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Identifying hotspots for spatial management of the Indonesian deep-slope demersal fishery

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Abstract

The Indonesian deep-slope demersal fishery targets mostly snappers and groupers and is vital for the wellbeing of millions of people. More than 100 species are captured at depths of 50–500 m along shelves and seamounts using mostly droplines and bottom longlines. The main target species are *Pristipomoides multidens*, *Pristipomoides filamentosus*, *Pristipomoides typus*, *Atrobucca brevis*, *Epinephelus areolatus*, and *Lutjanus malabaricus*. The fleet in this fishery is predominantly unlicensed small-scale (1–10 gross ton) vessels. The fishery is unmanaged and lacks data that would allow policymakers to formulate sustainable management strategies. Here, we use fisheries-dependent data on catch composition, as well as fishing location and gear type, to determine factors that dictate catch composition and catches containing high proportions of immature fishes. Results indicate that immature fish assemblages are caught in particular locations, or "hotspots," through a combination of fishing gear and habitat characteristics. The important "hotspots" occurred in the Java Sea-Makassar Strait area. Only 2.4% of marine protected areas (MPAs) were located within "hotspots." Our findings highlight places of high conservation priority, such as the Java Sea, where expansion of current MPAs would greatly benefit the deep-slope demersal fishery in Indonesia by reducing immature catches, thus identifying a preexisting management that is appropriate for the sustainability of this fishery. The modeling methods we developed are transferable to other fisheries that lack data on fish abundance in order to prioritize management and conservation.

KEYWORDS

data-poor fishery, demersal, Indonesian fishery, juvenile hotspot, marine protected areas, ontogenetic habitat shift, snapper fishery, spatial distribution, spatial management

1 | INTRODUCTION

The Indonesian deep-slope demersal fishery targets species of snappers and groupers at depths greater than 50 m across the entire archipelago (Wibisono, Mous, & Humphries, 2019). This fishery is economically important with a retail value of 500 million USD, positioning Indonesia as the world's second largest snapper and grouper exporter (Cawthorn & Mariani, 2017; Kearns, 2019). While more than 100 species are landed in this fishery, 75% of the catch consists of *Pristipomoides multidens*, *Pristipomoides filamentosus*, *Pristipomoides typus*, *Atrobucca brevis*, *Epinephelus areolatus*, and *Lutjanus malabaricus* (Wibisono et al., 2019). Like most deeper water fishes, these species have slow growth rates and later maturity, making them particularly vulnerable to over-exploitation (Haight, Kobayashi, & Kawamoto, 1993; Newman et al., 2016). To add to the overexploitation risk, a lot of smaller immature fish are caught to fulfill the market preference for "plate-sized" fish (Kindsvater, Reynolds, Sadovy de Mitcheson, & Mangel, 2017; Mous, Gede, & Pet, 2020). Most vessels in this fishery use droplines, longlines, or both concurrently (mix-gears). There is a wide range of vessel sizes, from small canoes to large commercial boats >100 gross ton (GT). However, based on the national fleet survey, 97% of fishers are unlicensed and considered small-scale (<10 GT).

Management of the deep-slope demersal fishery is based on the total allowable catch (TAC) per species group (e.g., TAC for "snappers"). The TAC limits the number of fishing licenses per fishery management area (FMA); however, it has data and implementation challenges rendering the fishery practically unmanaged. Unlicensed small-scale fishers are unregulated and will require a lot more changes in the current regulatory framework to manage. These gaps in the licensing system, variety in vessel sizes, combined with a wide geographical range of fishing grounds and landing sites, make it difficult to monitor, assess, and manage the fishery.

As an initial step toward sustainable management, fisheries scientists typically conduct stock assessments to set fishing limits by utilizing catch and abundance data. In the absence of abundance data, a length-based approach that uses life-history parameters can be a viable decision-making tool that is cost-effective and reliable (Hilborn & Ovando, 2014; Hordyk, Ono, Sainsbury, Loneragan, & Prince, 2015). Fish lengths in the catch, relative to important life-history parameters such as length at 50% maturity (L_{mat}), may highlight fishery trends (Froese, 2004). For example, a fishery with more fish caught at a size $< L_{\mathrm{mat}}$ could lead to growth overfishing, or at-worst, indicate overfishing that leads to truncation of size-classes (Barnett, Branch, Ranasinghe, & Essington, 2017; Berkeley, Hixon, Larson, & Love, 2004). In this fishery, assessments using life-history parameters indicated high risk of overfishing (Mous et al., 2020). Thus, in the absence of target or limit reference points, limiting the number of fish caught $< L_{\mathrm{mat}}$ is a viable first step toward managing the deep-slope demersal fishery, especially, because this fishery rarely exploits mega-spawners.

