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Minimising discards while taking revenue into account: Spatio-temporal assessment of catches in an artisanal shrimp trawl fishery in Peru

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ABSTRACT

Around 4.2 million tonnes of fish and other species, some of which are of conservation concern, are discarded every year in bottom trawl fisheries. This study focusses on a small-scale shrimp trawl fishery located in northern Peru that operates with high level of discards which causes conflict with other local fishers. Despite trawling being an illegal activity within the 5NM off the coast, this fishery has been operating in these inshore areas for over 40 years because it sustains the well-being of hundreds of fishers. This study aimed to identify the factors that affect the spatio-temporal variation in catches in order to propose recommendations that can be adopted by fishers to minimise their impact on the ecosystem while still providing economic opportunities. The spatial distributions of shrimp, main commercial species and discards were modelled over time using hierarchical generalised additive models. Strong spatio-temporal variation was observed for all catch components and moon phase affected commercial species and discards differently. The results show that, to reduce the environmental impacts of this fishery in the short-term, the fishing area could be divided into north and south and that fishing activities should be limited to the southern area in the autumn. Other recommendations rely on temporal closures during the week of the first quarter of the moon phase. Finally, considering the institutional weaknesses in monitoring, control and surveillance, we suggest that the only realistic approach to reduce the fishery's environmental impacts in the short-term is to foster the willingness of fishers to adopt responsible fishing practices. Yet, long-term solutions will require comprehensive co-management efforts.

1. Introduction

It is estimated that about 4.2 million tonnes of fish and other marine life are thrown overboard usually dead or dying in bottom trawl fisheries (Pérez Roda, 2019). Shrimp trawl fisheries in particular, display the greatest rate of discards, with more than half of their catches being discarded (Gillett, 2008; Pérez Roda, 2019). As discarding contributes to preventing recovery of depleted stocks and affects populations of protected, endangered and threated species such as sea turtles, seabird, marine mammals, and sharks (D'Agrosa et al., 2000; Lewison et al., 2014; Rivalan et al., 2010), much effort has gone into developing approaches to reduce or avoid this unnecessary loss.

One of the most common approaches used to mitigate discards is the establishment of spatio-temporal measures such as areas or times when fishing is not permitted (Dunn et al., 2011; Suuronen and Gilman, 2020). Incorporating different explanatory variables such as moon phase, bathymetry, time of the year, time of day or even spatially explicit effects in predictive models improves our understanding of discard dynamics (Benoît et al., 2010; Erzini et al., 2002; Feekings et al., 2012; Paradinas et al., 2016; Pennino et al., 2014; Rezende et al., 2019), and can be used to inform management. While spatial management approaches are in place for different stocks (Little et al., 2015), these are mostly applied in large scale fisheries in developed countries. In Small-Scale Fisheries (SSF), where livelihoods directly depend on fishing activities for poverty alleviation and food security (Béné, 2007), applying such approaches without taking into account of their socio-economic impact is challenging and it is important to understand the complex trade-offs between protecting livelihoods and securing fisheries management measures that are sustainable.

In Peru, trawling is prohibited within the 5 nautical miles from the

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shore but around 105 artisanal vessels operate within this area in the northern region of Piura. This artisanal shrimp trawl vessels operate at night, using bottom otter trawls and landed 49–313 tonnes of coffee shrimp (*Penaeus californiensis)* annually between 2014 and 2018 (IMARPE, 2019). While the main target species is coffee shrimp, two other bycatch species are also commercially valuable: sand-perch (*Diplectrum conceptione*) and flounder (*Etropus ectenes*), and these three species comprise ~40 % of the total capture (Mendo et al., 2020). This fishery operates with high levels of bycatch (~6 kg of bycatch per kg of shrimp) composed primarily of juvenile fish and invertebrates that are not of marketable size (Mendo et al., 2022). Some of these species are targeted as adults by other local fishers using hook and line or gillnets, and therefore conflict arises between these groups of fishers. In this context, the shrimp trawling fisheries Association ("Asociación de Pescadores Artesanales de la Caleta Constante, Sechura") contacted members of the National Agrarian University, to identify ways to improve the sustainability of the fishery with a view to reducing bycatch and identify sustainable measures that would persuade Government to facilitate formal regulation and legitimisation of the fishery. This study aimed to identify the factors that affect the spatio-temporal variation in catches of commercial species and discards. Due to the lucrative economic incentives associated with coffee shrimp trade (Mendo et al., 2020), suggest that fishers are likely to continue to flout the prohibition on fishing in the absence of effective policing. Therefore, our aim was to work with fishers to identify spatio-temporal measures that would mitigate the ecological impacts of the fishery.

