Abstract:

Introduction

Fisheries by-catch has an important impact on the marine fauna and has been responsible for the decline of many species of megafauna including seabirds, marine mammals or sea turtles (Lewison et al., 2004). Hall (1996) defines by-catch as "the portion of the capture that is discarded at sea dead (or injured to an extent that death is the most likely outcome), because it has a little or no economic value or because its retention is prohibited by law". Other factors than by-catch lead to the decrease of abundance or biomass, such as habitat modification, pollution, or competition for resources. In July 2020, the European Commission started an infringement procedure against three member states, including France, for failing to protect common dolphins (*Delphinus delphis*) in the Bay of Biscay (European Commission, 2020). This infringement procedure resulted from the massive stranding events of bycaught dolphins along the Atlantic seaboard in France in the last few years. Dolphin by-catch is a conservation issue at the junction of environment, social and economic considerations: it remains complex and sensitive (Dolman et al., 2016). Stakeholders, including civil servants, professional fishermen and Non-Governmental Organizations (NGOs) have high expectations on science to propose efficient management measures that will help in decreasing current by-catch levels in the Bay of Biscay. The study focuses on the development of a method for setting a by-catch limit, that is a number or biomass of animals that can be removed by anthropogenic activities, while meeting conservation objectives such as ensuring population viability in the long-term.

Abundance/Biomass estimation

The abundance of common dolphins in the North-East Atlantic has been estimated in the SCANS/CODA surveys in 2005 and 2016 (Hammond et al., 2021). Abundance remained stable with 470,000 (coecient of variation 33%) common dolphins in 2005 and 487, 000 (coefficient of variation 25%) in 2016.

The common dolphin: a protected species

Many regulations have been promulgated to protect common dolphins, at different scales (national, European or international). These vary in scope and aim at improving knowledge, management and conservation to different degrees.

At the supra-national level, several conventions address the conservation of the marine life in general: it is the case, among others, of the United Nations Convention on the Law of the Sea, the Convention on Biological Diversity, the Convention on International Trade in Endangered Species of Wild Fauna and Flora (regulates the trade of protected species such as dolphins), the Bonn convention (Convention on the Conservation of Migratory Species of Wild Animals) (ICES, 2020). ASCOBANS (a sister instrument to the Bonn Convention under the aegis of the United Nations) promotes cooperation between countries to protect wild marine species. A regional sea convention in the North-East Atlantic also covers cetaceans: the Oslo-Paris (OSPAR) convention. In its North-East Atlantic Environment Strategy, OSPAR aims at keeping this part of the ocean clean, healthy and biologically diverse as well as making it a productive area, used sustainably and resilient to both climate change and acidification. In particular, OSPAR will work with relevant competent authorities and other stakeholders to minimise and if possible eliminate incidental by-catch of marine mammals, birds, turtles and fish so that it does not represent a threat to the protection and conservation of these species. OSPAR also works towards strengthening the evidence base concerning incidental by-catch by 2025 (OSPAR, 2021).

One of the most important European legislation on the conservation of wildlife is the Directive on the Conservation of Natural Habitats and of Wild Fauna and Flora, also known as the Habitats Directive. Common dolphins are part of the Annex IV, "Animal and Plant Species of Community Interest in Need of Strict Protection". Species that are in this Annex have to be monitored to maintain a favourable conservation status. Also, according to the Marine Strategy Framework Directive (Directive 2008/56/EC of the European Parliament and of the Council of 17th June 2008 establishing a framework for community action in the field of marine environmental policy; MSFD), the priority "should be given to achiev- ing or maintaining good environmental status in the Community’s marine environment, to continuing its protection and preservation, and to preventing subsequent deterioration" (Directive, 2008, p. 20). Good Environmental Status (GES) is assessed with a suite of so-called descriptors covering biological diversity (including marine mammals), elements of marine food webs, eutrophication, contaminants, etc. Though utilitarian in philosophy, the MSFD is the current backbone of marine conservation in the European Union. The common dolphin was assessed as not at GES in 2018 in France (as well as in Spain and Portugal) due to by-catch. The next evaluation is due for 2024 with no expected improvement respecting GES because by-catch remains too high (ICES, 2021).

