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The effect of illegal fishing on the sustainability of small scale fisheries

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Abstract

Marine ecosystems, biodiversity and fisheries are under pressure worldwide. To manage these ecosystems and fisheries in a more sustainable way, many scientists and stakeholders advocate the use of an ecosystem-based fishery management (EBFM). The idea underlying EBFM is to account for several complexities, including trophic, habitat and socio-economic interactions. Illegal fishing is an important ingredient among these complexities. We advance the EBFM on the small-scale fishery of French Guiana, by taking into account the high impact of illegal fishing in this case study. To achieve this, we rely on a multi-species resource based dynamics and, multi-fleet model. The model is calibrated using data of fishing landings and efforts from 2006 to 2017 for 3 species and 4 fleets, as well as a Illegal, Unreported and Unregulated (IUU) study. The model exhibits the impact of illegal fishing on the ecosystem and fishery dynamics. Our results highlight the extensive potential gains in catches and profit linked to the reduction of illegal fishing. Policy recommendations are derived.

Keywords: Small scale fisheries; IUU; Sustainability; Multi-species; Multi-fleet; Swim Bladder

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The effect of illegal fishing on the sustainability of small scale fisheries

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Abstract Marine ecosystems, biodiversity and fisheries are under pressure worldwide. To manage these ecosystems and fisheries in a more sustainable way, many scientists and stakeholders advocate the use of an ecosystem-based fishery management (EBFM). The idea underlying EBFM is to account for several complexities, including trophic, habitat and socio-economic interactions. Illegal fishing is an important ingredient among these complexities. We advance the EBFM on the small-scale fishery of French Guiana, by taking into account the high impact of illegal fishing in this case study. To achieve this, we rely on a multi-species resource based dynamics and, multi-fleet model. The model is calibrated using data of fishing landings and efforts from 2006 to 2017 for 3 species and 4 fleets, as well as a Illegal, Unreported and Unregulated (IUU) study. The model exhibits the impact of illegal fishing on the ecosystem and fishery dynamics. Our results highlight the extensive potential gains in catches and profit linked to the reduction of illegal fishing. Policy recommendations are derived.

Keywords Small scale fisheries; IUU; Sustainability; Multi-species; Multi-fleet; Swim Bladder

1 Introduction

The livelihoods, nutrition and food security of billions of people depend on the sustainability of fisheries [FAO, 2020b]. Small scale fisheries play a key role in that regard [Béné et al., 2007,

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Jacquet and Pauly, 2008]. They employ 25 times more people in the world than large scale fisheries and represent the same amount of annual catches for human consumption as industrial fisheries, but using less fuel [Chuenpagdee et al., 2006][1]. Small-scale fisheries are however facing increasing challenges questioning their sustainability. In many coastal developing countries, the combined effects of pollution, climate change and overfishing indeed affect marine habitats and reduce resources and diversity [Halpern et al., 2008, Badjeck et al., 2010, Srinivasan et al., 2010, Hardy et al., 2013, Halpern et al., 2015]. In some places, this situation is exacerbated by the rapid demographic transition that characterizes the developing world [Sunderlin, 1994, Botsford et al., 1997, McClanahan et al., 2015] and the lack of regulation and public policy.

To promote the sustainability of fisheries, Ecosystem-Based Fishery Management (EBFM) has been advocated for several years by many scientists and stakeholders. This approach takes into account various levels of complexity, both ecological and socio-economic, in order to allow for a sustainable management of fisheries [Smith et al., 2007, Pulvenis, 2016, Link et al., 2017, Doyen et al., 2017]. To implement an effective EBFM strategy, it is necessary to reduce the uncertainty regarding the estimation of the global catches affecting the ecosystem and thus improve the estimation of the Illegal, Unreported and Unregulated (IUU) fishing pressure [Beddington et al., 2007, Pramod et al., 2008, Worm et al., 2009]. The 14 Sustainable Development Goal (SDG) also points out that reducing illegal fishing and supporting small scale fisheries is key for the achievement of this goal. The general objective of our paper is to examine the pivotal role of IUU mitigation for the sustainability and ecosystem based management of small scale fisheries.

Illegal fishing refers to a situation where fishermen work without authorization and in contravention of laws and regulations of a country. The IUU fishing is indeed a challenge in the management of fishery [Sumaila et al., 2006, FAO, 2020a]. IUU puts a high pressure on ecosystems and impedes the implementation of an effective fishery management [Cisneros-Montemayor et al., 2013, Petrossian, 2019]. Illegal fishermen do not take into account the fishery management policies to protect the ecosystems and therefore contribute to the decline of stocks [Le Gallic and Cox, 2006]. Moreover, fishermen who respect the regulations and act responsibly are at a disadvantage because the resource is diminishing due to this illegal fishing [Oliver and Jacobs, 2019]. The losses due to current IUU activities worldwide are estimated between 10 and 23.5 billions USD annually, which represents between 11 and 26 million tons of catches [Agnew et al., 2009]. Finding sustainable solutions to eliminate IUU fishing requires an improved understanding of its causes. The causes are to be found in i) economic factors, linked to overcapacity, ineffective management and subsidies, ii) institutional factors, linked to gaps in the international legal framework for the sea, to insufficient level of monitoring, control and surveillance and the existence of tax havens, iii) social factors such as poor economic conditions and prospects in developing countries with sometimes opportunity costs of labour close to zero and finally, iv) increasing cooperation between actors engaged in illegal operations reducing the transaction costs to enter in IUU fishing [Le Gallic and Cox, 2006]. Unclear supply chains of fishery resources is a key driver of IUU. The case of IUU related to swin bladders

[1] See Figure 7.1 from [Jacquet and Pauly, 2008] in Appendix for an enlightening comparison between small scale fisheries and large scale fisheries.

is interesting in that respect. Swim bladder trade in the world is expanding because of the growing demand [de Mitcheson et al., 2019], as they are used more and more often as a substitute for shark fins, which are becoming scarce [de Mitcheson et al., 2018]. The swim bladder is an internal pouch of the oesophagus, below the spine of bony fish, it is the fourth most consumed seafood product in China. This dish is very popular in Asia for its supposed health properties and is sold at a high price. It can be a luxury product, a large bladder with no imperfections can sell for 10,000 USD. Hong-Kong is the main importing country of swim bladders, and according to the Hong-Kong census and statistics department, Surinam (10%), Brazil(16%), and Guyana (5%) represent 31% of importations to Hong-Kong [Constant, 2020].

This paper aims to analyse the impact of IUU related to swim bladder trade in The Guianas, tropical region located on the north-central coast of South America. To achieve this, we rely on a multi-species and multi-fleet dynamic model in line with EBFM. The model is calibrated using data of the small-scale fishery in French Guiana including quarterly time series of fish landings and fishing effort from 2006 to 2011 as in [Gomes et al., 2021] . We also use data on foreign illegal fishing from Brasil and Suriname in french guianese waters,collected by the customs and the army. As well as reports from the public prosecutor's department of Cayenne and the study [Levrel, 2012]. The model makes it possible to evaluate the ecological and economic losses that IUU represents for small-scale coastal fisheries in this case study. It also highlights the benefits that could be gained by the local community by continuing to pursue efforts to develop the legal trade of swim bladder for export to Asia (Hong Kong, China).

The paper is structured as follows: Section 2 introduces the case study by describing the coastal fishery in French Guiana and swim bladder trade; Section 3 details the ecological-economic model used and the calibration methods and calibration results integrating illegal fishing; Section 4 presents an analysis of different predictions. Section 5 contains a discussion of the results and Section 6 offers a conclusion.

2 Case study

French Guiana is located in South America between Surinam and Brazil. "French Guiana's coast is characterised by warm waters with high turbidity and low salinity caused by the large river discharges from the Amazon and nearby estuaries" [Le Joncour et al., 2020].

The fishing industry represents the main export commodity in the primary sector of French Guiana [Ton et al., 2016]. More than 30 coastal species are exploited and about 15 species, including weakfish, catfish and sharks, represent more than 90% of the production [Cissé et al., 2015]. In recent years, a new market has appeared in French Guiana with the collection and resale of swim bladders of three coastal species already fished for their flesh. In 2018, the fleet of this coastal fishery was composed of 153 boats including Pirogues, Canots Créoles (Creoles Canoes), Canots Créoles améliorés (Improved Creole Canoes) and Tapouilles, most of them (70 %) measuring between 9 and 12 meters; around 371 fishermen worked on these boats. Most of them (75%) worked in the area of 12 miles from the shore and were qualified as coastal fishery ([Ifremer-SIH, 2019a]). The



Fig. 1: Map of French Guiana



Fig. 2: Swim bladders: The main target of illegal fishing in French Guiana (Source : Gendarmerie Nationale)

small scale coastal fishery uses mostly drift nets and to a lesser extent fixed nets.