2. Methods

The study focused in the area between Cabo Blanco and Máncora, northern Peru (Fig. 1). Around 30 small-scale vessels operate in this area, these are generally <10 m long, with a storage capacity of 7 tons and engine power of 120 HP. A total of 22 skippers agreed to host two on-board observers between April 2019 and March 2020. Data from 331 hauls in 79 trips was collected.

For each haul, the weight of the net and the catch including the net were recorded with a digital scale (KAMBOR 1 tonne capacity, +/- 0.5 kg accuracy). The total catch weight was calculated by subtracting the weight of the net from the weight of the total catch and net. The total catch consists of the target species coffee shrimp and bycatch, defined by Pérez Roda et al. (2019) as the sum of discarded organisms and non-target commercial species that are retained and marketed or consumed. When the catch was on-board, the fishers placed the coffee shrimp, sand-perch, flounder, and other commercial species into 0.08 m^3 PVC boxes, which were weighed by observers. The remaining part of the catch constituted the discards and for each haul, a sample (on average 11.0 +/−2.4 kg SD) was taken using an 18 l capacity bucket and weighed with a digital scale (KAMBOR 100 kg capacity, +/−20 gr accuracy). This sample represented on average 14.0 % of the bycatch weight + /- 8.9 kg SD. The number and weight of individuals by species or taxon were recorded and weighed and their total weight and number estimated as function of the total catch. For each haul, position, deployment times and the time of the day were recorded. Depth (m) was estimated using a Lucky Fish Finder.

Total discards were estimated as follows:

Total discards (kg) = Total catch (kg) – (coffee shrimp (kg) + commercial bycatch (kg))

Using the catch data and the swept area (a) of the trawl, Capture per Unit Area was estimated (CPUA, ton.km^{-2}) for each component of the catch. The swept area was estimated using the following equation (Sparre and Venema, 1997):

$$a = V * t * rs * X2$$

where V represents trawl speed (km/h), t trawl duration (h), rs the length of the head rope (km) and $X2$ is the deformation factor of rs (set to 0.5 according to Pauly (1980)).

