each cell of the study area, the density of bycaught dead dolphins was correlated to the fishing effort of the fisheries operating in the area. Because of the exploratory nature of this work, a variable selection was not conducted: the primary aim was to identify fisheries positively correlated with common dolphin mortality.

Gaussian GAMs with an identity link were used to describe the relationships between the different fishing gear types and the mortality areas of bycaught common dolphins. The GAMs were fitted using the *mgcv* library, version 1.8−23 (Wood, 2011), using penalized thin-plate splines with basis dimension (k) set to 4 to prevent excessive wiggliness.

3. Results

3.1. Stranding events

Winter storms Kurt, Leiv and Marcel (February 3rd, 4th and 5th, 2017) and then Zeus (March 6th, 2017) generated west winds of up to 150 km h^{-1}. These meteorological phenomena brought ashore all cetacean carcasses drifting in the Bay of Biscay, inducing two great stranding events along the Atlantic coasts. Between the February 1, 2017 and the 31st of March, 793 cetaceans were found stranded along the French Atlantic coasts (from western end of Brittany to the Spanish border). Two main events were recorded: from February 3rd to 10th, and then from February 28th to March 14th (Fig. 1). During these events, 573 small cetaceans were recorded from 44.2°N to 47.4°N (Fig. 2), 84% of which were common dolphins (n = 483). Most of them were examined by trained volunteers of the French stranding network (89%, n = 431). Two thirds of these examined common dolphins were fresh or slightly decomposed (69% n = 297), and among these 95% presented evidence of death by fishing gear (n = 281).

3.2. The mortality areas of stranded animals

According to the decomposition status of the carcasses, only locations corresponding to the death to stranding time (Table 3) were retained as likely mortality areas. Prior to the early February stranding event, all drift trajectories showed a large loop pattern (Fig. 3). During the last days before stranding, the trajectories were fairly straight with a general WSW to ENE orientation and were only altered by oscillations related to tidal currents. The trajectories of carcasses in the time leading up to the early March stranding event had smaller loops which occurred during late February, followed by a general W to E drift orientation in early March.

The likely at-sea origins of stranded common dolphins are represented separately according to carcass decomposition status (fresh and slightly decomposed) and February or March events (Fig. 4). During the February stranding event, fresh carcasses mostly originated from coastal areas, between the Gironde and Loire estuaries, while slightly decomposed carcasses mostly originated from the continental slope of the Bay of Biscay. The common dolphins that stranded in March originated mostly from the continental shelf, but the mortality areas of slightly decomposed dolphins were more widespread over the continental shelf and slope and had lower densities than those of fresh carcasses.

3.3. Estimated total common dolphin mortality at sea

The total mortality of small cetaceans at sea from the tip of Brittany to the Spanish border between mid-January (*i.e.* 15 days prior to the onset of the February multiple stranding event) and early March 2017 was estimated at 4430 small cetaceans (IC95% [2750; 8530]), including 3690 common dolphins (IC95% [2230; 6900]).

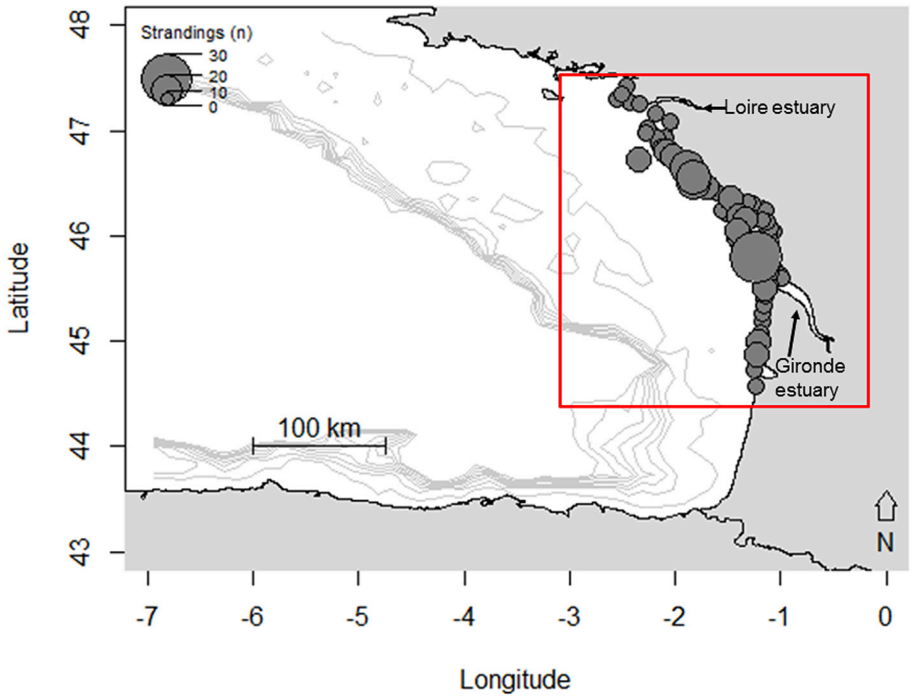

Fig. 2. Stranding locations of common dolphins found stranded between the 1st of February and March 31, 2017 (n = 483). The red box delineates the study area.

3.4. *Spatial co-occurrence of at-sea origin of stranded dolphins and active fisheries*

The results of the GAMs revealed that the fishing effort of six fisheries correlated with the likely origin of bycaught dolphins found stranded (Table 4). These fisheries were the French, German and Spanish otter bottom trawlers (OTB_FR, OTB_DEU, OTB_ESP respectively), the French otter twin trawlers (OTT_FR), the French midwater pair trawlers (PTM_FR) and the French Danish seiners (SDN_FR). All fisheries accounted for approx. 39% of the variance.

The spatial and temporal correlation between the origin of stranded bycaught dolphins and fishing effort distribution during the two stranding events was positive for French midwater pair trawlers, Spanish otter bottom trawlers and French Danish seiners, but negative for French and German otter bottom trawlers and French otter twin trawlers (Fig. 5). Because of limited data availability for German otter bottom trawlers, their relationship to the mortality areas of bycaught dolphins must be considered with caution.

4. Discussion

4.1. *General*

The daily figures of common dolphin strandings reported during the unusual stranding events are up to 10 times higher than the average numbers recorded so far in the same area and season (Dars et al., 2018). The total number reported for these two months is about two to nine times greater than the yearly totals recorded in the last two decades (range 85–548; http://www.observatoire-pelagis.cnrs.fr/les-donnees/(Dars et al., 2018)). However, unusual stranding events similar to this one have been recorded before, although of lower intensity. The criterion used to qualify an unusual stranding event was a minimum of 30 common dolphins recovered over 10 consecutive days along a maximum distance of 200 km in the Bay of Biscay (Peltier et al., 2014). It must be noted that bycatch mortality is not restricted to these events, it was estimated that 30–50% of stranded common dolphins reported outside of unusual stranding events displayed bycatch marks.

Two general areas of origin were identified according to carcass decomposition state, used here as a proxy of time elapsed between death and stranding: one coastal and one offshore. The coastal area stretches approximately from the coast to off the 100 m isobaths. The offshore area is mostly located from the 100 m isobaths to the continental slope. These limits have to be considered with caution because the resolution of the grid is fairly coarse ($0.4^\circ \times 0.4^\circ$).