With the growing demand for swim bladders (Fish maw) [Wen et al., 2015], the competition for this resource is increasing and illegal fishing from Surinam and Brazil is on the rise, despite the controls and supervision from the FAG (French army in Guiana). Interviews with French Guianese fishermen have shown that, according to them, one of the major problems in the fishing area of French Guiana is the IUU fishing [André, 2018]. Illegal fishermen set their nets at night to limit the risk of controls, and raise them the following night to keep only the bladders of the species of interest[2], Acoupa Weakfish (*Cynoscion acoupa*) and Green Weakfish (*Cynoscion virescens*), Crucifix Sea Catfish (*sciades proops*), the rest of the fish being discarded (IFREMER Fisheries Information System(SIH)). These illegal fishing practices lead to excessive fishing times and nets that do not respect the legal length. There are precedents for the disappearance of certain species due to the removal of bladders, such as the Acoupa MacDonald (*Totoaba macdonaldi*), considered critically endangered, and the Bahaba (*Bahaba taipingensis*) [Findley, 2010, Tuuli et al., 2016]. This illegal fishing practice can also lead to the collapse of a species because of gillnet bycatch, as was the case for vaquitas(*Phocoena sinus*) [Taylor et al., 2017].The collection of swim bladders is an important motivation for illegal fishing fleets. Acoupa Weakfish is the most targeted species by illegal fishing fleets, because of the high value of its swim bladder. Acoupa Weakfish is considered vulnerable, partly due to illegal fishing activities and the difficulties encountered in discouraging them, but also due to the degradation of the mangrove nursery habitat by anthropogenic activities (such as oil extraction) [Chao, 2021]. Swim bladders of Green Weakfish and Crucifix Sea Catfish are also collected, but sold at a lower price than the ones of the Acoupa Weakfish.These 3 species represented 74% of the landings of legal boats in 2019 [Ifremer-SIH, 2019a] (72% in 2018 [Ifremer-SIH, 2020]) for Canots Créoles, Canots Créoles Améliorés and Tapouilles [3]. Thus our analysis focuses on these three species. Acoupa Weakfih swim bladders sell for between 130 and 150 EUR per kilo for the largest ones, and between 50 and 70 EUR for the smallest. Although the price can

[2] See Appendix 7.2

[3] We don't take into account Pirogues'catch in the model as it only represents 0.3% of the landing.

also vary according to quality, reports from the public prosecutor's department of Cayenne in 2017 give us an average price for each species of 100 EUR for 1 kg of fresh swim bladders for Acoupa Weakfish, 30-35 EUR per kilo of fresh swim bladders for Green Weakfish and 2 EUR per kilo of fresh swim bladders for Crucifix Sea Catfish.
The Figure 3 illustrates the links between the ecosystem, fisheries and distribution networks to help understand the context.

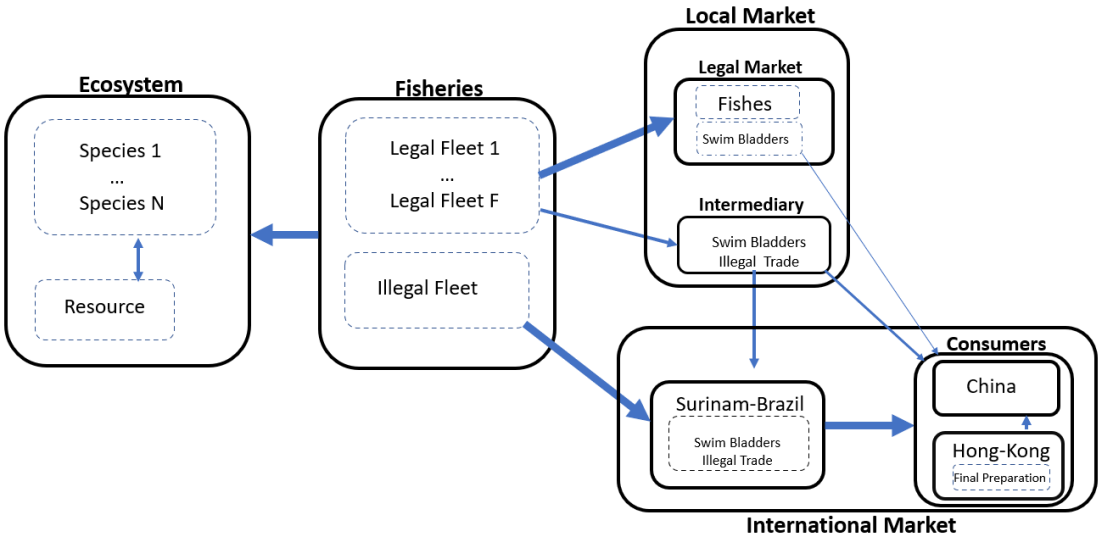

Fig. 3: Fisheries and distribution network

3 Model and Calibration

3.1 The Ecological-economic model

We here rely on a Model of Intermediate Complexity(MICE) as in [Plagányi et al., 2014, Doyen et al., 2017]. Such a modeling choice is particularly accurate because of the limited group of fished species in this study [Gomes et al., 2021]. The MICE assumed that the N fish species compete for the consumption of a common resource, denoted by res. In line with a resource-based models [Tilman, 2020]. Fished species are denoted by $i = 1, \ldots, N$ while fleets are denoted by $f = 1, \ldots, F$. For every species i the biomass $B_i(t+1)$ at time t+1 depends both on the biomass $B_i(t)$, the state of the resource $B_{res}(t)$, and harvesting $H_i(t)$ as follows:

$$B_i(t+1) = B_i(t)\Big(1 - M_i + g_i * a_{res,i} * B_{res}(t)\Big) - H_i(t). \tag{1}$$

In the equation (1), M_i stands for the mortality rate of the stock i. In the part of the equation representing the resource consumption of the species, i, g_i stands for the growth efficiency of i, $a_{res,i}$

is the consumption rate of the predator i on the resource. In the ecosystem of French Guiana, [Cissé et al., 2015] have shown that the interspecific interactions between fishes species have a very low impact, we thus decided not to include interactions as in [Gomes et al., 2021].

The catches $H_i(t)$ of the species i at time t are derived from the harvests $H_{i,f}(t)$ of the different fleets f:

$$H_i(t) = \sum_{f=1}^{F} H_{i,f}(t) \tag{2}$$

The catches $H_{i,f}(t)$ of the stock i by the fleet f at time t are based on the Schaefer production function:

$$H_{i,f}(t) = q_{i,f} E_f(t) B_i(t) \tag{3}$$

where the variable $E_f(t)$ is the fishing effort of fleet f (time spent at sea) and $q_{i,f}$ measures the catchability of the stock i by the fleet f, which is the probability of a biomass unit of the stock i being caught by a boat of fleet f during one fishing effort unit.

The dynamics of the biomass $B_{res}(t)$ of the resource depends on the consumption of the different fish species through the relation:

$$B_{res}(t+1) = B_{res}(t)\left(1 - \sum_{i=1}^{N} a_{res,i} B_i(t)\right) + I(t) \tag{4}$$

where $I(t)$ is the external input (source) for this resource.

3.2 Calibration Method

The model was calibrated using data and time series of landing and fishing effort from the IFREMER Fisheries Information System on a quarterly basis. The period of calibration goes from the first quarters of 2006 to the last quarters of 2011, so that we can verify the relevance of our calibration on the period from 2012 to 2017.

We use [Levrel, 2012] to obtain the historical values for illegal fishing fleets. The estimates in this article use aerial (and maritime) observations made by the army in 3 separate areas in the EEZ (Exclusive Economic Zone) of French Guiana and thus estimates the average number of boats fishing illegally in the area per day. The strong assumption of illegal boats returning with catches equivalent to their maximum storage capacity is made, which may lead to a slight overestimation of this illegal fishing. The frequency of maritime operations increases significantly between 2002 and 2008, which may explain the leap on estimate of illegal fishing (see 4).The frequency of controls is much more important and stable between 2008 and 2011, which improves the reliability of the results for this period. The annual data of illegal fishing are disaggregated into quarterly data to match the time step of the data provided by IFREMER. To calculate illegal fishing by species, and not only a global amount, we consider that the proportion of each species in illegal catches at each

time t is equal to the distribution of this species in legal catches[4].

$$H_{i,IUU}^{data}(t) = H_{IUU}^{data}(t) * \frac{H_i^{data}(t)}{\sum_i^{N=3} H_i^{data}(t)} \tag{5}$$

We are aware of the limitations of using these estimations as historical IUU data, but they represent an acceptable proxy and allow us to conduct an exploratory analysis of the impact of illegal fishing on the ecosystem and the catches of French Guianese fishermen.
To calibrate this model, we apply the least squares method in order to minimize the mean square error between historical catches and the catches estimated by our model.

$$\min \sum_{i=1}^{N=3} \sum_{f=1}^{F=4} \left(H_{i,f}^{data} - H_{i,f}\right) \tag{6}$$

The parameters estimated in the calibration are the mortality rate M_i of each species i, the catchability $q_{i,f}$ of each species relative to each fleet f, the terms of interaction $a_{i,res}$ between the species and the resource, the growth efficiency g_i of each species, the initial biomass $B_i(t_0)$ of each species, the external input of the resource I(t) and the fishing effort of illegal fleet $E_{IUU}(t)$(in days).We used a genetic algorithm from the Scilab software to solve numerically the minimization problem (6).