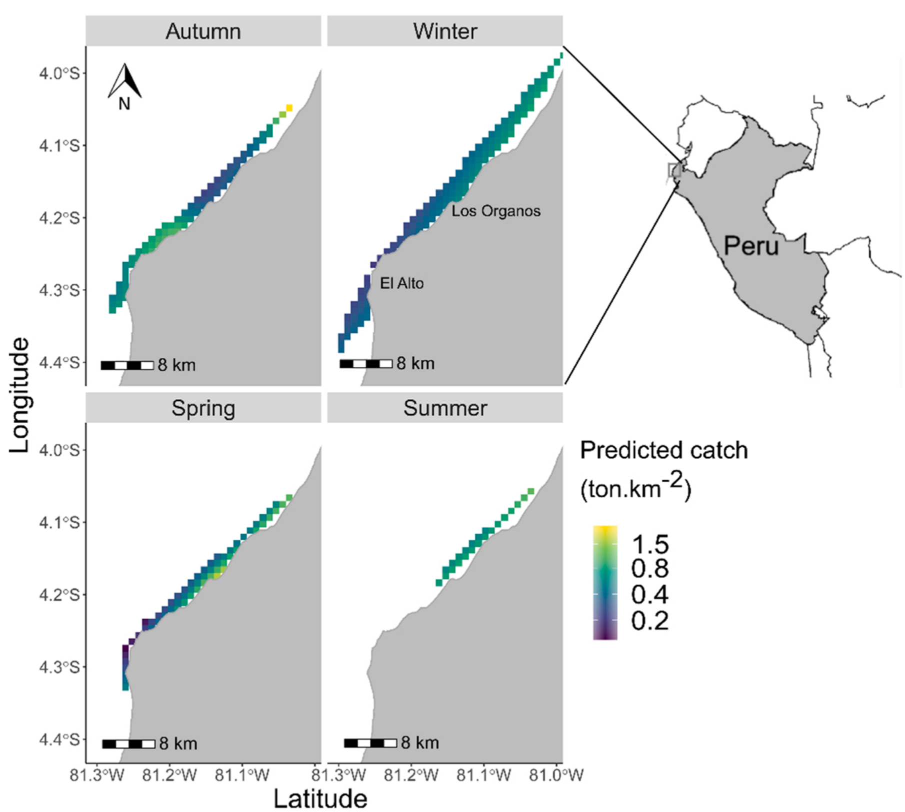

Fig. 1. Predicted coffee shrimp CPUA (ton.km^{-2}) in Los Órganos, Peru, for each season.

2.1. Spatio-temporal analysis

The spatial distribution of coffee shrimp, sand-perch, flounder, and discards per season were modelled using hierarchical generalised additive models (HGAMs) using the R package mgcv (Wood, 2011). HGAMs were used to account for the potential operational or behavioural differences between skippers. We considered longitude, latitude, season, time of day, depth, vessel, and moon phase as potential explanatory variables. The response variable CPUA (ton.km^{-2}) was assumed to follow a Tweedie distribution with log link and was chosen as it can uniformly deal with zero-catch data (Shono, 2008). The moon phase during each haul was estimated using the package "lunar" in R (Lazaridis, 2014), which returns values between 0 (referring to new moon) to $3\pi/2$, which refers to the last quarter.

The complexity of the space-time interaction was tested by comparing three different structures. Either a space only model (not including season), or an additive (2D) space-time effect was modelled where the spatial pattern was fixed but the intensity could change by season or a three-dimensional (3D) space-time effect was modelled, here the spatial pattern could change by season (Sup. Mat, Table S1, e.g. Models cs1, cs2 and cs3, respectively). Space was modelled as a thin plate regression spline with shrinkage to reduce edge effects which might be produced by having unusually high catches in a particular location at a particular time. Season was included as a cubic regression spline, moon phase and hour were added as cyclical factors, and depth was restricted to $k = 8$. Vessel was included as an unstructured random effect as recommended by (Pedersen et al., 2019).

Smoothing parameter selection was performed by restricted maximum likelihood (REML) (Wood, 2011). Model selection was based on Akaike's Information Criterion (AIC) and started with the full model and checked for possible simplification. Normality of residuals and homogeneity of variance were assessed visually with Q-Q and Residuals vs Fitted plots. Autocorrelation function plots (acf in R) were used to assess temporal autocorrelation. To assess for spatial autocorrelation, we carried out a residual analysis, modelling the residuals as a function of time and space using HGAM. When there is little spatial autocorrelation the resulting spatial contour plots of residuals should reflect very little structure and the effective degrees of freedom should be small. Prediction surfaces were generated with a resolution of 1 km^2 and restricted to the area that was covered by the fishers per season.

2.2. Estimating revenue

For each grid cell in each season, the predicted CPUA (ton.km^{-2}) was used to estimate the predicted revenue from selling the commercial catch. Monthly prices for each of the three commercial species were obtained from (IMARPE, 2020) and averaged to provide an estimate per season (Sup. Mat. Table S2). The predicted total revenue for coffee shrimp, sand-perch and flounder was added for each grid cell. Differences between the different moon phases and predicted revenues were evaluated using a Kruskal-Wallis test, which is recommended when the assumptions required conduct an ANOVA test are not met. Comparisons between each moon phase were conducted using a Wilcoxon rank sum test.

3. Results

The best models (lower AIC values) for all response variables (coffee shrimp CPUA, sand-perch CPUA, flounder CPUA and discards CPUA) always included an interaction between space and season. In summer, the number of trips was reduced due to an increase in navy surveillance activities which limited the areas that fishers could go to.