Multiple strandings occurred in the aftermath of winter storms Kurt, Leiv, Marcel and Zeus that hit the French Atlantic coasts in early February and early March 2017. Although these storms were not a likely cause of mortality in common dolphins, they revealed the magnitude of bycatch-induced mortality by creating conditions that favoured the drifting of carcasses from their at-sea mortality areas to the coast.

Table 3
Dates of stranding, drift durations and likely dates of mortality events of common dolphins with bycatch evidences.

Event/Condition	Dates of stranding event	Drift duration (days)	Dates of mortality event	Common dolphin examined, fresh or putrefied with bycatch evidences (n)
February/Fresh	03/02 to 10/02	[1; 5]	30/01 to 10/02	65
February/Slightly decomposed	03/02 to 10/02	[6; 15]	20/01 to 05/02	100
March/Fresh	28/02 to 14/03	[1; 5]	24/02 to 14/03	53
March/Slightly decomposed	28/02 to 14/03	[6; 15]	14/02 to 09/03	63

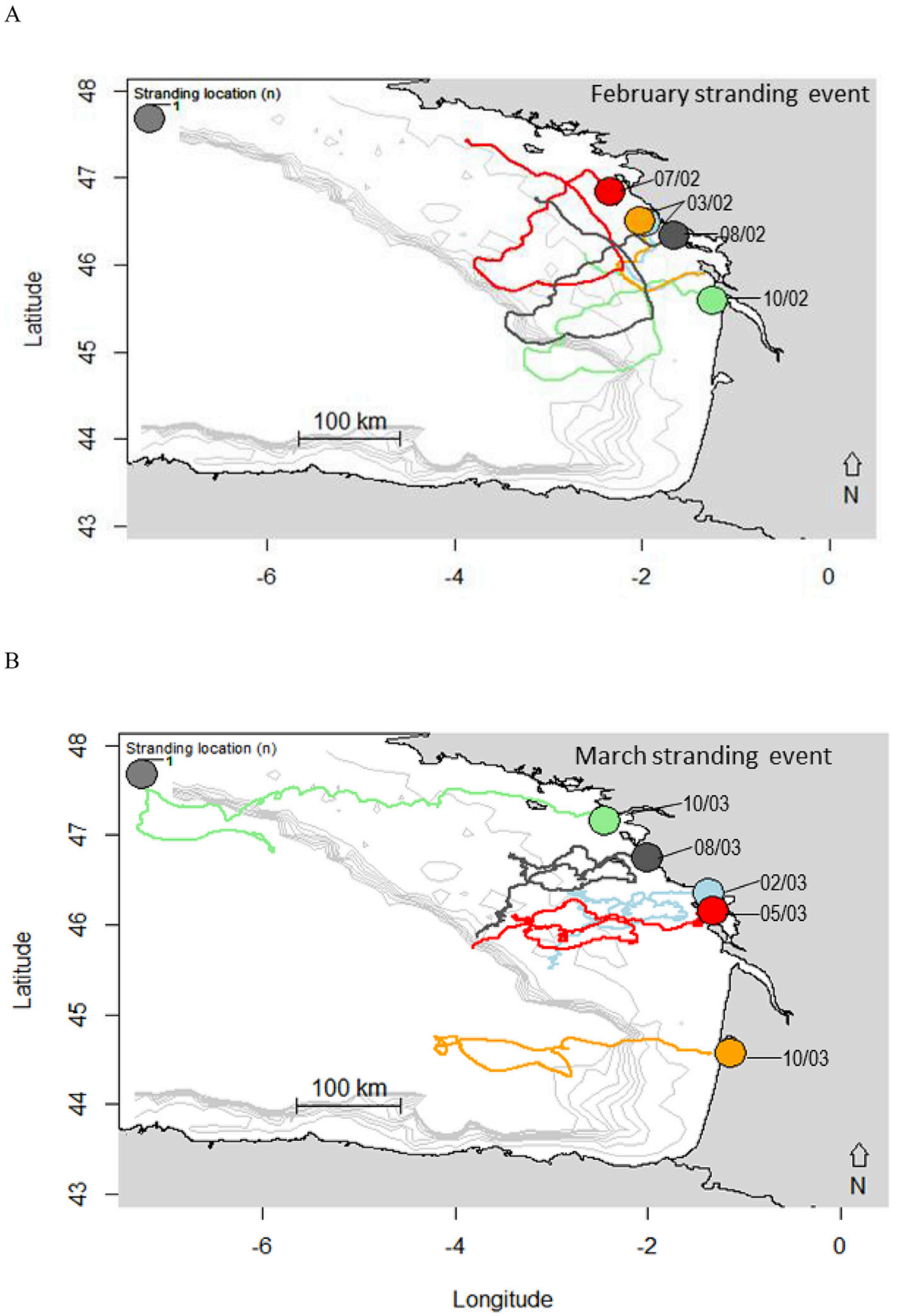

Fig. 3. Examples of 30-day drift predictions of common dolphins found stranded during the February (A) and March (B) stranding events (n = 10).