3.3 Calibration Results

From 2006 to 2017, we have data of fishing landings and efforts for three species and the three legal fleets provided by Ifremer. We use the period from 2006 to 2011 to calibrate our model, which represents 24 quarters, since this is the period covered by [Levrel, 2012], and therefore for which we have so-called historical illegal fishing data. We can thus verify the relevance of our results on the three other fleets called CCA (Improved Creole Canoes), CC (Creole Canoes) and T (Tapouilles) from 2012 to 2017.Figure 4 shows the aggregated catches by species and the aggregated catches by fleet. We see that the historical and estimated catches are close and follow the same trend. To evaluate the quality of our modeling, we calculate the mean relative errors on catches by fleet and by species. These results, in Table 1, show the interest of taking into account the illegal fishing fleet. We calculate the mean relative errors on catches, between 2006 (first quarter) and last quarter of 2011 (24th quarter), with ε_k:

$$\varepsilon_k = \frac{1}{24} \sum_{t=1}^{24} \left| \frac{H_k^{Data}(t) - H_k(t)}{H_k(t)} \right| \tag{7}$$

In 7, the error ε_k can relate to $k = f$ for catches by fleet, $k = i$ for catches by species. The inclusion of this illegal fishing fleet reduces the mean relative error for aggregated catch and also for Acoupa

[4] In average from 2006 to 2012, $H_{i,IUU}^{data}$, is around 59.3% for Acoupa Weakfish, 24.6% for Green Weakfish and 16.1% for Crucifix Sea Catfish (IFREMER Fisheries Information System(SIH))

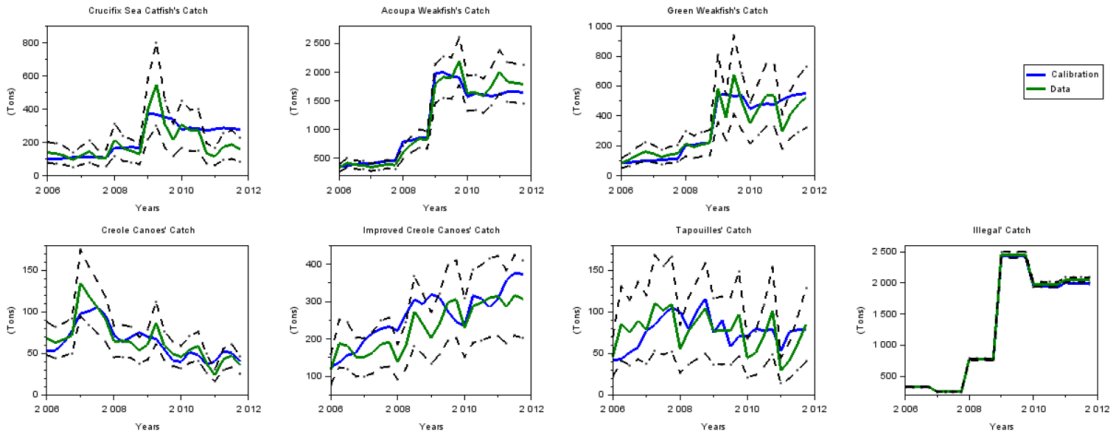

Fig. 4: Comparison of the catches by species and by fleet from the first quarter of 2006 to the last quarter of 2011. The blue line represents the catches, H(t), derived from the model. The green line represents the historical data, $H^{data}(t)$. The dotted black lines represent the 95% confidence intervals (see Equation 8).

Parameters	Mean relative error	Mean relative error without illegal catches
CC	0.151	0.151
CCA	0.174	0.174
T	0.267	0.267
Illegal	0.010	
AW	0.095	0.169
GW	0.198	0.319
CC	0.233	0.256
Aggregated	0.04	0.148

Table 1: Comparison of mean relative error, ε_k (Equation 7), taking into account illegal catches, or not

Weakfish and Green Weakfish. The Acoupa Weakfish and Green Weakfish are the two species most targeted by illegal fishing to collect swim bladders. It is therefore consistent that accounting for illegal fishing improves the calibration for these species. We obtain 95% confidence intervals (CI), the dotted black lines on Figure 4, using the mean relative errors through the equation:

$$CI_k = [1 - 1.96 * \varepsilon_k, 1 + 1.96 * \varepsilon_k] * H_k^{data} \tag{8}$$

For more precise results regarding a comparison by species and by fleet, see the Figures in subsection 7.3 of the Appendix, see the Table in subsection 7.4 of the Appendix for estimated parameters and the sensitivity analysis in subsection 7.5 of the Appendix . According to the sensitivity analysis, the model is stable. Perturbations on the calibrated parameters lead to a small change in the output of the model (Catches and Biomass). This sensitivity analysis emphasizes the

fact that initial biomass parameters and natural mortality rate parameters have a lower impact on the economic outputs, average catches by species and by fleets (see Figure 14). Conversely, catchability parameters, estimated illegal effort, growth efficiency and I (external input of the resource) matter more. Regarding the impact on the biomass outputs (see Figure 15), the Green Weakfish biomass is more sensitive to the perturbations of the parameters. Initial biomass, trophic relations, growth efficiency rate, external input of the resource I, and natural mortality rate parameters have a greater impact on the biomass output.

4 Predictions

The following projected trajectories of catches, from 2012 to 2018, contribute to the evaluation of the impact of illegal fishing on the ecosystem and the amount of catches of legal fishery, which can be used to quantify the loss of earnings for French Guianese fishermen due to illegal fishing.We first compute predicted trajectories over the period 2012-2017 from the calibrated model and historical efforts including IUU fishing. We then compare this prediction with a theoretical scenario without illegal fishing over the same period.

4.1 Prediction of catches with historical effort for legal fleets

In this predictive scenario of catches, we used historical efforts from 2006 to 2017 for the three legal fleets. For the illegal fishing fleet, from 2006 to 2011 (first 24 quarters), we used the fishing efforts estimated during the calibration phase. From 2012 to 2017, for the illegal fishing fleet, we used a logarithmic trend regression based on fishing efforts estimated during the calibration phase [5]. We have, from 2012 to 2017 :

$$E_{f=CC,CCA,T}(t) = E^{data}_{f=CC,CCA,T}(t) \tag{9}$$

$$E_{IUU}(t) = 1961,6 * ln(t) - 980.87 \tag{10}$$

All the other parameters used come from the calibration over the 24 first quarters. Regarding $I(t)$, that represents the external input of the resource, a random value included between min(I) and max(I) calibrated is considered at each time t.
We have quarterly historical catches from 2006 to 2017 for the 3 legal fleets, excluding illegal fishing, and can thus verify the relevance of our results with this predictive scenario.

[5] $E_{IUU}(t)$ is the value of the effort (expressed in days of fishing) estimated by the dynamic and t is expressed in quarters. t takes values between 24 and 48 for the prediction. R^2 is equal to 0.53 for this regression.

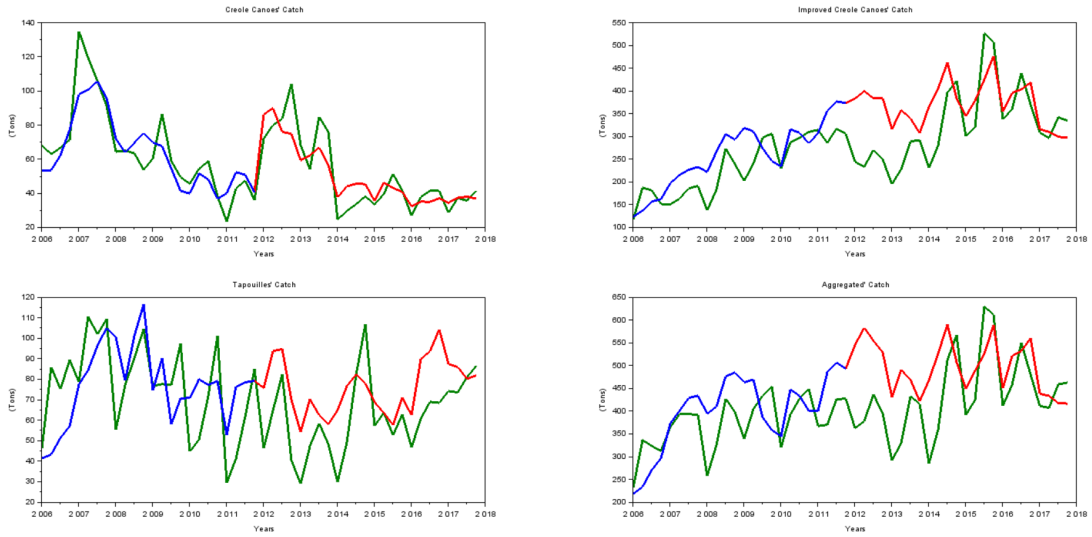

Fig. 5: Comparison between historical and predicted trajectories of catches by fleet from 2006 to 2018. The blue line represents the catches derived by the model. The green line represents the historical data. The red line represents the predicted trajectory from the model using historical efforts of legal fishing.

Figure 5 and Table 2 show the relevance of our model, through the predictions from 2012 to 2017 using estimated parameters and historical effort on legal fleets are consistent with the historical catch. The mean relative error ε on aggregated data shows a relatively low value of 0.169.

Parameters	Mean relative error from 2006 to 2011 (for legal fleets) (Calibration Period)	Mean relative error from 2012 to 2017 (for legal fleets) (Predictive Period)
CC	0.151	0.169
CCA	0.174	0.189
T	0.267	0.227
AW	0.169	0.328
GW	0.319	0.272
CSC	0.256	0.700
Aggregated	0.148	0.169

Table 2: Mean relative error on prediction with historical effort for legal fleets

For more precise results regarding a comparison for each species for each type of fleet, see the Figures in subsection 7.6 of the Appendix.