Fishing activity and the problem of by-catch

There are many possible threats which can impact cetaceans but it is clear that anthropogenic activities are the main cause of additional mortality (Avila et al., 2018). Each year since 2016, over 1, 000 strandings of cetaceans were registered along the French Atlantic seaboard (ICES, 2020). More than 800 common dolphins were estimated to be bycaught in fishing gears in 2020 in the Bay of Biscay (Peltier et al., 2020). Estimated at-sea by-catch of common dolphins using strandings highlights an increase in by-catch since 1990s. The majority of strandings of bycaught dolphins come from the continental shelf of the Bay of Biscay and correlations have been evidenced between fishing activities (French gill- netters, especially those targeting hake (*Merluccius merluccius*), Spanish bottom trawlers, Danish sennes, etc.) and by-catch (Peltier et al., 2021).

Dolphins are trapped into the gears and die from asphyxia. When released from gears, between one fifth and one fourth of carcasses remains afloat, with the remainder sinking. Floating carcasses drift and may eventually be washed ashore on the French Atlantic seaboard. A majority (75%) of stranded common dolphins have evidence of by-catch (in winter) (Peltier et al., 2021). In France, the survey of the dolphin’s strandings is conducted by the French Stranding Network (*Réseau National Échouages* in French). It was created in 1972 and is now operated by Observatoire Pelagis (UAR 3462 La Rochelle University - CNRS). It aims at registering all marine mammal strandings in France, at collecting data on the stranded species including a necropsy of the carcass, when possible, to assess the cause of death (among others pieces of information). Pelagis also carries out large-scale surveys (either ship-based or plane-based) to estimate marine mammal abundance and distributions in French waters (Laran et al., 2017a).

The ASCOBANS Conservation and Management Plan, under the heading "Habitat conservation and management" coined the term "unacceptable interaction". ASCOBANS defined, according to the best available scientific evidence, "unacceptable interactions" as being, in the short term, a total anthropogenic removal above 1.7% of the best available estimate of abundance

(Res.3.3) and underlines the intermediate precautionary objective to reduce by-catch to less than 1% of the best available population estimate (Res.3.3 and Res.5.5). The current rate of additional mortality due to fisheries by-catch exceeds 1%, much more than what is viable for small cetaceans (Peltier et al., 2019).

Current management of cetacean by-catch

Management procedures for cetaceans have been developed, in particular within the work of the International Whaling Commission. A management strategy is a set of rules which aim at making agreed-upon objectives achievable (Punt, 2006; Bunnefeld et al., 2011). This strategy defines management objectives in the form of not-to-be exceeded thresholds that managers can track from available data. The process of evaluating a management strategy (Management Strategy Evaluation, MSE) relies on modeling and computer simulations (Cooke, 1994; Hilborn and Mangel, 1997): it is commonly used to compute biological reference points or, in the context of by-catch, removal limits. A complication in the management of by-catch stems from the fact that by-catch, unlike catch, is not usually monitored (no log-book). Data on by-catch is not systematically collected by onboard observers: these data, if not collected systematically and in a dedicated scheme, are usually of low quality and biased (Basran and Sigurosson, 2021). This is especially true in European waters where there are no dedicated schemes to monitor by-catch at the relevant scales, especially marine mammal by-catch (Murphy et al., 2022). There are two main harvest control rules currently used for managing marine mammal by-catch: the Potential Biological Removal (PBR; Wade, 1998) and the Removals Limit Algorithm (Cook, 1995). Both rules are evaluated with operational models that are *Surplus Production Model*. The data used for PBR and RLA procedures are estimations of abundance/biomass and by-catch, which are usually scarce and can be imprecise, biased or both. Another complication arises from stochasticity (demographic and environmental, which are not taken into account in the previous models) and yet describe natural variability of the environment. Finally both the PBR and RLA control rules hinge on an estimate of r which is unknown in practice for most species. This knowledge gap may be exploited to argue against the use of either of the rules (M. Authier personal observation). Devising a new rule to set a removal limit, a rule that does not hinge on knowledge of this input is thus desirable.