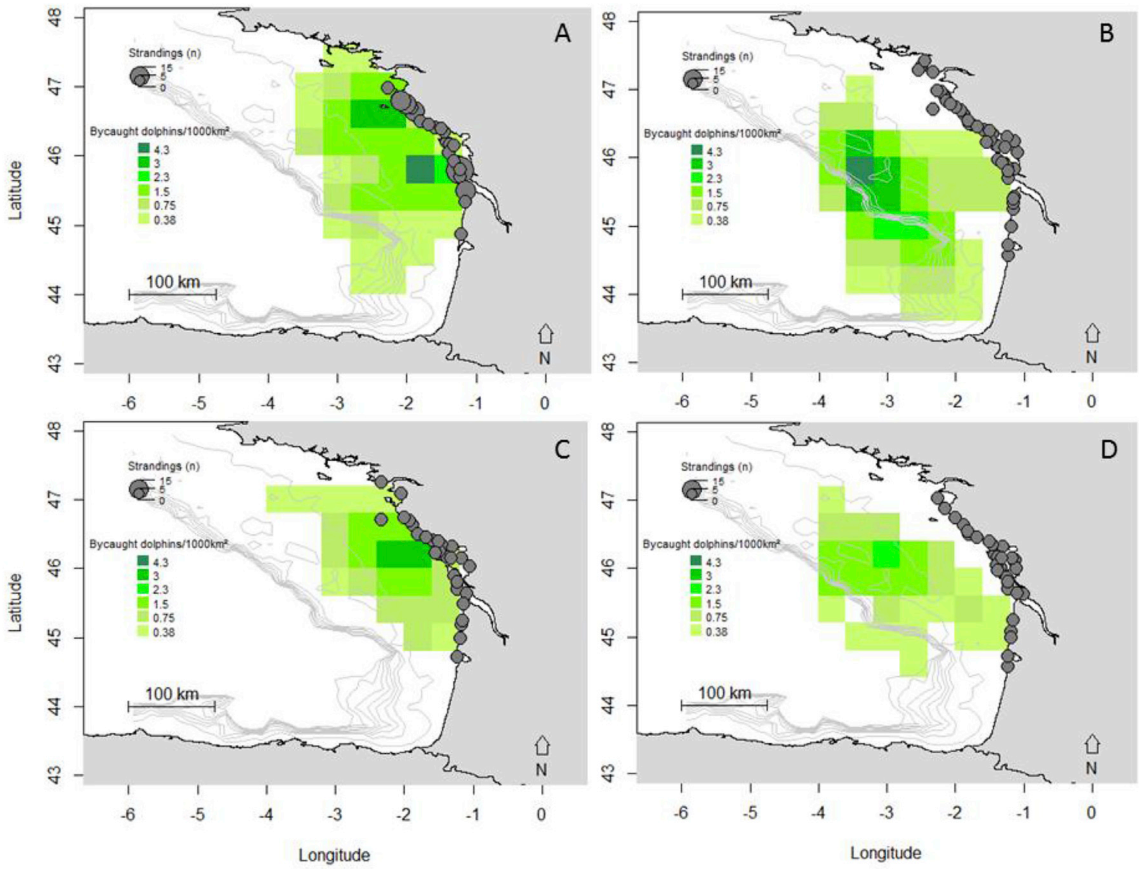

Fig. 4. The estimated origin of stranded common dolphins with evidence of bycatch: fresh dolphins during the February event (A; n = 65); slightly decomposed dolphins during February event (B; n = 100); fresh dolphins during March event (C; n = 53); slightly decomposed dolphins during March event (D; n = 63).

During February and March 2017, some 4430 small cetaceans (CI95% [2750; 8530]) were estimated to have been bycaught; which is of the same order of magnitude as the estimated average annual common dolphin mortality related to fishing activities between 1990 and 2009 (Peltier et al., 2016).

Mortality estimates were corrected using the buoyancy rate of dolphins, based on an *in situ* experiment (Peltier et al., 2016, 2012), which estimated the probability of a dolphin to float (see section 2.3). This correction factor has a major effect on final estimates and could be updated by increasing the number of experimentally released carcasses and by refining the estimates of the proportion of floating carcasses. Two recent small-scale studies (n = 17 in 2018; n = 26 in 2019) with similar protocol in coastal areas of Bay of Biscay in winter 2018 and 2019 highlighted both higher and lower recovery rates of dead dolphins according years; the results of the 2018 study revealed a higher recovery rate and the 2019 study revealed a lower recovery rate than the estimate in Peltier et al. (2016), which suggests that the buoyancy rate of dolphins can be variable.

The VMS data allowed for the distribution of fishing effort to be considered in the analysis (Gerritsen and Lordan, 2011; Hintzen et al., 2012; Kroodsma et al., 2018) in order to identify fisheries with the highest level of risk to cetaceans. However, the algorithms used to identify fishing effort in hour analysed all fishing vessel types similarly (*e.g.* trawls, seines, nets, longlines). The interpretation of net fishing effort has to be carefully considered. Moreover, false-positive results (where vessels were travelling at fishing speeds, but were not actually engaged in fishing) cannot be detected, although it is unlikely that this occurred often (Bertrand et al., 2008; Gerritsen and Lordan, 2011).

The European Commission (EU) decided to require automatic monitoring of fishing vessels in 1997, which was implemented aboard all fishing vessels >24 m in overall length in 2000 (Commission Regulation (EC), 1997), >18 m in 2004 (Commission Regulation (EC), 2003), >15 m in 2005 and > 12 m in 2010 (Commission Regulation (EU), 2009). The resulting VMS data therefore represent the fishing effort only of larger vessels, which was only 27% of the French fishing fleet in 2016 (SIH-Système d'Informations Halieutiques). Small scale and artisanal fisheries have long been overlooked as well as recreational and subsistence fisheries, which can also jeopardize marine mammal populations (Cruz et al., 2018; Mangel et al., 2010; Zappes et al., 2013).

The identification of bycaught stranded dolphins allowed us to spatially correlate and overlap an impact indicator with maps of a set of candidate pressures. The analysis of VMS data provided relevant information on the co-occurrence of

Table 4
Results from the GAM fitted to estimated densities of bycaught dolphins and the 10 fisheries operating in the Bay of Biscay in February and March 2017.

Fishery	Flag	Code	Approximate p-value
Danish seines	French	SDN_FR	**0.031**
Drift nets	French	GND_FR	**0.006**
Set gillnets	French	GNS_FR	0.111
Trammel nets	French	GTR_FR	0.313
Otter twin trawls	French	OTT_FR	0.177
Pair trawls midwater	French	PTB_FR	0.297
Pair trawls bottom	French	PTM_FR	**7,00E-06**
Otter trawls bottom	German	OTB_DEU	**0.012**
Otter trawls bottom	Spanish	OTB_ESP	**0.003**
Otter trawls bottom	French	OTB_FR	**0.002**
Residual σ			0.193
R^2			0.391