3.1. Coffee shrimp CPUA

The best model to explain the variability in coffee shrimp CPUA included a 3D space and season interaction and random effect of vessel that explained 51.1 % of the total variance in catches (Sup. Mat., Table S1). In general, higher CPUA are predicted in spring and summer. The predicted spatial distribution of coffee shrimp shows higher CPUA in the southern and northern parts of the study area in autumn, and in the northern parts in winter, while in spring and summer the hotspots are predicted closer to the shore, and in northern parts (Fig. 1).

3.2. Main commercial bycatch species CPUA

The best models to explain the variability in sand-perch and flounder CPUA included a 3D interaction of space and season, vessel and moon phase, which explained 74.9 % and 52.1 % of the total variance in catches, respectively (Sup. Mat., Table S1). For both species, higher CPUA were predicted in autumn and winter (Fig. 2a, b). The predicted spatial distribution of sand-perch and flounder showed a more uniform pattern and a higher CPUA in the whole study area in autumn and winter, compared to spring and summer, when higher values were predicted further from shore and low catches close to shore (Fig. 2a, b). For both species, higher CPUA were predicted when the moon was on its third quarter (Fig. 2c, d).

3.3. Discards CPUA

The best model for discards CPUA included an interaction between space and season, vessel, moon phase and time of the day, which explained 58.6 % of the total variance (Sup. Mat. Table S1). The highest CPUAs were estimated for autumn. In general, higher discard CPUAs were predicted to the north of the study area, and further offshore from the coast (Fig. 3a). Higher CPUAs were predicted when the moon was on its first and third quarter (Fig. 3b). Mean predicted discard CPUA decreased with time of day, with highest predicted CPUA occurring at 7 pm and the lowest at 7 am (Fig. 3c).

3.4. Revenue

The predicted revenue obtained from the three commercial species varied between moon phase ($F=8.392$, $df=3$, $p < 0.001$), with highest revenues predicted during the third quarter (~2600 US dollars compared to ~2300 in the other moon phases, Fig. 4). In autumn, the highest revenues were obtained in the southern parts of the study area, while during all other seasons, highest revenues were predicted in the northern areas (Fig. 5).

4. Discussion

In this study, we first assess which factors affect CPUA of coffee shrimp and the two main bycatch commercial species (sand-perch and flounder) and the amount of discards (fish and invertebrates). We show that an interaction between space and time (season) affects the CPUA of all these catch components and that moon phase affects commercial species CPUA and discards CPUA in a different manner. We then predicted the combined revenue generated from the three commercial species for each season and location. Unfortunately, data on the cost structure for each vessel on a trip basis was not collected, which precluded our ability to evaluate profit, which is a more appropriate economic indicator to evaluate the fishery (D'Andrea et al., 2020). However, we provide for the first time, spatio-temporal estimations of revenue which is a good proxy to evaluate the economic importance of the fishery at the finest scale.

In general, discards are greater in the northern part of the region and towards the deeper areas, while revenue varies according to the season. For spatio-temporal management purposes, we suggest a division of the study area into north and south of Los Órganos (see Fig. 1). During autumn, the highest revenue is estimated in the south, while highest discards are estimated in the north. Therefore, we suggest limiting