Avoiding the exploitation of immature individuals requires an understanding of contributing factors to catch composition, such as the spatial distribution of nurseries. Many juvenile fish populations utilize certain habitat types (e.g., for protection against predation), and undergo ontogenetic habitat shifts as they mature (Misa, Drazen, Kelley, & Moriwake, 2013; Moore, Drazen, Radford, Kelley, & Newman, 2016; Oyafuso, Drazen, Moore, & Franklin, 2017). For example, juvenile *P. filamentosus* prefer low sloping soft-substrates at shallower depths (60–100 m) before moving to deeper hard-substrate habitats (90–210 m) as adults (Misa et al., 2013; Moffitt & Parrish, 1996). *L. malabaricus* are often found in silty, shallow areas (<10 m) or sea-grass beds as juveniles (Fry et al., 2009; Newman & Dunk, 2002). Then, as adults, they move to deeper areas (>140 m) and are more typically associated with flat bottom areas (Newman, 2002). These ontogenetic habitat shifts can thus lead to segregation between immature and mature populations, which are best managed using spatial approaches such as marine protected areas (MPAs) (Holland & Brazee, 1996).

MPAs in Indonesia can be a viable tool to manage small, unlicensed fishing vessels like those found in this fishery. MPAs, when enforced, can increase fisheries yields especially where overfishing is rampant (Carvalho et al., 2019; Di Lorenzo, Claudet, & Guidetti, 2016). In Indonesia, MPAs are part of the national target to achieve 200,000 km^2 of protected areas by 2020. Even though Indonesia has fulfilled 96% of this target (191,400 km^2), the criteria for MPA establishment and prioritization has been primarily focused on conserving coral reefs and coastal habitats (Newman, 2002). By directing more attention toward identifying areas where juvenile populations of commercially important fishes are abundant, MPAs across Indonesia could be a precursor to the sustainability of the fishery.

This study seeks to combine the best-available data on the stocks of the deep-slope demersal fishery in Indonesia to identify and prioritize areas for conservation and management of the six dominant species in this fishery (*P. multidens*, *P. filamentosus*, *P. typus*, *A. brevis*, *E. areolatus*, and *L. malabaricus)*. We aim to identify fishing and environmental variables that lead to different catch assemblages and high proportions of immature fish in the catch. This information can be directly used by policymakers to decide where to designate the remaining 9,600 km^2 of MPAs in Indonesia. Our modeling method is also transferable to other data-poor fisheries where abundance data is lacking.

2 | METHODS

2.1 | Data collection

The study area spans all of the 11 FMAs within the Indonesian Exclusive Economic Zone (Figure 1). The FMAs are defined marine boundaries with similar bathymetry within each area. The bathymetry of FMAs 573, 713, 714, 715, 716, and 717 are characterized by mostly narrow coastal shelves, seamounts, and deep trenches (>1,500 m). The bathymetry of FMAs 571, 711,712, and 718 are mostly comprised of shallow waters (50 m depth).

Catch and fishing variables data were collected from 384 vessels (dropline = 230, longline = 97, mix-gears = 57), which represented 6, 14, and 8% of the total vessels in the deep-slope demersal fishery from October 2015 to January 2020 (5,457 fishing trips). The Nature Conservancy Indonesia developed a crew-operated data recording system (CODRS), which collected data using initial interviews, photographs of catch, and GPS trackers (Wibisono et al., 2019). CODRS depended on the voluntary participation of fishers; therefore, the CODRS dataset was not exactly proportional to the distribution of fishing gears in each FMA (Wibisono et al., 2019). To compensate fishers for the work and to ensure data quality, we provided stipends proportional to the vessel size. During the initial interview for CODRS deployment, research technicians collected fishing information such as vessel size estimates (GT) and fishing gear types. When fishers are out at sea, they take photographs of their catch on a measuring board. Research technicians then use the photographs to identify the species, measure the fish length, and record fishing dates.

Fishing gear designation for each vessel was done during the initial interview. Three major types of fishing gears were utilized in the fishery: dropline (*n* = 3,496), longline (*n* = 675), and mix-gears (*n* = 658) (Table S1). Mix-gear fishers typically drop lines in addition to static fishing gears (i.e., longlines). From the CODRS data, we focused on the six dominant species in the fishery which make up ~75% of the total catch: *Lutjanus malabaricus* (*n* = 428,501), *Pristipomoides multidens* (*n* = 322,596), *Atrobucca brevis* (*n* = 270,264), *Epinephelus areolatus* (*n* = 180,870), *Pristipomoides typus* (*n* = 174,773), and *Pristipomoides filamentosus* (*n* = 62,153) (Table S2; Figure S1).