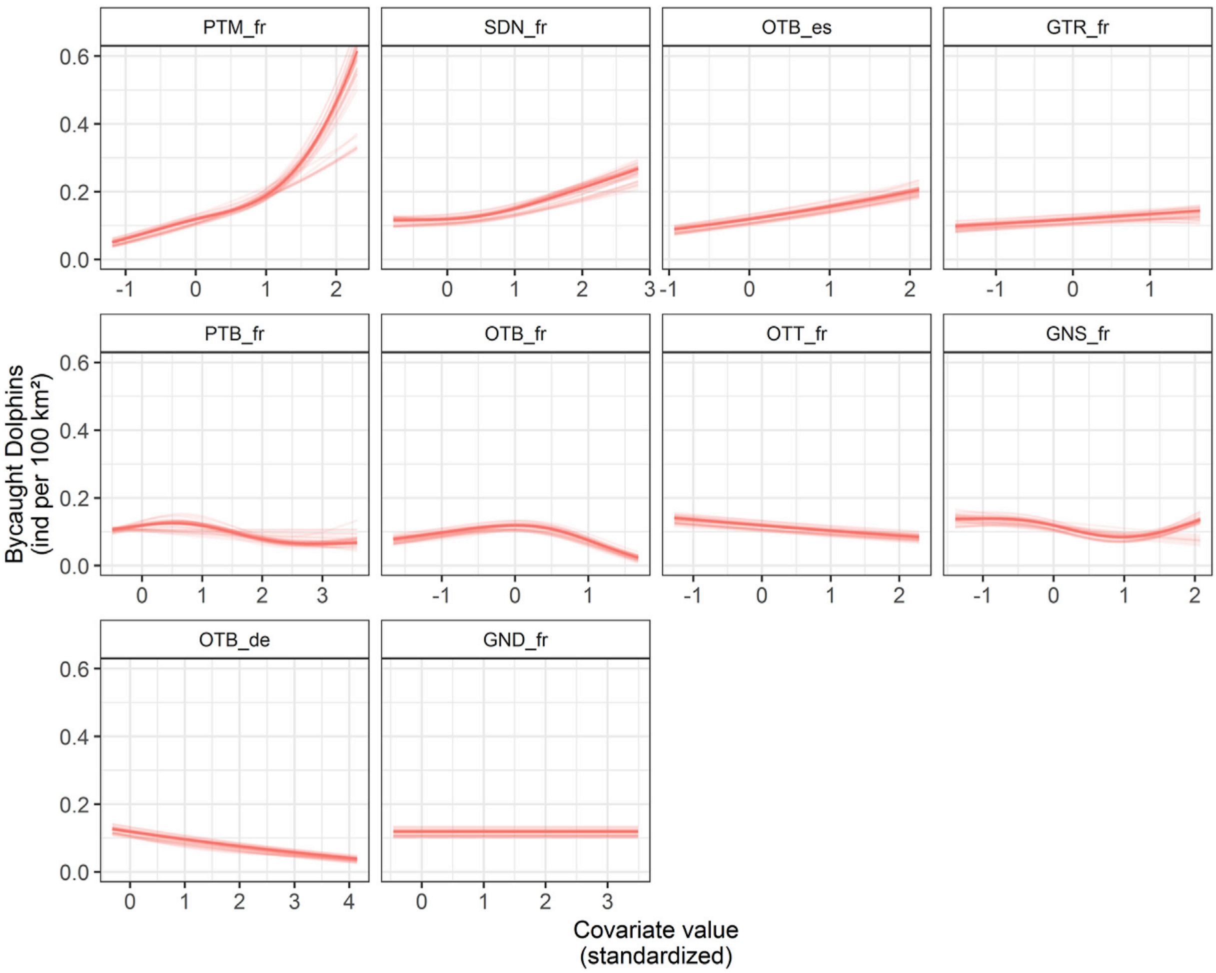

Fig. 5. Correlations between the mortality areas of bycaught common dolphins and fisheries active in the area. The thick line is estimated from the complete data. Thin lines are jack-knifed estimates (with one cell removed) to assess the robustness of results.

bycaught common dolphins and fishing effort of various fisheries in the French EEZ, which does not provide direct evidence of a causal relationship but highlights a risk a lethal interaction. Further investigation should be undertaken to identify the nature of the relationship between common dolphins and the fisheries that have been identified.

Three of the considered fisheries were positively correlated with bycaught dolphin mortality areas: the French pelagic trawl fishery, the French Danish seine fishery, and the Spanish bottom trawl fishery. Three others were negatively correlated: The French otter twin trawl fishery and the French and German bottom trawl fisheries. The negative relationships may have been the result of a different spatial distribution of these fisheries in the Bay of Biscay during these events. During the time of mortality these three fisheries were mostly operating in the middle of the continental shelf, while common dolphins were estimated to be caught at locations more inshore and offshore (Annex 1).

4.2. Co-occurrence of European fisheries and bycaught dolphins in the Bay of Biscay

The fishing effort in the Bay of Biscay (ICES areas VIII a, b and d) is one of the most intense in the world (Kroodsma et al., 2018) and includes the use of a large variety of fishing gear and vessels operating under various flags. Between February and March of 2017 alone, up to 19 fishing vessels from eight different countries were operating in the area. In the recent past, French vessels from the Bay of Biscay landed over 200 species (Daurès et al., 2009). The diversity of fisheries operating in this area makes it difficult to interpret the cetacean bycatch process as documented in stranding records; the present work is an endeavour to disentangle the complexity of potential relationships between fisheries and bycatch incidents.

The fishing effort of French pelagic pair trawlers and French Danish seiners overlapped with bycaught common dolphin mortality areas in shallow waters (50–100 m isobaths) from the Gironde to the Loire estuaries, while the overlap with Spanish otter bottom trawlers was mainly located along the continental slope of the Bay of Biscay (Annex 2).

The seabass in the Bay of Biscay is mainly targeted by French vessels with more than 96% of international landings in 2016 (ICES, 2017b). The interaction between common dolphins and French pelagic pair trawlers in the Bay of Biscay has already been documented. European Union funded projects including PETRACET (Pelagic TRAwl and CETaceans) and NECESSITY estimated the annual fishing effort among the main French, Irish, British, Danish and Dutch pelagic trawl fisheries in the Celtic Sea and Bay of Biscay (NECESSITY Report, 2008; Northridge et al., 2006). The PETRACET project revealed that most common dolphin bycatch incidents were recorded aboard French pelagic pair trawlers targeting sea bass (Morizur et al., 1999; Northridge et al., 2006). These fisheries operate in winter when spawning fish aggregate (Fritsch et al., 2007; ICES, 2017b), mostly in coastal areas between the Loire and Gironde estuaries (Morizur et al., 1999). The interaction between common dolphins and pelagic trawlers is mainly driven by trophic relationships, as dolphins and sea bass target the same prey species during sea bass spawning season (Spitz et al., 2013). Most bycatch incidents occurred at night, which is likely related to the nychtemeral activity pattern of small pelagic fishes hunted by the two top predators (Morizur et al., 1999). However, sea bass only represented an average of 14% of pelagic pair trawler catches during the two 2017 mortality events (SIH-Système d'Informations Halieutiques).

The European hake *Merlucius merlucius* is the main demersal species supporting trawl fleets in the Bay of Biscay and off the Iberian Peninsula. Recently, Spain was estimated to land around 60% of commercial hake and France 30% (www.fao.org). High levels of dolphin bycatch on French pelagic pair trawlers targeting hake were reported in the mid 1990s (ASCOBANS, 2015; Murphy et al., 2013). Following a major drop in hake stock in the NE Atlantic, landings were almost halved between the mid 1990s and early 2000s (www.fao.org). Since mid-2010, hake stock recovery has led to increased catches (www.fao.org) and allowed for a diversification of target species for French pelagic pair trawlers in winter. European hake is now the most abundant species (by weight) in landings recorded along the French Atlantic coasts (19% of total landed weight; Fishery Information System/Ifremer). European hake was the primary species caught by French pelagic pair trawlers (48–81% of catches) during the dolphin mortality events (SIH-Système d'Informations Halieutiques).

Danish seiners were first recorded to be operating in the Bay of Biscay in 2009 in the French fishing fleet (SIH-Système d'Informations Halieutiques, Leblond et al., 2008). Danish seiners are known to fish on demersal and pelagic species. Along the French Atlantic coasts, Danish seiners landed 9% of the total sea bass weight, whereas pair trawlers landed 26% of the seabass weight in 2017 (FranceAgriMer, 2018). In some harbours in 2017, Danish seiner sea bass landings were double that of trawler landings, suggesting that this gear developed rapidly in the Bay of Biscay despite being fairly recently introduced. During the 2017 dolphin mortality events, sea bass represented up to 11% of fishes caught by French Danish seiners, whereas hake constituted up to 25% of catches. The predominant species caught was the whiting (*Merlangius merlangus*) with between 8 and 31% of landings (SIH-Système d'Informations Halieutiques). The main fishing ground of Danish seiners in the Bay of Biscay is located between the Loire and Gironde estuaries, mostly between the 50- and 100-m isobaths (SIH-Système d'Informations Halieutiques, Annex 1). Depending on vessel characteristics and target species, the vertical opening of the seine can reach several meters. The high vertical opening of Danish seines and their use to target seabass and hake in winter suggest that this new gear might be similar to pair trawls in terms of common dolphin bycatch risk.

Spanish fisheries in the Bay of Biscay are among the most prominent fisheries in the European fishing industry. In the 2011/2012 fishing season, Spain landed 20% of the catch selling value in Europe; while France landed 11% (FranceAgriMer, 2014). Spanish otter bottom trawlers mainly operate along the continental slope of the Bay of Biscay (see Annex 1). Bottom trawls are not generally considered to generate high levels of cetacean bycatch, particularly when fishing in deeper water close to the continental slope. Nevertheless, the otter bottom trawl gear category includes several types of trawls, including High Vertical Opening and Very High Vertical Opening trawls towed by single or paired vessels. This method of fishing has increased in the Bay of Biscay in recent years (ICES, 2017b). Because the trawl operates in contact with the seabed, the gear is classified as otter bottom trawl, but the high opening of the trawl creates a risk of cetacean bycatch, particularly when targeting European hake.