We obtain Figure 6, using equation 11. This boxplot shows that illegal fishing effort from 2006 to

2017, is around 1.8 higher than legal fishing effort (2.1 higher from 2012 to 2017).

$$\beta_1 = \frac{E_{illegal}(t)}{\sum_{n=1}^{3} E_f(t)} with\ f = CC,\ CCA,\ or\ T \tag{11}$$

We obtain Figure 6, using equation 12.

$$\beta_2 = \frac{H_{illegal}(t)}{\sum_{n=1}^{3} H_f(t)} with\ f = CC,\ CCA,\ or\ T \tag{12}$$

Figure 6, which represents the catch multiplier applied to the catches, shows that the fishing pressure from illegal fishing is on average, for the 24 last quarters, 4.5 times higher than the fishing pressure from the other fleets for these 3 particular species (Acoupa Weakish, Crucifix Sea Catfish, Green Weakfish). A warning here needs to be raised: illegal fishing is 4.5 times higher than legal fishing for these 3 species only.

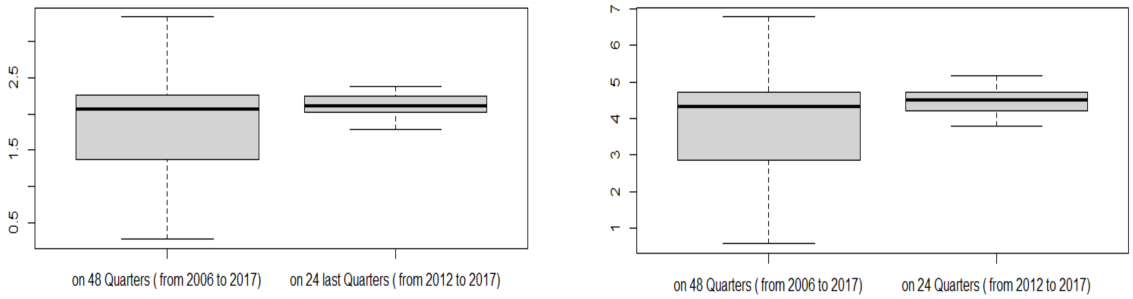

Fig. 6: To the left, Fishing effort multiplier, coefficient β_1 between legal fishing effort and illegal fishing effort. See equation 11. To the right, Fishing catches multiplier coefficient β_2 between legal fishing catches and illegal fishing catches. See equation12.

4.2 **Comparison of scenarios taking into account or not illegal fishing**

Figure 7 shows that, depending on the predictive scenario used, with or without illegal fishing, a significant change in biomass is observed. For the scenario without illegal fishing, called No Illegal scenario (NI scenario), we have:

$$E^{NI}_{f=CC,CCA,T}(t) = E^{data}_{f=CC,CCA,T}(t) \tag{13}$$

$$E^{NI}_{IUU}(t) = 0 \tag{14}$$

We can see that illegal fishing has a significant impact on the biomass and especially on the biomass of Acoupa Weakfish. From an ecological point of view, the most favorable solution is undoubtedly the scenario of closure for illegal fleet, but we note that the competition on the resource is higher between species, and this situation is not necessarily the most favorable for Crucifix Sea Catfish.

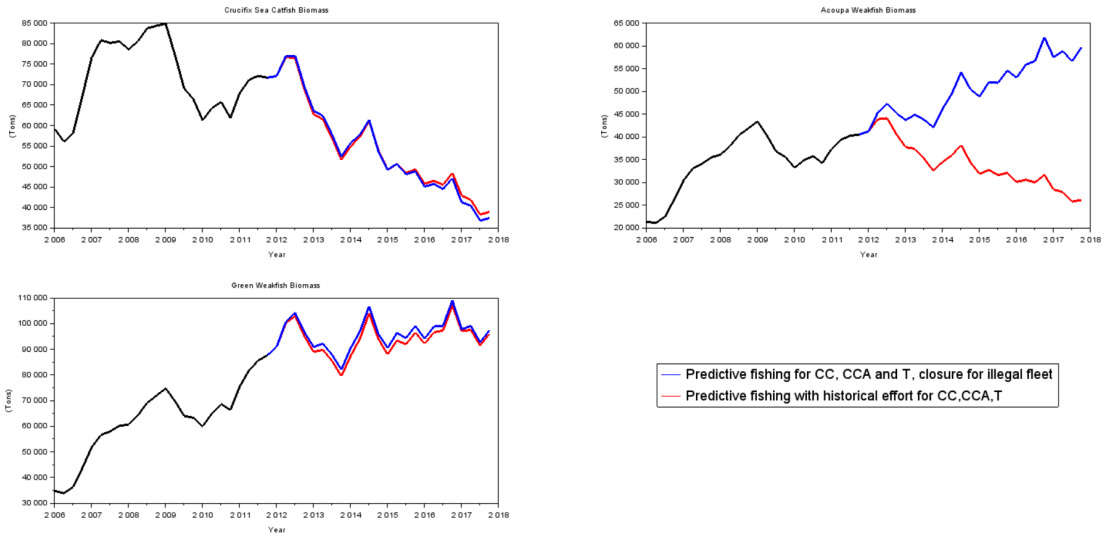

Fig. 7: Biomass trajectory from 2006 to 2018. The red line represents the predictive fishing scenario using historical effort for CC, CCA and T and trend of effort for illegal fishing. The blue line represents scenario NI with closure for the illegal fleet only.

We note that suppression of illegal fishing (blue line) have a significant impact on the Acoupa Weakfish' biomass. From an economic standpoint, the most profitable solution for the fishing sector is to increase the surveillance efforts in order to limit illegal fishing.

The blue line represents the catches from the legal fleets (CC, CCA, T), using their historical efforts in the prediction, assuming that the illegal fishing is null. The comparison with the predictive fishing catches (red line) shows a significant increase in catches for the legal fleets, while spending the same number of days at sea (we used a similar fishing effort for these fleets for the blue and red lines). These simulations allow us to quantify the illegal fishing and evaluate the related losses. The controls have an important impact in deterring illegal fishing, given the numerous missions organized, but the tonnage seized is negligible in comparison with the tonnage of illegal fishing (see table 5 for the amount of fish seized in tons). It is considered that to produce 1 kilo of fresh Acoupa Weakfish swim bladders, 30 kilos of Acoupa Weakfish are required, for Crucifix Sea Catfish and for 1 kilo of fresh Green Weakfih swim bladders, 20 kilos of fish are needed. Using data from reports of the public prosecutor's department of Cayenne in 2017, we get a price of 100 EUR for 1 kilo of fresh swim bladders for Acoupa Weakfish, around 32.5 EUR per kilo of fresh swim bladders for Green Weakfish and 2 EUR per kilo of fresh swim bladders for Crucifix Sea Catfish. As the price can vary according to the intermediary, we will apply a ratio of +/- 20% to estimate the benefits from the bladders. The legal fishing fleets, T, CC and CCA, legally fish the three species of the study. These fleets resell the product of their fishing mainly to processing plants, local markets, supermarkets, and fishmongers. For swim bladders, the distribution network is different. Fish is for the local market and swim bladders are for exportation, as it is the case in Brazil [Jimenez

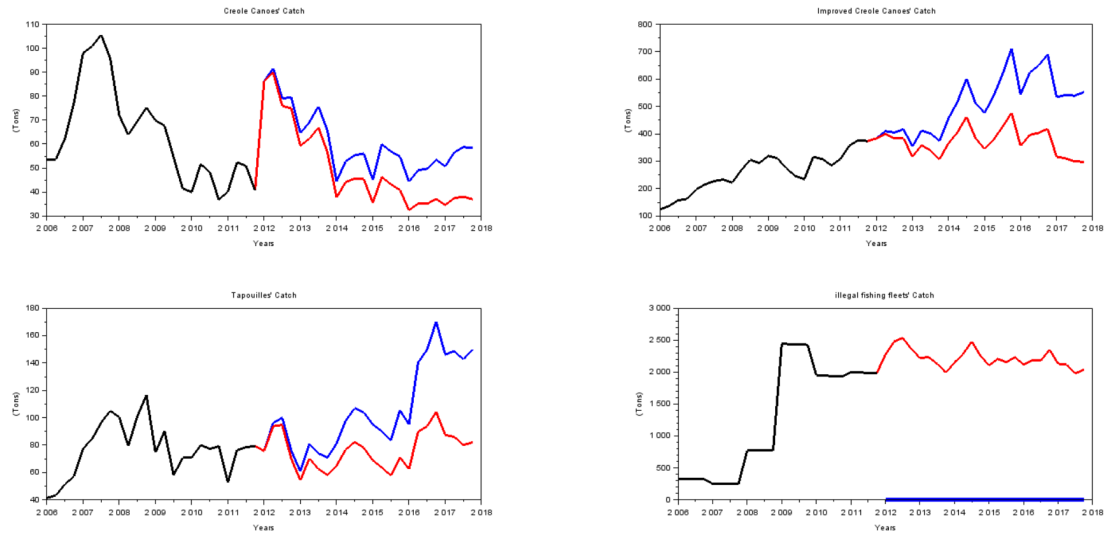

Fig. 8: Catch trajectory from 2006 to 2018. The red line represents the predictive fishing scenario using historical effort for CC, CCA and T and trend of effort for illegal fishing. The blue line represents scenario NI.

et al., 2020]. Some shipowners sell fish to processors: said processors buy the equivalent in swim bladders per kilo of fish purchased. The shipowners and the fishermen then share the income from this sale 50/50 (IFREMER Fisheries Information System(SIH)). Other shipowners also share the sale income 50/50 with fishermen, but leave the swim bladders to the fishermen, to be resold for the most part on the parallel market (see Figure 3).