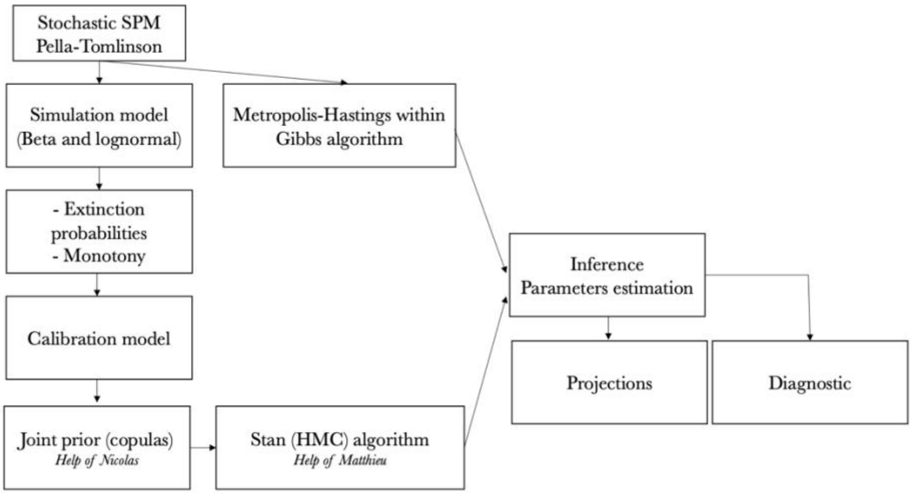
Internship objectives

The two existing management rules (PBR and RLA) have some limitations. Ideally, we would like to propose new management rules to handle cetaceans bycatch but in this study we focused on exploring the use a specific type of models, Surplus Production Models (SPM) to manage bycatch, in the conservation context discussed above (80% of the carrying capacity (K) after 100 years with the probability of 0.8).

One innovation of the study is to focus on the use of strandings of common dolphins on the Atlantic seaboard of France (Peltier et al., 2016a) as a data in-put, which is new when assessing management rules for cetaceans. An obvious advantage of stranding data is that it does not rely on dedicated onboard observer schemes, which are lacking in Europe for monitoring cetacean by-catch.

We therefore need a model with few parameters because the data are few, and which incorporates environmental variability (stochasticity). The choice of a Bayesian framework therefore seems appropriate, as it allows us to manage uncertainty, the small amount of data and the precautions to be taken in a decision-making framework (Harwood and Stokes, 2003). It provides interesting and applicable management options (Carlin and Louis, 2010). It is then

interesting to evaluate the feasibility of such a model to estimate parameters and project abundance. The use of stochastic SPM models have already been made in several studies and have shown good results for providing estimations of stochastic MSY (Polacheck et al., 1993; Millar and Meyer, 2000; Bousquet et al., 2008; Bordet and Rivest, 2014).
This study focuses on the common dolphin, which is a cetacean species heavily aected by by-catch, particularly in the Bay of Biscay.
The work undertaken during the projet can be summarized as follow:



Available data for the motivating case study
Abundance estimations are outputs of the international SCANS surveys. SCANS' objective is to estimate abundance of small cetaceans, with plane and boat surveys.

Survey	Season	Date	Estimation of common dolphin's abundance	Coefficient of variation
SCANS-II/CODA	Summer	July 2005 & July 2007	468356	33,3
SCANS-III	Summer	July 2016	473461	26,1

Data on strandings are collected by the the French Stranding Network (RNE) coordinated by Observatoire Pelagis (UAR 3462 CNRS-La Rochelle Université) which is in charge of registering every strandings occurring on the French coasts. Each stranded carcass has to be examined following a precise protocol. The data set used for the study is a chronological series of 31 years of strandings recorded by Pelagis.

Surplus production models (SPM)
Surplus production models (SPM) are standard models of population dynamics in situations of strong uncertainty and low information and can be used with the data available for the study (10 years of strandings and a handful of abundance estimations). First, we developed a deterministic SPM, without taking into account stochasticity. Then, a stochastic SPM was used to better take into account variability in abundance. The use of this kind of aggregated model can be justified by the scarcity of available data (*e.g.*, population structure by age, stage or

length) that has been (or that can realistically be) collected on some species. In the frame of the study, motivated by the fact that we dispose mainly of by-catch data to estimate the unknown parameters common to all SPM (growth rate, carrying capacity), we focused on the specific Pella-Tomlinson model. The deterministic approach of abundance or by-catch dynamics previously proposed remains however very crude. For example, the concept of deterministic MSY has been criticized because its (too optimistic) value use may lead to population-level extinction. MSY ignores the natural variability in abundance/biomass, for example caused by environmental conditions so that true MSY is much lower than computed under a model wherein environmental stochasticity is ignored (Singini et al., 2013). The inclusion of environment stochasticity (so-called "process noise") in MSY calculation results in a decrease (Hubley and Heaslip, 2018). Including environmental stochasticity is therefore necessary to propose a correct simulation model for abundance.

The set of parameters that can vary in our model is : $\{K, \phi, \sigma, r\}$, *i.e* the parameters of the equation of the stochastic Pella-Tomlinson model, written with the captures C_t^e :

$$C_{t+1}^e = \left\{ C_t^e + \frac{\gamma+1}{\gamma} r C_t^e \left(1 - \left(\frac{C_t^e}{Kq\phi} \right)^\gamma \right) - \phi C_t^e) \right\} \varepsilon_t$$

K is the carrying capacity, ϕ the extraction rate, σ the environmental stochasticity and r the intrinsic growth.