Some fisheries known for having high bycatch levels were not identified in the analyses, mostly because their fishing effort, albeit significant, was widely distributed (Lewison et al., 2004a, b). This was the case mainly for set gillnets and trammel nets landing hake (96.7% of set gillnet landings during these events) and seabass (up to 19% of landings for trammel nets during these events) (SIH-Système d'Informations Halieutiques). Adult European hake feed on small pelagic fish and therefore share, at least partially, the same trophic niche as seabass and common dolphin (Hubans et al., 2017).

4.3. A co-operative approach to fisheries management and cetacean conservation

The present work was based on a joint analysis of two independently acquired datasets, cetacean stranding data and fishing effort from VMS data. This was only made possible by the collaborative spirit that developed within the newly created working group on cetacean bycatch initiated by the French Ministry in charge of the environment. The analysis of co-occurrence allowed us to assess how dolphin mortality areas, determined by calculating the drift trajectory of dolphin carcasses prior to stranding, could help identify the fisheries potentially involved in bycatch incidents. To our knowledge, this is the first time that this approach has been attempted. The approach is promising because it provides a new way to investigate bycatch incidents and better understand the interactions between dolphins and fisheries. More developments and tests are needed before one can fully delineate the role that this approach could have compared to more conventional methodologies, including on-board observer schemes. Still, this is a major step forward that identified several fisheries for which intensive monitoring programmes, through observers or e-monitoring, and precautionary mitigation actions can be implemented. This work stemmed from a bycatch working group constituted of all the main stakeholders involved in the Bay of Biscay bycatch issue at national level. It is a step toward a shared diagnosis of the situation combining the efforts of scientists and working group stakeholders, a collaboration which is crucial to the move toward acceptable mitigation decisions.

5. Conclusion

This work described and tested a new method of identifying fisheries involved in dolphin bycatch using cetacean stranding records and commercial fishing effort statistics during one of the most intense stranding events ever recorded along the French Atlantic Coasts. Vessel Monitoring System data was used to analyse the spatiotemporal correlation of fishing effort and the likely mortality areas of stranded common dolphins. The fisheries identified as having spatial and temporal correlation with the dolphin mortality events included vessels which varied in gear type and target species. However, two characteristics appeared to be shared: the targeting of predatory fishes (sea bass and hake) in winter and the use of high vertical opening gear.

In order to refine our understanding of the interactions of cetaceans with fisheries and to more accurately identify the segments of the fleets that pose the greatest bycatch threat, landed species related to fishing effort should be incorporated into analyses, particularly for the three fisheries positively correlated with bycaught cetaceans and fisheries known for high cetacean bycatch levels.

One must also keep in mind that the present work, designed as a proof of concept, only dealt with a particular and unusual mortality and stranding event and its conclusions are not directly applicable to all bycatch cases in the Bay of Biscay. The bycatch incidents associated with unusual stranding events recorded in the Bay of Biscay since the late 1980's could likely differ greatly in their mechanism to the background bycatches that are continuously revealed in the stranding records.

Declaration of competing interest

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.

Acknowledgments

Authors warmly thank the French working group on cetacean bycatch, including the Directory of marine fisheries and aquaculture (Direction des Pêches Maritimes et de l'Aquaculture — DPMA-from the Ministry in charge of fisheries), the Directory of water and biodiversity (Direction de l'eau et de la Biodiversité - DEB - Ministry in charge of the environment), the French Institute for marine research and exploitation (Institut Français de Recherche et d'Exploitation de la Mer - IFREMER), representatives of the industry from the Committee for marine fisheries and fish farming (Comité National des Pêches Maritimes et des Elevages Marins - CNPMEM), the French agency for biodiversity (Agence Française pour la Biodiversité - AFB), a regional grouping of professional fishermen (Pêcheurs de Bretagne, OP Vendée,Pêcheurs d'Aquitaine), Interregional Maritime Services and Observatoire Pélagis (University of La Rochelle and CNRS).

We thank the Fisheries Information System from IFREMER (http://sih.ifremer.fr/) and specially Emilie Leblond for preparing and providing the data on fishing effort distribution and for her availability and her help in managing and analyzing this data set.

We particularly thank all members of the French stranding scheme for their continuous effort in collecting data on stranded cetaceans.

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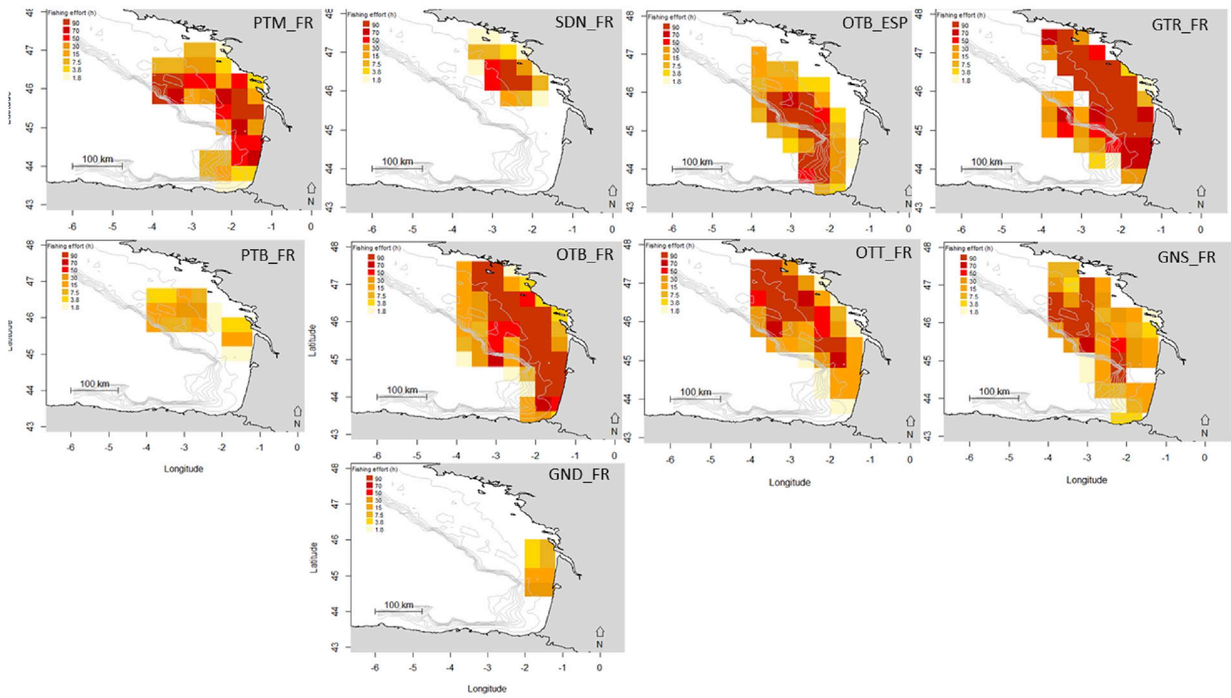
Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2019.e00843.