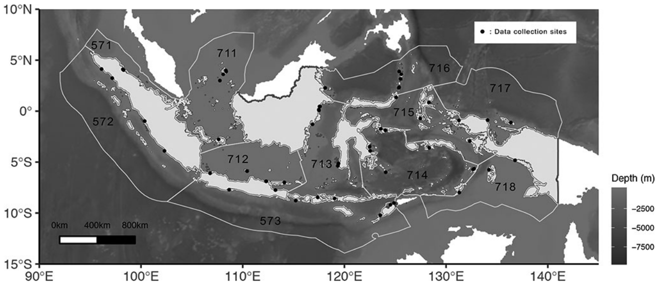
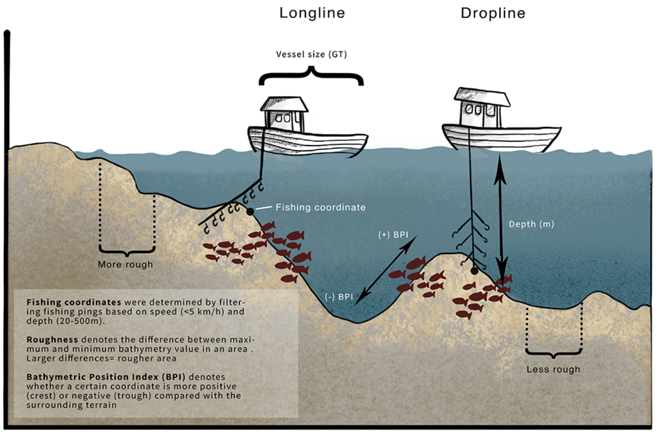


FIGURE 1 Crew-operated data recording system (CODRS) deployment sites in Indonesia. Each number represents a fishery management area (FMA). Sampling sites are ports represented by dots, illustrating the geographic spread of the data collection system

Vessel coordinates were recorded hourly by the GPS trackers on each CODRS vessel. To identify fishing coordinates, we filtered the coordinates based on speed (<5 km/hr) and depth (>20 m and <500 m). Each fishing coordinate is denoted as a fishing event. To match the fishing event with the species caught, we paired the fishing coordinates with the date on the fish photographs. Totally 1,782 out of 8,077 fishing events (22%) had exact date matches. For fishing trips with at least one matching fishing event, we used the matching fishing coordinates as the coordinates of the catch from the fishing trip. For the remaining fishing trips, we used mean latitude and longitude of the vessel's fishing coordinates.

Environmental variables such as depth, roughness, and Bathymetric Position Index (BPI) were obtained using the General Bathymetric Chart of the Oceans (GEBCO)'s (GEBCO, 2014) 30 arc-second interval grid (Figure 2). We calculated roughness and BPI using the "raster" package in R with an eight-cell neighborhood (Hijmans, 2020). Roughness quantifies the difference in maximum and minimum depth within a region (eight-cell neighborhood) (Wilson, O'Connell, Brown, Guinan, & Grehan, 2007). BPI provides an indication of whether a fishing location was on a positive (e.g., crest) or negative (e.g., trough) feature compared to its surrounding areas (Wilson et al., 2007). BPI and roughness represented a focal mean analysis on bathymetry and slope, or



Fishing coordinates were determined by filtering fishing pings based on speed (<5 km/h) and depth (20-500m).

Roughness denotes the difference between maximum and minimum bathymetry value in an area . Larger differences= rougher area

Bathymetric Position Index (BPI) denotes whether a certain coordinate is more positive (crest) or negative (trough) compared with the surrounding terrain

FIGURE 2 Depiction of the different fishing and environmental predictors that were used in the canonical correspondence analysis and the generalized additive model to determine where juvenile "hotspots" occur in the deep-slope demersal fishery of Indonesia indicators of habitat complexity that have been used to characterize essential fish habitat (Howell, Holt, Endrino, & Stewart, 2011).

2.2 | Catch composition

We used fishing gear and fishing ground characteristics as covariates to explore differences in the catch composition. We conducted a canonical correspondence analysis (CCA) by presenting combinations of the explanatory variables (fishing gear, vessel size, fishing coordinates, depth, roughness, and BPI) as linear axes. Other environmental factors, such as sea surface temperature and primary productivity were not considered because the fishes in this fishery are not as sensitive to these as they are to habitat characteristics (Oyafuso et al., 2017). The CCA was conducted using the "vegan" package in R (Oksanen et al., 2019).

2.3 | Model creation

To determine what fishing and environmental factors best describe the amount of mature fish in the total catch per day, we constructed a generalized additive model (GAM). Our GAM included a binomial distribution and a logit-link function to model the response variable (the ratio of the number of fish $\geq L_{\mathrm{mat}}$ of a species in a catch to the total number of fish in the catch) and account for the spatial autocorrelation of fishing ground coordinates. Using a ratio as the response variable was necessary to set an upper bound of the total number of mature fish that are caught in this fishery.