The captures C_t^e are related to the abundance B_t by the expression:

$$C_t = \phi B_t$$

The main goal of the study is to estimate these parameters, especially ϕ which is very useful for by-catch management.

Simulation model

We first developed a simulation model. The goal of defining a simulation model is to generate abundance and observed by-catch conditional on parameters.

A Pella Tomlinson SPM model was chosen for the simulation model. This stochastic model depends on several variable parameters: the carrying capacity K, the extraction rate ϕ, the intrinsic growth rate r, the environmental stochasticity σ, the shape parameter λ (fixed at 2.4, (Genu et al., 2021)), the fraction of by-caught dolphins which float q (fixed at 24%, (Peltier et al., 2016b)), the initial depletion D0 and the coefficient of variation for the observed abundance cv.

Simulation model is precious to better understand the influence of certain parameters on data, in terms of extinction or monotony. Given a context of data scarcity, Bayesian inference is attractive to estimate the set of parameters {K, ϕ, σ, r} with a careful choice of priors. It is also recommended by many researchers to take into account uncertainty accurately (Millar and Meyer, 2000).

Bayesian inference

Bayesian inference was conducted to estimate the parameters: {K, ϕ, σ, r}. A bibliographic review was first conducted to look for similar cases of study that used SPM in a Bayesian framework. Prior were chosen so that they respect two conditions: the population does not

die out before 30 years and there is a similar monotonicity of the simulated and observed by-catch time-series, computed by the mean of Kendall's tau.
3D prior copula were chosen for the parameters ϕ, σ, r. This joint prior takes into account the dependence between the parameters. A vine decomposition of the underlying 3D copula was conducted using the R package Vinecopula Schepsmeier (2016).
The decomposition in so-called trees (see for instance Benoumechiara et al. (2020) for detailed explanations) with the best AIC criterion is described in the following table.

Tree 1: unconditional pair copulas		
ϕ, σ	$\sim$	Rotated Gumbel 90 degrees copula with parameter $\theta_{RG} = -1.21$
ϕ, r	$\sim$	Gaussian copula with parameter $\theta_G = 0.39$
Tree 2: conditional pair copula		
$r, \sigma \vert \phi$	$\sim$	Rotated Tawn type 2 180 degrees copula with parameters $(\theta_{RT,1}, \theta_{RT,2}) = (2.97, 0.18)$

We made the usual choice to sample using Markov Chain Monte Carlo (MCMC) algorithms (Robert and Casella, 1999). More precisely, we first used a Gibbs scheme to sample iteratively from each dimension of the set of parameters, each sampling step being hybridized by a Hastings-Metropolis step. Then, to simplify the process of estimation, we used the Markov chain Monte Carlo (MCMC) algorithms available in Stan (Carpenter et al., 2017): the Hamiltonian Monte Carlo (HMC) algorithm. Running MCMC chains with the Metropolis-Hastings algorithm, compared to HMC algorithm with Stan, provided worse results and there were important auto-correlation in the MCMC chains. It could be explained by the length of the MCMC chains, that are longer with Stan and the computational performance of the HMC algorithm, which is higher than Metropolis-Hasting. It vindicates our choice to estimate the parameters with Stan.

Main results

The main results are described in the complete document of the study, available after September 2023. The following paragraphs explain what types of results are obtained thanks to the model.

Extinction risk
One of the main risks for the common dolphin's populations is to go extinct, that could occur in particular conditions. The simulation model allows to test different sets of parameters and the corresponding abundance trajectories. Then, extinction probabilities are calculated, considering a given set of parameters, for example the couple (environmental stochasticity σ, intrinsic growth r).

Simulation tests
Running Stan HMC algorithm with simulated data allows to control the parameters of the population's dynamics and to modify the monotony of the abundance and by-catch

trajectories. Moreover, it enables to choose the size of the data set, which means the number of abundance estimation (for realism), since usually one abundance estimation is produced every 10 years. Therefore, three simulation cases were tested, corresponding to different trajectories of by-catch and abundance. These simulations allow to test the fiability of the estimation, by comparing the value of estimation to the value of simulation.

Case study: common dolphins in the North-East Atlantic
Two types of data were used to estimate the parameters: data on strandings (31 years) and abundance estimations (2 estimations, in 2005 and 2016). Convergence and auto-correlation tests were conducted. Posteriori distributions were obtain thanks to the model and two priors were tested: a uniform prior and the joint prior (3D copula). This allows to compare estimations and the performance of the two different priors.
Abundance were projected by running the simulation model with the estimated parameters.

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