A



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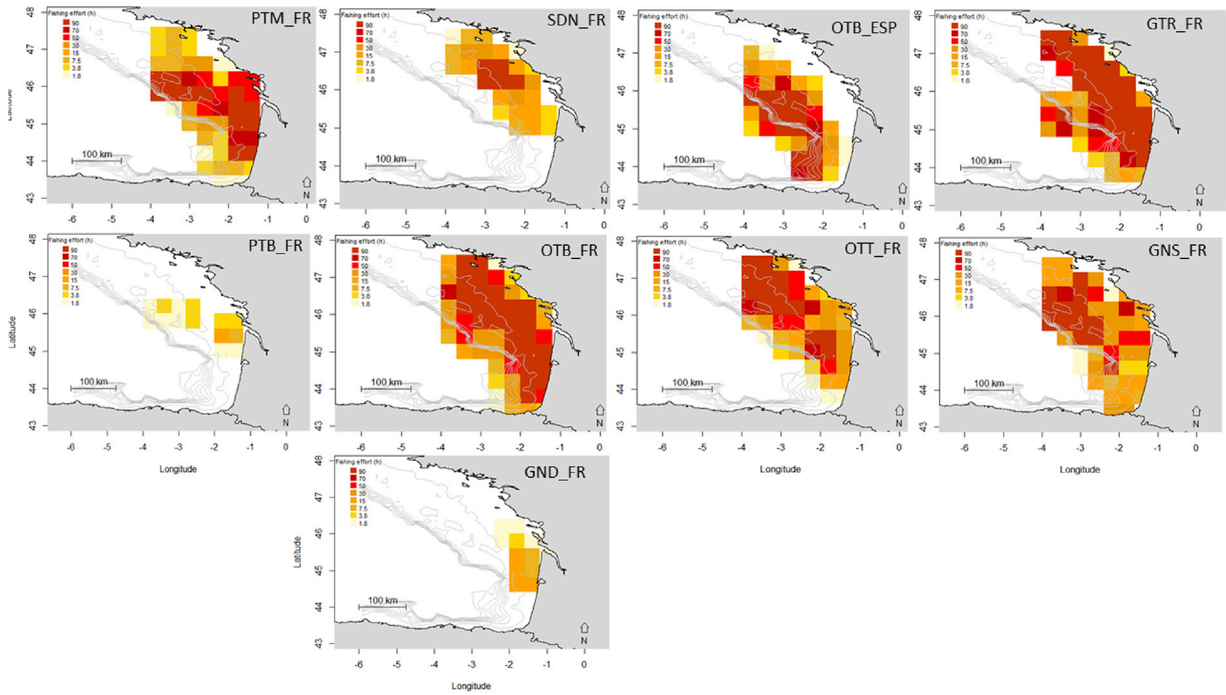

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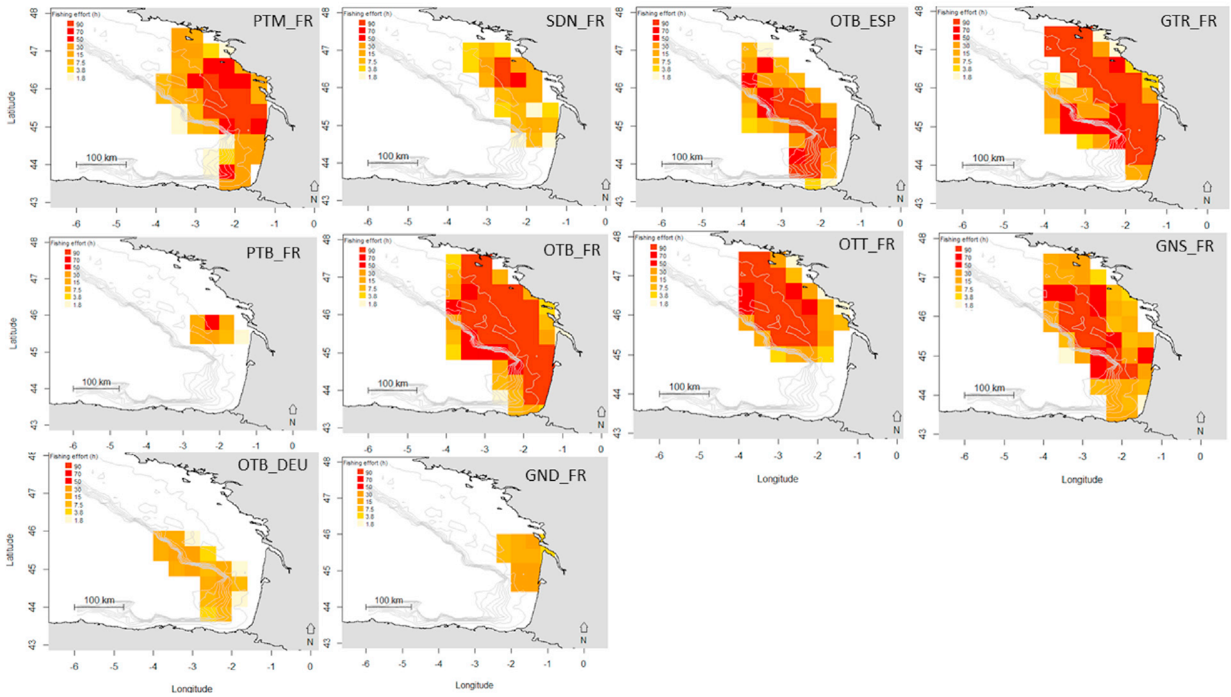