We chose fishing and environmental predictors that may impact species distribution based on the literature. Different fishing gears operate at different habitats and depth ranges (Mous et al., 2020). Vessel sizes also impact the travel distance, number of set lines, fishing depth, and fish storage capacity, and may impact target species and size. Year was incorporated as a predictor to capture annual changes in environmental conditions or exploitation rates. In addition to fishing coordinates and depth, we included roughness and BPI to quantify structural complexity in habitats, which affect species distribution particularly for demersal species like snappers and groupers (Oyafuso et al., 2017). The GAM was constructed using the following equation:

$$g(\mu)=\beta_0+\beta_1\cdot\text{fishing gear}+\beta_2\cdot\text{vessel size}+\beta_3\cdot\text{year}+\beta_4\cdot\text{roughness}+\beta_5\cdot\text{BPI}+s(\text{longitude},\text{latitude})+\beta_6\cdot\text{depth}+\beta_7\cdot\text{species}_i$$

where g is the link function, μ is the expected ratio between total mature fish of species_i in catch_j and total fish of species_i in catch_j, β_0 is the intercept, β_k is the kth explanatory variable, and s is a smoothing function for the interaction between the latitude and longitude variable.

To create a "training" and "testing" dataset we randomly assigned half of the CODRS dataset to each. The GAM was developed in R using the "mgcv" package using the "sos" smoother for the latitude- longitude interaction term (Wood, 2017). Model accuracy was tested by calculating the root mean square error (RMSE) on the predicted catches based on the "testing" dataset.

2.4 | Model simulation

To simulate the number of mature catches across the Indonesian EEZ, we designated a 0.1° grid as fishing coordinates. Depth, roughness, and BPI were interpolated for each fishing coordinate. We assigned fishing gear and vessel sizes to each coordinate based on the ratio of vessel sizes per fishing gear per FMA in the national fleet survey (Table S1). This ratio constraint was based on the assumption that the distribution of fishing gears are not random and limited by the physical features of the ocean floor, the traditional fishing gear used in the area, and/or access to the fishing gear technology. Fish species were sampled randomly from a uniform distribution. We set the year to 2020 and the total catch at 100 fish for each vessel before running the simulation.

To determine "hotspots," or areas that led to high incidence of immature fishes in a catch, we filtered the simulated fishing coordinates for catches containing >75% immature fish. We chose this value to delineate areas where the majority of the catch was immature. To delineate "hotspot" boundaries, we created a density object through univariate density estimation with Gaussian kernels and converted the objects into polygons. Last, we overlapped pre-existing MPA boundaries on the hotspot boundaries to calculate the total area of overlap and percentage of "hotspots" that are within pre-existing MPAs (MPAtlas, 2020). These "hotspots" were visualized using the 2D kernel density estimator in R using the "ggplot2" package (Wickham, 2016).

3 | RESULTS

3.1 | Catch characteristics

Catch assemblages were distinct among the three fishing gears (Figure 3). Differences in catch assemblages were driven by differences in the dominant species in the catch, which differed based on fishing and environmental predictors. Dropline catches were associated with high