The graph 9 represents the estimated landed values (ELV) of fish. Such ELV relies on equation 15 (taking into account Acoupa Weakfish, Green Weakfish and Cucifix Sea Catfish) and swim bladders of these fish and equation 16, for the period from 2012 to 2017.

$$ELV_i(t) = p_i * H_i(t) \tag{15}$$

$$ELV_i^{SB}(t) = p_i^{SB} * \frac{H_i(t)}{\gamma_i} \tag{16}$$

We assumed that p_i represents the price of the species, p_i^{SB} is the price of the swim bladder of this species, and γ_i is the ratio to obtain the amount of swim bladders from the total amount of catches.

Two situations are represented. The first situation is the historical situation where the estimated landed values are calculated from the historical fish catches and the 2017 fish species prices. The prices are the following : 1.6 €/kg for Crucifix Sea Catfish flesh, 3.4 €/kg for Acoupa Weakfish flesh and 1.9 €/kg for Green Weakfish flesh [Ifremer-SIH, 2019b]. The second situation is the situation where the illegal fishing fleet does not occur. Figure 7, shows us that illegal fishing has a strong impact on the biomass of Acoupa Weakfish. Acoupa Weakfish is the species with the highest value

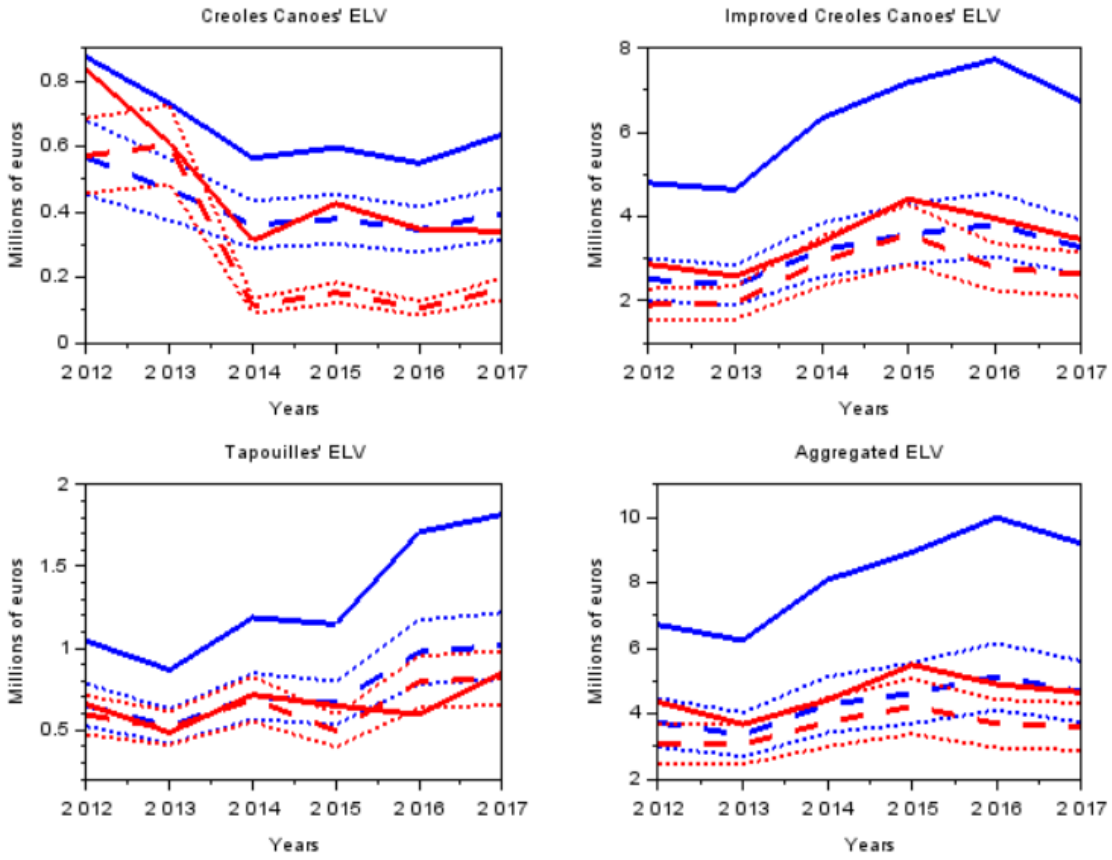

Fig. 9: Estimated Landed Value (ELV) in millions of euros for Acoupa Weakfish, Green Weakfish, Crucifix Sea Catfish and swim bladders by legal fleet in French Guiana from 2012 to 2017. Red lines represent the historical situation. Blue lines represent the ELV in the situation of scenario NI. Solid lines represent the ELV of the 3 species (fish flesh). Dashed lines represent the ELV due to illegal bladder trade. Dotted lines represent the ELV due to illegal bladder trade with (+/- 20 %) on the price.

per kilo, and the one with the highest swim bladder value and the highest catch tonnage. A decrease in its biomass, strongly due to illegal fishing pressure, therefore leads to significant economic losses. The figure 9 compares the loss of income due to illegal fishing for the same fishing efforts by the legal fleets. On average over these 6 years, the difference in estimated landed values of fish flesh for the entire legal fishing fleet, with or without illegal fishing, was 3.62 million euros.

An important contribution of this study is an approximation of the values of swim bladders landed in French Guiana. The majority of bladders are sold on the parallel market. The value of the bladders represent a high proportion of estimated landed value (ELV), meaning several million euros escape the legal market. The swim bladders significantly contribute to the increase of income of fishermen, and by this fact to their food security.

5 Discussion

5.1 Ecological impacts of IUU

Firstly, this paper studies the consequences of IUU fishing for the main fish stocks exploited of the French Guiana coastal fishery. Although the small-scale fishery in French Guiana has an impact on the biomass of these three species, it is very limited compared to the impact of illegal fishing fleets. Indeed, we can see (on Figure 7) that for the last year of the model in 2018, in the hypothesis of total absence of illegal fishing, the biomass of Acoupa Weakfish is 2 times higher than in the presence of illegal fishing, the biomass of green weakfish is slightly higher in the absence of illegal fishing. When we consider that illegal fishing is null, this affects the resource biomass. Without illegal fishing, the biomass of Green Weakfish and Acoupa Weakfish increase,and by this fact their consumption on the resource biomass also. So, the biomass of the resource decreases. The biomass of the Crucifix Sea Catfish slightly decreases due to the decrease in the resource. It's due to the fact that g_i, the growth efficiency of this species, is weaker than the g_i of other species. This species is also less impacted by fishing than the two others, so the suppression of illegal fishing has less impact on it.

Illegal fishing has a strong impact on the biomass of Acoupa Weakfish. Reducing illegal fishing already has a very beneficial effect on the biomass of Acoupa Weakfish, and the total elimination of illegal fishing is obviously the most favourable solution for Acoupa Weakfish.

Illegal fishing also has an impact on the structure of the ecosystem in French Guiana, as it is already the case in the rest of the world [Coll et al., 2008, Pascoe et al., 2008, Sumaila et al., 2020]. Indeed illegal fishers throw a large part of fish flesh in the water when they remove their net, in order to keep only the swim bladders, which have a higher value. This large amount of dead fish attracts scavenger fish (like rays)(IFREMER Fisheries Information System(SIH)). It will be interesting to study this impact more precisely from a biological point of view. French Guiana is the French overseas department with the highest implication in bycatch of sea turtles [Senko and Nalovic, 2021]. Actually, a few organisms work in collaboration with French Guianese fishermen to find solutions to limit bycatch. IUU seems to have a high impact on this point, according to french Guianese fishermen [André, 2018], because of the use of non-conforming large nets and non-compliance with new strategies and advice to limit bycatch.

5.2 Economic impacts of IUU

In a second time, this paper quantifies the legal production in weight and value, as well as the national and foreign IUU observed in the French Guiana EEZ. The graph 9 shows Estimated Landed Value in French Guiana.

IUU has important consequences for the economy and livelihoods of many small-scale fishers around the world [Dyck and Sumaila, 2010, Daniels et al., 2016]. Figure 9 shows that the estimated landed values of fish are almost twice as high in the total absence of illegal fishing. Due to the low price

of fish and the difficult working conditions, it is becoming less and less attractive to work in the fishing industry in French Guiana. The sale of swim bladders on the illegal market has become a way for French Guiana fishermen to supplement their salaries and for boat owners to make their boats profitable. The development of the legal swim bladder trade is an opportunity for fishermen and the fishing sector in French Guiana. The swim bladder trade represents a commercial opportunity for different countries around the world, for example Tanzania and Uganda [Food Safety Associates Ltd, 2018], Brazil [Jimenez et al., 2021] or Mexico [Martínez and Martínez, 2018] where unfortunately the resource has been over-exploited. This study highlights the potential significant loss of income due to the sale of swim bladders on the illegal market. Indeed, the values of swim bladders landed in French Guiana, according to our study, is on average just 25% lower than the values of fish flesh landed for the historical situation and 50% lower on the hypothesis of suppression of illegal fishing.