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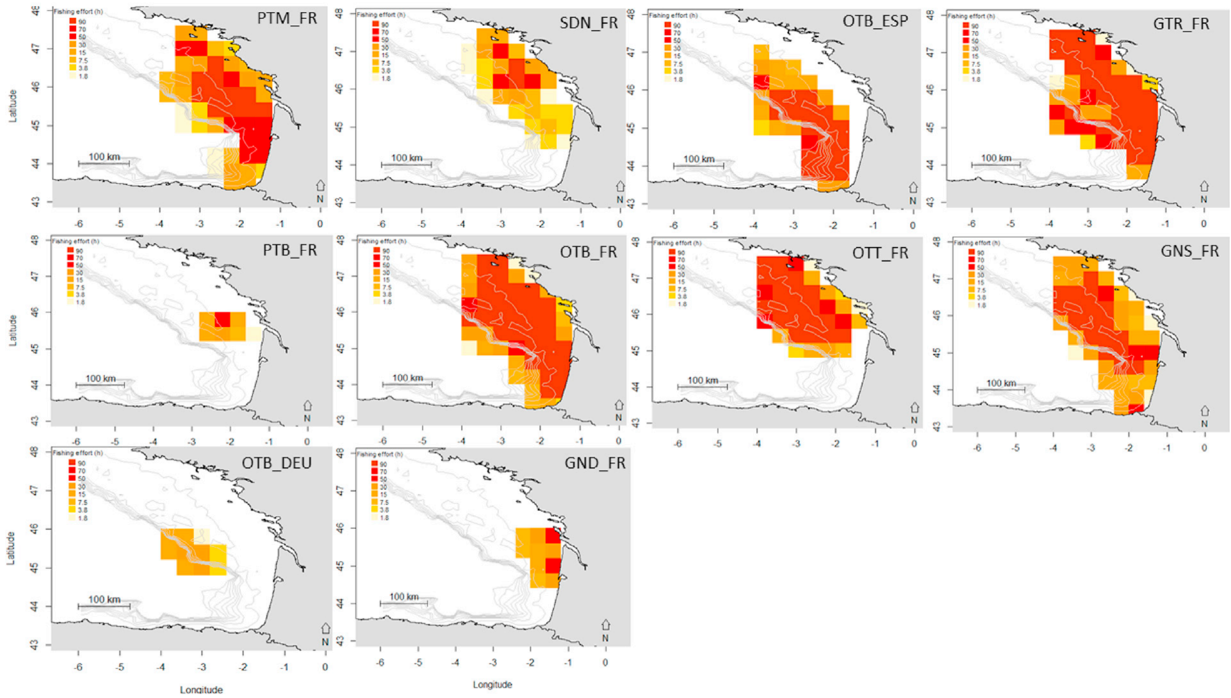
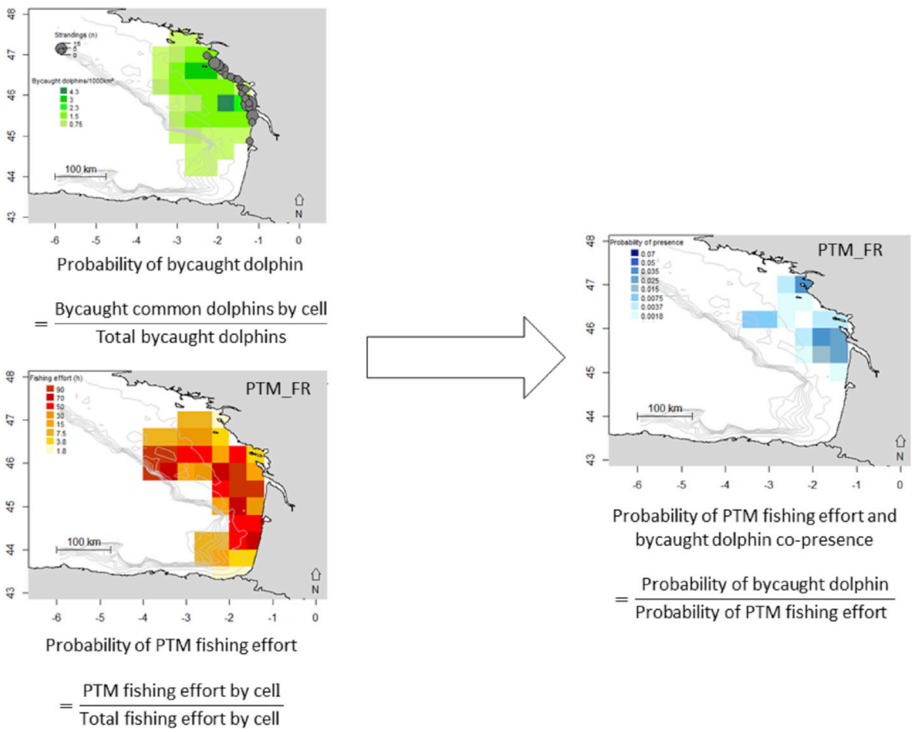
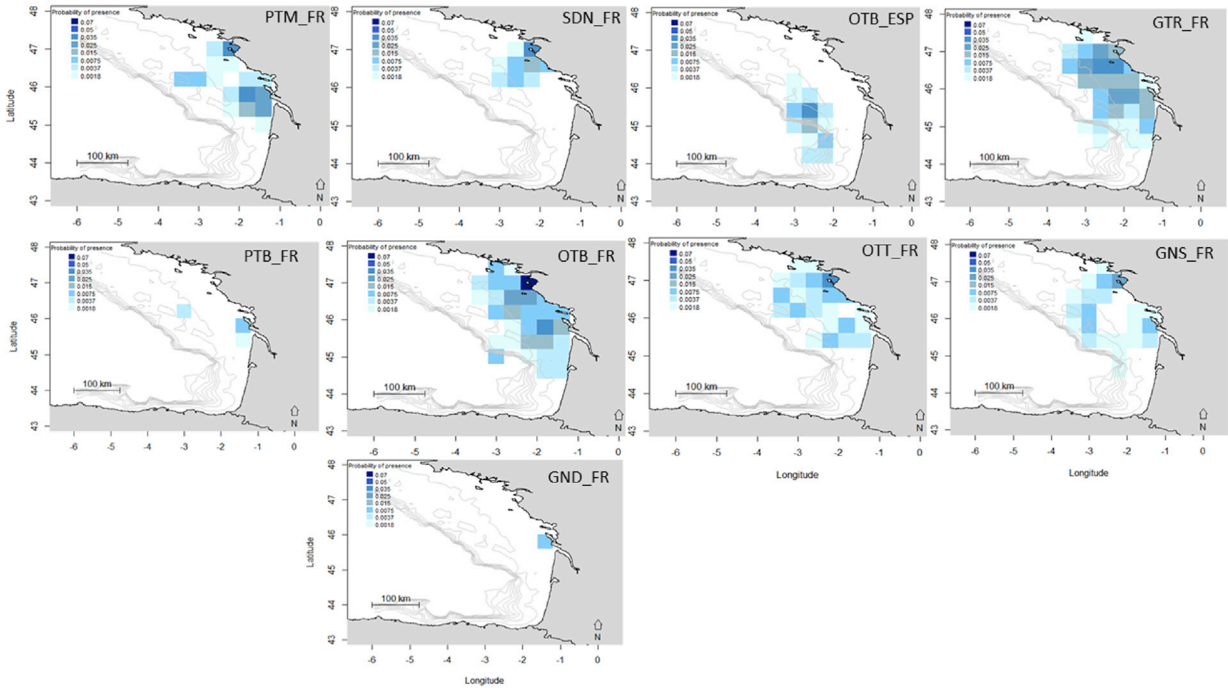


Annex 1. Fishing effort of ten tested fisheries during February mortality event of dolphins recovered fresh (A) and slightly decomposed (B), and March mortality event of dolphins recovered fresh (C) and slightly decomposed (D).

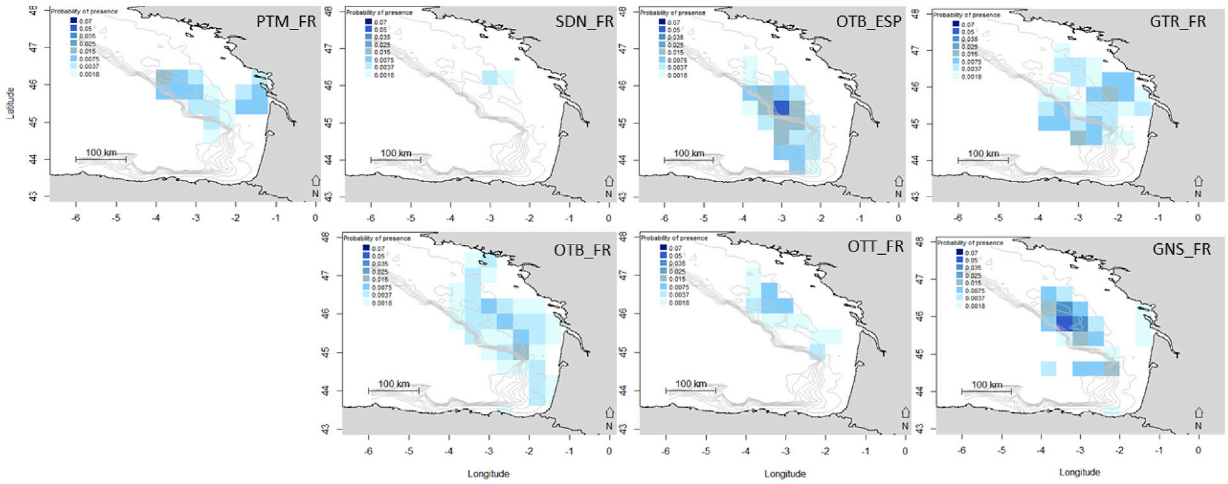
Appendix A


Strandings (n)
Bycaught dolphins/1000km²
100 km
N
Probability of bycaught dolphin
= Bycaught common dolphins by cell / Total bycaught dolphins
Fishing effort (h)
PTM_FR
Probability of PTM fishing effort
= PTM fishing effort by cell / Total fishing effort by cell
Probability of presence
PTM_FR
Probability of PTM fishing effort and bycaught dolphin co-presence
= Probability of bycaught dolphin / Probability of PTM fishing effort