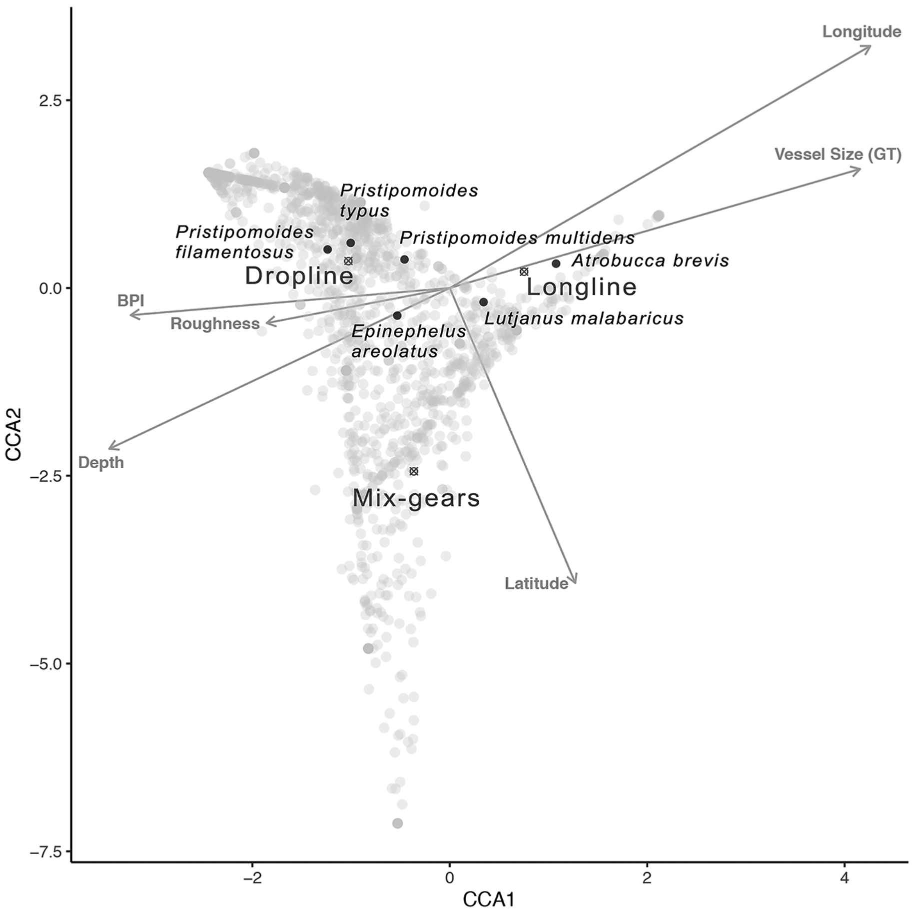


FIGURE 3 Canonical correspondence analysis (CCA) of the catch in the deep-slope snapper grouper fishery in Indonesia. Each grey point represents one catch ($n = 6{,}299$). Distance between catches on the plot represents the similarity of species assemblages. Each black point represents one species. Arrows represented the continuous predictors, and arrow length represented the significance of the variable as a predictor. Each crossed circle represented the categorical predictor (fishing gear)

Prisipomoides typus and *Pristipomoides filamentosus* abundance. Compared to the other four main species in this deep-slope demersal fishery, *P. typus* and *P. filamentosus* were found in the deepest waters with intermediate structural complexity (roughness and BPI). *Pristipomoides multidens* was also associated with dropline catches but more abundant in shallower habitats with less structural complexity. Longline catches were characterized by a high prevalence of *Atrobucca brevis* and to a lesser extent, *Lutjanus malabaricus*. *A. brevis* occurred almost exclusively in longline catches from large vessels fishing in eastern Indonesia. *A. brevis* fishing ground habitats comprised shallow areas with low structural complexity (i.e., Arafura Sea). *L. malabaricus* were caught in similar habitats as *A. brevis* but in central Indonesia. *Epinephelus areolatus* was associated with both dropline and longline catches, and to a lesser extent mix-gear catches. A high abundance of *E. areolatus* was caught by small vessels operating in western-central Indonesia at areas with intermediate structural complexity. Despite high catch rates of *L. malabaricus* and *E. areolatus* in mix-gears (Table S2), *L. malabaricus* and *E. areolatus* were more closely associated with longline or dropline catches due to larger abundances of those two species in longline and dropline catches.

3.2 | Modeling the proportion of mature fish in the catch

Based on the different species assemblages by fishing gear, we tested the effects of a combination of fishing and environmental factors on the proportion of mature fish in a catch by constructing a GAM. We found that all fishing and environmental factors were statistically significant predictors (Table 1). We found that even though all fishing gears were positively correlated with more mature fish, longlines tended to capture the most mature fish in its catch. Fishing in deeper waters, crests (higher BPI), and areas with low roughness leads to higher proportions of mature fish ($p < .001$ for each predictor). Fishing trips that targeted and caught *E. areolatus* ($p < .001$) or *A. brevis* ($p < .001$) had a higher proportion of mature fish in the catch. The combination of predictors explained 77.3% of the variation in the data. Predicting catches using the "testing" dataset resulted in an RMSE (prediction error) of 159 fish. The mean number of fish per catch is 326.

TABLE 1 Generalized additive model coefficient estimates from fitting the proportion of mature fish in a catch to different fishing and environmental variables[a]

	Estimate	*SE*	*z* value	*p*
(intercept)	44.068	9.789	4.502	<.001
Vessel size	0.045	0.010	4.594	<.001
Fishing gear				
Longline	0.946	0.024	39.115	<.001
Mix-gears	0.320	0.040	8.104	<.001
Depth	−0.166	0.011	−14.467	<.001
BPI	0.049	0.018	2.749	<.001
Roughness	−0.084	0.019	−4.350	<.001
Year	−0.021	0.005	−4.369	<.001
Fish species				
Epinephelus areolatus	3.350	0.038	87.523	<.001
Lutjanus malabaricus	−1.458	0.018	−83.109	<.001
Pristipomoides filamentosus	−2.598	0.029	−88.774	<.001
Pristipomoides multidens	−1.925	0.020	−98.237	<.001
Pristipomoides typus	−1.591	0.022	−73.162	<.001

Approximate significance of smooth terms:			
	Edf	Chi-sq	*p*
s (latitude, longitude)	48.92	18,081	<.001
R^2 (adjusted) = 0.786			
Deviance explained = 77.3%			

Abbreviations: BPI, bathymetry position index; edf, estimated degrees of freedom.