Sustainable exploitation of these swim bladders is needed to avoid economic issues. The example of Indonesian fishermen show us the consequences of unsustainable exploitation of swim bladder. Indeed, the swim bladder is a substitute for shark fins, which for many decades were an important source of livelihood for small-scale Indonesian coastal fishermen until they were overexploited [Jaiteh et al., 2017]. Indonesian fishermen will have to adapt again after economic losses.

5.3 Policy recommendations

The causes of illegal fishing in French Guianese waters can be found in the report developed by the OECD and presented by [Le Gallic and Cox, 2006]. These include institutional factors such as an insufficient level of control in the face of the scale of the phenomenon. There are also social factors such as poor economic conditions, the attractiveness of French Guianese waters due to the high amount of fish and increasing cooperation between actors engaged in illegal operations reducing the transaction costs for swim bladder trade.

From an ecological point of view, the most appropriate solution, according to our study, is one involving reinforced controls on illegal fishing. The FAG are already very present in this area, but in view of the scale of the phenomenon, even greater measures must be taken to deter illegal fishermen. These controls are not without risk, however, since in view of the value of swim bladders, compared to the "aquatic cocaine" [Margulies et al., 2019], illegal fishermen are becoming increasingly violent and arrests can be dangerous.

A fishery governance that takes into account all fishery stakeholders of the Guiana Shield (Venezuela, Brazil, Guyana, Suriname and French Guiana) must be pursued in order to preserve one of the key species of these fisheries, the Acoupa Weakfish. A majority of the illegal vessels in the coastal zone come from Brazil and Suriname, and it should be noted that these vessels are often also illegal in their own countries [Chao, 2021], which further complicates the management of the fisheries and makes the traceability of the products of this fishery (notably swim bladders) even more complicated. The fishing pressure on the EEZ of Brazil and Surinam and French Guiana is indeed very

different: in Brazil there are 30 fishermen per kilometre of coastline, in Surinam, 60 and only 1 in French Guiana [Sénat, 2021]. There are very strong links between French Guiana, Suriname and Brazil, with several families and communities living on the borders and crossing them several times a day [Polidori and Noucher, 2020]. Consequently, cohesion in fishery policy decisions between these two countries and France is essential for the management and cooperation of French Guiana's small-scale coastal fisheries. During interviews lead in the state of Amapá (Brazil, border state), Brazilian fishermen complained about illegal french Guianese fishermen in this state, they propose an agreement between Brazilian and French governments to release Small Scale Fishery in this transboundary region [Jimenez et al., 2019].

Following the rational choice theory, the decision to fish illegally is influenced by several factors. The first is the effort required to resell the illegal catch and access the consumer market, the second is the accessibility of the resource and the third is the risk of being arrested at sea or when reselling in the port [Petrossian, 2015]. Regarding the risk of controls, the problem of illegal fishing is taken very seriously by the armed forces in French Guiana, notably with the renewal of the fleet with two new patrol boats (in 2016 and 2017) and, above all, the entry into service of a net boat (in 2015) specifically set up to fight this practice. Convictions for illegal fishing can be a fine, a ban from the territory or even a prison sentence [Assemblée Nationale, 2010]. Some illegal fishermen leave their nets down for several hours, then come and retrieve them at night when there is less risk of checks; they spend the day hidden in the mangrove, so increasing the number of checks in the mangrove during the day could contribute to a reduction of illegal fishing. Illegal fishermen are becoming increasingly violent during inspections, and in view of this increase in violence, it would be more effective to step up inspections with teams equipped to deal with uncooperative and violent illegal fishermen. Increased controls at the port landing could be interesting in order to limit informal reselling. The granting of a licence to some illegal Brazilian and Surinamese fishermen, with a percentage catch condition for landing in French Guiana, could allow for a better visibility and therefore a better management of the stock.

With regard to the reselling of illegal catches and access to consumers, the valuation and traceability of swim bladders is important. Swim bladders are exported dried and require processing, so the fishermen must go through an intermediary (or several) so that the bladders can be dried and exported to Asia. The establishment of a reselling market for fresh swim bladders in the legal sector, which would offer competitive prices compared to the informal market, would encourage fishermen to move towards the legal route. This route is improving with a steady increase in applications for approval to export swim bladders. In 2017, companies were approved in French Guiana and several applications are currently being processed. The sector is gradually being built up to encourage the sale of these bladders through the legal distribution channel, with the efforts of several organisations such as the DAAF (Direction of Food, Agriculture and Forestery), the Maritime Affairs and the Regional Fisheries Committee of French Guiana. However, at present, the purchase prices of bladders charged by legal companies are not attractive compared to the prices on the informal market. Progress is slow and the majority of stakeholders remain in the informal sector. A stronger

incentive to sell bladders on the legal market could encourage shipowners to modernise their fleets and equipment. By reducing the intermediaries between the final consumers of swim bladders and the French Guianese fishermen, this would increase the benefits going directly to the fishermen. The market for swim bladders would directly benefit the entire fishing sector in French Guiana (as explained in [Barone et al., 2017] for Brazil).

5.4 The benefits of models of intermediate complexity (MICE Analysis)

The ecological-economic model used for the analysis of IUU fishing is a model of intermediate complexity (MICE). This type of model is advocated by many scientists for implementing an Ecosystem-Based Fishery Management (EBFM) [Cissé et al., 2013, Plagányi et al., 2014, Doyen et al., 2017, Gomes et al., 2021]. For a small group of species (<10), a MICE is accurate to describe ecological processes subject to fishing pressure. MICE answers more specific questions than global ecosystem models (such as Ecopath with Ecosim [Christensen et al., 2005] or Atlantis [Fulton et al., 2011]). The model used here limits complexity by focusing only on the minimal components and interactions necessary to address the research problem: IUU fishing. The dynamics of the three fished stocks and a resource is integrated in the modelling. The trophic interactions are incorporated through the competition for the resource. The impact of 4 fleets harvesting the fish species, including illegal fishing, is taken into account. Understanding, quantifying and reducing illegal fishing is necessary to promote the sustainability of fisheries. Supporting small scale fisheries is key for the achievement of Sustainable Development Goal (SDG) 14. Limiting the uncertainty related to the estimation of global catches affecting the ecosystem is necessary to apply an effective EBFM strategy. Our model, developed in section 3.1, by integrating the pivotal role of IUU for the sustainability and ecosystem-based management of small-scale fisheries, provides important insights into that issue.

5.5 Limits

These results improve the quantification and understanding of the impact of illegal fishing on the French Guiana ecosystem. They also allow us to identify the benefits that could accrue to the fishery in French Guiana if illegal fishing were to be eliminated. The study of illegal fishing is a study that, by its very nature, is done with a high degree of uncertainty regarding data. The use of a stronger database, especially concerning the precise military control effort and aerial observations would allow for a more accurate estimation of illegal fishing.
The number of species in the model is limited, although the 3 species represent 72% of the landings in 2018. It would be interesting to increase the number of species and to add intraspecific and interspecific trophic interactions in the model to be able to analyse the French Guianese ecosystem in a more detailed and global way. It would be interesting to refine the dynamic of the resource, for

example by integrating data about the biomass of shrimp and the stock of other fishes as a resource.

In the Prediction section 4, we use data from reports of the public prosecutor's department of Cayenne in 2017 and from [Ifremer-SIH, 2019b]. Prices are constant and, in the case of swim bladders, not depending on the size and quality. For the moment, illegal retailers buy swim bladders in big bags, without differentiation of the quality at the landing area. It will be interesting to integrate differentiation of price according to size and quality and to have a dynamic price. Since 2018, prices have reached up to 150 EUR per kilo with some retailers, for the largest and best quality fresh Acoupa Weakfish swim bladders. This increase in price is not taken into account in the Projection section and we can not quantify the level of control: that can limit the reliability of the result.

The importance of global warming on the French Guianese case study has been demonstrated [Diop et al., 2018, Gomes et al., 2021], it would be important for future projections to integrate this global warming into the model in particular whenever long term scenarios would be considered. .

6 Conclusion

This article uses a MICE model to take into account illegal fishing in the estimation of catches of the small-scale coastal fisheries of French Guiana. We use a multi-fleet, multi-species model based on quarterly time series data from 2006 to 2018. Predictions with and without illegal fishing highlight the ecological and economic impacts on the small-scale fisheries of French Guiana and more broadly to contribute to EBFM of small-scale fisheries, thus allowing to recommend various policies to limit this behavior.
The impact of illegal fishing is particularly severe for the biomass of Acoupa Weakfish, a species targeted for its flesh, but also for its swim bladders. We suggest short-term public policies to reduce illegal fishing, notably the implementation of more specific controls: in the mangrove, with a specific intervention team at sea, as well as on the reselling of swim bladders at the ports. Long-term strategies should also be applied, such as the development of a solid distribution network for swim bladders and granting licences to a small proportion of illegal fishermen in collaboration with surrounding countries namely Surinam and Brazil.