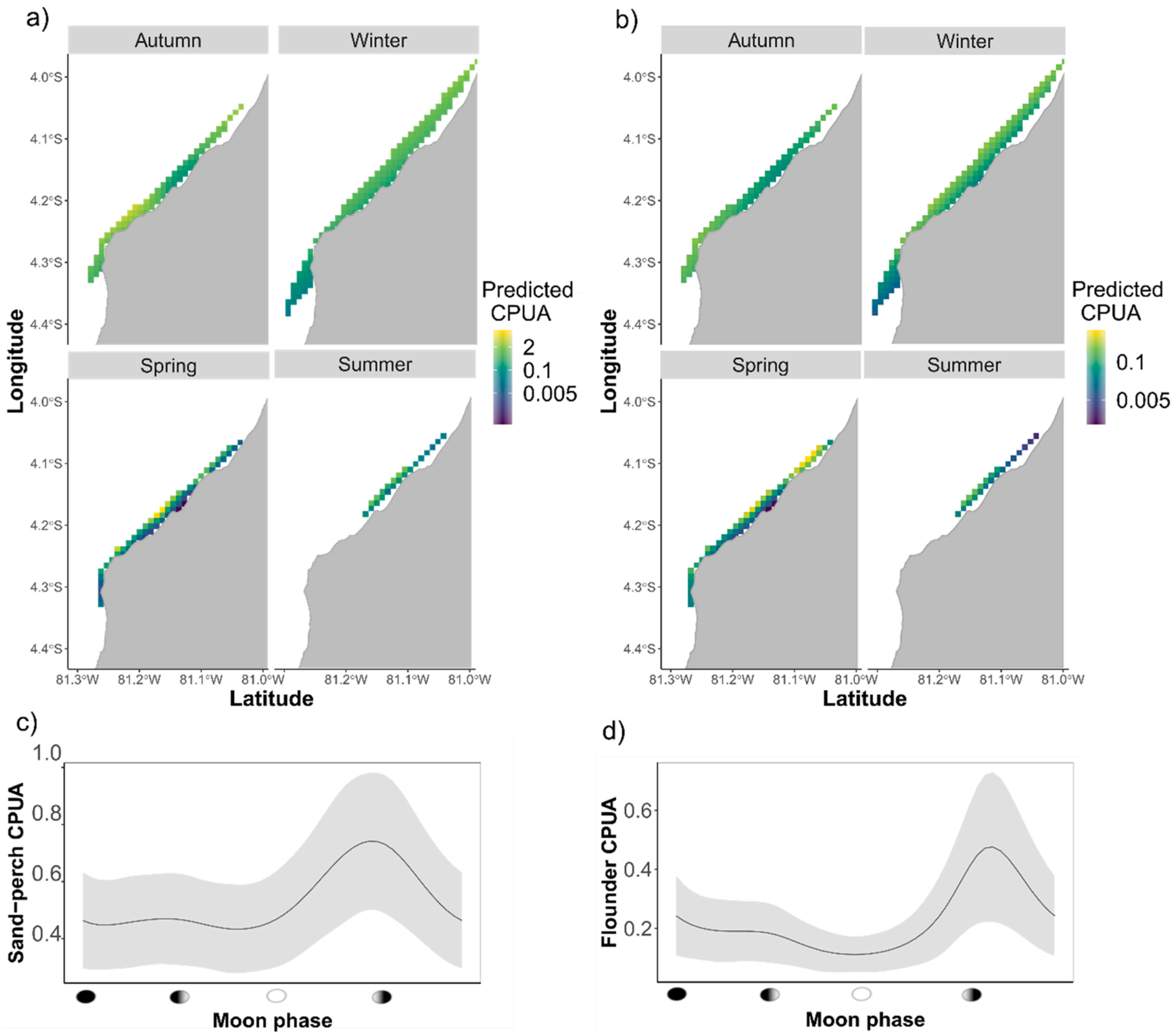

Fig. 2. Predicted spatio-temporal distribution of a) sand-perch CPUA (ton.km^{-2}), b) flounder CPUA (ton.km^{-2}) in Los Órganos, Peru; c) predicted effect of moon phase on sand-perch CPUA, d) predicted effect of moon phase on flounder CPUA. Moon phases (from left to right: new moon, first quarter, full moon, third quarter).

fishing in the north during this season. For all other seasons, highest estimated revenue areas overlap with highest discard areas, thus we suggest that specific temporal management recommendations (explained below) are put in place for these seasons to minimise the potential negative economic impact to fishers.