[a] We used binomial distribution with a smoothing function on the interaction between latitude and longitude. The intercept denotes the baseline–fishing gear: dropline and fish species: *Atrobucca brevis*.

3.3 | Catch simulation

Using the GAM, we predicted the proportion of mature fish in catches for the Indonesian EEZ across different fishing gears. Simulation results revealed fishing locations, or "hotspots," that led to >75% immature catches (Figure 4; Figure S2). However, these "hotspots" vary in importance for potential fisheries management. For example, low management priorities could be attributed to "hotspots" at the Savu Sea, Arafura Sea coast, Indian Ocean, and FMA 716 and 717 because of their lack of overlap with common fishing grounds (Figure 5). Only the edges of the Savu Sea "hotspot" located on the Indonesian-Australian border and coastal areas are frequently exploited in this fishery (Figure 4). In contrast, the Java Sea – Makassar Strait "hotspot" should be prioritized because of the overlap with common fishing grounds (Figure 4).

By overlaying pre-existing MPA boundaries on juvenile "hotspot" boundaries, we calculated that 2.4% of the hotspots were within existing MPAs (Figure 4). The Savu Sea hotspot has pre-existing MPAs (Savu Sea MPA and Komodo National Park) and represented most of the overlap between the juvenile hotspots and protected areas. While the Java Sea- Makassar Strait hotspot overlapped with several MPAs, each overlap was very small.

4 | DISCUSSION

4.1 | Catch characteristics

Our results highlighted different fishing and environmental parameters that effect catch assemblage and proportions of mature fish. In addition to differences in species assemblages between longlines, droplines, and mix-gears, each fishing gear had differing (positive) associations with mature catches. Longlines, physically constrained by how the gear operates, fish in much shallower areas (between 50 and 150 m) on shelf areas and the top of slopes (Mous et al., 2020). High proportions of mature fish in longline catches could be attributed to the dominant longline species' (*A. brevis*) shallow preferred adult depth. In other shallow habitats where *A. brevis* is not found, longlines caught immature fish. Droplines operate in a wider range of depths (50–500 m) can operate in

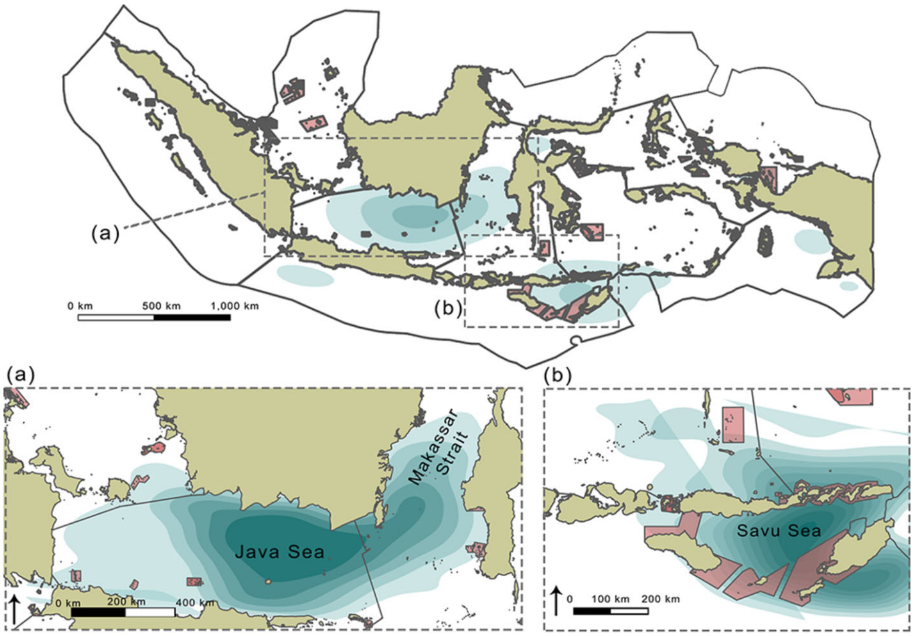


FIGURE 4 Predicted proportion of immature fish in the total catch for the Indonesian EEZ in 2020. Blue shaded areas denote areas with >75% immature fish in the total catch and darker portions represent the greatest probability of catching juvenile fishes; red polygons denote pre-existing MPA boundaries. Inset maps show some of the overlap between pre-existing MPAs in the (a) Java Sea and Makassar Strait and (b) Savu Sea with the immature catch "hotspots." The Savu Sea "hotspot" overlapped with the Savu Sea MPA and Komodo National Park. However, most of the fishing occurs in the Java Sea-Makassar Strait "hotspot"