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7 Appendix

7.1 Appendix - Comparison small scale fishery versus large scale fishery

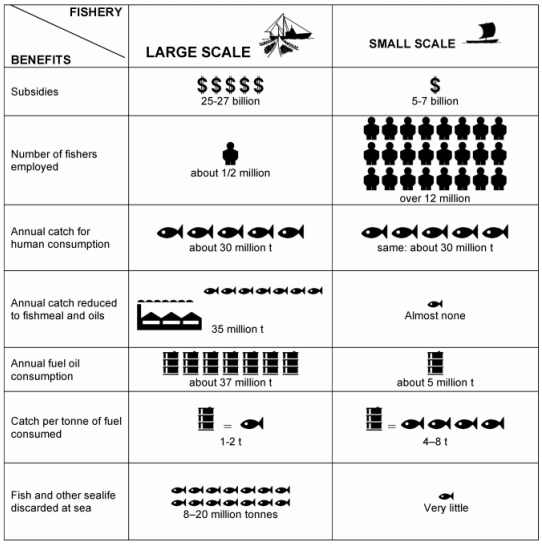

Fig. 10: Figure from [Jacquet and Pauly, 2008] "Schematic illustration of the duality of large and small-scale fisheries prevailing in most countries of the world (statistics are global). Adapted from graph in [Pauly, 2006]."

7.2 Appendix : Species

Common name	Scientific name	Trophic level ±0.7
Crucifix sea catfish	Sciades proops	4.4
Acoupa weakfish	Cynoscion acoupa	4.1
Green weakfish	Cynoscion virescens	4.0

Table 3: Three species selected in the model (Fish Base)

7.3 Appendix - Calibration by fleet and by species

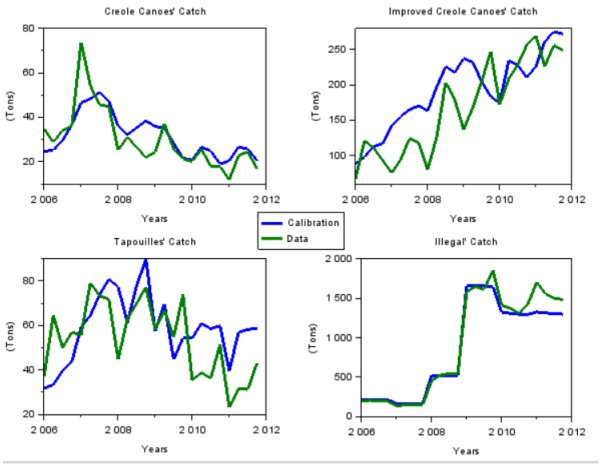

Fig. 11: Comparison by fleet for the Acoupa Weakfish, the blue line represents calibration and the green line represents the historical data

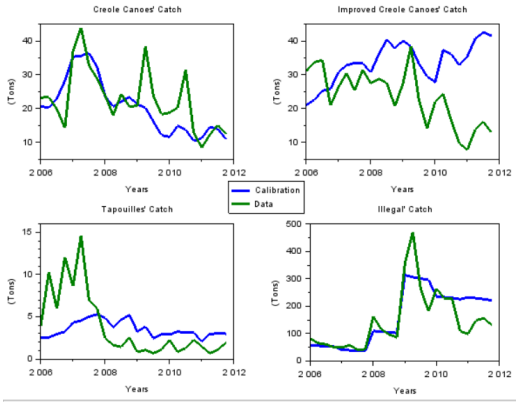

Fig. 12: Comparison by fleet for the crucifix sea catfish, the blue line represents calibration and the green line represents the historical data

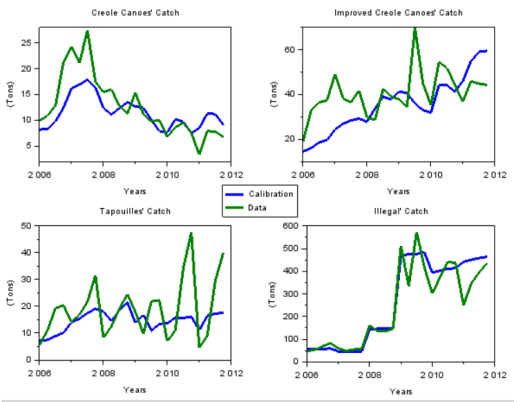

Fig. 13: Comparison by fleet for the green weakfish, the blue line represents calibration and the green line represents the historical data

7.4 Estimated Parameters

Calibrated Parameters	Acoupa Weakfish	Green Weakfish	Crucifix sea Catfish	Resource
$a_{res,i} * 10^6$	2.4	7.6	7.0	
$q_i CC * 10^6$	1.5	0.3	0.4	
$q_i CCA * 10^6$	3.6	0.4	0.3	
$q_i T * 10^6$	7.1	1.0	0.2	
$q_i Illegal * 10^6$	6.7	1.1	0.7	
$M_i * 10$	0.9	1.4	1.6	
$g_i * 10$	1.4	0.5	0.5	
$B_i(2006)$	21594	34695	59212	300 611
$I(t)$	$min(I(t)) = 204615.48$		$max(I(t)) = 711804.03$	
$E_{illegal}(t)$	$min(E_{illegal}(t)) = 696.13$		$max(E_{illegal}(t)) = 6850.2$	

Table 4: Details on Estimated Parameters

7.5 Sensitivity analysis One-factor-at-a-time (OAT) on calibration results

A sensitivity analysis is carried out over the calibration period from 2006 to 2011, varying all the parameters of the same group simultaneously. We compare the relative change between the average aggregate catches obtained with the new parameter value and the average aggregate catches obtained during the calibration (Figure 14), we also compare the relative change between the average biomass obtained with the new parameter value and the biomass obtained during the calibration (Figure 15). As the variation of the results is small, we can conclude that the model is stable.

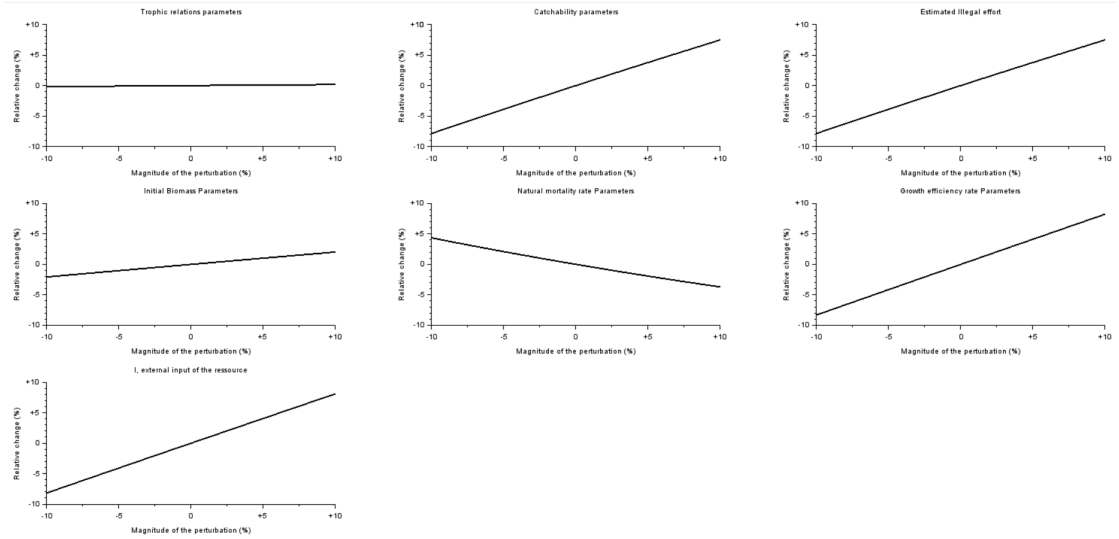

Fig. 14: Relative change in average catch per quarter $\bar{H}$,with variations in input parameters by 1% increments from -10% to +10%.

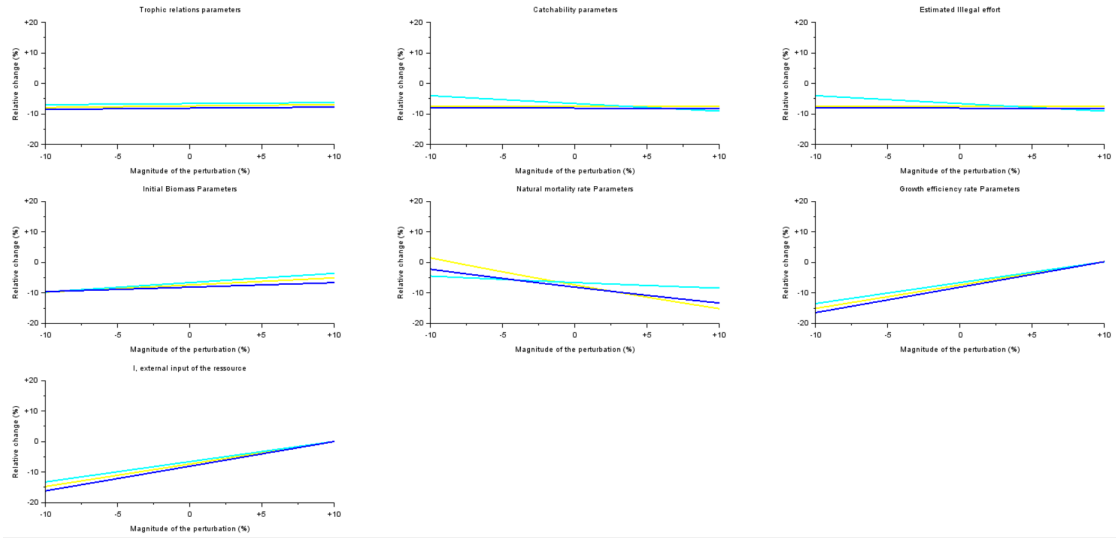

Fig. 15: Relative change in average Biomass per quarter,with variations in input parameters by 1% increments from -10% to +10%.