The main discarded species in this study were fishes such as the Pacific drum (*Larimus pacificus*) and lumptail searobin (*Prionotus stephanophrys*), and crustaceans such as the swimming crab (*Portunus stephanophrys*), daisy midshipman (*Porichthys margaritatus*), and the crab *(Hepatus kossmanni*) (Mendo et al., 2022a). Lunar periodicity has been shown for several species, albeit high inter-species variability exists (Branco-Nunes et al., 2021; Ferreira et al., 2017; Fraser, 1997; Griffiths, 1999; Johnston et al., 2021; Pennino et al., 2014; Samanta et al., 2018). While no previous study could be found that assesses the relationship between the lunar cycle and the main species discarded in this study, (Salini et al., 2001) assessed the effect of lunar periodicity on 26 other species caught using trawl nets in Australia. Two main patterns were found for different fish assemblages: one showing a distinct peak in mean catch rates during the first quarter moon, and another shoring a last-quarter peak. These findings agree with those presented in this study.

A direction to maintain revenue and minimise discards could rely on the promotion of fishing activities during new and full moon. As these shrimp fishers work an average of 21 days a month (Mendo et al., 2020), they could adapt their days off to the first and third quarter moons (i.e., when the maximum discards occur). Nevertheless, the third-quarter moon week shows higher sand perch and flounder catches per unit area, thus fishers may not be incentivised to voluntary stop fishing during that time. A more realistic approach could include self-imposed temporal closures only during the week of the first quarter of the moon phase. Whilst piloting this recommendation it would be important to continue assessing their effectiveness (i.e. reducing discards without negatively affecting revenue) and monitoring the ability/practicality of fishers to adapt to a new monthly schedule. It is important to note that this temporal management measure would not reduce monthly fishing effort (days spent fishing each month) but would require changes working patterns.

Another temporal management recommendation could be to alter the time (hour) of fishing operations. Discards as a function of CPUA were higher at the beginning of the fishing trip while shrimp and commercial species CPUA were not affected by time of day. This would suggest that starting fishing activities later could decrease levels of discards. However, as fishers tend to trawl in the same areas during a fishing trip, it is not clear whether reduced discards are related to time of day or an artifact of disturbance caused by earlier trawling activity.