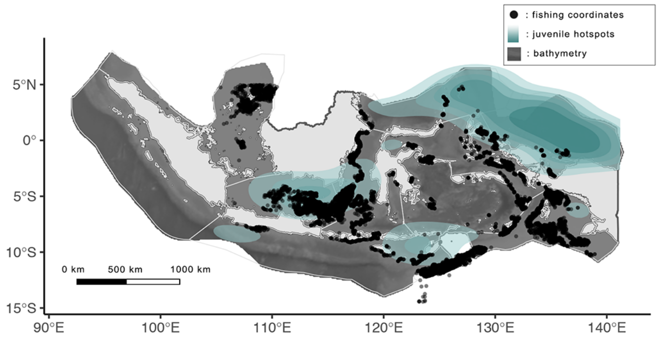


FIGURE 5 Fishing grounds (black dots) superimposed on juvenile "hotspots" of the deep-slope demersal fishery in Indonesia. Some hotspots did not overlap with fishing grounds and therefore have less management importance

deeper waters where mature populations are more likely to be found (Mous et al., 2020). However, when droplines operate in shallower areas, the catches are associated with species that are caught $< L_{\text{mat}}$ (*P. filamentosus*, *P. multidens*, and *P. typus*). Mix-gears (concurrent use of droplines and longlines) operate in shallow shelf areas. Here, our results indicate the usage of multiple gears allows for a broader sampling of the fish assemblage and that fishers are catching individuals from the water column as well as along the benthos (Clement, Pangle, Uzarski, & Murry, 2014; Weaver, Magnuson, & Clayton, 1993).

Based on the catch composition, catching *E. areolatus* and *A. brevis* was positively correlated with more mature fish in the catch. This correlation could be explained by ontogenetic habitat shift (Snover, 2008). *E. areolatus* spends its juvenile life stage in coral reefs and seagrass habitats and migrates to the deeper slopes after maturity (Mous et al., 2020; Nuraini et al., 2007). Thus, because *E. areolatus* only spends its adult phase in deeper demersal habitats, this fishery catches very few juveniles. Very little habitat information is available for *A. brevis*; however, several other Scianids are known to use estuaries as their nursery grounds and migrate to deeper areas (Sasaki, 2001). On the contrary, juvenile habitat and depth ranges for the rest of the dominant species (*P. multidens*, *P. filamentosus*, *L. malabaricus*) overlap with the pre-existing fishing grounds on shallow and flat areas. In the Great Barrier Reef, juvenile *L. malabaricus* is frequently found in headlands or rocky shore habitats (Newman & Williams, 1996). Immature *P. filamentosus* is also found in shallower areas with flat banks, featureless sand, and mudflats, unlike adults, which preferred the 90–210 m depth range (Misa et al., 2013; Moffitt & Parrish, 1996).

The positive correlation of mature fish with BPI and negative correlation with roughness, indicated higher proportions of adult fishes in crests or seamounts with lower roughness. Seamount hydrodynamics can create localized upwellings, enhancing turbulent mixing and eddies, which trap plankton and increase primary productivity in the area (Boehlert & Genin, 1987; Roden, 1987; White, Bashmachnikov, Aristegui, & Martins, 2007). However, BPI and roughness were calculated on a relatively broad-scale due to the low resolution bathymetry data (30-s arc raster). Higher data resolution is necessary to discern fine-scale habitat differences to pinpoint high-priority locations within the "hotspots." In the Hawaiian demersal reef fishery, the correlation between habitat rugosity and species assemblage was only significant when calculated at a 4-m resolution (Wedding, Friedlander, McGranaghan, Yost, & Monaco, 2008). The combination of fishing and environmental factors affecting immature catches suggests that only managing the fishing gear or fishing depth are inadequate.

4.2 | Marine protected areas

Spatial protection of juvenile "hotspots" should be a part of the management of the deep-slope demersal fishery. These areas, determined by catches comprised of >75% juveniles in this study, indicate the presence of nurseries and/or overfishing (Dahlgren et al., 2006)—both are fishery conservation priorities. Without fisheries-independent surveys and data on how much the juvenile "hotspots" actually contribute to the adult populations, we cannot conclude with certainty that the "hotspots" are in fact nurseries (Beck et al., 2001; Dahlgren et al., 2006). However, the reoccurrence and high density of juveniles and the presence of ontogenetic habitat shifts for some species suggest that the areas are still worthy of conservation prioritization (Colloca et al., 2009; Norton et al., 2012).