The yellow line represents the magnitude of the change for the average Crucifix Sea Catfish biomass after a perturbation. The dark blue line represents the magnitude of the change for the

average Green Weakfish biomass after a perturbation. The light blue represents the magnitude of the change for the average Acoupa Weakfish biomass after a perturbation.

7.6 Appendix - Prediction with historical effort for CC, CCA, T and trend effort for illegal

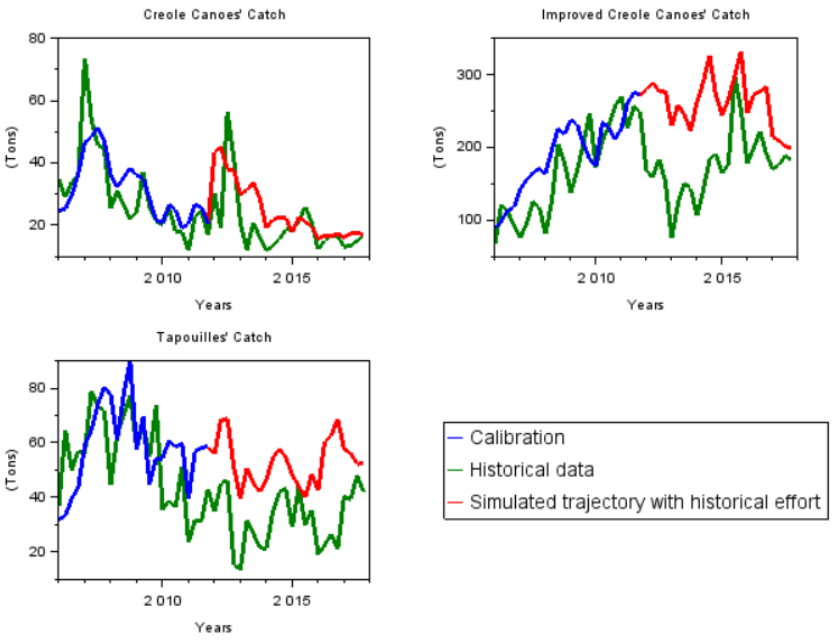

Fig. 16: Comparison by fleet for the Acoupa Weakfish from 2006 to 2017 (48 quarters)

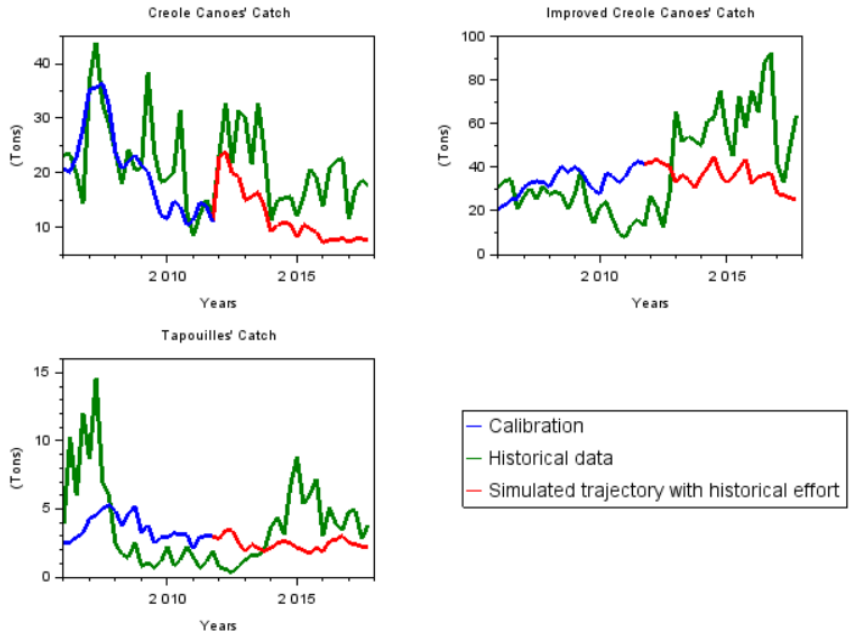

Fig. 17: Comparison by fleet for the Crucifix Sea Catfish from 2006 to 2017 (48 quarters)

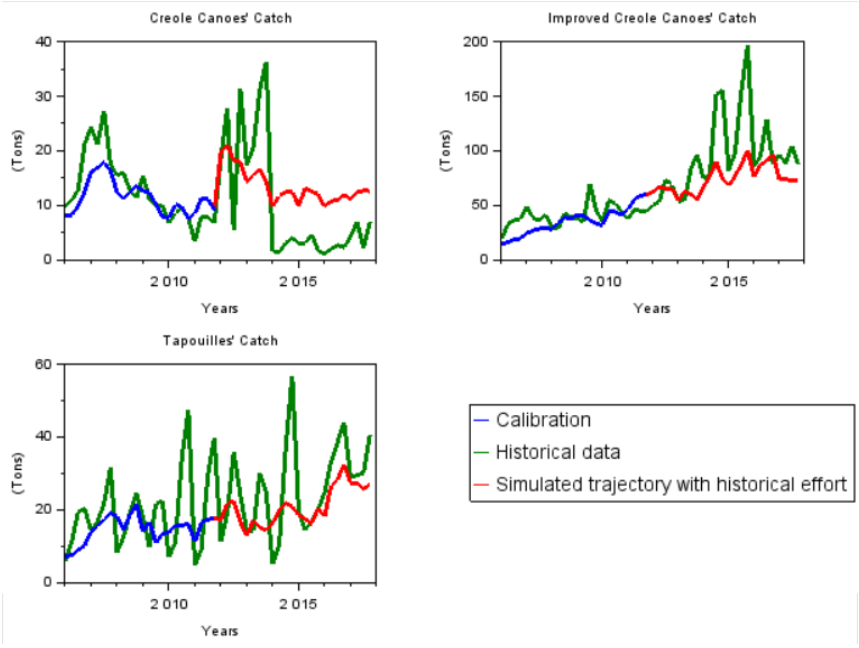

Fig. 18: Comparison by fleet for the Green Weakfish from 2006 to 2017 (48 quarters)

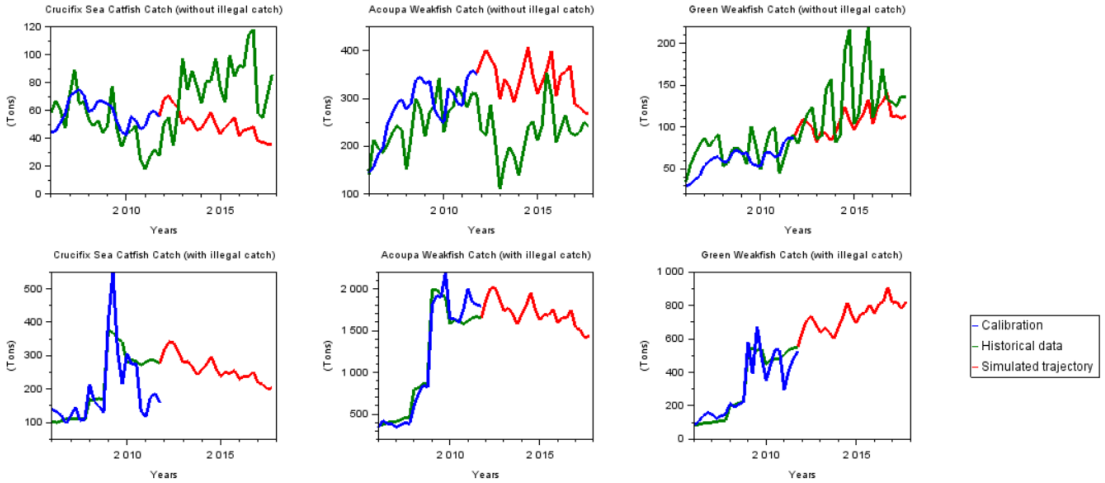

Fig. 19: Comparison by species from 2006 to 2017 (48 quarters)

7.7 Maritime law enforcement

Table 5: Data gives by AEM (Action Etat en Mer, Maritime law enforcement)

Year	Seized net in kilometers	Seized catches in tons of fish	Checked Boats
2007	42.8		
2008	68.5	33	
2009	49.1	60.8	
2010	89.8		
2011	47.25	24.2	
2012	76.5	51.62	112
2013	143.7	69.5	107
2014	127.9	47.18	
2015	156	86	
2016	276	109.743	138
2017	259	127.996	148
2018	216	85.734 (including 848kg of swim bladders)	158
2019	255	80.649 (including 1073kg of swim bladders)	173

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