The current study only evaluated spatio-temporal changes from April

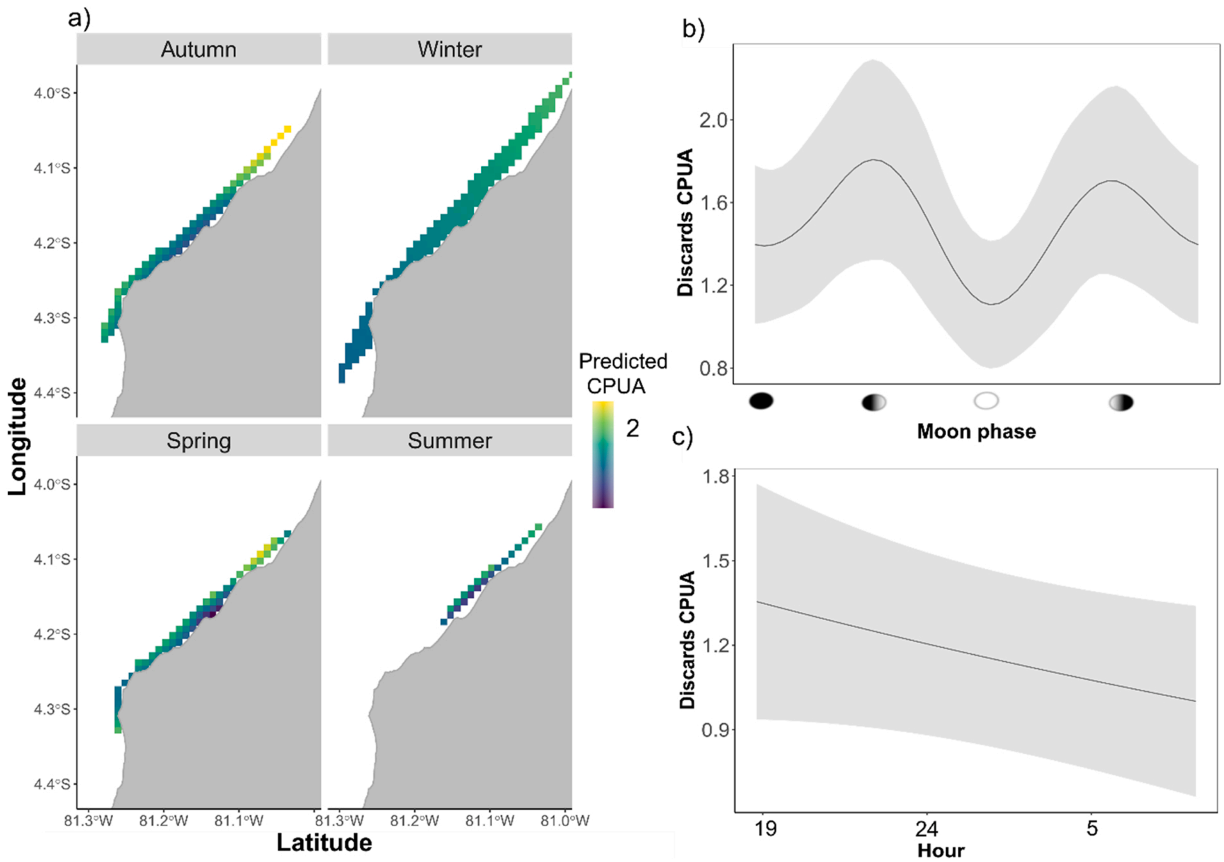

Fig. 3. Predicted spatio-temporal distribution of a) discards CPUA (ton.km^{-2}) in Los Órganos, Peru, b) predicted effect of moon phase on discards CPUA, c) predicted effect of time of the day on discards CPUA. Moon phases (from left to right: new moon, first quarter, full moon, third quarter).

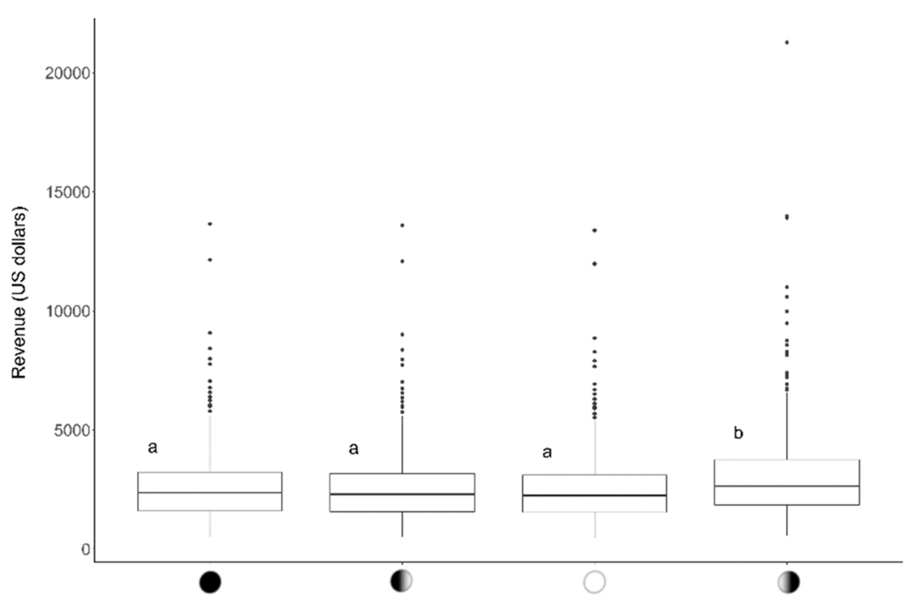

Fig. 4. Predicted revenue (in US dollars) and moon phase. Moon phases (from left to right: new moon, first quarter, full moon, third quarter). Different letters above boxes indicate significant differences between moon phases.

2019–March 2020. Long-term information is needed to assess if these trends persist over time. As the collection of these data is expensive and requires significant on-board observer effort, a simplified approach, using fisher-led reporting through mobile Apps to collect information could be used (Mendo et al., 2022b). Spatio-temporal information on catch and bycatch can be obtained from fisher led data collection with high levels of agreement with on-board observer records (Mendo et al., 2022b), which would facilitate an adaptive management strategy for this fishery.

The lucrative nature of this illegal activity, coupled to institutional weaknesses such as the absence of co-management, corruption and weak monitoring, control and surveillance systems suggests that it will persist.