The degree to which spatial protections benefit juvenile fishes depends largely on the size of the MPA and species' home ranges and dispersal (Hastings & Botsford, 2006). In this deep-slope fishery, most species (except for *P. filamentosus*) have localized ranges and would benefit from even small MPA establishments where their nurseries exist. The stock structure of *P. multidens* shows genetic distinctions in small spatial scales (<500 m) and is sedentary across its different life stages (Ovenden, Salini, O'Connor, & Street, 2004), making it a species that could benefit greatly from MPA protection. There are no genetic distinctions between *P. filamentosus* populations across the Indo-Pacific. However, like other species in this fishery, there are little to no data on home ranges and connectivity between the different life stages.

The juvenile "hotspot" with the highest management priority occurred in the Java Sea- Makassar Strait. Currently, only minimal overlap exists between pre-existing MPAs and the Java Sea – Makassar Strait "hotspot" (0.5 km^2). As one of the most historically exploited fishing grounds in Indonesia, the Java Sea is well-positioned to gain more benefits from MPAs than less exploited areas (Apostolaki, Milner-Gulland, McAllister, & Kirkwood, 2002; Fogarty & Botsford, 2007). Implementation of MPAs in the Java Sea can also act as a feasible solution to regulate small unlicensed vessels and a buffer for drawbacks in current policies that are ineffective in restricting effort. Zoning regulations based on vessel size, for example, may not be effective in protecting the bottom longline fishery in the Java Sea region. Even though 10–30 GT vessels with <10,000 hooks are required to fish 4–12 nautical miles from the coast, because of the shallow bathymetry of the Java Sea, at this distance the juvenile population is still exploited.

However, the current juvenile hotspots are still too broad to establish specific MPAs. To pinpoint specific juvenile nurseries, we need additional research using higher resolution bathymetry data and additional data such as sediment type. Also, the juvenile hotspots are conservative estimates because we might be overestimating *A. brevis* in the catches, which would make fishing grounds more sustainable than the reality. In our catch simulation, we sampled catch species from a uniform distribution. However, CODRS contained a higher proportion of longline catches compared to the national fleet survey thus we may be overstating the importance of *A. brevis* (caught predominantly by longlines in this fishery).

Drawbacks of MPA establishment in Indonesia could stem from low monitoring and enforcing capacity, and effort translocations to other fishing grounds. Successful no-take zones in Indonesia (e.g., shark no-take zones in Raja Ampat) required large monetary resources and good collaboration between stakeholders in the tourism industry, non-governmental organizations, and local communities. A similar monumental effort must be taken to ensure successful MPA establishment for this fishery. To ensure that the MPA does not increase overall fishing effort, other effort controls must be implemented in conjunction with the MPA (e.g., improving the current system to limit fishing licenses for larger vessels).

Our research illustrated the potential of using fishery-dependent data from a data-poor fishery to identify "hotspots" for protection. Especially for fisheries targeting demersal fish that do not undergo vast migrations, our methods could be a powerful tool for managers to highlight priority areas. A similar modeling approach was used in a black sea bass fishery to track spatial dynamics and showed annual and seasonal variability and in-shore and off-shore migration of the target species (Bacheler & Ballenger, 2015). Thus, the use of generalized additive models (GAM) could also be integrated with monitoring efforts to identify unsustainable fishing areas and track the progress of those areas compared to predictions.

While realizing that MPAs alone are not the solution to fisheries management, our results support prioritizing MPA establishment in Indonesia at locations that would help increase the sustainability of the deep-slope demersal fishery. Given the characteristic of the fishery and current management system, MPAs are also more feasible. First, size limits are unfeasible because of high post-release mortality due to the barotrauma that occurs to deep-water fish (Moffitt, 1993). Second, only instituting gear-restrictions, such as limiting mix-gears without any spatial component, may not protect the greatest proportion of immature populations as our results suggest. Another type of gear restriction, changing hook sizes, has been ineffective at changing fish sizes in the Hawaiian deep-slope demersal fishery (Ralston, 1982). Additionally, gear-restrictions can require more sophisticated monitoring and enforcement because small-scale fishers—the majority in this fishery—are spread throughout the Indonesian coastline and may land their catches anywhere. Last, by using a collaborative data collection approach as we have done in this study, policymakers and fishery managers can instill stewardship over the MPA designations and boundaries, thus contributing to better implementation and compliance from fishers (Fauzi & Anggraini Buchary, 2002).

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CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

AUTHOR CONTRIBUTIONS

Elle Wibisono: Led the writing, data analysis, the discussion among co-authors, and the submission and publication of the manuscript. **Gavino Puggioni:** Provided guidance and input on the statistical methods used in this manuscript. **Edwison Firmana**: Reviewed the manuscript and added information on how our findings relate to the current fisheries management systems in Indonesia. **Austin Humphries:** Advised the direction of the study, and reviewed and edited the writing.

ETHICS STATEMENT

The authors are not aware of any ethical issues regarding this work.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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