A


PTM_FR
SDN_FR
OTB_ESP
GTR_FR
PTB_FR
OTB_FR
OTT_FR
GNS_FR
GND_FR
Probability of presence
0.07
0.05
0.035
0.025
0.015
0.0075
0.0037
0.0018
100 km
N
Latitude
Longitude

B


PTM_FR
SDN_FR
OTB_ESP
GTR_FR
OTB_FR
OTT_FR
GNS_FR
Probability of presence
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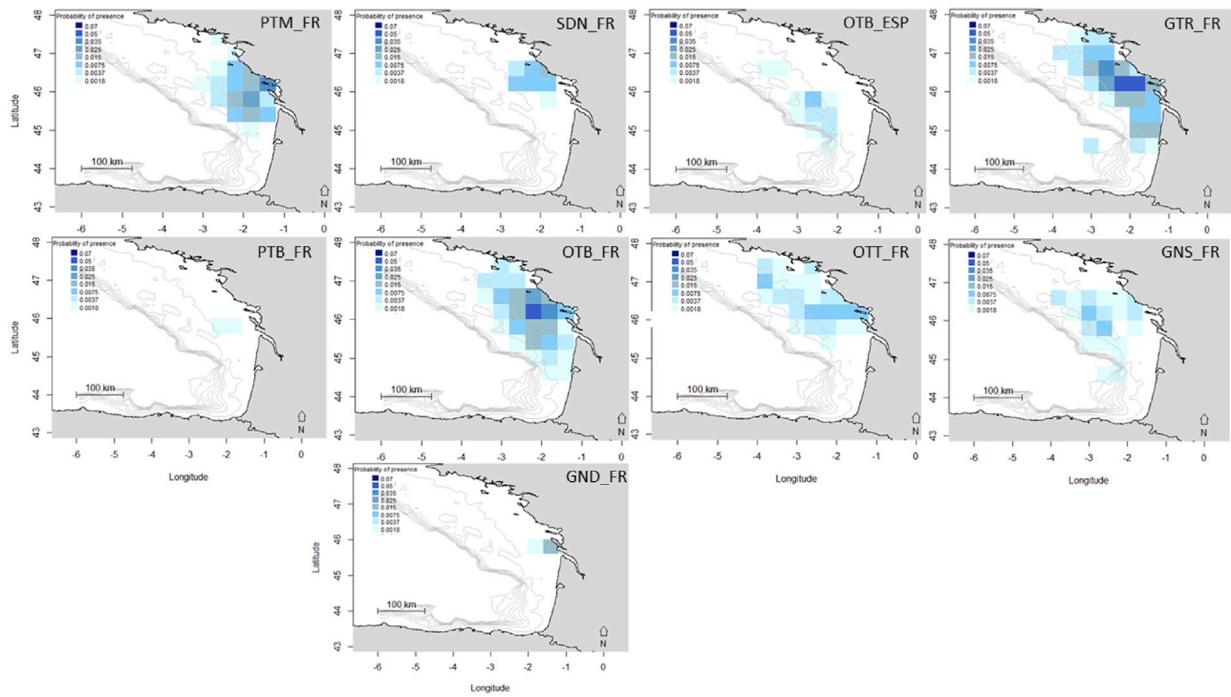
0.0075
0.0037
0.0018
100 km
N
Latitude
Longitude

C



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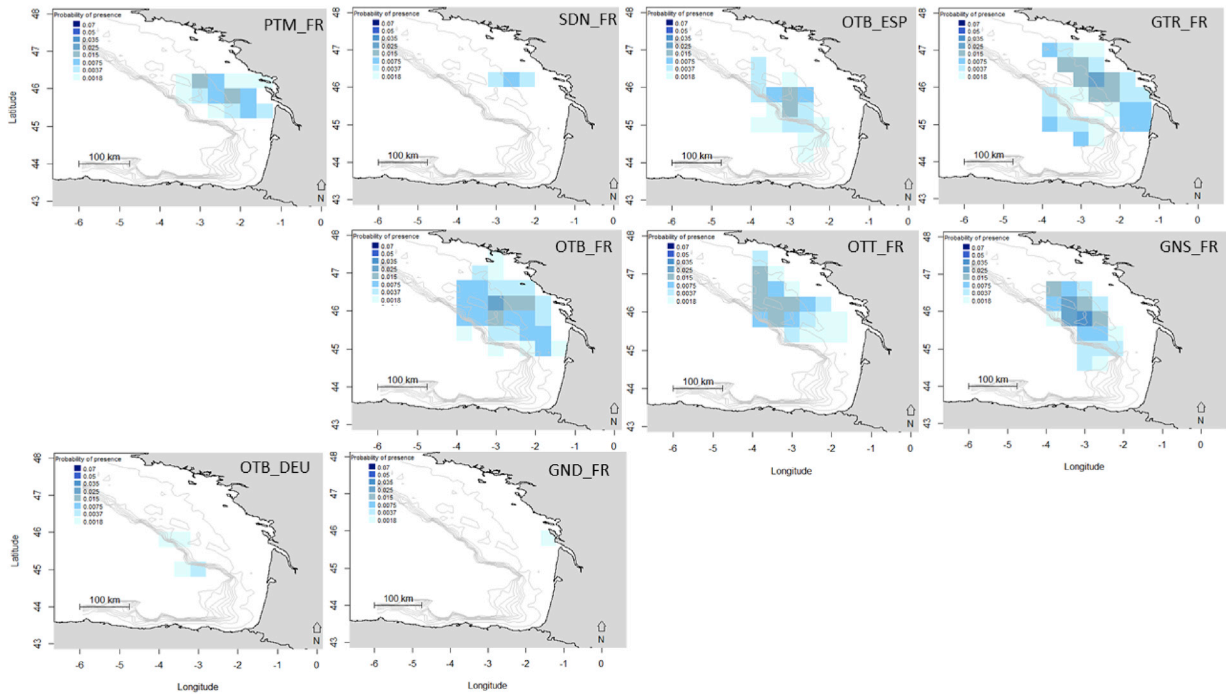

Annex 2. Co-occurrence between the mortality areas of bycaught common dolphins and fishing effort of the ten different fisheries during February mortality event of dolphins recovered fresh (A) and slightly decomposed (B), and March mortality event of dolphins recovered fresh (C) and slightly decomposed (D). Maps with no spatial and temporal co-occurrence were not presented. Construction of these maps:

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