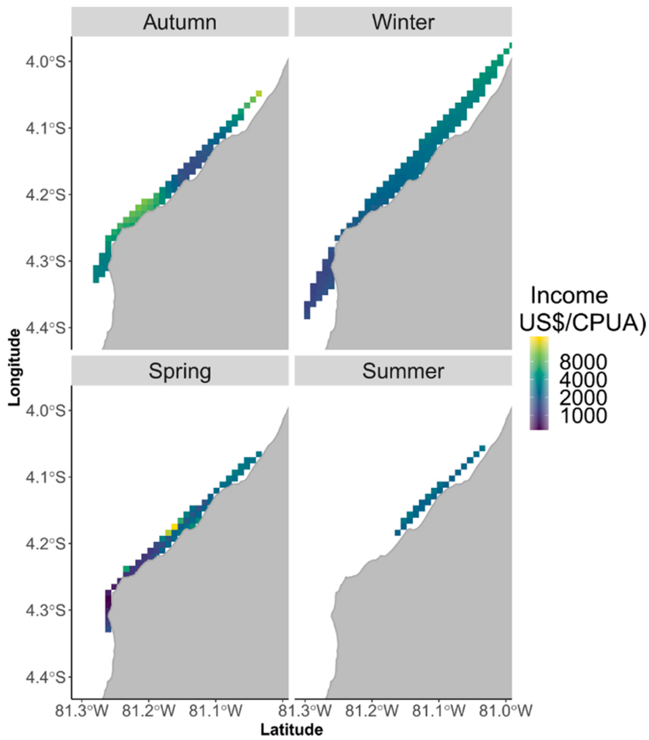

Fig. 5. Predicted revenue for the three commercial species in Los Órganos, Peru for each season.

Due to this reality, we suggest that the only realistic approach to reduce the fishery's environmental impacts in the short term, is to foster the willingness of fishers to adopt more responsible fishing practices. This, of itself, provides a foundation on which to build trust between fishers and those charged with regulating Peru's coastal waters to find co-management solutions for this complex environmental and socio-economic problem. Researchers will continue to play a crucial role in providing objective evidence and finding technical solutions that 1) may allow fishers to either catch shrimp outside 5NM where trawling is allowed, or 2) to only use gears authorized by law within 5NM, or, as a more controversial option, 3) to permit trawling within 5NM but in a way that reduces to acceptable levels its impact on other fishing activities and the ecosystem. The latter will require regulatory changes, supported by objective evidence and should be part of a co-management arrangement founded upon the participation of fishers involved in illegal trawling together with other small-scale fishing communities that perceive that the illegal trawling (as it currently works) impacts materially and economically their own fishing activities. To support option 3, a modified trawling net has been developed with fishers which reduces discard levels by 50 % (Travezaño et al., in prep). A mandatory requirement to use this net combined with robust data collection and the assessment of the implementation of the spatio-temporal measures recommended in this paper, could be used to inform co-management discussions.

Unless there is an incentive for the illegal shrimp fishery to change and the legal framework continues to preclude, but fails to effectively police and prevent, trawling within 5NM, this practice will continue. In this instance, those involved in the illegal fishery have proactively sought to find ways of mitigating the impacts of their trawling and collect data to help inform co-management should this become an option. If the illegal fishers see no potential for such measures to be recognised and accepted as part of formalising and legitimising their fishing activities, it will be challenging to maintain their interest in collecting data or implementing voluntary management recommendations to mitigate and reduce their economic and environmental impacts. Pragmatically, if this fishery and similar fisheries globally are not policed to prevent trawling within specified limits, establishing co-management frameworks and incentives that encourage and facilitate compliance with fishing practices that are less environmentally damaging and socially and economically divisive may need be considered in the short-term, even if they are legally and politically unpalatable.

CRediT authorship contribution statement

Conceptualization: **Tania Mendo, Jaime Mendo, Mark James**, and **Janneke Ransijn**. First draft: **Tania Mendo**. Writing - review & editing - all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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.

Data Availability

The data that has been used is confidential.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2023.106623.

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